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Charging infrastructures for electric buses

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Abstract

The rapid urbanization process has had a profound impact on the global environment. It is estimated that 78% of global greenhouse gas emissions originate from cities. And transportation is the main source of urban carbon emissions. At the same time, as the most common means of transportation in urban traffic, public bus system has become an important source of urban air pollution. With the environmental pressure becoming more and more urgent, the development of sustainable vehicles using clean energy has become the key to solve this problem. Under this background, with the decrease of fossil fuel storage and the proposal of energy-saving and emission-reduction strategies around the world, electric vehicles are gradually replacing traditional fossil fuel vehicles into the market, and electric buses are increasingly becoming the development trend of new types of buses. Therefore, the in-depth study of pure electric bus is very important. This paper is divided into three chapters to study pure electric bus.

Chapter1 mainly introduces the research background, research significance, research purpose and related research status at home and abroad.

Chapter2 aims at comparing the performance of different types of pure electric bus with different energy storage system, which have been put into operation in China. Lithium-ion battery bus and super-capacitor

bus are two kinds of pure electric buses which are put into operation at present. Because of the difference of energy storage system, the performance of them are also very different in actual operation.The research content is divided into two parts: First, the charge and discharge experiments of lithium-ion battery and super-capacitor are carried out, and the performance of the two is compared according to the experimental results. Secondly, the real-time energy consumption of two kinds of pure electric buses is studied by analyzing the energy efficiency of each component involved in electric energy transmission. At last, we get the conclusion of their performance.

Chapter3 introduces the fast charging mode of electric bus, in this chapter, the characteristics of lithium-ion battery of pure electric bus are analyzed. Combined with the actual operation data of the charging station, the charging model, charging power model, back to station SOC model and other models of the battery of electric bus are built. Combined with the departure schedule and time-of-use electricity price, finally, a pure electric bus fast charging model with the goal of minimizing the daily charging cost is built. When calculating the daily charging cost of electric bus, the genetic algorithm is used to optimize the model, and finally the optimal solution is obtained, showing the best charging scheme.

Chapter4 introduces the battery switching mode, which starts from

the battery switching demands analysis. The optimization of battery switching mode consists of two sections, i.e. the battery switching sequence optimization and charging optimization. More specifically, the optimization of charging is divided into two stages. In the first stage, the objective function of charging optimization is to minimize the charging cost and obtain the lowest charging cost.In the second stage, under the constraints of the lowest charging cost obtained in the first stage, the final optimal charging control strategy is obtained by smoothing the charging load curve. And finally, the optimal charging scheme is obtained with an example demonstration.

Keywords: pure electric bus; battery; fast charging mode; battery switching mode; charging cost; charging optimization

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Chapter1   Introduction

1.1 Research background

With the increasing shortage of global energy and the continuous deterioration of the natural environment, energy conservation, emission reduction and ecological protection have become two major issues facing the world[1]. Electric vehicles are the best means of transportation to achieve energy conservation, consumption reduction and environmental protection, and also one of the breakthrough points to adjust energy structure and cope with environmental degradation[2]. With the strong support and promotion of the state, China's electric vehicle industry has entered a period of rapid development. The ‘12th Five Year Plan for the development of electric vehicle science and Technology’ issued by the Ministry of Science and Technology in March 2012 points out that: in 2010-2015, electric vehicles are experimentally operated in buses and taxis; in 2016-2020, large-scale operation of electric vehicles is realized in buses and taxis. In 2015, the Ministry of Transport issued the ‘implementation opinions on accelerating the promotion and application of new energy vehicles in the transportation industry’, which pointed out that by 2020, the number of new energy city buses will reach 200000.

Although the large-scale operation of the electric bus plays an important role in improving the urban environment, however, compared with the traditional bus, the electric bus still has the following problems: First of all, due to the limitation of battery capacity, the single charging range of the electric bus is shorter, so the frequency of energy supply is higher, and it needs to go to a special electric bus charging station. It affects the reliability and scheduling flexibility of electric buses. Secondly, electric buses generally need special charging and battery changing facilities to supply electric energy, which increases the cost of supporting construction. Thirdly, the disordered large-scale charging of electric buses may have some impact on the power grid, so the charging scheme of electric buses should not only meet the needs of bus operation, but also consider the cooperation with the power grid[6]. To sum up, compared with the traditional bus, many factors such as the endurance mileage, charging and battery changing time, battery performance and so on should be considered in the charging and operation design of electric bus.

1.2 Research Status at Home and Abroad

1.2.1 Charging optimization of charging station for electric vehicle

The operation of electric vehicle charging station is mainly faced with private electric vehicles. Due to the mutual restriction of different brand types, charging modes, battery capacity, charging demand and operation modes, the optimized charging of electric vehicle charging station has its own characteristics[3]. An electric vehicle charging station is shown in the following figure:

Figure 1-1 electric vehicle charging station

Xu Zhiwei and Hu Zechun set up an optimized mathematical model for orderly charging of electric vehicles in charging station, aiming at maximizing the operating revenue of electric vehicles charging station. By dynamically responding to the time-sharing tariff of the power grid, the optimized ordered charging control method can significantly improve the economic benefits of the charging station of electric vehicles, and has a high calculation efficiency. However, due to the incentive of relatively cheap tariff, orderly charging at night may also result in a large number of electric vehicles charging intensively. Thus another peak of electricity consumption occurs at night[6]. With the development of society and the proposal of national environmental protection concept, the research of electric vehicle charging station has attracted much attention. For small and medium-sized charging stations, Zhang Peiran and others considered the uncertainty of charging behavior of electric vehicles. Based on the real-time interactive data between charging stations and electric vehicles, a controllable charging load model was established. With the goal of maximizing daily operating income of charging stations, minimizing daily user dissatisfaction and smoothing load fluctuation, a Hierarchical Control Architecture was proposed, in which data layer, dynamic ranking layer and optimal control layer are presented. Greedy algorithm and improved genetic algorithm are used to balance and optimize multiple objectives[4].

Foreign CLEMEN-NYNS K, HAESEN E and others compare each electric vehicle to a relatively independent energy consumer, charging unified by the electric vehicle control center real-time control, can effectively reduce the operating loss of the distribution system, reduce charging charges of charging stations and increase the revenue of charging station operators[5]; ROTERING E, ILIC M and others proposed by having sequence control method to reduce the charging cost of electric vehicle users.Besides, they also studied the orderly charging and discharging control method of electric vehicles providing ancillary services. In addition, the orderly charging control strategy of electric vehicles is used to cooperate with new energy sources that can be used to reduce the adverse effect caused by the uncertainties of new energy output and the space-time distribution of electric vehicles charging[7].

Above is the introduction of the research status of the optimization charging of electric vehicle charging station both inside and outside, from which we can learn the theory and method of the optimization charging of electric bus charging station.

1.2.2 Charging optimization of pure electric bus battery switching station

There are some differences between electric bus battery switching station and electric vehicle charging station. The service object of electric bus battery switching station is mainly the battery of electric bus. When the power battery of pure electric bus is insufficient to support normal operation, the battery should be replaced by the battery pack which is full of electricity. Pure electric bus power station still occupies a considerable share of the new energy vehicle supplementary energy market. The power exchange station of an electric bus is shown in the figure:

Figure 1-2 electric bus battery switching station

Based on the current electricity price policy, Zhang Weige and others in China, on the basis of analyzing the waiting time data of the actual backup batteries of the electric bus battery switching station after full charging, and according to the running time of the electric bus in different periods and the average energy consumption in different periods, set up the running time of the whole day in different periods and correction coefficients for different energy consumption. For the purpose of minimizing the daily charging cost and peak-valley difference of pure electric bus, a genetic optimization algorithm is proposed to optimize the starting charging time of standby batteries, so as to achieve the economic operation of pure electric bus battery switching station[8].

On the premise of ensuring the normal operation of pure electric bus, Zhang Di and others set up an economic operation model of electric bus battery switching station with time-sharing price as the guiding factor, and adopt genetic optimization as reference for the arrangements of the start charging time of batteries according to the working condition of variable power charging (CC-CV), to realize the lowest charging cost of electric bus substation throughout the day[9].

On the premise of ensuring the daily operation of pure electric buses, Miaosen and others analyzed and calculated the daily exchange demand of electric buses in pure electric bus battery switching station. Aiming at minimizing the daily charging cost of electric bus battery switching station and reducing the fluctuation of charging load, a dual-objective charging optimization model under peak-shaving and valley-filling theory was established. The genetic algorithm of weight coefficient transformation improves the economy of electric bus substation operation[10].

Since the emergence of new energy vehicles, pure electric bus substation has attracted close attention of scholars at home and abroad. Schneider K, Gerkensmeyer C and others pointed out that some specific charging modes would affect the reliability of distribution network. The reliability of distribution network under different conditions (different permeability, different charging modes) was analyzed[11]. Callaway D S, Caramanis M and others analyzed the cost and time distribution on the pure electric bus and their impact on the load of the power grid with different initial SOC (charging state) according to the driving rules of pure electric bus.

1.2.3 Charging optimization of pure electric bus fast charging station

At present, pure electric vehicles are the most popular green travel tools for energy saving and environmental protection. Under the stimulation of the national policy, the pure electric bus in the new energy automobile industry has a strong driving force. With the further promotion of the fast charging pure electric bus, the State Grid will continue to put into the construction of the fast charging station.

Pure electric bus rapid charging station charges the pure electric bus with a charging gun loaded on the charging pile. The charging capacity reaches 750V/600A, which means that a pure electric bus can be charged quickly in 15~20 minutes. The pure electric bus fast charging station has attracted the attention of many scholars because of its convenient and fast charging, fully satisfying the normal operation, zero emission, green environmental protection and other characteristics. Researchers have carried out extensive research on fast charging station. A fast charging station of electric bus is shown in the figure:

Figure 1-3 pure electric bus charging station

The speed of construction and development of fast charging stations represents the popularity of electric vehicles at a certain level. However, there are some problems such as intermittent charging load in fast charging station, which can be alleviated by fast charging station with energy storage system. Bao Zhiwei and other researchers take this as the research object, adopt appropriate energy management strategy and use energy storage system to optimize the charging load of fast charging station in real time[3]. Aiming at the problem that disorderly charging in the fast charging station of pure electric bus will lead to high charging cost in the charging station, Li Bin and other researchers set up a mathematical model of orderly charging of pure electric bus in the fast charging station of pure electric bus, aiming at minimizing the daily charging cost of the fast charging station of pure electric bus. According to the battery usage information of the pure electric bus in the fast charging station and the electricity demand data predicted by the current departure timetable, under the constraints of satisfying the charging demand of the pure electric bus and no load of distribution transformer, continuous charging process and normal operation of the pure electric bus, the goal of reducing the daily charging cost of the pure electric bus fast charging station is achieved by controlling the on-off of each charger in the fast charging station, charging the pure electric bus in the fast charging station orderly[12].

Li Bin and others put forward the charging optimization strategy of fast charging station for pure electric buses, which simplifies the charging process of battery packs to constant power charging, but there may be errors. In addition, the power consumption of pure electric buses per cycle is defined as the average power consumption of pure electric buses from this departure to the next return station, and there is a certain space for optimization of the pure electric bus fast charging station.

Above is the research status of theory and method of optimizing charging for electric vehicle charging station, pure electric bus battery switching station and pure electric bus fast charging station at home and abroad.

The optimal operation of electric bus battery switching station involves bus operation, battery replacement and battery charging. Considering the operation rule and power consumption characteristics of buses, it is necessary to quantitatively analyze the daily change demand of buses, and then deduce the optimal replacement sequence of batteries based on the principle of balanced use of batteries and favorable battery charging. In order to minimize the charging cost, two-stage and two-objective optimization charging models are established by considering the smooth charging load curve. In addition, it is necessary to analyze the impact of the optimization by considering the optimized charging start time and the number of backup batteries. The simulation results show that the method can effectively reduce the charging cost and the impact of charging load on the power grid.

When the bus power consumption in the mode of battery switching reaches a certain level, it will drive into the battery switching and charging station to replace the batteries. In order to realize the mathematical model of charging and switching optimization, this paper divides the problem into two parts: charging optimization and switching optimization.The mathematical model is easy to solve and realize. It can not only meet the bus power supply, but also improve the impact of a large number of battery charging on the power grid, and improve the economy of electric bus operation.The validity of the proposed method is demonstrated by an example of a charging and switching power station serving two buses with different routes.

Chapter2 Batteries of Pure Electric Bus

According to the main energy storage technology currently used, the lithium-ion battery bus and super-capacitor bus are the two mainstreams of pure electric bus system. So here we focus on comparing the performance of electric bus with these two different power sources.

The main content is divided into the following two parts:

Firstly, the energy storage system of pure electric bus was studied, which is composed of lithium-ion battery or super-capacitor. Lithium titanate battery and double-layer super-capacitor were selected as the research objects. The charging and discharging experiments were designed and completed. The energy efficiency and coulombic efficiency under different discharge conditions were studied.

Secondly, by using the energy consumption estimation model, compared the energy efficiency and total loss of two types of electric buses.

2.1 Introduction of Lithium-ion Battery Electric Bus System

Lithium-ion batteries are the main power source of lithium-ion batteries. Because of the relatively large energy density of the energy storage system, this type of bus can complete the whole operation with a single charge and has a relatively long endurance of more than 100 kilometers. Because the operation mode of this type of electric bus is similar to that of the traditional bus, it does not need to be recharged during operation. At present, there are many successful cases of lithium-ion battery bus in the world.

2.1.1 Application background

In 2005, China established the early bus to power station in Lanzhou for two pilot buses. By the 2010 Shanghai World Expo, the largest pure electric bus power station in China was built to serve 120 pure electric buses. During the 2008 Olympic Games, Beijing built the first domestic battery switching station for commercial vehicles to serve 50 pure electric buses. In 2013, Sihui pure electric bus battery switching station was built. As a supporting facility of Sihui transport hub, the station can handle 160 buses a day, and it is estimated that the annual cumulative carbon emission reduction is about 10800 tons. At present, 64 electric bus battery switching stations have been built in Beijing, with a total capacity of 3000 pure lithium-ion electric buses. In addition, in order to promote the use of electric vehicles throughout the country, in January 2009, the Ministry of science and technology, the Ministry of finance, the national development and Reform Commission, and the Ministry of industry and information technology jointly launched the "ten cities and one thousand vehicles" energy saving and new energy buses application project. It is planned to develop 10 cities every year, and each city will launch 1000 new energy vehicles for demonstration operation. It involves public transport, taxi, municipal administration, public affairs and other fields. On December 9, 2009, the plan expanded the number of pilot cities from 13 to 20.

In foreign countries, in 2004, the French Agency for Environment and Energy Management (ADEME) issued a plan of 100 electric buses, which implemented a subsidy policy of 20% more for the bus operating companies using electric buses than for the companies using ordinary buses. Subsequently, Lyon, Grenoble, Bordeaux and other large and medium-sized cities in France have successively promoted the pilot of small and medium-sized lithium-ion battery bus lines.

The German government actively promotes the development of new energy automobile industry. Since 2012, BYD lithium-ion battery buses have been purchased and introduced, and have been put into operation in Pinneberg, Munich, Bremen and other places near Hamburg.

The first wireless charging electric bus fleet in the UK started trial operation in January 2014 in Milton Keynes, England. The night charging mode of the lithium-ion battery bus is similar to that of the ordinary plug-in lithium-ion battery bus, which is fully charged in the garage. In addition, before and after the operation in the daytime, the bus needs to be charged for 10 minutes at the starting point and the ending point of the route through the inductive charging board embedded in the ground.

2.1.2 Problems to be solved

The initial purpose of promoting lithium-ion battery buses is to reduce carbon emissions and energy consumption. Therefore, in order to quantitatively estimate the impact of this type of bus on the energy conservation and emission reduction target, it is necessary to estimate the real-time energy consumption of the vehicle and the overall energy consumption, so as to understand its energy conservation level.

The energy consumption of vehicles in the actual operation process is influenced by many factors. The running speed, acceleration, road condition and other parameters of the vehicle all affect the real-time energy consumption. In addition, the working condition of each component in the vehicle will lead to different energy utilization, thus changing the overall energy consumption of the vehicle. Therefore, how to accurately estimate the energy consumption of vehicles in actual operation has become an important content of quantitative estimation of energy saving and emission reduction targets of lithium-ion battery buses.

2.2 Introduction of Super-capacitor Electric Bus System

Super-capacitor bus takes super-capacitor as its main power source. Considering the characteristics of fast charging speed and high charging and discharging efficiency of its energy storage system, this bus does not need to undergo a long charging process, but only needs to set up short charging facilities at bus stations. The top of the bus is equipped with a bipolar pantograph which can be lifted quickly. When the bus stops at the bus station, the pantograph rises and contacts the charging line of the station to complete charging within the short time. Since the operation mode of this type of bus is different from that of traditional bus, and the construction cost of charging station is high, there are relatively few cases of super-capacitor technology application. However, compared with lithium-ion batteries, super-capacitors have long service life, almost zero pollution in production process and excellent low temperature resistance, which make this type of bus have good application prospects.

2.2.1 Application background

Super capacitor bus system is the first new electric bus system designed and successfully operated in China. In 2005, the project was initiated by Shanghai Municipal Science and Technology Commission and implemented by Shanghai Municipal Transportation Administration. So far, the world's first capacitor electric bus with actual commercial operation value and its supporting rapid charging station system were completed.

After that, the super-capacitor electric bus system has been extended to Hong Kong, Jiangsu, Shandong and other domestic provinces and cities, and exported to Israel, Bulgaria and other European countries. In April 2015, the 10 second flash charging super capacitor energy storage modern electric bus of CRRC Zhuzhou Electric Locomotive Co., Ltd. was officially launched in Ningbo production base, which provides the possibility to develop a faster and more convenient super capacitor public transportation system.

2.2.2 Problems to be solved

Like lithium-ion battery bus, the effect of super-capacitor bus on energy saving needs quantitative study. At present, the research of super capacitor bus is still in the initial stage, and the current research work mainly focuses on the internal structure design of the vehicle, without considering the energy consumption of the bus in the operation process. In addition, the current super capacitor bus lines are equipped with charging equipment at all stops, which makes the utilization rate of some charging stations low and greatly increases the construction cost. Therefore, how to build less charging stations and ensure the normal operation of vehicles is also a problem that the super capacitor bus system needs to solve.

2.3 Performance Comparison between Lithium-ion Battery and Super-capacitor

Worldwide research on lithium-ion batteries began in 1912. As one of the lightest elements in the metal group, lithium has larger electrochemical potential energy and can provide higher specific energy.

Therefore, the energy density of lithium-ion batteries is much higher than that of other batteries. In addition, lithium-ion batteries have the characteristics of good charge acceptance, small self-discharge and stable operation under high charge. The battery has no memory effect and has a cycle life of more than 2000 times. However, long-term operation at high temperature will seriously affect its cycle life. Moreover, the low temperature characteristics of lithium-ion batteries are poor because of the high impedance of organic electrolytes.

Unlike conventional capacitors, super-capacitors can store tens to tens of thousands of times the capacitance of the latter, which is a new type of energy storage element between traditional capacitors and batteries. In 1879, Helmholtz discovered the phenomenon of interface double layer, and proposed a model of flat-plate capacitor, which provided a theoretical basis for the invention of new capacitors. The working principle of super-capacitors is mainly to store electric energy by using the double layer formed by the interface of electrodes and electrolytes due to charge separation. Therefore, as a new energy storage device, super-capacitors have the following characteristics: high capacity ((0.1-50000F), which is 2000-5000 times the capacity of traditional capacitors of the same volume; high power density, discharge current up to 1000 amperes; fast charging and discharging speed, which can achieve rapid charging in a short time; super long cycle life, charging and discharging times can be more than 100,000 times; the working temperature range is wide, ranging from - 40℃ to 70℃, which is larger than the temperature range of lithium-ion batteries; the main material of super-capacitor is graphite, which does not cause environmental pollution.

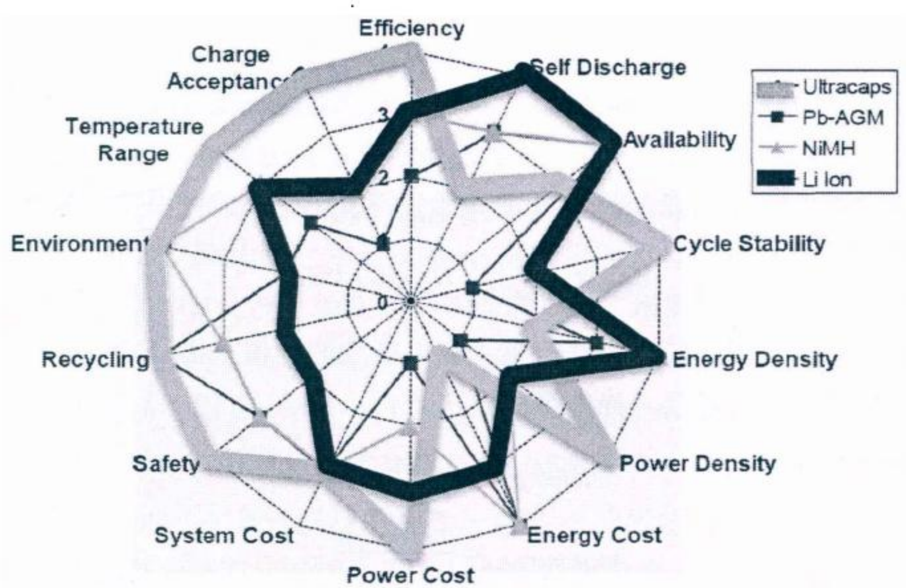


Figure 2-1 Properties of lithium-ion battery and super-capacitor

Figure 2-1 compares the parameters of lithium-ion batteries and super-capacitors. The black and grey thicker solid wires describe the performance characteristics of lithium-ion batteries and super-capacitors respectively. As can be seen from the figure, the main advantages of lithium-ion batteries are: less self-discharge during storage, long storage time of batteries; high energy density, unit mass can store more energy; compared with super-capacitors, its manufacturing cost is low. Super-capacitors are superior to lithium-ion batteries in terms of energy efficiency, applicable temperature range, cycle life, power density and environmental impact.

The energy storage system composed of lithium-ion batteries or super-capacitors is the main energy source in the operation of electric buses, and plays an important role in the whole electrical transmission process. Energy efficiency, the ratio of charge to discharge energy of energy storage unit, is used to evaluate the energy loss during charging and discharging. Higher energy efficiency means less energy loss and lower operating costs, so how to improve the energy efficiency of energy storage unit is the key to maintain the efficient operation of the system. Coulomb efficiency is the ratio of charging and discharging capacity of energy storage unit, which reflects the utilization rate of its capacity. It is often used to evaluate the performance of energy storage unit. Therefore, the study of energy efficiency and Coulomb efficiency of energy storage unit is the basis of establishing the energy consumption model of pure electric bus.

2.4 Charging and discharging experiments and data analysis

2.4.1 Lithium titanate ion battery experiments

At present, the common cathode materials of lithium ion batteries are lithium manganate, lithium iron phosphate and nickel manganese, while the common cathode materials are graphite and lithium titanate. Compared with lead-acid batteries, nickel-cadmium batteries and nickel-hydrogen batteries, lithium-ion batteries outperform traditional rechargeable batteries in terms of energy density, power density, life cycle, operating temperature range and safety. Because of these advantages, lithium-ion batteries are widely used as basic energy storage components in transportation applications. The lithium-ion battery group is shown in figure 2-2 below.

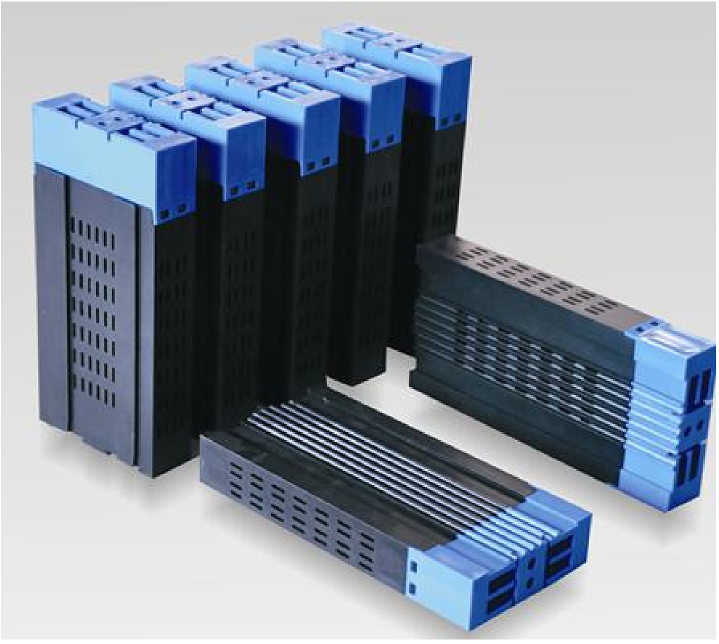


Figure 2-2 Lithium-ion battery group

In addition, modern transportation applications put forward higher requirements on the safety, power density and energy efficiency of energy storage system. Traditional lithium-ion batteries with graphite cathode are liable to damage or even cause explosion due to thermal runaway caused by high temperature or internal short circuit, which has potential safety hazards. In contrast, the new lithium-ion batteries using lithium titanate instead of traditional graphite cathode materials have a sharp rise in internal resistance during thermal runaway, which can effectively prevent explosion and is considered to have higher safety. Compared with traditional graphite cathode lithium ion batteries, lithium titanate ion batteries also have significant advantages such as higher power density and longer service life. Because of these advantages, lithium titanate ion batteries are more suitable as basic energy storage components of modern transportation systems[13]. The following lithium titanate batteries are taken as examples to design battery charging and discharging experiments and put forward the research method of energy efficiency of lithium ion batteries. The properties and parameters of the tested lithium titanate battery are shown in table2-1:

Table 2-1 Main properties of lithium titanate battery example

characteristics	parameters
rated voltage	2.3V
rated capacity	8.5Ah
energy density	75Wh/kg
AC internal impedance	<=0.6mΩ
cycle life	>=10,000 times
power density	>=2000W/kg
maximum charging voltage	2.8V
minimum discharging voltage	1.5V
operating temperature	-20~60℃

During the whole test process, the battery was placed in a constant temperature and humidity box, and the temperature was controlled at 25℃.

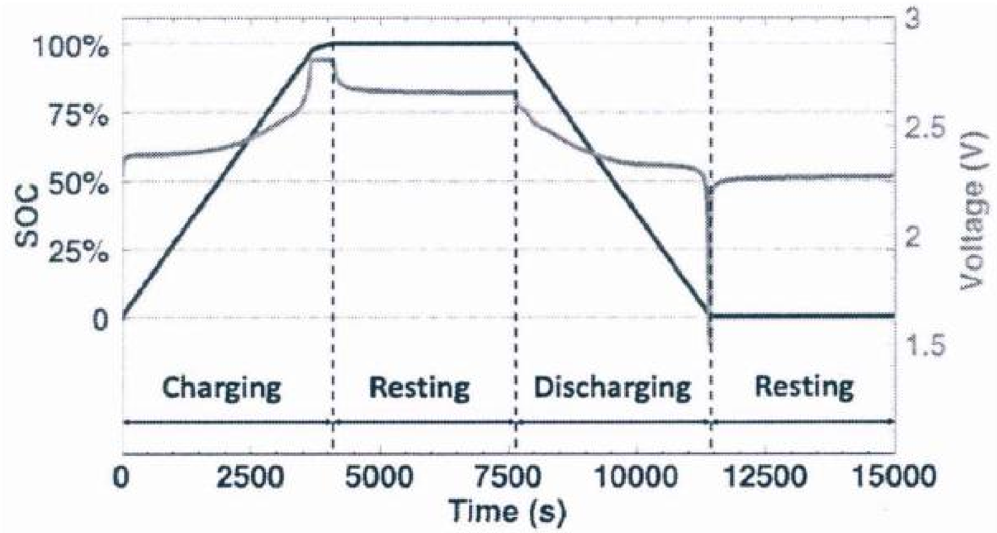


Figure 2-3(a) Cycle of activation procedure

Figure 2-3(a) shows the variation of battery parameters in a single full activation cycle. The working voltage of lithium titanate battery is between 1.5V and 2.8V. In the activation process, the battery is charged with a constant current of 1C (according to the rated capacity of the experimental sample, 1C equals 8.5A in this paper), and then charged with a constant voltage of 2.8V until the current is less than 0.1C. The static process between charging and discharging makes the battery achieve electrochemical equilibrium. After that, the battery is discharged to 0% SOC at a constant current of 1C.

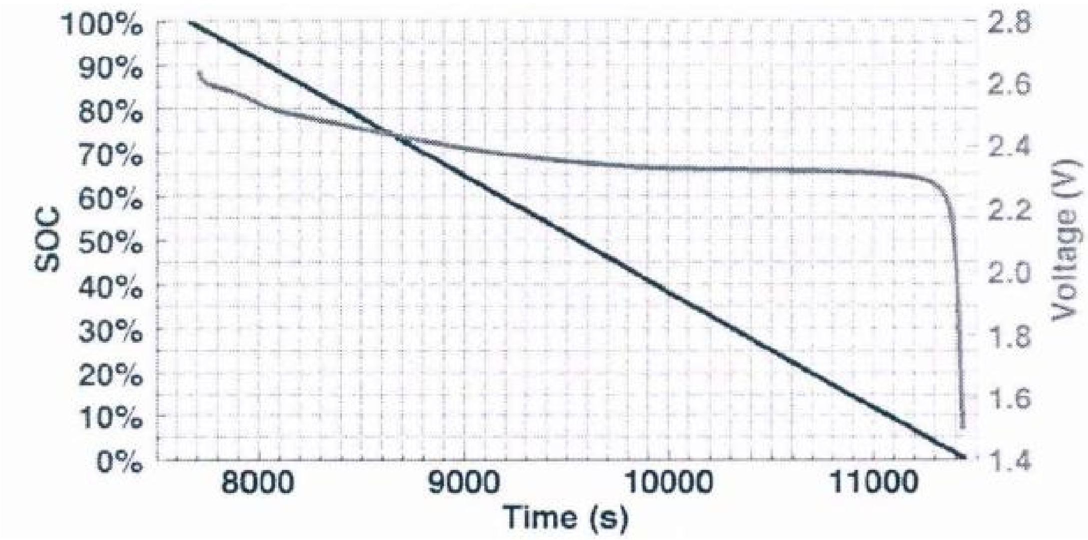


Figure 2-3(b) Discharging procedure of activation cycle

Figure 2-3(b) is the discharge process of the activation cycle. When the discharge process becomes from 100% to 0% SOC, the battery voltage decreases slowly from 2.6V to 2.3V. When the SOC decreases to less than 10%, the voltage reaches the critical point and drops rapidly until it approaches 1.5V.

- Full Charge/Incomplete Discharge Test

Considering that the voltage will drop sharply when SOC is very low, this paper first tests the battery under the condition of voltage stability, that is, the minimum SOC of battery discharge is more than 10%. In this section, SOC region and discharge current are considered as two main variables affecting efficiency. SOC intervals of this test are [100%, 10%], [100%, 20%], [100%, 30%] and [100%, 40%]. For each SOC interval, the battery discharges at different discharge rates from 1C to 11C, which covers the maximum discharge rate achieved during the operation of electric buses.

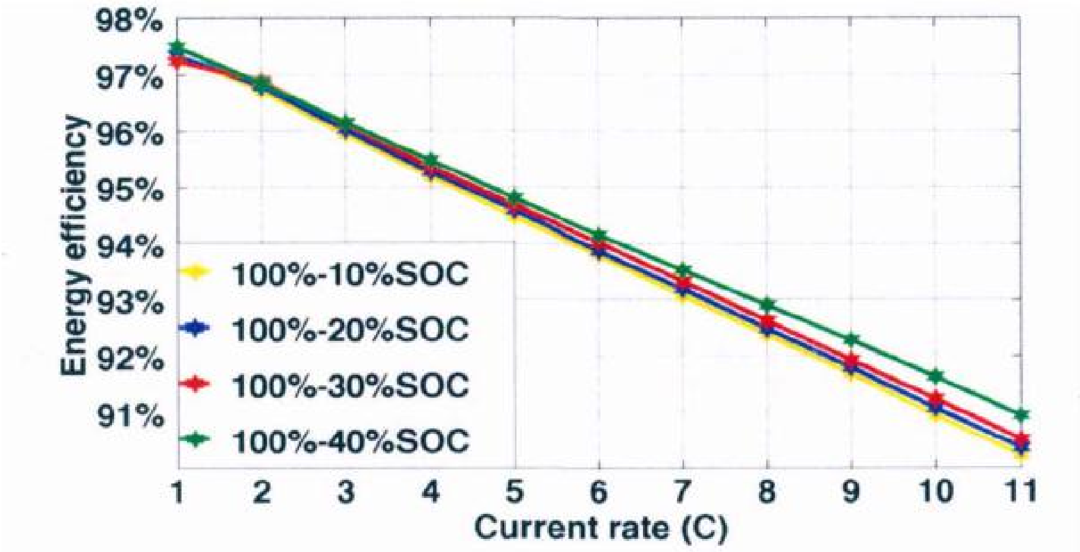


Figure 2-4 lithium titanate battery energy efficiency of full charge/incomplete discharge test

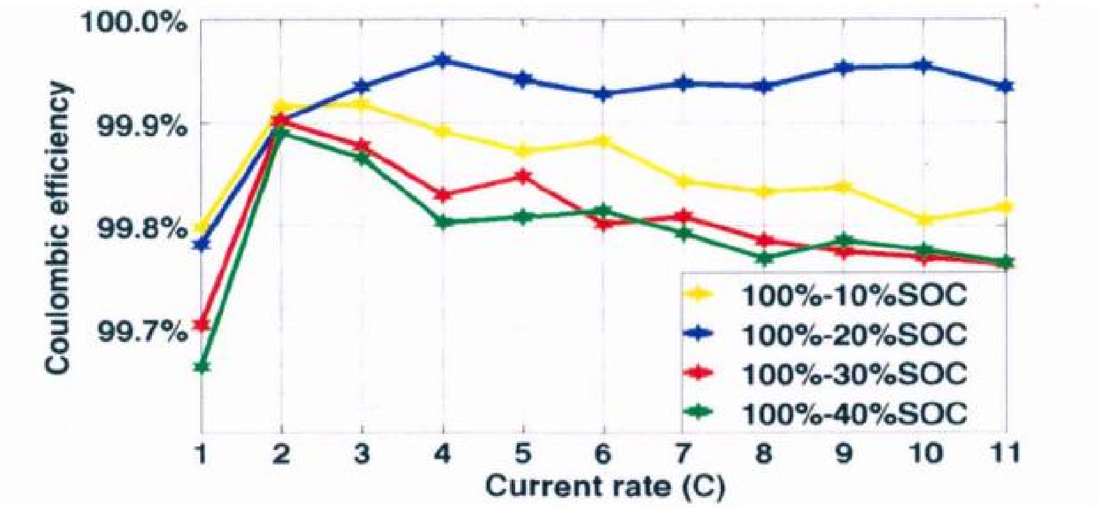


Figure 2-5 lithium titanate battery coulombic efficiency of full charge/incomplete discharge test

Figure 2-4, 2-5 compares the efficiency curves of batteries at the SOC intervals of [100%, [10%], [100%, [20%], [100%, [30%] and [100%, [40%]. Since the minimum values of these SOC interval ranges are greater than or equal to 10%, according to the activation curve in Figure

2-3, the battery operates in the range of 2.3-2.8V voltage in this set of experiments. Figure 2-4 shows the energy efficiency change curve in the full charge/incomplete discharge SOC region. The results show that there is a linear relationship between energy efficiency and discharge rate in these experiments. When the discharge current increases from 1C to 11C, the energy efficiency decreases from 97-98% to 90-91%. Figure 2-5 shows the Coulomb efficiency comparison curve in the SOC region of full charge/incomplete discharge. The results show that the coulomb efficiency of the battery varies little in the experimental period and exceeds 99%, which indicates that the battery is in good working condition without full discharge.

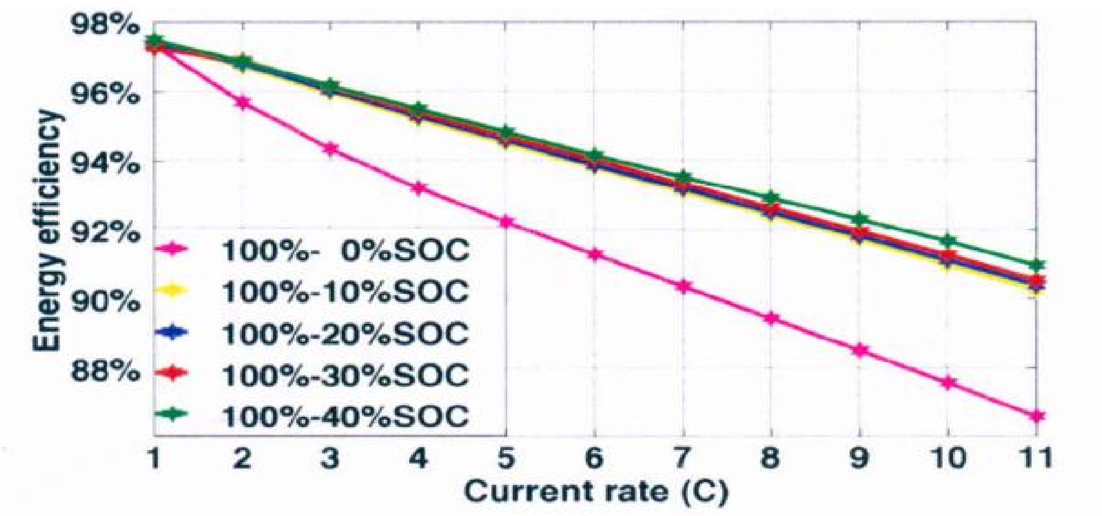


Figure 2-6(a) energy efficiency comparison

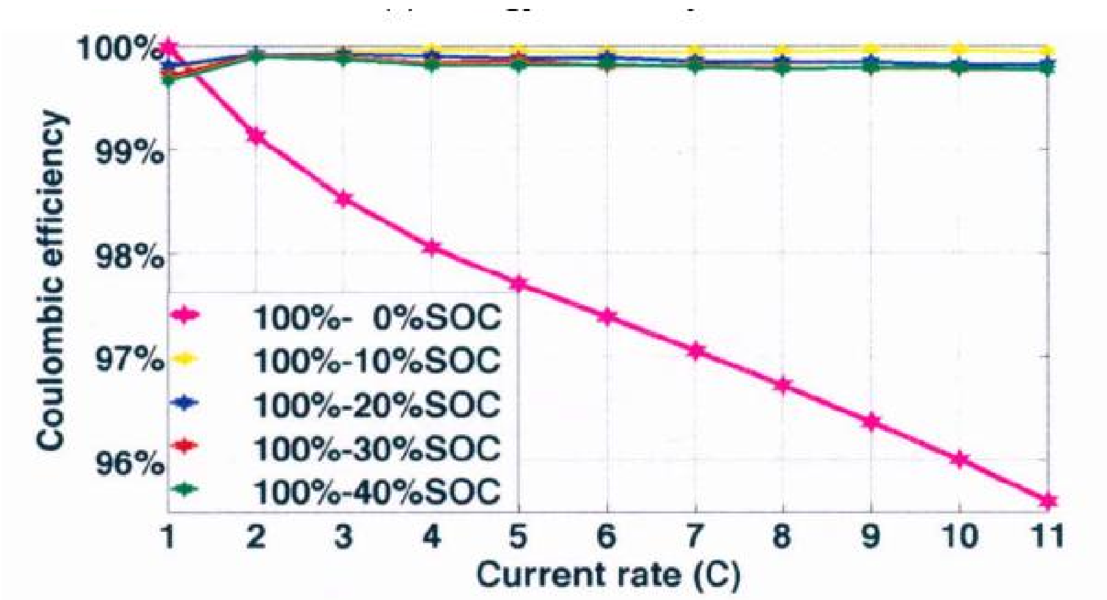


Figure 2-6(b) coulombic efficiency comparison

Figure 2-6(a-b) compares the energy efficiency and coulombic efficiency of lithium titanate battery monomer under full charge/incomplete discharge test and full discharge test respectively. The SOC interval for complete discharge test is [100%, 0%]. The results show that there are obvious differences between the full discharge test cycle and the incomplete discharge test cycle. Under the condition of full discharge, the energy efficiency and coulomb efficiency of lithium titanate ion batteries decrease greatly. Considering the relationship between SOC and battery internal resistance, when the battery discharge reaches a certain threshold, electrochemical changes occur inside the battery, and the internal resistance rises sharply, resulting in a corresponding decrease in efficiency. According to the results shown in Figure 2-6, the energy efficiency and Coulomb efficiency are both lost by more than 5%. Compared with the full discharge SOC test cycle, the internal resistance of the battery maintains a relatively stable range when the SOC of the battery decreases during the full charge/incomplete discharge test cycle. Since most of the energy loss is caused by the thermal loss of the internal resistance, the energy efficiency will gradually decrease when the cut-off discharge SOC is lower, but the scope of decline is limited.

- Incomplete Charging/Full Discharge Test

Due to the limitation of charging time in practical operation, the battery can not be fully charged before it is put into operation. This section considers the changes of energy efficiency and coulombic efficiency during the battery incomplete charging/discharging test cycle. The SOC intervals of the test cycle are [100%,0%], [95%,0%], [90%,0%], [85,0%] and [80%,0%]. For each SOC interval, the experimental samples were discharged at different rates from 1C to 11C.

The test process is similar to that of fully charged/incompletely discharged batteries. Before the experiment begins, the test batteries must be activated first.In each test cycle, the battery is charged at a constant rate of 1C to the maximum SOC of each test. After that, the battery is stationed for an hour to ensure that the electrochemical balance is restored. When the battery is discharged to 0% SOC at the selected discharge rate, it will be stationary for another hour. Because the high current used in the test cycle can not make the battery discharge completely, it is necessary to discharge the battery completely with a low current of 1C ratio after the rest. In addition, a complete charge-discharge cycle should be added between individual test cycles to ensure that the initial state of the battery is consistent during each test cycle.

Figure 2-7(a-b) shows the changes of energy efficiency and coulombic efficiency of lithium titanate battery monomer in the [100%,0%], [95%,0%], [90%,0%], [85%,0%] and [80%,0%] SOC intervals during the incomplete charge/complete discharge test cycle. Figure 2-7(a) shows the energy efficiency curves of different discharge intervals. Under the influence of internal resistance, when the discharge rate increases, the energy efficiency decreases due to the increase of internal heat loss. Compared with the complete charge/incomplete discharge test cycle, the energy efficiency of the battery decreased from 97%-98% to 80%-87% in the incomplete charge/fully discharge test cycle due to the change of internal resistance caused by the electrochemical changes in the battery during deep discharge.Figure 2-7(b) shows the Coulomb efficiency curves of different discharge intervals. According to the experimental results, the Coulombic efficiency of incomplete charge/fully discharge test cycle is in the range of 93%-96%, which is much lower than that of incomplete discharge cycle. Contrary to energy efficiency, when the cut-off SOC interval decreases, the Coulomb efficiency increases. In each test cycle, [100%,0%] SOC cycle shows the smallest Coulomb efficiency.

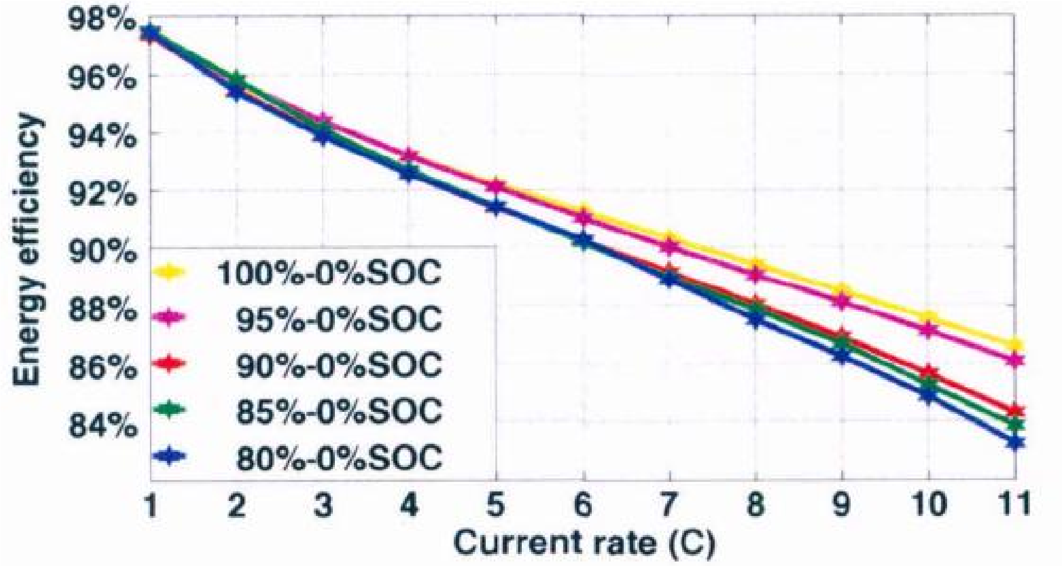


Figure 2-7(a) energy efficiency of incomplete charge/fully discharge

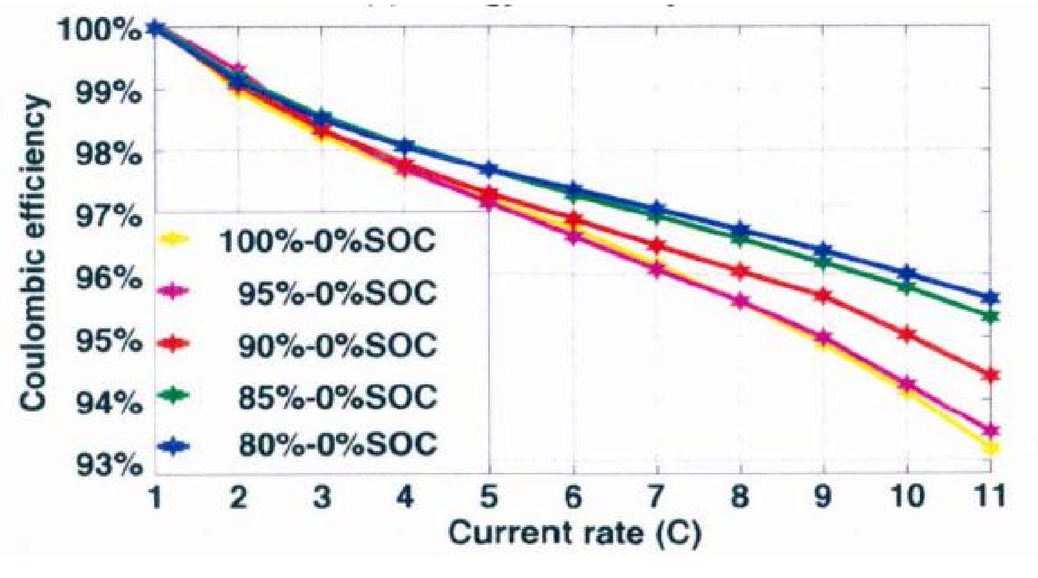


Figure 2-7(b) Coulombic efficiency of incomplete charge/fully discharge

2.4.2 Double layer super-capacitor experiments

Super-capacitors are superior to lithium-ion batteries in power density, cycle life, operating temperature range and environmental impact. Because of these advantages, super-capacitors have special advantages as basic energy storage components for transportation applications. Super-capacitors group is shown as follow figure 2-8.

Figure 2-8 Super-capacitor group

The biggest difference between super-capacitors and traditional electrostatic capacitors is their huge energy storage capacity. According to the difference of energy storage principle, the commonly used super-capacitors are mainly divided into the following two types:

(1)Electric Double Layer Capacitor

Helmholtz put forward the theory of double layer at the end of the 19th century. The model points out that the net charge on the metal surface can absorb some irregular ions from the solution and arrange them on the solution side of the interface between the electrode and the solution. They are arranged in a row at a certain distance from the electrode to form an interface layer with equal number of charges and opposite symbols to the residual charge on the surface of the electrode. Therefore, a so-called "double layer" is formed on the electrode and in the solution to store capacitance.

(2) Faraday quasi capacitor

In electroactive substances, there are chemical changes of Faraday charge transfer. In the electrochemical process, redox reaction or underpotential deposition occurs on the polarized electrode, and its charge-discharge behavior is similar to that of a capacitor. The voltage on the polarized electrode of the capacitor has a linear relationship with the electric quantity.

Because the carbon materials used in the double-layer capacitors have less impact on the environment, the double-layer capacitors are used as test samples. Its rated voltage is 2.7V and rated capacity is 7500E. The properties and parameters of the super-capacitor sample are shown in the following table.

Table 2-2 Main properties of super-capacitor sample

Characteristics	Parameters
Rated voltage	2.7V
Rated capacity	7500F
Energy density	5.89Wh/kg
AC internal impedance	<=0.13mΩ
Storage life	10 years
Power density	>=2000W/kg
Maximum short-circuit current	6000A
Rated current	300A

Operating temperature	-40~65℃

The testing process of super-capacitors is similar to that of lithium-ion batteries. During the whole testing process, the capacitors are placed in a constant temperature and humidity box at 25℃. First of all, the experimental capacitors need to be activated. In the activation process, the super-capacitor is charged with a constant current of 1C to a rated voltage of 2.7V, i.e. 100% SOC. In order to facilitate the comparative test with lithium titanate battery, the same charge-discharge ratio as that of lithium battery is selected here, i.e. 1C is equal to 8.5A.

Because there is no chemical change during the charging process of the super-capacitor, the static time of 5 seconds can ensure that the battery reaches equilibrium state. After that, the battery is discharged to 0V at a constant rate of 1C, i.e. 0% SOC.

Unlike lithium titanate batteries, the relationship between SOC and terminal voltage of super-capacitors is simpler. During discharge, the terminal voltage gradually decreases from the maximum to 0V, and the relationship between terminal voltage and SOC is linear. Similar to the lithium titanate battery test, the changes of energy efficiency and coulombic efficiency under two operating conditions, i.e., full charge/incomplete discharge test cycle ([100%, 50%] SOC interval) and incomplete charge/complete discharge test cycle ([50%, 0%] SOC interval), were verified during the test process.

Figure 2-9 shows the trend of energy efficiency and coulombic efficiency of super-capacitors in [100%,50%] SOC and [50%, 0%] SOC, respectively. From the energy efficiency curve of Figure 2-9 (a), it can be seen that the energy efficiency of super-capacitors in high SOC range is slightly higher than that in low SOC range; the energy efficiency decreases linearly with the increase of discharge current; However, compared with the energy efficiency of lithium-ion batteries at the same discharge rate, the energy efficiency of super-capacitors in the same discharge state is higher than that of lithium-ion batteries with less energy loss. Figure 2-9 (b) shows the change of coulombic efficiency of super-capacitors. The results show that the Coulombic efficiency of super-capacitors decreases with the increase of discharge current, but it remains above 96% during the test period of two SOC intervals.

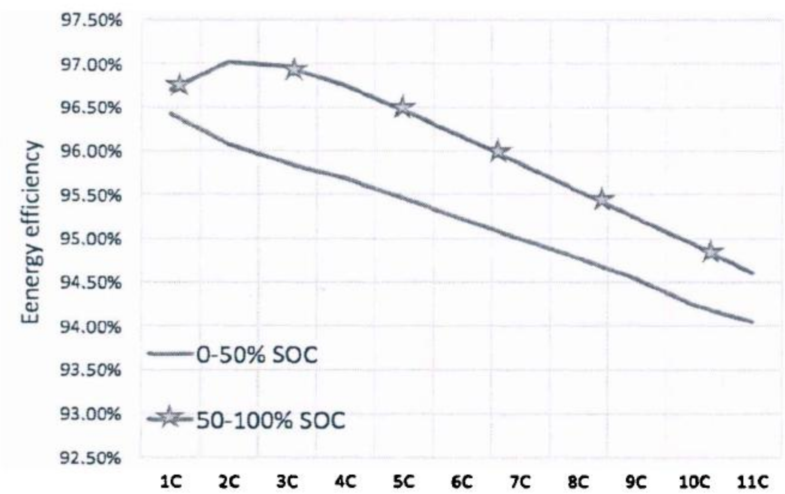


Figure 2-9(a) energy efficiency of super-capacitors in different SOC intervals

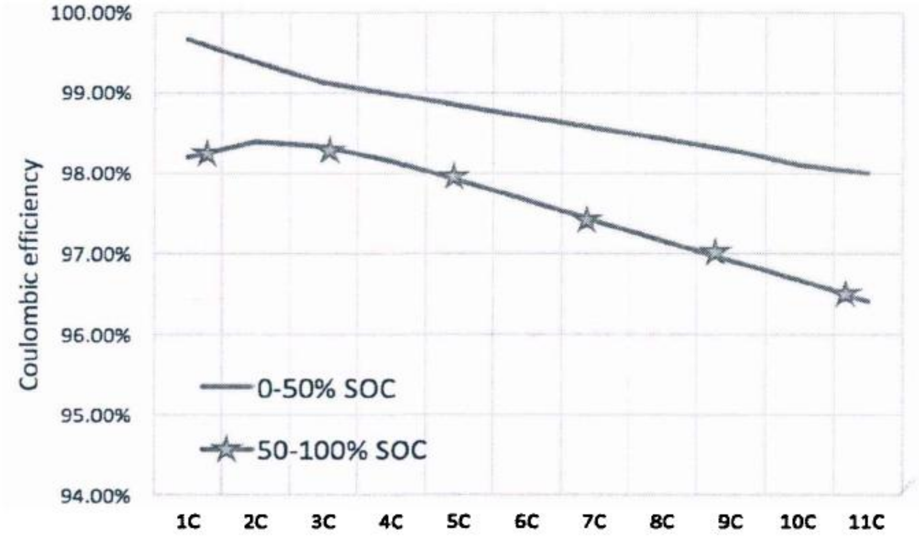


Figure 2-9(b) Coulombic efficiency of super-capacitors in different SOC intervals

2.5 Energy Storage System Efficiency of These Two Types of Buses

According to the internal composition of the vehicle, the main difference between lithium-ion battery bus and super-capacitor bus is energy storage system. Therefore, this section mainly analyses the efficiency changes of the energy storage system of two types of buses under typical working conditions. Figure 2-10 shows the changes of SOC of these two types of bus energy storage systems under typical working conditions.

As shown in Figure 2-10(a), the SOC of lithium-ion battery bus energy storage system decreases from 100% to 95% under typical operating conditions. Figure 2-10(b) shows the SOC curve of the super-capacitor bus energy storage system. Because the energy density of super-capacitors is much lower than that of lithium-ion batteries, their

SOC decreases more greatly. In this case, the lowest SOC of super-capacitor reaches 50%. In addition, during each stop, the energy storage system composed of super-capacitors is charged to restore the SOC to more than 95% before departure. At the same time, according to the change of SOC with the vehicle running process, it can be seen that in the acceleration stage, in order to increase the thrust, the system needs to provide more energy. At this time, the SOC of the energy storage system decreases fastest; At the uniform speed stage, the system thrust is only used to overcome the resistance to maintain the motion state, and then the SOC decreases slowly.

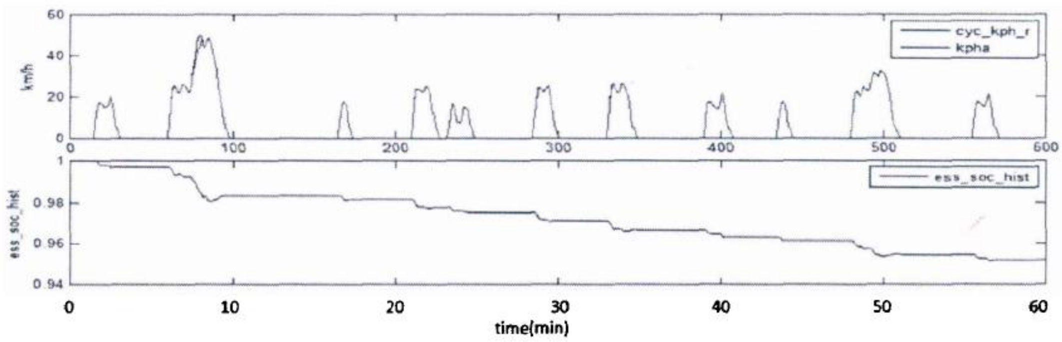


Figure 2-10(a) Lithium-ion battery bus SOC trend

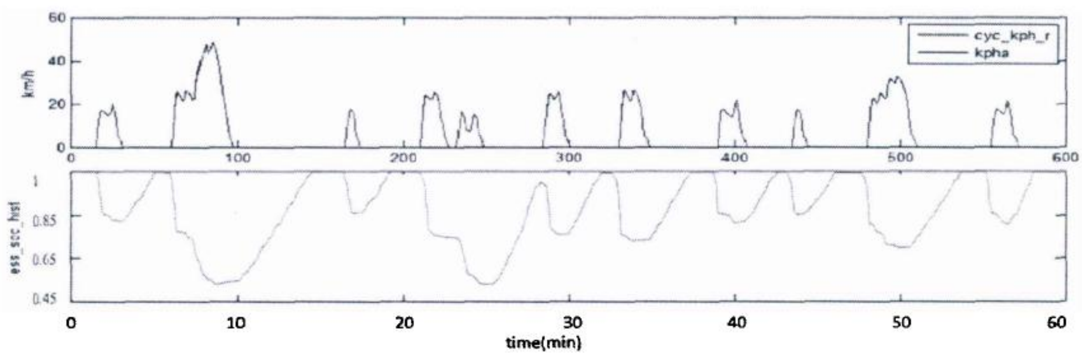


Figure 2-10(b) Super-capacitor bus SOC trend

Figure 2-11(a-b) shows the change of energy storage system efficiency of two types of buses under typical working conditions. Figure 2-11(a) shows the efficiency change of Lithium-ion battery energy storage system. It can be seen from the figure that the efficiency of the energy storage system is maintained above 92% under typical working conditions; the efficiency increases gradually with the speed stabilization in the course of vehicle driving; and the overall energy loss of the energy storage system is small. Figure 2-11(b) shows the efficiency change of the energy storage system consisting of super-capacitors. The lowest efficiency is 90%, and the overall efficiency distribution is in the higher range of 90% - 100%.

Combining with the typical speed curve of Figure 2-10, the bus needs more energy to overcome the resistance and provide acceleration during the acceleration process. At this time, the discharge current of the energy storage system increases. As shown in Figure 2-10, the efficiency of the acceleration process is obviously less than that of the speed stabilization stage, and the efficiency of the energy storage system increases with the decrease of the acceleration. In the stage of speed stabilization, the output driving force of the vehicle is only used to overcome the resistance to maintain the operation of the vehicle, and the discharge current of the energy storage system is relatively small, and the efficiency is relatively high. In the uniform driving stage with higher running speed, the motor needs more input power to provide higher speed. At this time, the discharge current of the energy storage system is larger than that of the low-speed uniform driving stage, and the system efficiency is slightly reduced.

Compared with the energy storage system composed of lithium-ion batteries, the overall efficiency of super-capacitor energy storage system is relatively low. Because the real-time output power of the energy storage system is the same under the same operating conditions, the efficiency of the two systems is mainly caused by the difference of operating. Under typical operating conditions, SOC of super-capacitor decreases much more than that of lithium-ion battery, so the effect of SOC on efficiency is one of the reasons for the difference between the two energy storage systems. At the same time, the voltage of super-capacitor decreases sharply during discharge. When the SOC of super-capacitor decreases by 50%, the output voltage of energy storage system will also decrease by 50%. Therefore, when the output power is the same, the output current of the super-capacitor energy storage system will multiply. The increase of output current is the main reason that its operating efficiency is slightly lower than that of lithium-ion battery energy storage system.

According to estimates, under typical conditions, the total energy loss of lithium-ion battery bus is slightly less than that of super-capacitor bus, and the energy loss of lithium-ion battery bus can be saved by 2-3%.

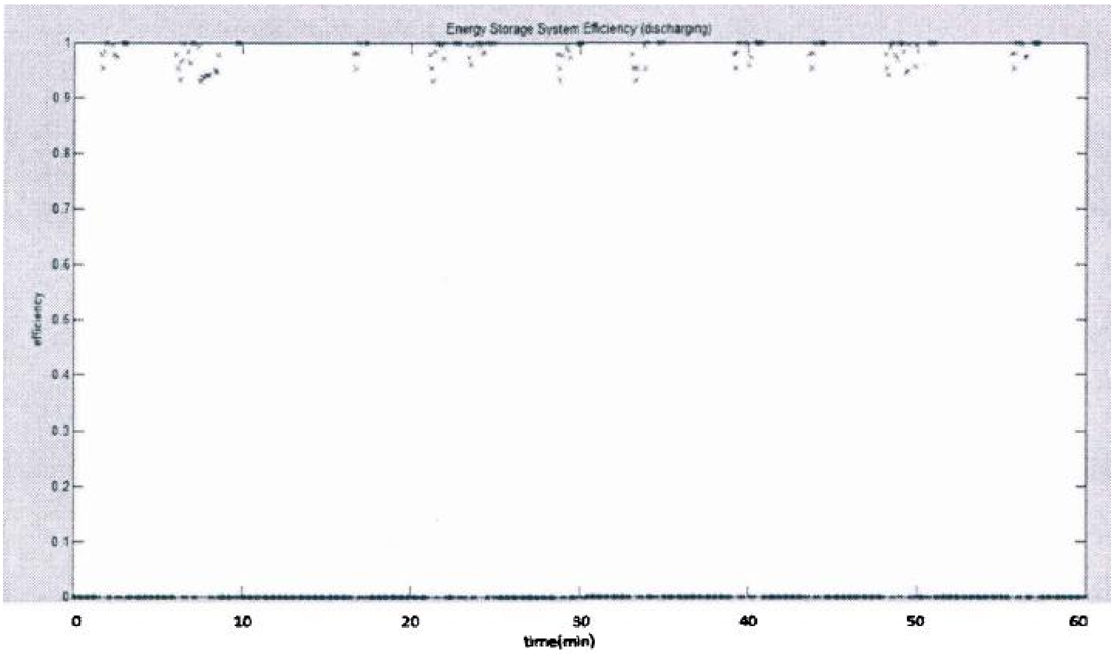


Figure 2-11(a) Energy storage system efficiency of lithium-ion battery bus

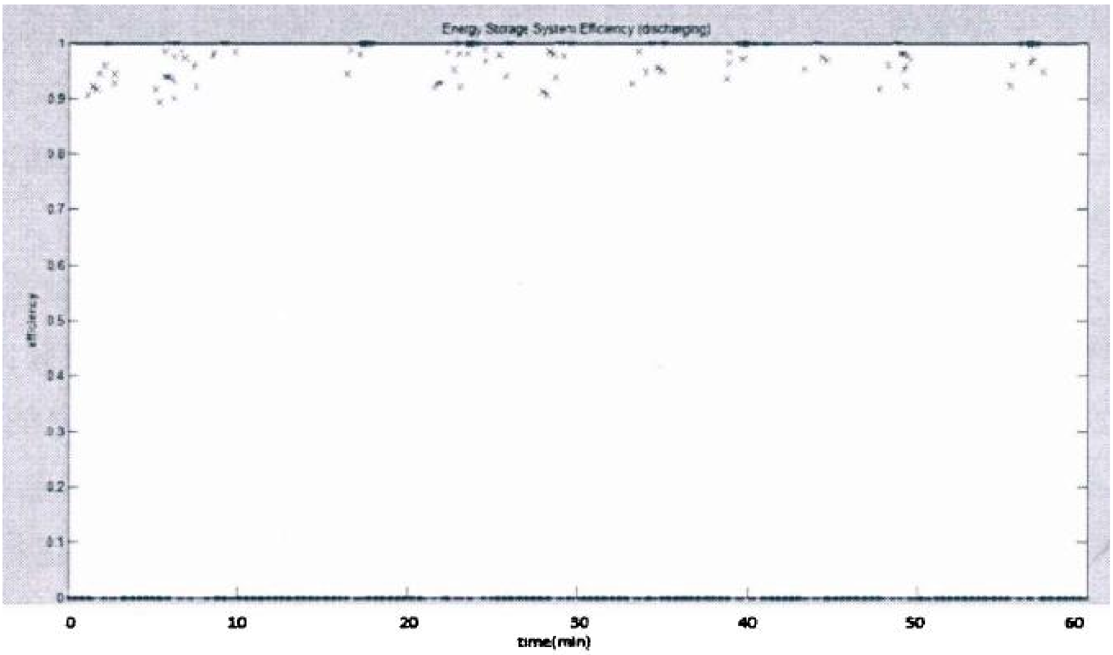


Figure 2-11(b) Energy storage system efficiency of super-capacitor bus

Compared with these two pure electric buses, the efficiency of energy storage system has a direct impact on the overall vehicle loss. According to the charge-discharge experiment of energy storage unit in last section, although the energy efficiency of super-capacitors is slightly higher than that of lithium-ion batteries at the same discharge current, the characteristics of the voltage drop of super-capacitors with discharge process make the output current of super-capacitors much higher than that of lithium-ion batteries, which leads to their actual use. So that operating efficiency of super-capacitor in reality is relatively low.

Chapter3 Fast Charging Mode Optimization

3.1 Introduction of Fast Charging Mode

The fast charging mode considers the battery and vehicle as a whole, and the charging process mostly occurs in the bus parking lot. According to the charging time and power, the whole vehicle charging mode can be further divided into conventional charging mode and fast charging mode. The conventional charging mode of the whole vehicle generally adopts constant current or voltage to charge with small current. During the charging process, the battery has less heat, which is beneficial to prolong the battery lifespan. The slow charging of the whole vehicle can make full use of the low power load at night with a relatively low electricity price, but the charging time is too long, which will bring some inconvenience to the use of the vehicle.

The vehicle fast charging mode is to charge the battery with large current, which has the characteristics of high charging power and short charging time. This kind of charging mode can quickly supplement electric energy for electric vehicles and meet the demand of emergency charging. For the private electric vehicle with small battery capacity, the charging time is only about 30 minutes. For the electric bus with large battery capacity, the charging time is generally not more than 2 hours, which is convenient to use. However, fast charging needs to be equipped with special charging facilities with high cost. And the battery will overheat during the charging process, which is not beneficial to the extension of battery lifespan. The battery cost of electric vehicles is generally high, accounting for about 30% - 50% of the total vehicle cost. The shortening of battery lifespan will increase the operating cost of the whole vehicle. In addition, fast charging will also lead to the problem of harmonic pollution, and the larger charging power may bring a certain impact on the distribution system.

3.2 Optimization of Fast Charging Mode

3.2.1 Analysis of lithium-ion battery model

The battery model is established to determine the mathematical relationship between the environmental factors and the characteristics of the battery more intuitively. The equivalent circuit model is to describe the volt ampere relationship of the power battery during operation by establishing an equivalent circuit, mainly including: Rint model, RC model, PNGV model, Thevenin model, etc., as shown in Figure 3-1 to figure 3-4 respectively. The equivalent circuit model is widely used because of its simple structure and the ability to reflect the dynamic characteristics of the battery.

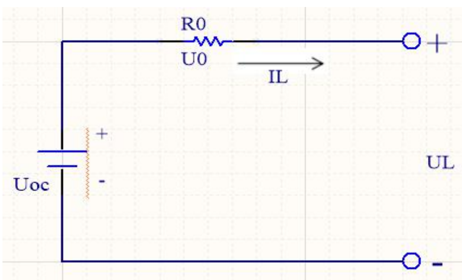


Figure3-1 Rint equivalent circuit model

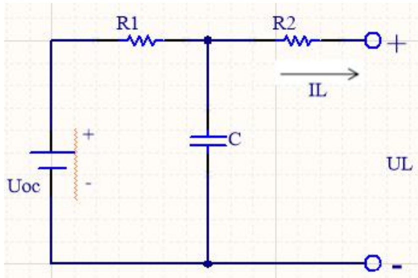
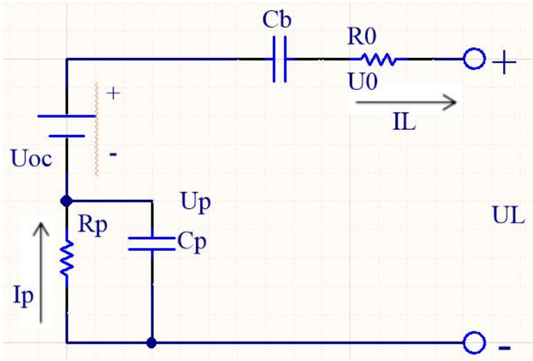


Figure3-2 RC equivalent circuit model



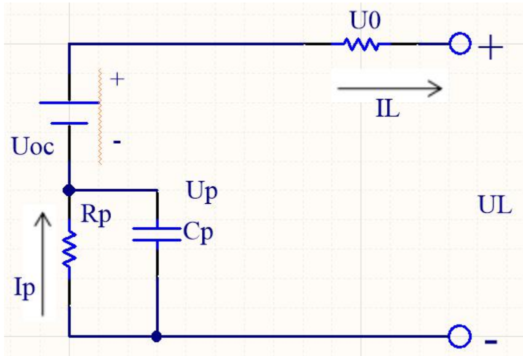


Figure3-3 PNGV equivalent circuit model

Figure3-4 Thevenin equivalent circuit model

The battery charging model in this paper is based on the fact that a long charging cable is laid between the charger and the charging pile during the actual construction of the fast charging station, as shown in Figure 3-5 below:

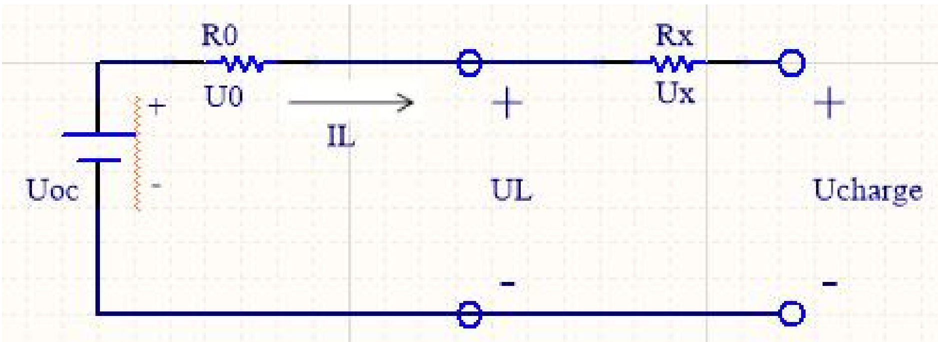


Figure3-5 Charging model

In Figure 3-5, R0 represents the internal resistance of the battery pack. According to the battery data of lithium titanate electric bus, R0 is 50[15], and Rx represents the line resistance of the charging circuit (for example, the charging cable of the fast charging station studied in this paper is 200m, and the resistance value is 8.75mΩ). The calculation is as follows:

$$R_x = \rho \times \frac{L}{S} \qquad 3\text{-}1$$

In the formula:

ρ is the resistivity of copper core, taken as 1.75×10^{-8};

S is the cross-sectional area of the copper core in the charging circuit;

L is the length of charging circuit;

Then the parameters of the charging model of the electric bus in the charging station studied in this paper are as follows:

$$\begin{cases} U_{Charge} = U_L - U_x \\ U_L = U_{oc} - U_0 \\ U_{oc} = f\left(SOC'\right) \end{cases} \quad 3\text{-}2$$

In the formula, $SOC' = SOC \times 100$.

3.2.2 Battery OCV-SOC test

(1) SOC(State of Charge). SOC is defined as the percentage of the remaining capacity of the battery to the total capacity, i.e.:

$$SOC = \frac{remaining\ capacity}{total\ capacity} \times 100\% \quad 3\text{-}3$$

When the battery is fully charged, SOC=100%, when the battery is fully discharged, SOC=0%.

(2) SOE(State of Energy). SOE is defined as the percentage of the remaining energy and the maximum available energy of the battery, namely:

$$SOE = \frac{remaining\ energy}{\max ium\ available\ energy} \times 100\% \quad 3\text{-}4$$

(3) OCV-SOC. OCV-SOC curve is the corresponding relationship

between the open circuit voltage and the state of charge of the battery.

(4) CC-CV; CC. The charging mode of the battery, namely constant current constant voltage mode and constant current mode.

(5) SOC_e . It is the SOC of the battery at the boundary between constant current stage and constant voltage stage when CC-CV mode is used for charging[14].

The relationship between the open circuit voltage and the state of charge of lithium-ion battery is the core part of lithium-ion battery modeling. The method to obtain OCV-SOC curve is mainly through the battery test[15]. The specific method is shown in table 3-1:

Table 3-1 OCV-SOC curve test steps

Step	Specific Operation
Step 1	Stand for more than 2 hours after fully discharged;
Step 2	Charge the battery with 1C constant current until the cut-off voltage, and record the voltage change S1 (charging terminal voltage);
Step 3	Discharge the battery with 1C constant current until the cut-off voltage, and record the voltage change S2 (discharging terminal voltage)
Step 4	OCV-SOC curve is S=(S1+S2)/2

For the 35Ah lithium titanate battery, the OCV-SOC curve is shown in Figure 3-6.

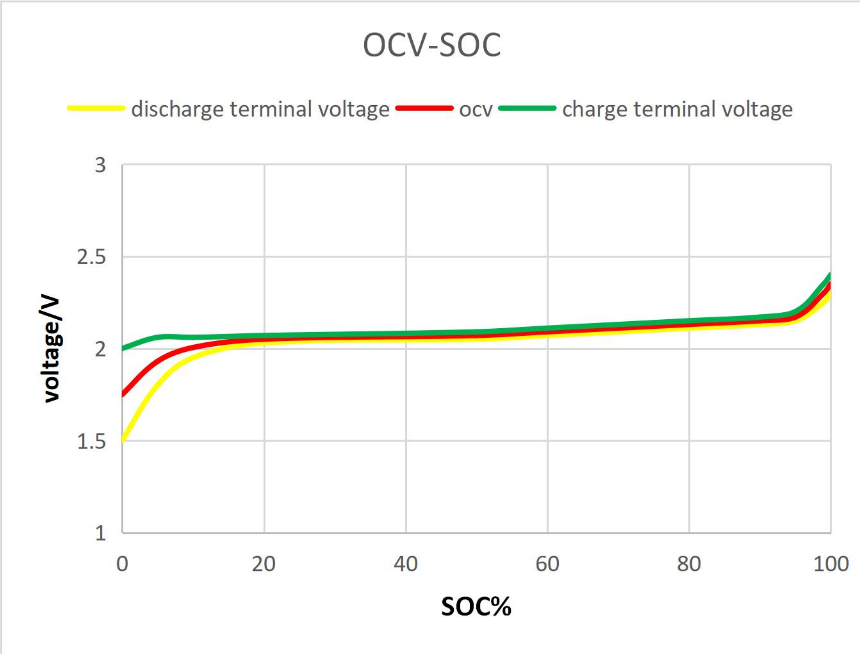


Figure 3-6 OCV-SOC curve

In order to describe the state of the battery when the model is built, the CFTOOL kit in MATLAB is used for function fitting, and the functional relationship between the internal potential Uoc and the state of charge SOC of the battery is obtained as follows:

$$Uoc = -a \cdot \ln\left(\frac{1}{b \cdot SOC' + c}\right) + d + e \cdot SOC' + f \cdot SOC'^2 + g \cdot SOC'^3 + h \cdot SOC'^4 \quad 3\text{-}5$$

In the formula:

$SOC' = SOC \times 100$; $a = 0.09665$; $b = 0.2161$; $c = 0.2192$; $d = 2.178$; $e = -0.006378$; $f = 0.0003492$; $g = -5.548e-06$; $h = 3.17e-08$

The R-square of the fitted equation and the test data is 0.9946, which shows that the fitted function can describe the change rule of OCV SOC curve.

3.2.3 Analysis of Charging Method

Fast charging has gradually become the consensus and direction of the international electric vehicle industry. Only by making the charging of pure electric vehicles as convenient and fast as refueling, can electric vehicles develop and popularize rapidly. At present, the charging mode of CC-CV (constant current constant voltage) is widely used in the electric bus fast charging station, while the average charging power of constant current section and constant voltage section is different in the process of electric bus charging.

Table 3-2 Comparison of different charging stages

Charging stages	$\Delta SOC(\%)$	Charging capacity(kWh)	Charging time(s)	Average power(kW)
CC	68	74.79	1100	244.77
CV	2	9.56	420	81.94

It can be seen from table 3-2 that the charging time of electric bus is mostly wasted in constant voltage stage, and the average charging power of the constant voltage section is far less than that of the constant current section.

The polarization of battery is the main reason that affects the charging power of battery. The polarization of battery will increase the voltage of battery terminal, which will cause the battery to be unable to be fully charged and the charging time will be longer. In addition, serious polarization will also cause serious heating of battery, leading to the change of internal chemical structure of battery, etc., which will have a significant impact on the safety and service lifespan of battery[16]. According to the polarization voltage change characteristics of the battery during charging from 0% SOC to full charge (100% SOC), the polarization voltage change pattern of the battery during charging presents a "bowl" distribution[21], as shown in Figure 3-7 below:

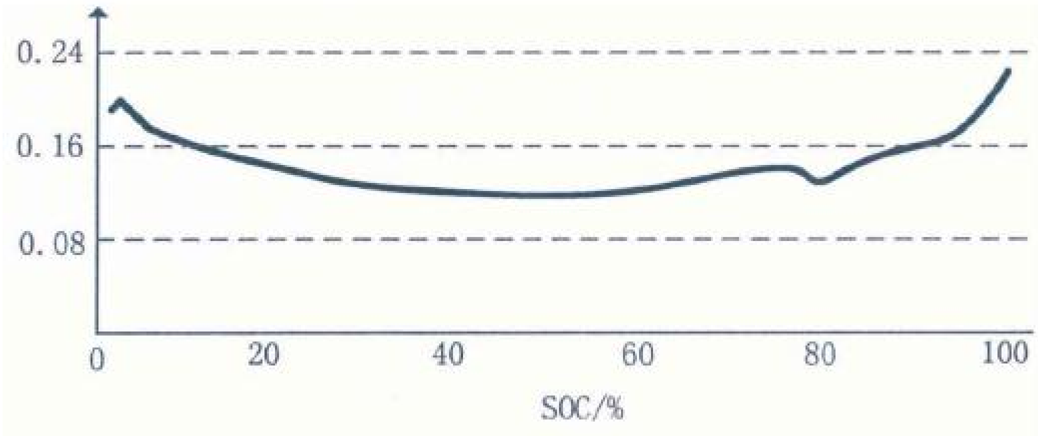


Figure 3-7 Polarization voltage changes with SOC

The polarization ratio coefficient γ represents the effect of the charging current ratio on the polarization voltage, i.e. the increment of the polarization voltage for each 1C increment of the charging current ratio, as shown in formula 3-6[15]. The steady-state value of polarization voltage is basically the same when charging from different initial SOC.

$$\gamma \equiv {\partial Vp}/{\partial i} \quad 3\text{-}6$$

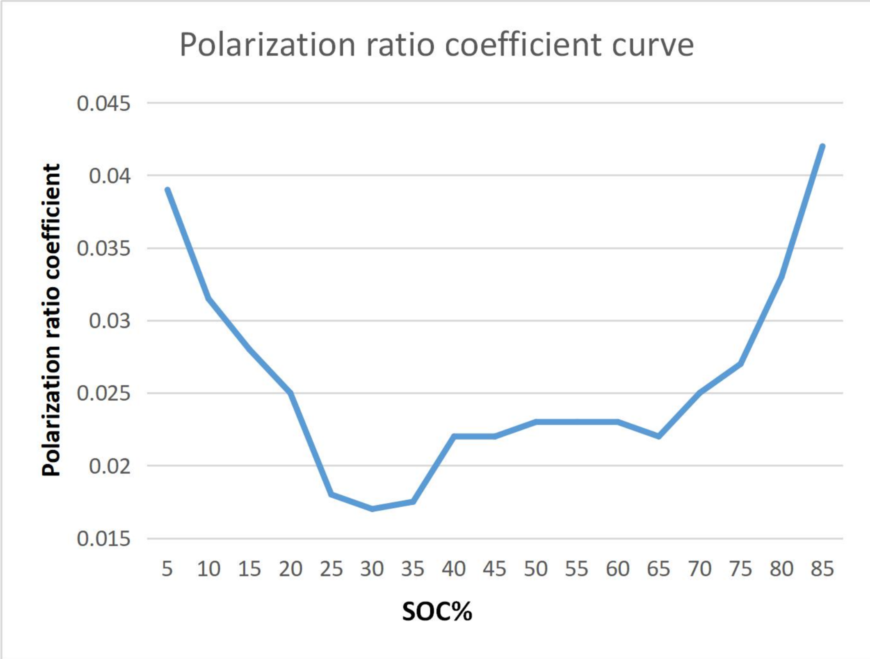


Figure 3-8 Polarization ratio coefficient with different SOC

From figures 3-7 and 3-8, it can be seen that the polarization voltage of the battery is relatively large at the initial stage and the end stage of charging, and the γ value in the middle SOC interval is less than the SOC interval at both ends.

Above, the CC-CV charging of electric bus is analyzed from two aspects of the actual operation of the fast charging station and the polarization characteristics of the battery. The charging mode (CC-CV or CC mode) should be determined according to the actual situation when charging the electric bus. In the process of electric bus fast charging, the transition point from constant current section to constant voltage section is defined as SOCe, when the SOE1 corresponding to the sum of the electric bus's charge demand and return power E1 (the energy when the electric bus leaves the station) does not reach SOCe, CC (constant current) mode is used to charge the electric bus, otherwise CC-CV mode is used.

3.2.4 Charging power analysis model

According to the charging history data of electric bus, when the SOC_0' of electric bus return to the station and charging current are known, the power model of formula 3-7 can be obtained as follows.

$$P(t)=\begin{cases} \dfrac{P_{\max}-P_0}{B(SOC_e'-SOC_0')/I_C}\cdot 100\cdot t+P_0 \ , 0<t<t_s \\ P_{\max}-\dfrac{P_{\max}}{T_{const}}\cdot(t-t_s)\ , t_s<t<t_s+T_{const} \end{cases} \tag{3-7}$$

In the formula:

$SOC_e'=SOC_e\times 100$, $SOC_0'=SOC_0\times 100$;

t_s is the charging time of constant current section, that is:

$$t_s=\frac{C\cdot(SOC_e'-SOC_0')}{I_C\cdot 100} \tag{3-8}$$

B is the rated capacity of the battery group;

$P_{\max}$ is the maximum power of the constant current-constant voltage turning point(kW);

P_0 is the power of the initial charging of the battery(kW);

T_{const} is the charging time of the constant voltage section;

$P_{\max}$ and P_0 can be calculated by formula 3-2.

3.2.5 Bus operation data and processing analysis

Investigate on a pure electric bus fast charging station in Beijing, due to the operation difference of pure electric bus between workday and weekend, the statistical analysis is divided into two parts. The following statistical analysis of return station SOC and power consumption is conducted on this basis.

- Statistical analysis of return station SOC

Aiming at the research goal of minimizing the daily charging cost of the electric bus fast charging station, the return station SOC of the electric bus is the core parameter[17]. In the following, the statistical data of the return station SOC of the electric bus based on a fast charging station in Beijing is analyzed and modeled.

After data processing, the SOC of electric bus return station is summarized and analyzed. The probability distribution of SOC of electric bus return station in workday is shown in Figure 3-9:

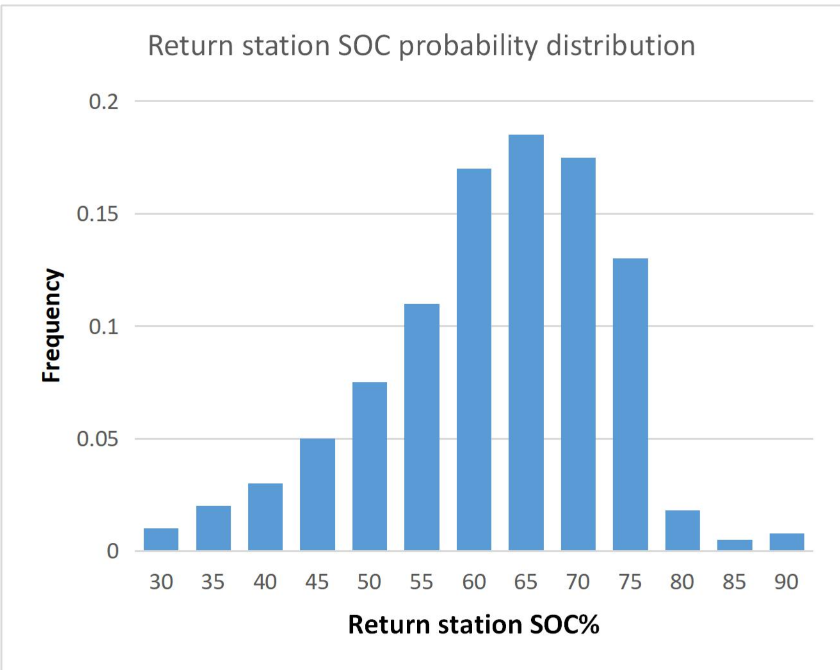


Figure 3-9 Workday return station SOC probability distribution

Through SPSS single sample K-S test, the probability distribution of return station SOC on workday conforms to the normal distribution, the probability density function of return station SOC of electric bus is as follows[18]:

$$y = y_0 + \frac{A}{\omega \cdot \sqrt{\pi/2}} \cdot e^{-2 \cdot \frac{(x-x_c)^2}{\omega^2}} \qquad 3\text{-}9$$

In the formula:

$y_0 = 0.0072$; $x_c = 61.95881$; $\omega = 18.52967$; $A = 4.49527$

It can be concluded that the return station SOC of electric bus is mainly distributed in [55%, 75%], accounting for 69.44% of the total number of samples, and the return station SOC which not lower than 60%, accounts for 53.7% of the total samples, and the expected value of return station SOC in workday is 61.96%.

The probability distribution of return station SOC at weekend is shown in Figure 3-10 below:

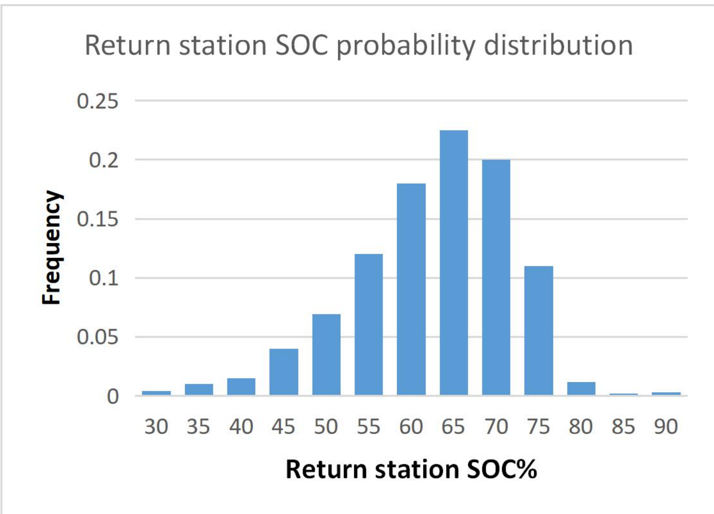


Figure 3-10 Return station SOC probability distribution on weekend

Through SPSS single sample K-S test, the probability distribution of return station SOC on weekend conforms to the normal distribution, the probability density function of return station SOC of electric bus is as follows:

$$y = y_0 + \frac{A}{\omega \cdot \sqrt{\pi/2}} \cdot e^{-2 \cdot \frac{(x-x_c)^2}{\omega^2}} \tag{3-10}$$

In the formula:

$y_0 = 0.00462$; $x_c = 61.92597$; $\omega = 16.4055$; $A = 4.67753$

It can be concluded that the return station SOC of electric bus is mainly distributed in [55%, 75%], accounting for 73.71% of the total number of samples, and the return station SOC which not lower than 60%, accounts for 55.61% of the total samples, and the expected value of return station SOC in workday is 61.93%.

According to statistics, the return station SOC analysis of electric bus on workdays and weekends is as follows:

1. On weekends, the return station SOC of electric bus is relatively concentrated;

2. Return station SOC of electric bus in a week which not be less than 60%, accounts for more than 50% of the total statistical samples;

3. During the week, the expected SOC of electric bus return station is about 62%.

- Statistical analysis of power consumption and time consumption of single circle

When calculating the electric power consumption of electric bus in a single circle, according to the current situation, the electric bus starts at full power every time, so the electric power consumption of electric bus in a single circle can be calculated according to the charging power in the charging record, that is, the charging power is the power consumption of the last single circle. The core idea of optimized fast charging of electric bus is "more charging in valley time and less charging in peak time". Therefore, the power consumption of electric bus is statistically analyzed based on time[19]. The departure time of electric bus is 5:30-22:00, and the power consumption of electric bus is calculated based on the interval of 15 min, as shown in table 3-3:

Table 3-3 Electric bus power consumption in single circle

Order number	Time interval	Workday(kWh)			Weekend(kWh)			Time consumption single circle(min)	
		max	mean	min	max	mean	min	workday	weekend
1	5:30-5:45	74	58.4	48	67	60.3	53	132.4	127.4
2	5:46-6:00	70	57.1	47	67	58.3	51	133.7	131
3	6:01-6:15	72	58.9	47	65	55.3	47	139.4	132.7
4	6:16-6:30	69	61.4	53	65	53.3	45	145.2	136.5
5	6:31-6:45	82	65.5	58	68	58.8	53	156.9	135.6
6	6:46-7:00	80	68.5	58	71	65.2	62	153.9	138.1
7	7:01-7:15	83	71.6	59	72	67.1	64	153.9	138.1

8	7:16-7:30	90	74.9	57	73	65.8	63	155.1	135.4
9	7:31-7:45	88	70.6	53	73	63.8	60	154.1	134.5
10	7:46-8:00	83	64.2	49	72	61	57	157.2	136.7
11	8:01-8:15	69	56	46	65	55.8	51	154.7	134.8
12	8:16-8:30	66	54.6	45	57	53.5	45	153.4	131.3
13	8:31-8:45	65	53.6	42	56	53	44	146.9	136.9
14	8:46-9:00	60	49	38	57	53.8	44	145.2	130.6
15	9:01-9:15	59	46.9	37	59	54.2	41	141.7	133.5
16	9:16-9:30	52	43.9	37	59	53.9	44	137.9	127.6
17	9:31-9:45	55	45.4	34	57	52.8	45	133.5	124.3
18	9:46-10:00	61	49	36	58	51.8	41	128.3	120.8
19	10:01-10:15	58	48.8	39	63	52.8	43	121.4	123.3
20	10:16-10:30	60	49	36	69	55.5	47	120.8	126.4
21	10:31-10:45	61	48	36	71	56.3	46	117.4	123.8
22	10:46-11:00	59	46.5	38	67.5	54.5	45	123.7	123
23	11:01-11:15	57	47.2	40	62.5	54.3	46	120.5	130.5
24	11:16-11:30	53	46.1	40	58	50.3	42	117.7	135.8
25	11:31-11:45	53	43.9	37	56	45.8	38	114.8	139.6
26	11:46-:12:00	52	42.3	34	55	44.7	38	119.1	145.1
27	12:01-12:15	53	42.3	33	54	44.7	38	122.3	144.1
28	12:16-12:30	50	42.6	35	55	45.5	39	131	142.1
29	12:31-15:45	56	42.9	35	59	47.3	38	136.9	138.5

30	12:46-13:00	59	45.8	36	60	47.5	37	137.7	132.6
31	13:01-13:15	56	47.3	36	54	46.2	41	133.4	138.7
32	13:16-13:30	60	47.2	34	51	46.3	42	132	137.3
33	13:31-13:45	60	45.7	34	56	49.7	41	131.8	138.6
34	13:46-14:00	54	45.2	36	59	51.5	43	130.1	140
35	14:01-14:15	58	48	39	56	49.1	43	135.3	133.6
36	14:16-14:30	59	49	40	54	47.4	41	135.3	138.3
37	14:31-14:45	61	49.6	40	55	48.5	42	136.3	142.7
38	14:46-15:00	66	49.4	39	56	48.3	40	137.4	139.4
39	15:01-15:15	66	48.5	38	53	46	37	134.9	141.1
40	15:16-15:30	61	47.1	36	53	47	39	137.4	143.3
41	15:31-15:45	62	47.8	37	61	50.5	41	137.9	139
42	15:46-16:00	66	52.4	38	67	55.3	43	136.6	142.2
43	16:01-16:15	66	53.6	38	65	55	42	133.3	139.5
44	16:16-16:30	65	52.6	43	57	50.2	41	133.4	133.4
45	16:31-16:45	66	54.5	48	53	49.1	44	133.7	135.5
46	16:46-17:00	71	57.1	48	55	53	45	141.7	132.4
47	17:01-17:15	79	59.4	46	62	58.8	48	140.6	138.5
48	17:16-17:30	78	59.9	46	63	57	52	139.3	131.7
49	17:31-17:45	74	57.8	46	56	53.3	51	143.7	127.5
50	17:46-18:00	66	55.3	45	55	51.7	49	140.8	132.8
51	18:01-18:15	63	55.5	47	60	51.7	46	142.8	134.3

52	18:16-18:30	66	55.6	47	62	51.5	44	141.4	132.2
53	18:31-18:45	65	53.1	43	55	49.5	44	139.7	129.3
54	18:46-19:00	63	51.7	43	57	52.2	45	135.9	129.4
55	19:01-19:15	62	51.4	45	67	60.2	51	134	129
56	19:16-19:30	63	55	47	65	56.5	49	136.1	131.1
57	19:31-19:45	64	55.4	47	58	49.3	43	131.8	128.6
58	19:46-20:00	65	54	45	57	50.5	44	128.3	121.7
59	20:01-20:15	64	53.7	44	63	56.1	47	124.2	120
60	20:16-20:30	64	53.4	46	69	60.9	51	122.8	115
61	20:31-20:45	66	54.5	46	69	61.8	52	118.8	122
62	20:46-21:00	71	57.7	46	72	65.3	56	116.8	120
63	21:01-21:15	79	65	51	74	67.5	58	111.4	120
64	21:16-21:30	81	67.9	55	77	69.8	61	115	110
65	21:31-21:45	81	65.3	54	77	69.5	61	114.4	110
66	21:46-22:00	80	63.2	52	76	68	59	106	105

The maximum, average and minimum single circle power consumption and single circle time consumption of electric bus on weekdays and weekends are shown in table 3-3 above. The trend chart of single circle power consumption on workdays is shown in Figure 3-11 below. The trend chart of single cycle power consumption on weekends is shown in Figure 3-12 below. The single cycle time consumption of electric bus is shown in Figure 3-13.

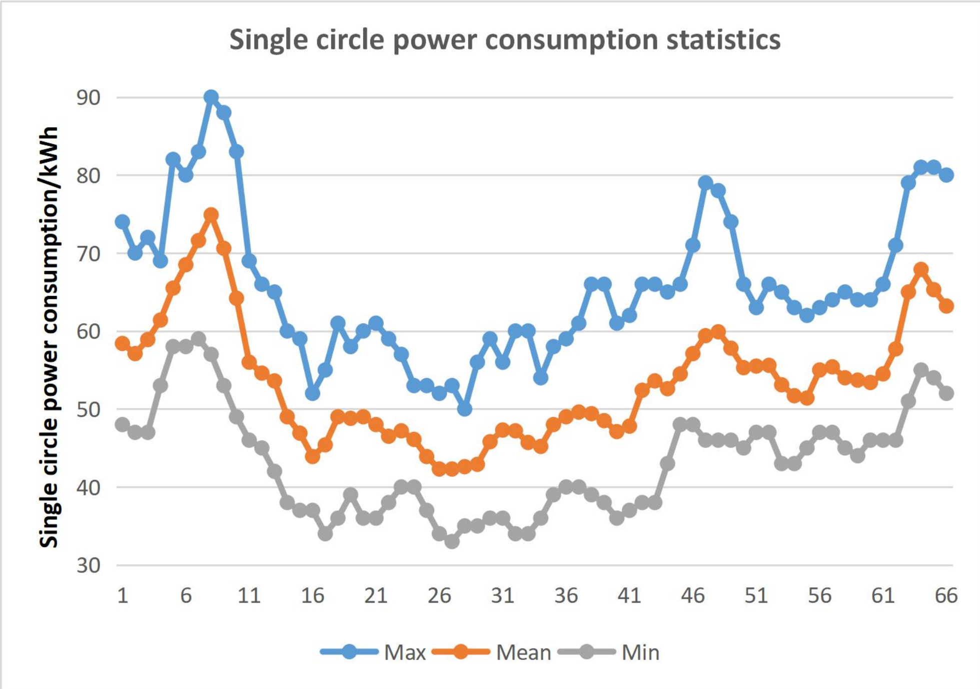


Figure 3-11 Single circle power consumption on workdays

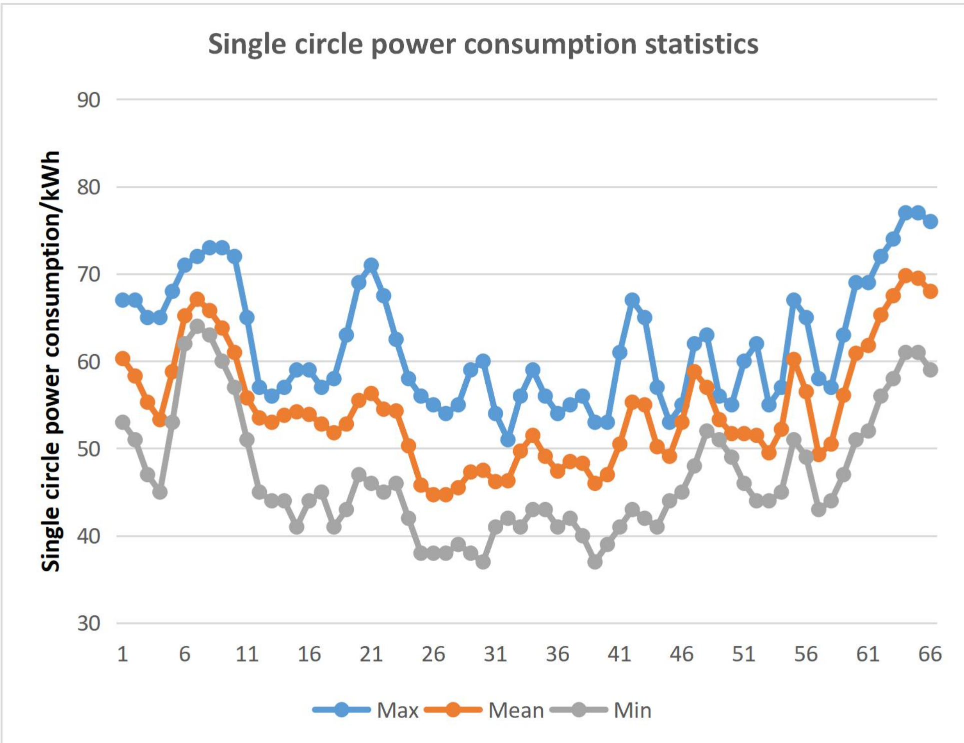


Figure 3-12 Single circle power consumption on weekends

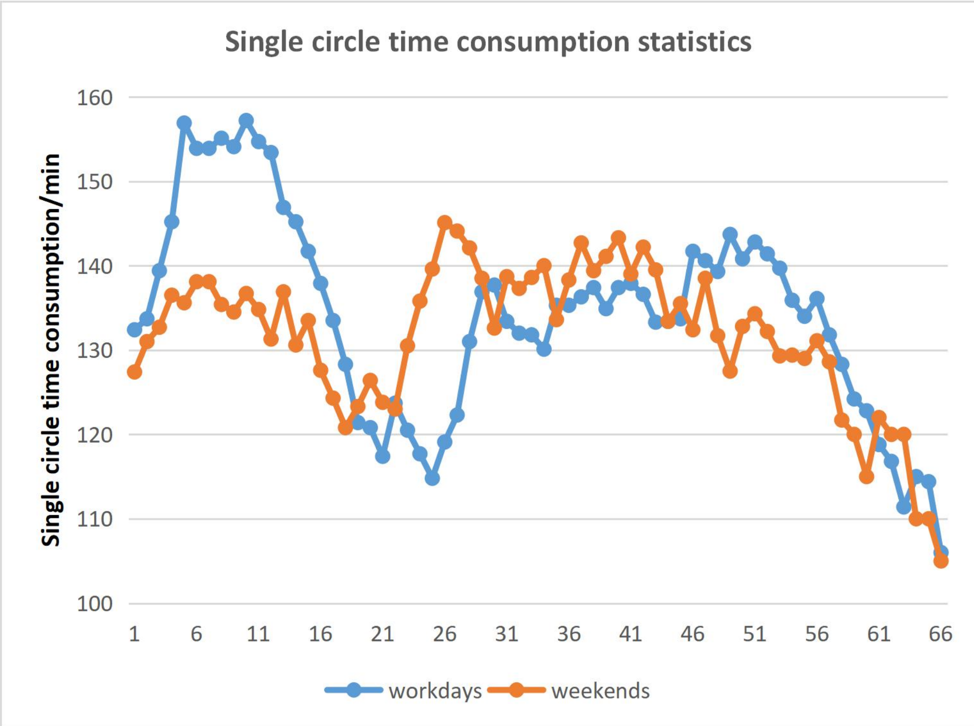


Figure 3-13 Single circle time consumption

From figures 3-11 and 3-12, it can be seen that the power consumption of electric bus in a single circle changes regularly with the departure time, and the power consumption in a single circle is relatively large in the early peak of travel. According to figure 3-13, the single circle time consumption of electric bus can be concluded: the time consumption during 7:00 to 8:20 on weekdays is relatively high, while the single circle time of electric bus during rest days is relatively stable; the single circle time consumption of electric bus starting from 18:00 is gradually decreasing; the time of electric bus starting from 9:00 to 10:45 appears a minimum value[20].

3.2.6 Fast charging optimization charging model and Implementation

At present, the number of pure electric bus fast charging stations is increasing, and the daily charging cost of electric bus charging stations is becoming more and more concerned by public transport enterprises. Based on this problem, a mathematical model is established to minimize the daily charging cost as the objective function, which satisfies the constraints of departure schedule, charging time and charging capacity of electric buses[22].

- Symbols explanation

During the building of electric bus fast charging optimization model, the following symbols are used:

N : Indicates the number of charging posts in the electric bus fast charging station;

M : Indicates the number of electric buses served by the fast charging station;

X : Indicates the number of operation routes of the electric buses;

S_T : Indicates the rated capacity of distribution transformer of electric bus fast charging station;

B_x : Represents the battery capacity of the electric bus, where x=1,2,...,X;

F_x : Indicates the battery capacity of the electric bus corresponding to the lowest SOC;

KS_{nh} : Indicates the H-th charge of charging post n;

J : Represents the number of time intervals divided in a day when the electric bus fast charging station is optimized. In this paper, j = 1440;

A : Set of departure times of electric bus, $A=\{1,2,...,a,...,A1\}$, where a is the a-th departure, $A1$ is the total number of departure;

a_m : Indicates the total number of stops for each electric bus in the next J time periods (the number refers to that the electric bus in and out of the charging station during the next J time periods), $m=\{1,...2,...,M\}$;

L : Set of departure times, $L=\{l_{10},l_{20},...,l_{mi},...,l_{MaM}\}$, in which l_{mi} indicates the i-th departure time of electric bus m;

T : Set of single circle time consumption, $T=\{t_{10},t_{20},...,t_{mi},...,t_{MaM}\}$, in which t_{mi} indicates the time consumption of i-th operation of bus m;

S : Set of arrival times of electric bus, $S=\{s_{11},s_{21},...,s_{mi},...,s_{MaM}\}$, in which s_{mi} indicates the i-th arrival time of bus m;

E : Indicates the single circle power consumption of different departure times of each bus, $E=\{E_{11},E_{21},...,E_{mi},...,E_{MaM}\}$, in which E_{mi} indicates the single circle power consumption of bus m during the the i-th operation;

W : Indicates the initial return station SOC of electric bus when it back to the station to charge, $W=\{SOC_{11},SOC_{21},...,SOC_{mi},...,SOC_{MaM}\}$, in which SOC_{mi} indicates the initial return SOC of bus m with i-th back to the charging station;

Y : Set of the remaining power capacity when bus back to station, $Y=\{Y_{11},Y_{21},...,Y_{mi},...,Y_{MaM}\}$, in which Y_{mi} indicates the remaining power capacity of bus m with i-th back to station(kWh);

D : Set of charging state of electric bus, $d_{mj}=1$,which means bus m is charged during the j-th time period, otherwise bus m is not charged during j-th time period;

C : Set of charging state of charging post, $C_{mj}=1$,which means charging post m is in charging operation to bus during the j-th time period, otherwise the charging post is not charging the bus during j-th time period;

H_d : Indicates the electricity price, H_{dj} means the electricity price during time period j;

Δt : Indicates the length of one time period,which equals 1 min;

P : Set of charging power of electric bus:

$$P=\begin{bmatrix} P_{11} & P_{12} & \dots & P_{1J} \\ P_{21} & P_{22} & \dots & P_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ P_{M1} & P_{M2} & \dots & P_{MJ} \end{bmatrix} \quad 3\text{-}11$$

P_{cj} : The maximum allowable charging power of the charger during j-th time period;

P_{aj} : The maximum allowable charging power of the charging station during the j-th time period;

P_{bj} : The maximum allowable charging power of the bus battery.

- Objective function

In this paper, the objective function of optimal charging of electric bus is to minimize the daily charging cost of electric bus charging station.

The objective function of the optimization model is as follows:

$$\min f = \sum_{j=t}^{J}\sum_{m=1}^{M}\frac{P_{mj}\cdot\Delta t}{\mu\cdot 60}\cdot H_{dj} \qquad 3\text{-}12$$

In the formula,

μ : Charging efficiency of electric bus;

H_{dj} : Indicates the electricity price during time period j;

t : Indicates the charging optimization starts from the t moment.

- Constraint condition

For the optimization model of the minimum daily charging cost of electric bus charging station, the constraints are as follows:

1. As the number of charging posts that can be used in the pure electric bus charging station is certain, it is necessary to ensure that the number of buses that are charged at the same time is not greater than the number of charging posts that can be used. The specific constraints are as follows:

$$\sum_{m=1}^{M} d_{mj} \le N, \quad j = 1,2,\ldots,J \qquad 3\text{-}13$$

In the constrain condition:

$$d_{mj} = \begin{cases} 1 & \text{bus } m \text{ is charged during time period j;} \\ 0 & \text{bus } m \text{ is not charged during time period j;} \end{cases}$$

2. As we all know, bus can not be charged before its first time back to the charge station. The specific constraints are as follows:

$$\begin{cases} d_{mj} = 0 \\ m = 1,2,...,M \\ j \in \{1,2,...,s_{m1} - 1\} \cup \{l_{m1},...,s_{m2} - 1\} \cup ... \cup \{l_{MaM},...,1440\} \end{cases} \quad 3\text{-}14$$

3. In consideration of the continuity of fast charging in the electric bus charging station, that is, it will not stop until the electric bus reaches the predetermined charging capacity or the charging time. The constraints are as follows:

We make:

$$\begin{cases} u_j \geq d_j - d_{j-1}; u_j \in \{0,1\} \\ v_j \geq d_j - d_{j+1}; v_j \in \{0,1\} \\ j \in \{s_{mi},...,l_{mi-1}\} \\ i = 1,2,...,a_m \\ m = 1,2,...,M \end{cases} \quad 3\text{-}15$$

Then the corresponding constraints are as follows:

$$\begin{cases} \sum_{j=s_{mi}}^{l_{mi}} u_j = \sum_{j=s_{mi}}^{l_{mi}} v_j \leq 1 \\ i = 1,2,...,a_m \quad ; \quad m = 1,2,...,M \end{cases} \quad 3\text{-}16$$

4. According to the enormous charging data, we found that there must be a time interval of 5 minutes between two continuous charging operation of the same charging post, the constraints are as follows:

$$KS_{n(h+1)} - KS_{nh} \geq 5 \quad 3\text{-}17$$

5. The SOC of electric buses after charging can not be lower than the the SOC lower limit F_x plus the electricity power consumed during one circle E_{mi}, the constraints are as follows:

$$\begin{cases} \left(\sum_{i=1}^{a_m} E_{mi} - Y_{mi} + F \right) \le \sum_{j=s_{mi}}^{l_{mi}} P_{mj} \cdot \Delta t / 60 \le \left(B_x - Y_{mi} \right) \\ i = 1,2,...,a_m \ ; \ m = 1,2,...,M \end{cases} \quad 3\text{-}18$$

However, in actual operation, the Y_{mi} value of other buses can not be obtained at the current time except for the newly arrived electric bus. In this case, E_{mi} is used to change inequality (4-9) to cumulative form (only containing Y_{m1}), as show in follows (4-10):

$$\begin{cases} \left(\sum_{h=1}^{i} E_{mi} - Y_{mi} + F \right) \le \left(\frac{\sum_{j=s_{m1}}^{l_{m1}} P_{mj} \cdot \Delta t}{60} + \frac{\sum_{j=s_{m2}}^{l_{m2}} P_{mj} \cdot \Delta t}{60} + ... + \frac{\sum_{j=s_{mi}}^{l_{mi}} P_{mj} \cdot \Delta t}{60} \right) \\ \le \left[\left(\sum_{h=1}^{i} E_{mi} - E_{mi} \right) + B_x - Y_{m1} \right] \\ i = 1,2,...,a_m \\ m = 1,2,...,M \end{cases} \quad 3\text{-}19$$

Inequality (3-19) means that when the electric bus returns to the station for batter charging, the total electricity shall not exceed the maximum electric capacity of the battery, i.e. $F_x + E_{mi} \le B_x$

6. From the aspects of the fast charging station, the total charging power of buses can not exceed the capacity of the distribution transformer, the constraints are as follows:

$$\sum_{m=1}^{M} P_{mj} \le \mu \cdot S_T \ ; \ j = 1,2,...,J \quad 3\text{-}20$$

From the aspects of electric bus, the charging power can not exceed the allowable charging power of the charger, the charging station and the bus battery, the constraints are as follows:

$$P_{mj} \le \min\{P_b, P_c, P_a\} \qquad 3\text{-}21$$

7. The total charging electricity should be the same with the total electricity used, the constraints are as follows:

$$\begin{cases} \dfrac{\sum_{j=s_{m1}}^{l_{m1}} P_{mj}\cdot\Delta t}{60} + \dfrac{\sum_{j=s_{m2}}^{l_{m2}} P_{mj}\cdot\Delta t}{60} + \ldots + \dfrac{\sum_{j=s_{MaM}}^{l_{MaM}} P_{mj}\cdot\Delta t}{60} = \sum_{i=1}^{a_m} E_{mi} \\ m = 1,2,\ldots,M \end{cases} \qquad 3\text{-}22$$

3.2.7 Model solution algorithm

According to the optimized fast charging model of electric bus in this paper, the process of genetic algorithm is shown in Table 3-4:

Table 3-4 Genetic algorithm solution process

Step	Calculation process
Step1	Insert the optimized charging data(number of buses,number of charging posts etc.), set initial control parameters: population size N, crossover probability P_c ,mutation probability P_m and maximum number of iterations $K_{\max}$;
Step2	Initialize the population: Randomly generate N feasible solutions $x_i(i = 1,2,...,N)$ and judge whether constraints are met, if not, then make $KS = KS_0 + Md$, otherwise calculate the fitness value of each individual f_i;
Step3	Set loop count variable K=0;
Step4	Selection operation: good individuals with high adaptability

	inherit to next generation with greater probability, and inferior individuals with poor adaptability copy to the next generation with smaller probability;
Step5	Crossover operation: Crossover operation will be conducted on individuals according to the probability of P_c , and judge whether the constraints are met, if not, $KS = KS_0 + Md$;
Step6	Mutation operation: Mutation operation will be conducted on individuals according to the probability of P_m , and judge whether the constraints are met, if not, $KS = KS_0 + Md$;
Step7	Calculate the fitness value of each new individual after selection operation, crossover operation and mutation operation;
Step8	If the target value does not change for 30 consecutive iterations, if yes, the algorithm stops and outputs the optimal solution, otherwise, it will turn to step 9;
Step9	If $K < K_{\max}$, then $K = K + 1$, and turn to step 4, otherwise the algorithm stops and outputs the relatively better solution.

3.2.8 Example

- Optimization parameter setting

The example object is the actual operation data of an electric bus fast charging station during one day in Beijing, the battery parameters of the electric bus is 580V/175Ah, F_x =0.2; There are 2 chargers in the station, the rated charging power is 450kW, and the charging efficiency of the charger is 0.98; The total number of served buses is 14 with only 1 route, and the total operation number is 67; J=1440(i.e. the time interval is 1 min). The electricity price change in one day is as follows:

Table 3-5 Parameters of electricity price

Time range	Electricity price(CNY/kWh) (1CNY=0.13EUR)
23:00-07:00	0.3944
07:00-10:00	
15:00-18:00	0.6944
21:00-23:00	
10:00-15:00	1.004
18:00-21:00	

1. Population size

According to the experience of researchers and combined with individual multiple simulation experiments, the population size is determined at 100, which can not only ensure that the population size is large enough, but also ensure that the optimal solution can be obtained within the specified time.

2. Iteration times

After 160-170 iterations, the optimal individual objective function value and fitness value tend to be stable, so the number of iterations is 250 in this paper.

3. Crossover probability and mutation probability

The common range of crossover probability is 0.5-0.8, which is selected as 0.8 in this paper; mutation operation is a random process in the thought of genetic algorithm, that is, changing some gene values on chromosome, the common range of mutation probability is 0.001-0.1, which is selected as 0.08 in this paper.

- Optimization results

The example in this chapter is the operation data of the fast charging station in a certain day. According to the operation data, two strategies of charging optimization are carried out.

Strategy 1: It does not change the charging current (400A), but only optimizes the charging power capacity and charging time of each bus.

Strategy 2: Optimize the charging current, charging power capacity and charging time of each bus.

According to the optimization of strategy 1, fitness curve of objective function value(i.e. daily charging cost of the fast charging station) is shown as figure 3-14:

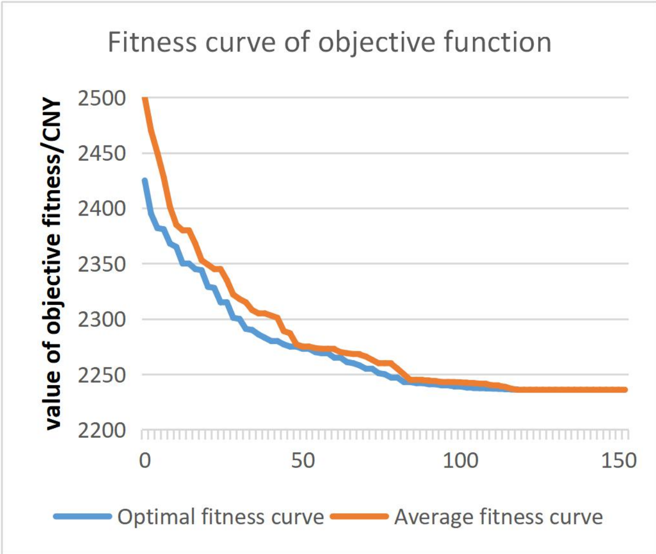


Figure 3-14 Strategy 1 objective function fitness cure

According to figure 3-14, strategy 1, that is, it does not change the charging current, only optimizes the charging time and charging power capacity, and when the number of iterations of the algorithm is 120, the target function value remains basically unchanged to 2236.19 CNY.

According to the optimization of strategy 2, fitness curve of objective function value(i.e. daily charging cost of the fast charging station) is shown as figure 3-15:

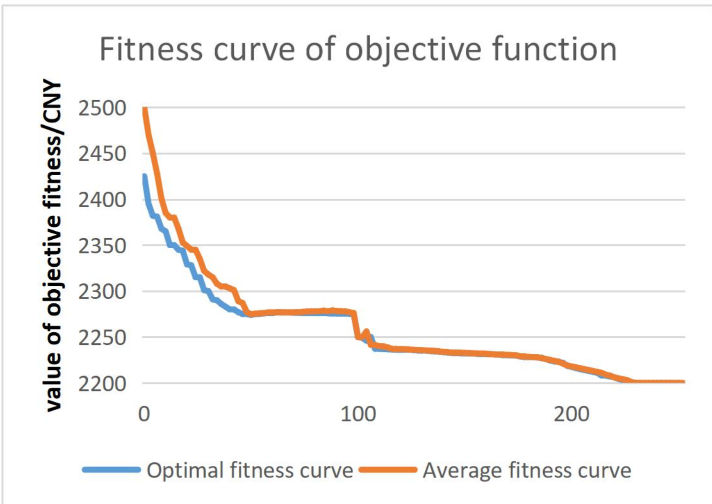


Figure 3-15 Strategy 2 objective function fitness cure

According to figure 3-15, strategy 2, that is, it optimizes the charging current, charging time and charging power capacity, and when the number of iterations of the algorithm is 230, the target function value remains basically unchanged to 2200.7 CNY.

- Comparative analysis

Under different optimization charging strategies, we can compare the optimized daily charging power capacity and charging cost of this fast charging station with the present situation, which is as follows:

Table 3-6 Comparison of charging power capacity

	Charging capacity at peak price(kWh)	Charging capacity at peace time(kWh)	Charging capacity at valley time(kWh)	Total capacity(kWh)
Present	1605.33	1554.12	2.55	3162
Strategy 1	867.43	1526.33	768.24	3162
Strategy 2	840.21	1495.99	825.8	3162

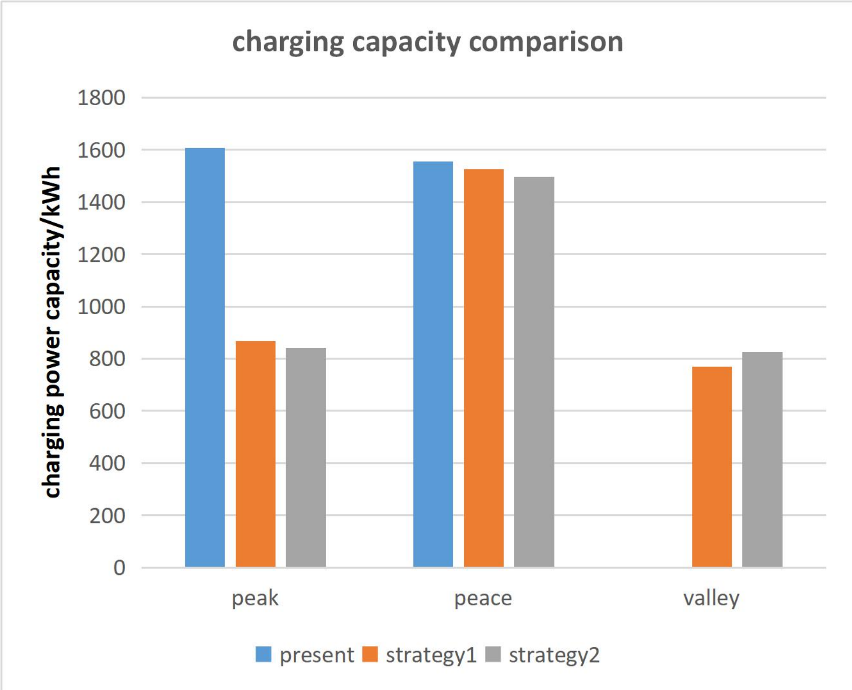


Figure 3-16 Charging power capacity comparison

It can be seen from table 3-6 and figure 3-16 that compared with the present charging status, the charging capacity of strategy1 of electric bus mainly moves from the peak price area to the valley price area; the charging capacity of strategy2 mainly moves from the peak price area to the valley price area, and the charging capacity of the peace price area is also significantly reduced.

The daily charging cost of the electric bus fast charging station is also compared in the follows:

Table 3-7 Comparison of daily charging cost at different area

	Cost at peak price(CNY)	Cost at peace price(CNY)	Cost at valley price(CNY)	Total cost(CNY)
Present	1612.39	1080.11	1.01	2693.51
Strategy 1	871.24	1060.80	303.15	2236.19
Strategy 2	829.43	1039.71	331.55	2200.7

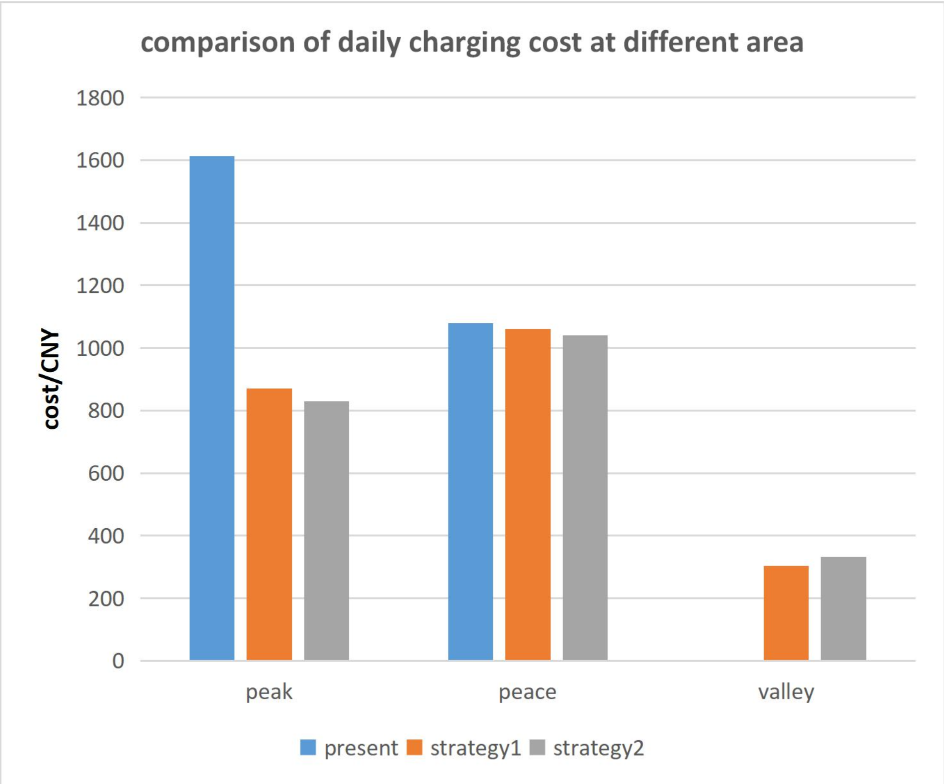


Figure 3-17 Comparison of daily charging cost at different area

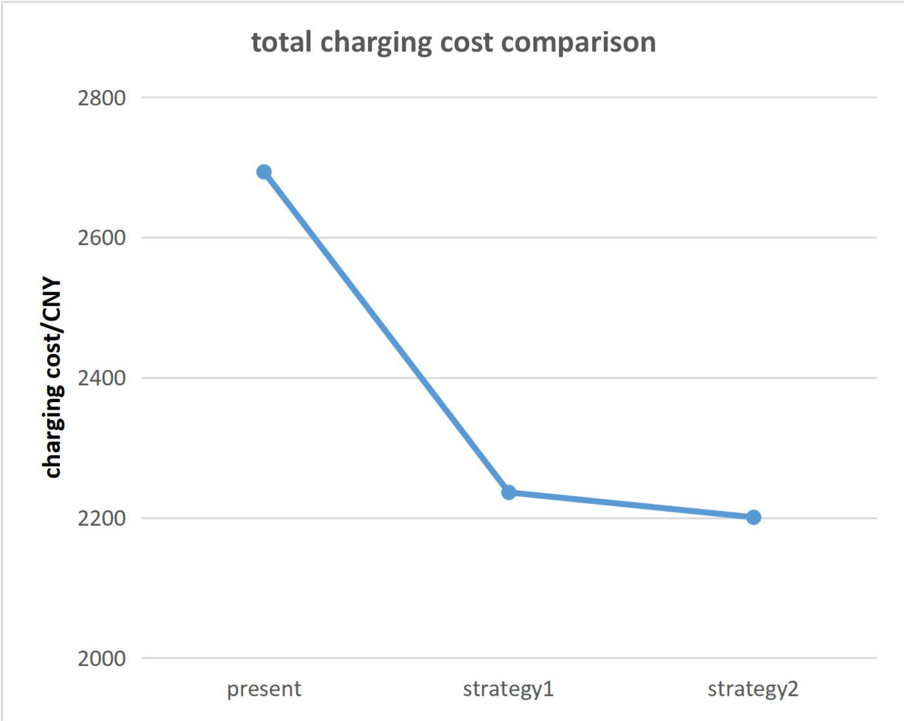


Figure 3-18 Comparison of total daily charging cost

It can be seen from table 3-7 and figure 3-17 that the charging cost of the two charging strategies at peak price area is much less than present status, and the charging cost in valley price area is significantly increased, and we can see from figure 3-18 that the overall charging cost during one day is greatly reduced.

Chapter4 Battery Switching Mode Optimization

4.1 Introduction of Battery Switching Mode

The battery switching mode adopts the way of replacing the bus battery directly. The vehicle does not charge itself. The replaced battery is charged and distributed uniformly. Replacing the battery is the fastest way to charge at present, which is used in the case that the vehicle can not have enough time to charge. It is difficult for the electric bus to have enough time to charge the whole vehicle in the daytime operation process, and the battery specifications and models of the electric bus are unified, which provides the premise for battery exchange. At present, most of the electric buses in our country use the battery exchange mode. During the daytime operation, their batteries need to be changed at least once, and the electric buses do not need to be changed during the rush hour.

The main advantage of power exchange mode is that centralized charging is convenient for unified scheduling, management and monitoring, and it can make full use of the low price period of power load at night. This not only saves the operation cost of the electric bus, but also can play the role of peak load reduction and valley filling to the greatest extent, improve the load rate of the power system, which is conducive to the safe and stable operation of the power grid and the optimal utilization of power resources. In addition, the use of electricity exchange can reduce the space needed for parking and charging, especially for cities with expensive land capital.

4.2 Optimization of Battery Switching Charging Mode

4.2.1 Analysis of Battery Switching Demand

Bus routing is fixed, and the same type of bus has similar conditions and strong running regularity. Therefore, we can use relevant information to simulate and calculate the operation process of the bus, and analyze the changing demand of each bus line, that is, the number of batteries that the bus line needs to replace in each unit period of time in a day. Furthermore, according to the requirements of battery replacement, balanced use of batteries and battery charging, the replacement sequence of batteries is optimized. In order to arrange the replacement sequence of batteries in each round reasonably and generate the optimal replacement sequence table of batteries, i.e. the optimization table of battery replacement, it is necessary to combine the operation law of electric buses and comprehensively measure the number of batteries used, the unloading period and the state of power consumption.

Considering that in the future, electric buses can be dispatched by the dispatching center of the bus company according to the passenger flow and road traffic condition of the running line, and the departure schedule can be worked out. Therefore, the battery energy loaded on the electric buses must meet the minimum energy requirement of this trip. If the energy does not meet the requirement, we need to replace it with a well-charged battery. Therefore, according to the departure schedule of the bus line, considering comprehensively the total number of vehicles, power consumption, speed and mileage of the bus line, an electric bus line can be analyzed. The calculation process of power exchange demand is shown in Figure 4-1.

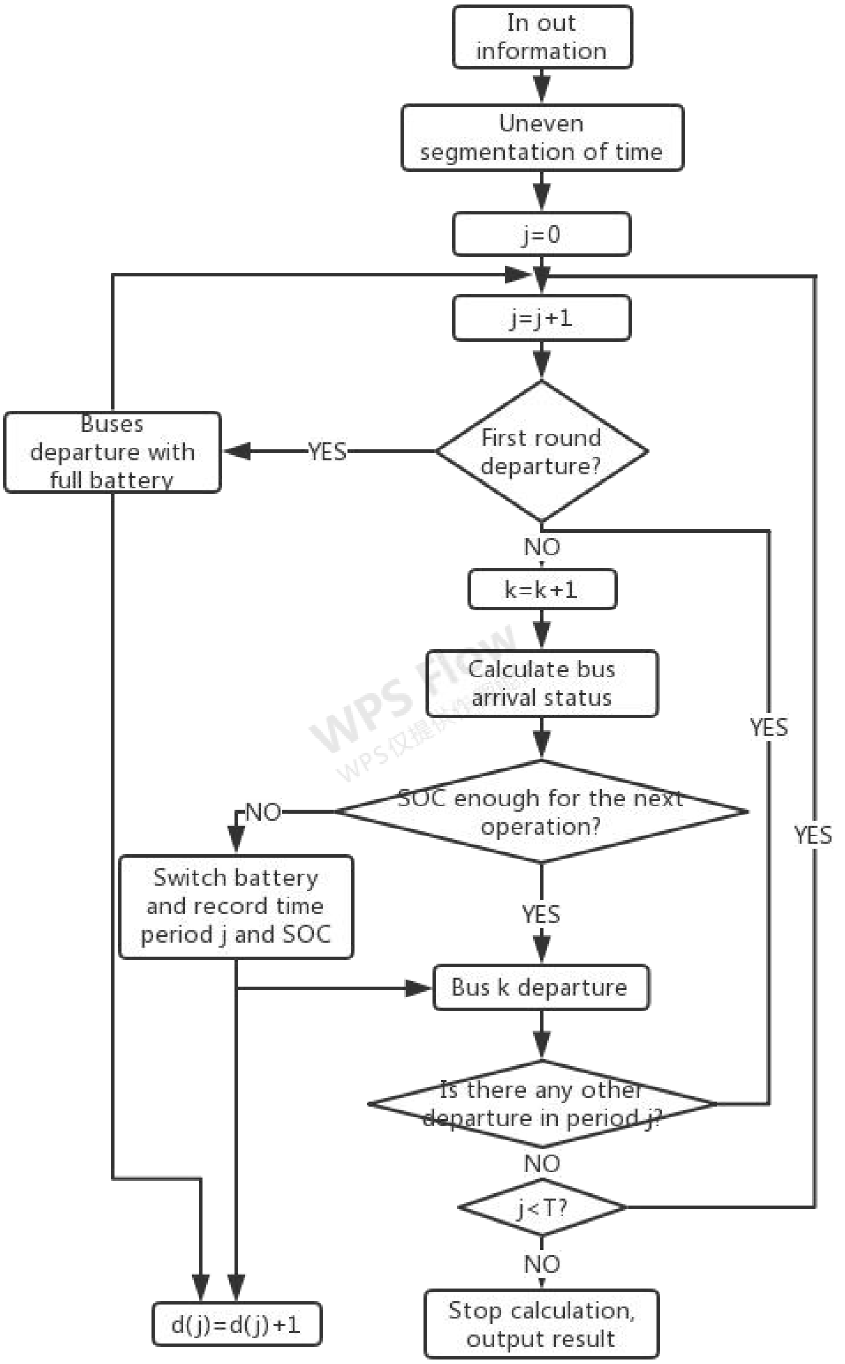


Figure 4-1 Calculation process of power exchange demand

The basic information input in the analysis and calculation of battery exchange demand includes the departure schedule of the route, the number of vehicles allocated of this route, the capacity of the battery pack, the initial state of charge (SOC) of the battery pack, driving mileage, speed and power consumption, etc.

Taking one day (1440 min) as the research cycle, the battery replacement of electric bus only occurs during the operation period. Therefore, two time intervals τ 1 and τ 2 (τ 1 < τ 2) are used to segment the operation and non-operation periods unevenly. This method can reduce the intensity of non-operation period segments, reduce the amount of calculation and ensure the accuracy of battery exchange demand analysis.

The relationship between bus departure and arrival time and battery SOC is described as follows:

$$w_i^k = \mu_i^k + \frac{R}{V_i}\frac{60}{\tau_1} \quad 4\text{-}1$$

$$S_i^k = S_i^{k-1} - \frac{RE_i}{B_i} \times 100\% \quad 4\text{-}2$$

In the formula: μ_i^k is the departure time of the k-th operation of the vehicle i; w_i^k is the arrival time of the k-th operation of the vehicle i. R is the expected run mileage; V_i is the average speed of vehicle i; s_i^k is the battery pack SOC of the k-th departure of vehicle i ; E_i is the power consumption per unit mileage of vehicle i; B_i is the battery pack capacity of vehicle i.

The battery SOC in each departure time period and arrival time period of each bus can be calculated. Assuming that the next normal bus operation requires the lowest SOC of the battery pack to be M, when the

S_i^k < M is measured, the battery pack need to be replaced, and the time for the vehicle i to replace the battery is obtained. Calculating each vehicle can get the demand for battery exchange of this bus line.

4.2.2 Battery Switching Sequence Optimization

Through the analysis of the demand for battery exchange, the number of batteries needed totally in a certain period of time can be predicted. Among the batteries not designated in the battery switching station, the batteries with the greatest remaining capacity should be selected as the reserve batteries to meet the next battery-changing demand. On the other hand, considering the service life of batteries and battery maintenance, all batteries should be used equally. To sum up, the principles of battery exchange sequence optimization include:

1. For the first round of battery changing in the station (with all vehicles changing batteries once for one round), the changing order is arranged according to the initial SOC size of the batteries;

2. When there are batteries in the station that are replaced by this round from the buses, priority should be given to batteries that are not replaced in the previous round;

3. The unloading time and residual power of the battery pack are considered comprehensively for the battery pack replaced in the same round.

According to the above principles, the battery replacement sequence table (battery replacement optimization table) can be formed by the following steps:

Firstly, the batteries are numbered according to the size of the initial SOC and the battery pack information, and the batteries numbered m and n are illustrated as examples.

$$S_m^{\ 0} > S_n^{\ 0} \Leftrightarrow m < n \qquad 4\text{-}3$$

Priority should be given to batteries with smaller number when arranging the first battery switching round.

For the k-th round of battery switching, two factors are considered: the remaining power of battery pack under k-1-th round unloading and the time period of replacement. Table 4-1 is a battery unloading information table. Taking the unloading information of battery m and n in the k-1 round as an example, the unloading time period and SOC can be seen from the table.

Table 4-1 Unloading information of battery

Battery	Time period						
	1	...	$t_m^{\ k-1}$	...	$t_n^{\ k-1}$	...	T
m	0	...	$S_m^{\ k-1}$	...	0	...	0
n	0	...	0	...	$S_n^{\ k-1}$	...	0

It is necessary to compare the advantages of batteries with different unloading time and different residual capacity in the next stage of charging process. The batteries with advantages can arrange earlier replacement time, that is, priority replacement and boarding. The variable $a_{mn}{}^{k}$ is introduced to indicate the switching advantage of battery m and battery n in K-th round:

$$\Delta t_{mn}{}^{k-1} = t_{n}{}^{k-1} - t_{m}{}^{k-1} \qquad 4\text{-}4$$

$$a_{mn}{}^{k} = \left(S_{m}{}^{k-1} B_{m} - S_{n}{}^{k-1} B_{n}\right) + P \frac{\Delta t_{mn}{}^{k-1}}{60} \qquad 4\text{-}5$$

In the formula, $S_{m}{}^{k-1}$ 、 $S_{n}{}^{k-1}$ and $t_{m}{}^{k-1}$ 、 $t_{n}{}^{k-1}$ are the remaining SOC and unloading time of battery pack m and n during the k-1 unloading. Formula 4-5 item 1 in the right side denotes the advantage of battery pack m over n in remaining electricity. Item 2 denotes that battery pack m uses the time of first return to the station to charge with power P to convert the advantage of time into the advantage of electricity. These two parts constitute the battery exchanging advantage of battery pack m to n in round k. If $a_{mn}{}^{k}$ > 0, it means that the battery pack m should be replaced first in the k-th switching round. Otherwise, the battery pack n should be replaced first. The following formula proves that the switching advantage of m and n two battery packs can be derived from the switching advantage of the third battery pack l respectively. Assume that the relationship $a_{ml}{}^{k} < a_{nl}{}^{k}$ is already known, then we have:

$$\begin{cases} a_{nl}{}^{k} = \left(S_n{}^{k-1} - S_l{}^{k-1}\right)B + P\dfrac{\Delta t_{nl}{}^{k-1}}{60} \\ a_{ml}{}^{k} = \left(S_m{}^{k-1} - S_l{}^{k-1}\right)B + P\dfrac{\Delta t_{ml}{}^{k-1}}{60} \\ a_{mn}{}^{k} = \left(S_m{}^{k-1} - S_n{}^{k-1}\right)B + P\dfrac{\Delta t_{mn}{}^{k-1}}{60} \\ \quad = \left(S_m{}^{k-1} - S_l{}^{k-1} - S_n{}^{k-1} + S_l{}^{k-1}\right)B + P\left(\dfrac{\Delta t_{ml}{}^{k-1}}{60} - \dfrac{\Delta t_{nl}{}^{k-1}}{60}\right) \\ \quad = a_{ml}{}^{k} - a_{nl}{}^{k} < 0 \end{cases} \tag{4-6}$$

In the formula, $a_{ml}{}^{k}$ and $a_{nl}{}^{k}$ represent the switching advantage of the battery pack m and n relative to the battery pack l in the k-th battery switching round, respectively. $a_{mn}{}^{k}$ represents the switching advantages of battery pack m to n in the k-th round. Formula(6) proves that when the relationship $a_{ml}{}^{k} < a_{nl}{}^{k}$ is known, we will have $a_{mn}{}^{k} < 0$,which means the battery pack n has the priority. In round k, the order of battery exchange can be obtained by calculating the battery exchange advantages of all batteries relative to a certain reference battery pack, and then the bus battery switching demand can be allocated according to the order. Then, according to the operation law of the bus, the unload time period of battery pack which is loaded on the bus in k-th round can be deduced in the next round.

In summary, according to the above principles and algorithms, the time period for each battery pack to be loaded and unloaded in each switching round process can be obtained by recursive calculation of the process of each switching round. Optimized battery switching table is shown in the below as table 4-2. Each battery pack corresponds to one row of the table. The load time period of the batteries is marked with number 1 and the unloading time period of the batteries is marked with number 2. Battery pack m is illustrated as an example.

Table 4-2 Optimal battery switching table

Battery	Time period						
	1	...	t1	...	t2	...	T
m	0	...	1	...	2	...	0

4.2.3 Charging optimization

- Two-stage charging optimization

By the optimal battery switching table, it can be seen that the first controllable charging period of any group of battery is from the start time to the first time when the batteries are loaded on the bus, and the later controllable charging period is from the unloading time of the previous round to the time when the batteries are loaded on the bus again. Charging optimization must be carried out within the controllable charging period of each battery to ensure the arrangement of the batteries according to the optimal battery switching table. On the other hand, taking the charging power of each group of batteries in each unit time period as the control variable, considering the different electricity price in different time periods and reducing the impact of battery charging on the power grid, the charging optimization can be divided into two stages and we can establish mathematical optimization models to solve the problems respectively. In the first stage, the objective function of charging optimization is to minimize the charging cost and obtain the lowest charging cost.In the second stage, under the constraints of the lowest charging cost obtained in the first stage, the final optimal charging control strategy is obtained by smoothing the charging load curve.

1. Charging optimization in the first stage

First stage optimization target

Under the conditions of different charging prices in different periods, the objective is to minimize the charging cost.

$$\min f = \sum_{j=1}^{T}\left(c_j t_j \sum_{i=1}^{N} x_{ij} \right) \qquad 4\text{-}7$$

Formula: x_{ij} is the decision variable to express the charging power of charger to battery group i in unit time period j; c_j is the electricity price in unit time period j; t_j is the time length of time period j; and N is the total number of batteries.

Constraint condition

Constraint equations are established for each battery group according to the optimal battery switching table. Formula 4-8 denotes that the battery pack i is fully charged in the k-th controllable charging time period; Formula 4-9 denotes that the charging power is 0 or varies between $P_{\min i}$ and $P_{\max i}$.

$$\sum_{j=r}^{g} \frac{x_{ij} t_j}{B_i} \geq S_{on}{}^{k} - S_{off}{}^{k-1}, \quad i = 1,2,\ldots,N \tag{4-8}$$

$$x_{ij} = 0 \ \ or \ \ P_{\min i} \leq x_{ij} \leq P_{\max i} \tag{4-9}$$

In the formula, r is the starting time of the charging of the battery group i in the k-th round, i.e. the (k-1)-th unload time plus the time of the switching operation(instant); g is the termination time of the charging of the battery group in the k-th round, i.e. the time of the load operation subtracts the time of switching operation(instant). $S_{off}{}^{k-1}$ is the SOC of the battery pack i when it is unloaded in the (k-1)-th round , that is, the initial SOC of the charging in k-th round, and $S_{on}{}^{k}$ is the SOC to be reached at the end of charging.

2. Charging optimization in the second stage

Second stage optimization target

On the basis of the first stage optimization, the objective of optimization is to reduce the fluctuation of charging load and smooth the curve of charging load.

$$\min f = \sum_{j=1}^{T} \left(\sum_{i=1}^{N} x_{ij} \right)^2 \tag{4-10}$$

Constraint condition

On the basis of formula 4-8 and formula 4-9 constraints, the minimum charge cost constraint obtained in the first stage is added. The expression of the constraints are as follows:

$$\sum_{i=1}^{N}\left(\sum_{j=r}^{g} c_j t_j x_{ij}\right) \le f_1 \qquad 4\text{-}11$$

f_1 is the optimal charging cost obtained in the first stage. In this way, the sum of charging cost in each controlled charging time interval (excluding the period when the battery can not be charged on the vehicle) can be less than the optimal charging cost.

- Two-target charging optimization

The essence of the two-stage charging optimization is to minimize the fluctuation of charging load when the charging cost is the lowest. Therefore, charging cost and load fluctuation can be regarded as two sub-goals, and a two-objective optimization model can be established. The weight coefficient is introduced to coordinate the proportion of the two objectives.

Optimization target

The objective function is:

$$\min f = \beta_1 \sum_{j=1}^{T}\left(c_j t_j \sum_{i=1}^{N} x_{ij}\right) + \beta_2 \sum_{j=1}^{T}\left(\sum_{i=1}^{N} x_{ij}\right)^2 \qquad 4\text{-}12$$

In the formula,item 1 on the right hand represents the charging cost target and item 2 on the right hand represents the load fluctuation target. β_1 and β_2 are weight coefficients of two targets respectively. According to the Linear Weighting Method, we got: $\beta_1 + \beta_2 = 1$. Then formula 4-12 becomes:

$$\min f = (1-\beta)\sum_{j=1}^{T}\left(c_j t_j \sum_{i=1}^{N} x_{ij}\right) + \beta \sum_{j=1}^{T}\left(\sum_{i=1}^{N} x_{ij}\right)^2 \qquad 4\text{-}13$$

Using the value of m to adjust the magnitude of the target value of load fluctuation, so that it is less than the magnitude of the target value of charging cost, so as to minimize the charging cost as a whole.

Constraints condition

The charging process is also limited by the optimal battery switching table above and charging power, so the constraints are the same as the first stage optimization constraints condition in the two-stage charging optimization, i.e. formula 4-8 and formula 4-9.

Analysis of Starting Time and Uncertainty Factors

4.2.4 Start time of optimization

In order to reduce the cost of charging on that day, the last round of charging will only charge some of the batteries needed for the last switching round, so the daily valley price period is not fully utilized. Therefore, it is important to determine the optimal starting time.

When the starting time of optimization is changed from 0-24p.m. to time period t of the previous day to time period t of today, there will be two situations: 1) there is no demand for battery exchange from t+1 period to 24p.m., which can be directly put forward as an extension of the first charging period; In the case that there is a power-changing demand, since the charging control on that day stops at the time period t, it is necessary to meet the later power-changing demand before t. So the later power-changing demand should be transferred to the time t, and then time period t is pre-positioned. According to the above method, the model is solved again to analyze the effect of optimization start time on the results.

4.2.5 Consider uncertainties

Considering the influence of uncertainties in actual operation, such as temporary departure of bus and failure of battery pack, it is required that the proposed optimal operation scheme can still provide enough battery packs for bus lines to be replaced under certain disturbances.

One method is to set up redundant available batteries, which requires more batteries to be charged than the actual demand before the start of each round of battery switching; the other method is to add fast charging facilities in the battery switching station to meet the switching demand beyond expectation.

4.2.6 Example

- Background of example

According to the characteristics of electricity load curve, the time-sharing price of a city in China can be divided into three time periods: peak time, normal time and valley time, each of which is 8 hours. Peak time: 10:00-15:00, 18:00-21:00; normal time: 07:00-10:00, 15:00-18:00, 21:00-23:00; valley time:23:00-07:00. Assuming that the standard of peak-valley price for industrial and commercial electricity in this city is adopted in the example, the valley price is 0.365 CNY, the peak price is 1.164 CNY and the average price is 0.754 CNY.

The electric bus line that has been put into operation in this city is circular, with a total length of 30 km and a departure interval of 10-15 minutes. After running a circle, the bus loads and unloads the batteries mechanically and carries out unified charging management. At present, the charging rate of conventional slow charging is 0.1-0.2C, and the theoretical fully charging time is about 5-10 hours. According to the current situation of electric bus, combined with the development of electric vehicle technology, the reasonable design of electric bus example is carried out.

The example considers the case that two bus lines running circularly with different routes share one battery charging and switching station. Assume that the relevant parameters of electric bus, battery, etc. and departure schedule are known as following table 4-3 and table 4-4.

Table 4-3 Bus departure time table

Time	Bus line 1		Bus line 2	
	Departure quantity	Departure interval/min	Departure quantity	Departure interval/min
06:00-07:00	20	3	15	4
07:00-08:00	30	2	20	3
08:00-09:00	12	5	12	5
09:00-10:00	10	5	10	5
10:00-11:00	10	6	10	5
11:00-12:00	10	6	9	6
12:00-13:00	10	6	9	6

13:00-14:00	8	7	8	7
14:00-15:00	6	9	6	9
15:00-16:00	6	9	6	9
16:00-17:00	15	4	10	6
17:00-18:00	20	3	15	4
18:00-19:00	6	9	6	9
19:00-20:00	4	15	4	15
20:00-21:00	3	20	3	20
21:00-22:00	2	30	2	30
22:00-23:00	1	60	1	60

Table 4-4 Relevant bus parameters

	Bus line 1	Bus line 2
Battery pack capacity/(kW.h)	220	200
Mileage of route/km	38	40
Average power consumption per kilometer/(kW.h)	1.3	1.2
Time of battery switching/min	10	10
Quantity of buses	50	45
Number of standby batteries	20	15
Average speed/(km/h)	30	45

At the same time, considering the actual situation, even for the same type of bus, there will be differences in power consumption and driving speed among different individuals. The corresponding parameters in the model are simulated by random numbers with bounded normal distribution. In practical application, the above parameters of each bus can be determined according to the operation data.

- Analysis of Battery Switching Demand

Firstly, the algorithm proposed in the above is used to analyze the battery switching demand of bus lines. In the operation period(06:00-23:00), the interval is 5 minutes, and in the non-operation period, the interval is 15 minutes. After the unequal segment of a day, 232 periods are obtained. The number of batteries that need to be replaced in each time period of the electric bus line is analyzed. The results are shown in Fig4-2 and 4-3.

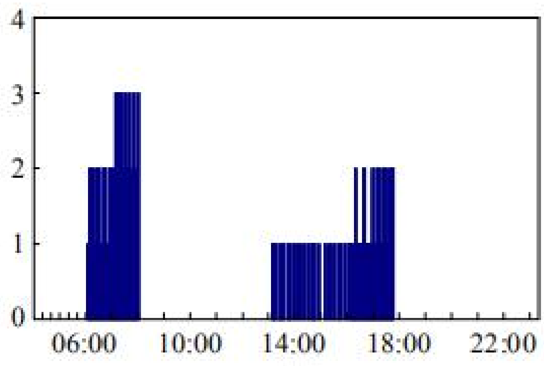


Figure 4-2 Battery demand of bus line1 during one day

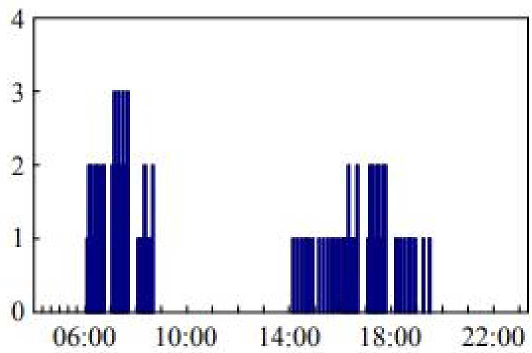


Figure 4-3 Battery demand of bus line2 during one day

Bus line1 gets 166 times of departure a day and battery packs are replaced 100 times; Bus line2 gets 141 times of departure a day and battery packs are replaced 90 times. All buses on the line departure at one time, which is called one-round departure. The first round of operation will generate the first demand of battery switching, but when the second round starts, there is no demand for battery switching because the remaining battery power after the first round of operation is enough for the second round. Because of the accumulated power consumption during several rounds of bus operation, the demand for battery switching of second time is formed at the third or fourth departure as shown in figure 4-2 and figure 4-3.

- Charging load without switching and charging optimization

No optimization means that the batteries will be charged immediately after they are replaced from the electric bus, and the batteries will be replaced and charged according to the principle of "first in first out". If necessary, the charging power will be increased to meet the needs of the following buses. Figures 4-4 and 4-5 show the charging load of electric bus line 1 and electric bus line 2 without switching and charging optimization.

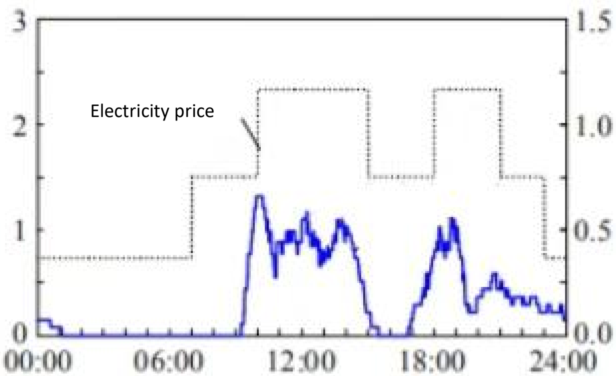


Figure 4-4 Charging load of bus line1 without optimization

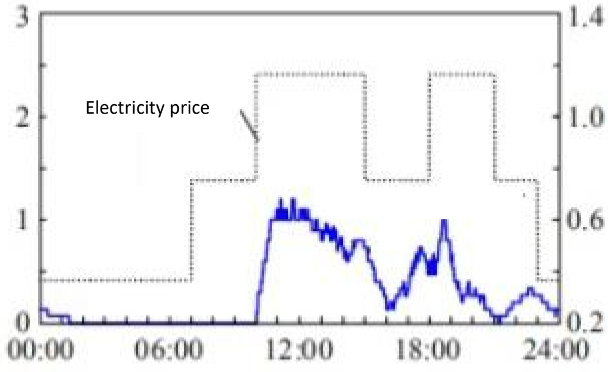


Figure 4-5 Charging load of bus line2 without optimization

The results show that the daily charging cost of electric bus line 1 without charging and switching optimization is 8471 CNY, and that of line 2 without charging and switching optimization is 7767 CNY. From the figure, it can be seen that the charging load is affected by the behavior of electric bus battery switching. Failure to make good use of the valley price time period to charge the batteries, and this will increase the load of the power grid during the peak price period.

- Charging load with switching and charging optimization

1. Two-stage charging optimization

The charging load of electric bus line 1 and line 2 after charging and switching optimization is shown in figure 4-6 and 4-7.

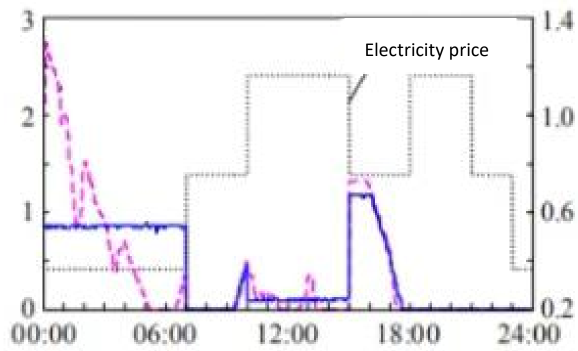


Figure 4-6 Charging load of bus line1 after two-stage optimization

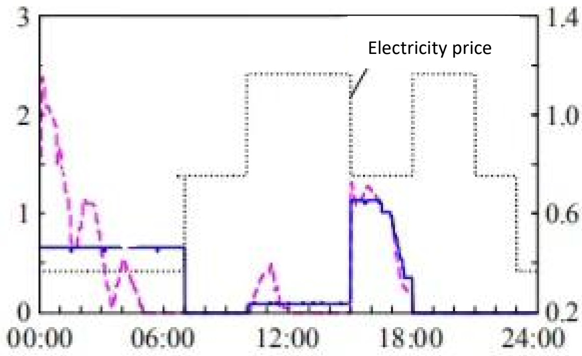


Figure 4-7 Charging load of bus line2 after two-stage optimization

The daily charging cost of electric bus line 1 is 4680 CNY after charging and switching optimization, and that of electric bus line 2 is 4199 CNY after charging and switching optimization. Compared with no optimization, the proposed optimal switching and charging method can distribute charging load reasonably in different time periods during one day, so that the charging load can be concentrated in the period of valley price and parity price, thus greatly reducing the charging cost, balancing the use of batteries and prolonging the service life. In addition, by smoothing and optimizing the charging curve in the second stage, the impact of charging power fluctuation on the power grid is greatly reduced, which is conducive to the stable operation of the power grid.

2. Two-target charging optimization

According to the two-stage charging optimization, the magnitude of the target value of charging cost is 10^3 and the magnitude of the target value of load fluctuation is 10^7, so the weight coefficient is $\beta = 1\times10^{-6}$. The result of two-target charging optimization of bus line1 with

$\beta = 1\times10^{-6}$ and $\beta = 1\times10^{-4}$ is shown in figure 4-8.

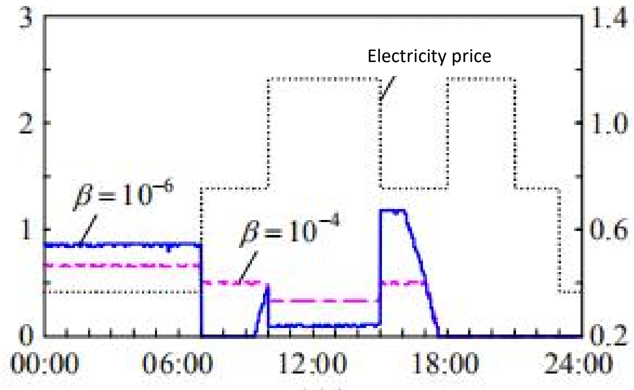


Figure 4-8 Two-target charging optimization of bus line1

When $\beta = 1\times10^{-6}$, the target value of charging cost is dominant. The calculated charging cost is 4,680 CNY, which is consistent with the result of two-stage charging optimization. When $\beta = 1\times10^{-4}$, the target value of charging cost is the same order of magnitude as the target value of load fluctuation, indicating that both the charging cost and fluctuation are equally important. At this time, the charging cost is 5,630 CNY. This is to reduce the fluctuation of charging load at the cost of increasing charging cost. So we have to choose a appropriate weight coefficient.

- Impact Analysis of Charging Starting Time

Figure 4-9 shows the starting time of 23:00 yesterday, that is, from 23:00 yesterday to 23:00 today, the charging diagram of electric bus line1 obtained by the same charging and switching optimization control strategy. At this time, the optimal cost is 4,680 CNY, which is the same of that from 0 to 24. However, compared with the charge curve in Fig4-8, the overall power is reduced. By advancing the starting time of charging, the charging time during the valley period is increased, and the charging power is reduced under the same charging energy. If the starting time is further advanced, the charging cost will increase because of the demand for battery switching during the period. Therefore, the period of the last battery switching of the bus line is regarded as the best starting time of daily optimal control cycle, which will not increase the charging cost, but also help to reduce the overall charging power and reduce the impact of charging on the power grid.

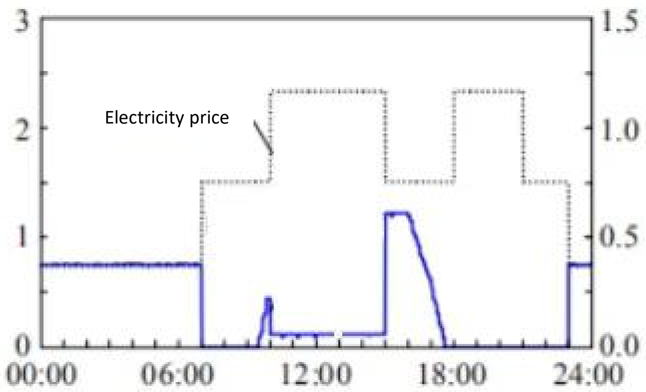


Figure 4-9 Charging figure of bus line1 with starting time from 23:00 of yesterday to 23:00 of today

- Impact analysis of the number of standby batteries

The number of standby batteries in the battery switching station is an important parameter affecting the replacement and charging arrangement of batteries. Fig 4-10 shows the change of optimal charging cost of electric bus line 1 in different number of backup batteries.

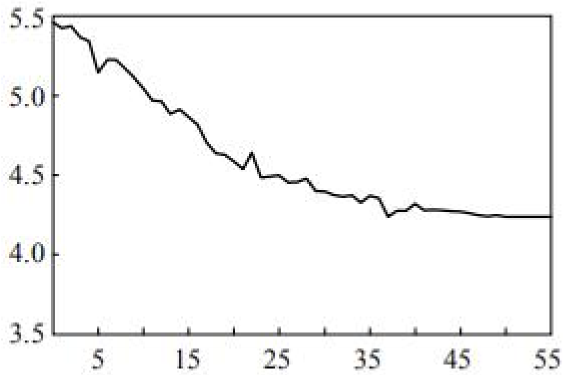


Figure 4-10 Impact of the number of standby batteries

On the whole, charging cost decreases as the number of standby batteries increases. The main reason is that the increase in the number of batteries makes more battery packs available for battery charging and switching. As a result, the impact of vehicle operation on charging is weakened, and more battery packs will be left in the station to make better use of the valley price period for charging.

It can also be seen from Figure 4-10 that when the number of standby batteries is small, the charging cost during one day decreases rapidly with the increase of the number of batteries, while when the number of standby batteries is large, the cost decreases slowly or basically unchanged. When the number of standby batteries of the line equals to the number of daily battery switching in the line, all the electricity energy needed in the day can be fully replenished in the period of low electricity price with the lowest charging cost; and increasing the number of batteries will not reduce the overall charging cost any more. In short, the number of standby batteries should be decided by taking into account the demand for battery switching, battery cost and charging cost.

Chapter5 Conclusion

Under the background of the rapid development of new energy vehicles and the promotion of energy conservation and emission reduction, aiming at the problem that the daily charging cost of electric bus charging station is on the high side, this paper studies the existing new energy electric buses in China and optimal charging strategy of electric bus charging station in combination with the research status of electric vehicle charging, electric bus battery switching station and electric bus fast charging station. On one hand, by comparing the charge and discharge experiments of lithium-ion battery and super capacitor, we can clearly know the advantages and disadvantages of lithium-ion battery electric bus and super capacitor bus, so as to make corresponding improvement and upgrading of these two buses in the future development of new energy vehicles, so as to achieve higher energy utilization and lower energy consumption. On the other hand, through the research of charging optimization strategies of electric bus battery switching mode and fast charging mode, we can see directly that the daily charging cost of electric bus is obviously reduced, the impacts on the power grid due to the large scale of charging buses at the same time is eased as well.

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