

Research on application of lithium titanate battery in auxiliary system of rail vehicle

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Abstract. By real-time acquisition information of lithium titanate battery packs and single battery in the auxiliary battery system of rail vehicles, we have extracted the operating condition of the train auxiliary battery system, and emphatically established the battery float charging test under the influence of temperature, voltage and other factors. Then have analyzed the aging state information of the battery. Combined with the thermodynamic and dynamics characteristics of the power battery, established the law of change of the battery characteristic parameter with the battery float charge, and determined the recession mechanism of battery

1. Introduction

At present, power accumulator is widely used in auxiliary power system in rail transit vehicles, its main function is to act as an emergency backup power for the vehicle load (such as air conditioning, ventilation, lighting, lift bow, etc.) power supply [1, 2] in case of the vehicle power supply network fault, lack of catenary voltage or current transformer fault,. The lead acid and nickel cadmium battery are still mainly applied in rail vehicles auxiliary power system, however, the two types of battery exist problems such as larger mass volume, longer charging time, shorter service life and heavy metal pollution [3]. Power lithium-ion battery has advantages of light weight, small volume, long service life, high voltage, high efficiency of charge and discharge and no pollution, so it has been widely used in the field of new energy vehicles and power grid energy storage, but its application in the field of rail transit is in its infancy [4]. Among a variety of power type lithium-ion batteries, lithium titanate battery that applies lithium titanate materials as the cathode of batteries, has better low temperature properties, and the battery cathode surface does not form the SEI film, so it has a higher security and longer service life and make it become one of the most potential applications of battery in rail transit field [5]. In order to meet the requirements for lightweight, pollution-free and long life of the rail vehicle batteries, the DC 110V auxiliary power source of the rail vehicle is gradually using lithium titanate battery as the battery power supply system. On the basis of ensuring the emergency power supply function of the system, it also provides preparation for the large-scale promotion of future rail vehicles and the formulation of the standard of lithium battery system.

2. Analysis for operating conditions of rail vehicle auxiliary battery system

The main technical parameters of each set of batteries for rail vehicles are shown in Table 1. The auxiliary power supply system mainly supplies power in three phases in the actual vehicle operation applications: first, the auxiliary power supply is required to provide the electric power to lift bow when the train starts; secondly, the auxiliary power supply is required to provide power for emergency load for the train in case of the vehicle power supply network fault, lack of catenary voltage or current



transformer fault; Thirdly, when the train ends running and rests, the auxiliary power supply is required to provide the electric power to drop bow. After the lifting bow discharge and emergency discharge, the battery will be charged through the pantograph and into the float charging state after reaching the cut-off voltage.

Table 1. The main technical parameters of each set of batteries for rail vehicles

Battery type	Lithium titanate battery	Max. charging current of battery pack	320A
Single voltage	2.3V	Undervoltage protection value of battery pack	67.5V (single 1.5V)
Battery group mode	45series (190Ah/110V)	Overvoltage protection value of battery pack	121.5V (single 2.7V)
Constant voltage control voltage of battery pack	112.5V	Battery operating temperature range	-40~55℃

Figure 1 is the operating conditions curve of two working days test for auxiliary battery system, the operating condition of Figure 1 (a) is relatively complex and changeable, wherein the symbol ① is the float charging condition, the battery voltage remains unchanged and the current is in a floating state; symbol ② is shelving conditions, the battery current is fixed value 0, and the voltage gradually diminishes due to polarization fading, the rest of the conditions is the battery discharging conditions; Figure 1 (b) is the second day's battery test conditions, the train is always in power state, so there is no shelving conditions, it is mainly float charging conditions. By analyzing the actual operating data collected, it is found that the auxiliary battery system operating conditions mainly include three conditions: shelving, float charging and emergency discharging, and the proportion of time spent on battery shelving and floating is relatively greater. Lithium titanate battery is used as an auxiliary battery system for rail vehicles, the train takes electricity from the catenary in normal operation, and the battery is generally in a float charging; After the train returning to the garage at night, the battery is disconnected from the load and will be in a shelved storage state. When the train needs lift and drop the bow or emergency situations, the battery should be discharged, after lifting bow, the battery will be fully charged and then into the float charging state. The operating conditions mainly include the above three types during the train actual operating. Due to discharge condition is less and the discharge depth is smaller, the conditions that affect the aging of the train battery are mainly two conditions of shelving and floating.

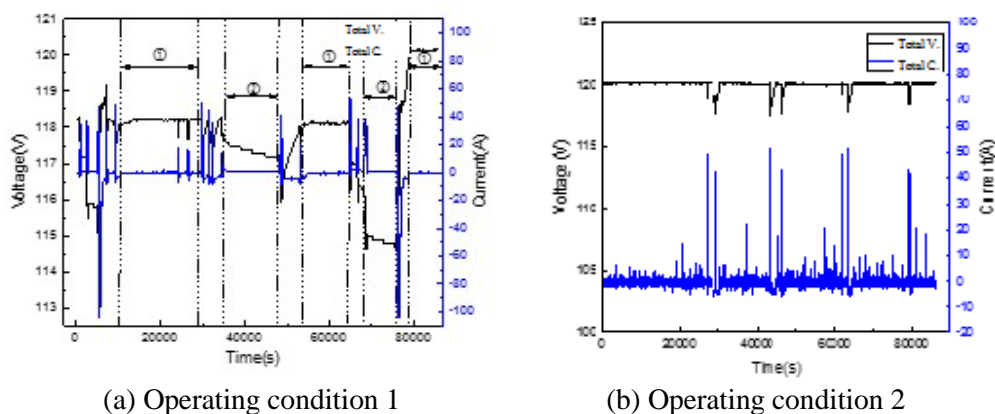


Figure 1. The operating conditions of the auxiliary battery system of the rail vehicle

At present, there are few research literatures on the aging life of lithium titanate batteries, and there are few literatures on the analysis of aging mechanism of batteries. This paper will focus on the test for lithium titanate battery floating condition, considering the influence of different temperature, voltage, such as stress; choose two different manufacturer of lithium titanate battery for test, comparative analysis of float charging condition battery aging characteristics and recession mechanism.

3. Lithium titanate battery float charging test

In the rail vehicle auxiliary battery system, the lithium titanate battery is in a float charging state for a long time when the train is in normal operation. Derived from use of the lead-acid battery system which has a large self-discharge, the definition of the float charging generally refers to that the charger is still recharging the battery with a small current after the battery is fully charged to make up the capacity loss of battery self-discharge. In the shelving process, battery still has a phenomenon of less self-discharge, float charging method is used by lithium titanate battery system in the train driving process. As a long-life, high safety lithium-ion battery, lithium titanate battery is used as a train auxiliary battery system, its research literatures on float charging is less. Some scholars have researched that lithium titanate batteries float charging for 250 days at 35°C, 45°C, its capacity retention rate is 100% and 98%. Taking into account China's vast territory, greater temperature difference between North and South, so the designed test temperature is 50°C highest and -40°C lowest, float charging to battery is carried out in extreme circumstances. The battery float charging test platform is shown in Figure 2, the setting temperature for left temperature box is 50°C, the right one is -40°C. The charging devices used are from Ningbo BaTe Test Equipment and switching power supply.



Figure 2. Battery float charging test platform

In this paper, two kinds of lithium titanate batteries were selected for testing, which were used to comparatively analyze the test results and aging mechanism of lithium titanate batteries for different anode materials. In addition, for the 20Ah lithium titanate batteries, different constant voltage points were selected for the float charging test to analyze influences of the battery aging under different constant voltage control voltage for float charging.

For 20Ah lithium titanate batteries, place the four batteries respectively for float charging at different temperatures and constant voltages, analyze the influences of battery life in different circumstances for float charging, comparatively analyze the battery aging evolution by the battery capacity test and capacity increment curve before and after the float charging. The specific programs of battery float charging test are as follows: 1) The four batteries are charged to the cut-off voltage of 2.7V in constant current and constant voltage (CCCV), constant current charging rate is 1C, the current in constant voltage phase drops to 2A, and then the voltage of 1C constant current was discharged to the cut-off voltage 1.5V, and the cycle was repeated three times, calibrate the battery initial capacity. At the same time, have a constant current charge and discharge capacity test for the battery at 0.05C rate to obtain the maximum battery capacity and capacity increment curve. 2) The # 1 and # 3 batteries were placed in a 50°C incubator and subjected to a float charging test at 2.7 V and 2.65 V respectively. After 60 days, the batteries were left at room temperature for 24 hours and

subjected to 1C and 0.05 C capacity tests. 3) The # 2 and # 4 batteries were placed in a -40°C incubator and float charging at 2.7V and 2.65V respectively. After 60 days, the battery was allowed to stand at room temperature for 24 hours, and have respectively capacity test at 1C and 0.05 C.

For 8.5Ah lithium titanate batteries, place the three batteries for float charging test at different temperatures, analyze the influences of battery life in different ambient temperatures for battery charging and aging evolution. The specific programs of battery float charging test are as follows: 1) The three batteries are charged to the cut-off voltage 2.8V in constant current and constant voltage (CCCV), constant current charging rate is 1C, the current in constant voltage phase drops to 0.85A, and then the voltage of 1C constant current was discharged to the cut-off voltage 1.5v, and the cycle was repeated three times, calibrate the battery initial capacity. At the same time, have a constant current charge and discharge capacity test for the battery at 0.05C rate to obtain the maximum battery capacity and capacity increment curve. 2) The three batteries were respectively placed in 50°C , -40°C and room temperature environment for float charging test with 2.8V for 100 days, then place the battery at room temperature for 24 hours, have a capacity test respectively by 1C and 0.05C.

4. Effect on float charging and aging of lithium titanate battery by different temperatures

4.1. Analysis for float charging test results and aging mechanism of 20Ah lithium titanate battery

Figure 3 shows the capacity test results before and after the battery experienced float charging, in which # 1 battery is floated at high temperature of 50°C ., and # 2 battery is floated at a low temperature of -40°C ., and the floating cycle is 60 days. Figure 3 (a) is the battery 1C rate capacity, the battery nominal capacity is 20Ah, but the actual test of the initial capacity of the battery were respectively 19.69Ah and 19.77Ah, after experiencing the float charging test, both batteries capacity were varying degrees of increase. Among them, the high temperature float battery capacity increases even more apparent. Figure 3 (b) shows the maximum usable capacity of the battery at 0.05C. Both batteries also show an increase in capacity. At high temperature, the capacity increases by 0.297 Ah, about 1.3%, and at low temperature the capacity increases by 0.21 Ah, about 0.9%.

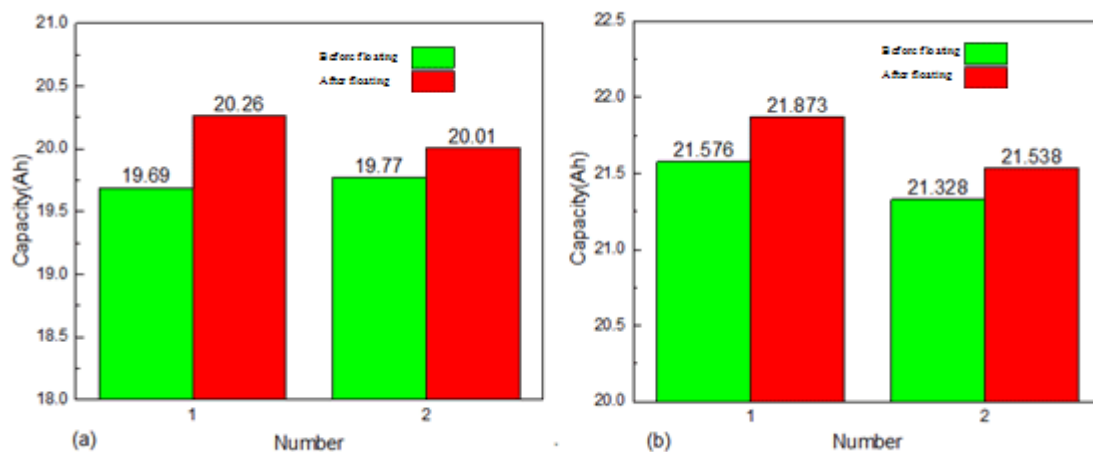


Figure 3. Test results of battery capacity before and after floating

Figure 4 shows the Incremental capacity (IC) curve and Differential voltage (DV) curves of # 1 battery before and after high-temperature floating. The left Figure shows the battery Incremental capacity curve. The anode material of the battery forms two IC peaks, the first IC peak corresponds to the platform of 2.2V voltage and corresponds to ternary material phase transition voltage. The second IC peak corresponds to the platform of 2.35V voltage and corresponds to the phase transformation platform of lithium cobalt oxide material. It is found in the Figure that the starting voltage of the first IC peak offsets to the right, but the entire peak did not offset, that indicates the offset was not caused

by internal resistance increasing, but due to inconsistencies in the initial capacity of the battery, the initial SOC is too large when measuring after floating, resulting in a higher voltage starting point. The second IC peak appears to some degree of decline, which may bring capacity attenuation. The IC curve obviously rises near the solid solution zone, indicating that the float charging causes the increase of capacity near the solid solution zone. In the Differential voltage curve of the right Figure, it is obvious that the positions of several peaks are staggered, indicating a change of capacity before and after floating. The capacity starting point of first voltage platform is always 0, until the end of the first platform, that is, when maximum value of dV/dQ appears, the floated curve arrives in advance, indicating that the ternary material has capacity loss after floating, the capacity is 0.23Ah reduction. In the following voltage platform, the DV curve after floating appears that first offsetting to left and then to right, which shows the decrease of the battery second peak capacity and the increase of solid solution zone capacity, which corresponds to the analysis of IC curve. Among them, the lithium cobalt oxide material formed a capacity loss of 0.27Ah, while a 0.8Ah capacity increase occurred in the solid solution zone. In the case of battery floating at high temperatures, it caused reduction of capacity produced from lithium cobalt oxide material, and increment capacity from parts of the ternary and solid solution zone.

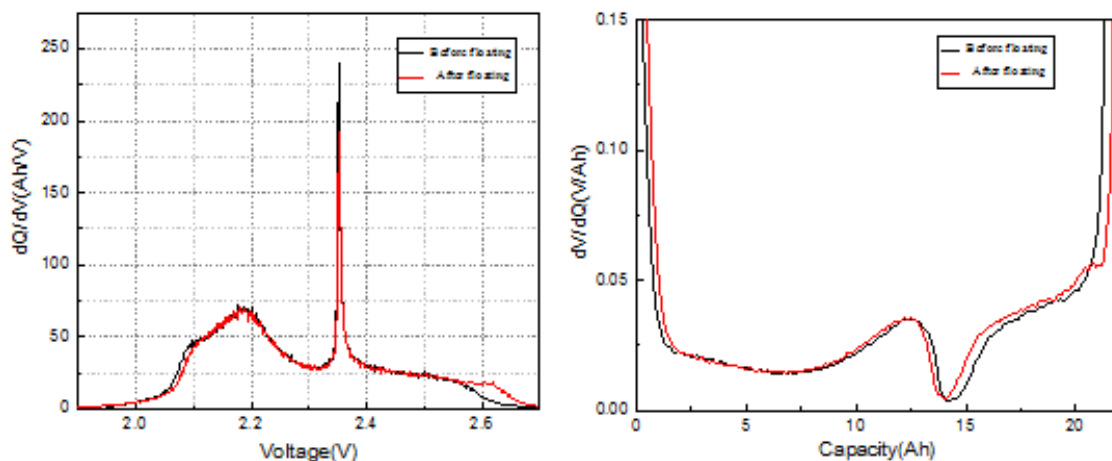


Figure 4. IC curve (left) and DV curve (right) of # 1 battery

The capacity of # 2 battery also increases after floating at low temperatures, the IC and DV curves of the battery as shown in Figure 5. Offset does not appear at the low end of the voltage in the IC curve of the battery, indicating that the initial SOC is consistent; offset does not appear in the overall curve, indicating the less influence on the internal resistance from low temperature floating. The coincidence of the first IC peak is higher, but different degrees of elevation of the second IC peak and the following solid solution zone appears, and the corresponding area increases. In the DV curve, the capacity of the ternary material increases by 0.07Ah, the capacity of the lithium cobalt oxide material changes less, reducing 0.01Ah, near the solid solution zone, the capacity of the battery increases by 0.16Ah.

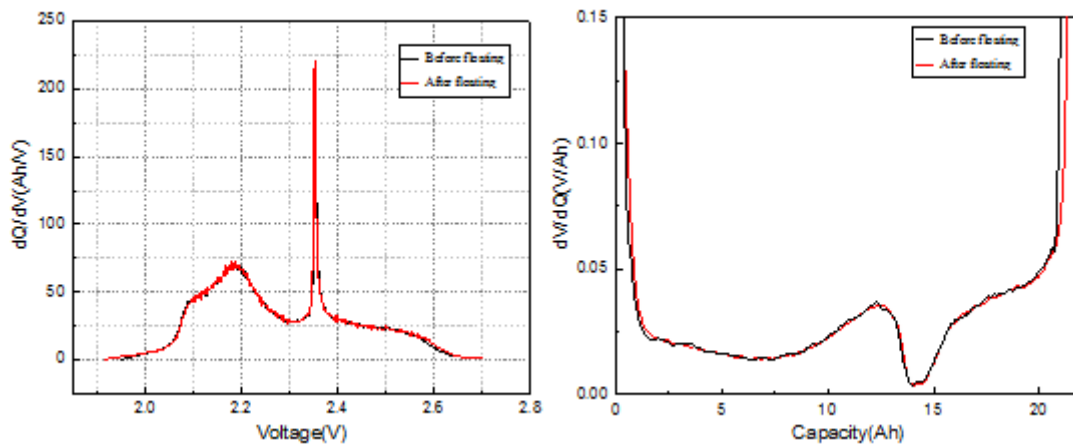


Figure 5. IC curve (left) and DV curve (right) of # 2 battery

After floating at different temperatures, the changes of capacity of the battery anode material are shown in Table 2. In terms of different materials, the lithium cobaltate shows a decreasing capacity after floating, the capacity increases near the solid solution zone, the ternary material is more complex, the capacity decreases under high temperature, but increases under low temperature, the increased value of capacity is less. On the other hand, the capacity of lithium cobalt oxide decreases under the high temperature environment, and the capacity of solid solution zone increases obviously. The temperature stress aggravates the progress and speed of the reaction and cause more anode material to have a side reaction in the negative terminal to form partial capacity increase in solid solution zone.

Table 2. Capacity changes of each part of the battery anode material

	Ternary material (Ah)	Lithium cobalt oxide (Ah)	Solid solution Zone (Ah)	Total capacity (Ah)
High temperature 2.7V floating	-0.23	-0.27	0.80	0.30
Low temperature 2.7V floating	0.07	-0.01	0.16	0.21

After floating, ternary materials and lithium cobalt oxide material of lithium titanate battery form a loss at high temperature, but the both materials do not obviously change at low temperature, due to in the reaction the current is always injecting into high-end SOC near the solid solution zone, the lithium-ion that corresponds to internal battery anode moves out to the negative electrode, but the negative electrode is saturated due to lithium intercalation, so that the reaction is formed on the surface of the electrode, resulting in increasing the capacity of the solid solution zone. The temperature affects the activity of the battery material; reaction is more active at high temperatures, resulting in more capacity.

4.2. Analysis for float charging test results and aging mechanism of 8.5Ah lithium titanate battery

By studying the floating characteristics of 20Ah lithium titanate batteries, the corresponding capacity of lithium cobalt oxide materials appears to be reduced, and 8.5Ah lithium titanate batteries also contain lithium cobalt oxide material. In response to this phenomenon, carry out the full power state float charging test of 8.5Ah lithium titanate battery at different temperatures to compare the stability of the anode lithium cobaltate material and the change of the battery floating characteristics of different materials. According to the test plan, batteries labeled # 1, # 2 and # 3, will be tested respectively at the ambient temperature of high temperature 50°C, low temperature -40°C and room temperature for

100 days, due to the pre-data recording is not accurate, only selected later 60 days data to have quantitative analysis.

Figure 6 shows the capacity test results of the battery before and after floating, Figure 6 (a) is the battery capacity of 1C rate, it can be seen that capacities of three batteries are greater than the nominal capacity in the initial state, with the float charging, capacity of # 1 battery shows a declining trend, and capacity of # 2, # 3 increased. Figure 6 (b) is 0.05C rate battery capacity, # 1 battery capacity decreased by 0.22Ah, # 2 battery capacity increased by 0.05Ah, # 3 battery capacity increased 0.2Ah, which is different with the 1C rate capacity increases, the greater battery resistance leads to not sufficient reaction and the capacity is not fully released.

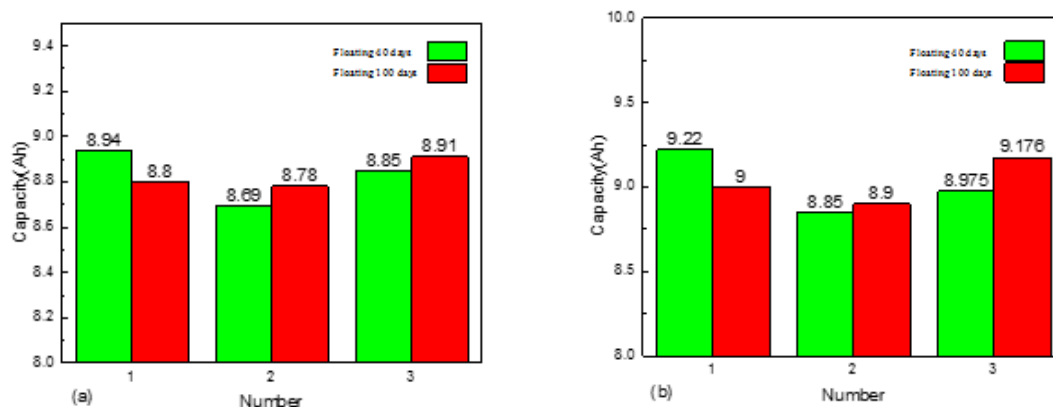


Figure 6. Test results of floating battery capacity: (a) 1C ratio and (b) 0.05C ratio

Figure 7 shows IC curve and DV curve of # 1 lithium titanate battery after floating for 40 days and 100 days at high temperature, three regions obviously appears. The IC curve in the left Figure shows that the height of the first IC peak decreases after floating and the second IC peak does not change significantly. After 100 days of floating, the capacity increases near the solid solution zone. The total capacity of the battery appears to decrease, which may be related to the lithium cobalt oxide capacity loss. In the right Figure, it can also be seen that change of the capacity in three stages. At the end of the peak 1, it can be seen that the reduction of the corresponding capacity is shown in the Figure with the capacity reduced by 0.32Ah, the corresponding to the capacity reduced from lithium cobalt oxide voltage platform on the IC curve. In the second stage, the capacity is reduced by 0.04Ah. In the third stage, the capacity is increased by about 0.14Ah, corresponding to an increase in the solid solution zone in the IC curve. From the perspective of the change of capacity of high-temperature floating, the floating has caused a significant drop in capacity of lithium cobaltate platform, while capacity increases in the other solid-solution platforms, but the volume decrease is more than that of incremental volume, and the overall performance is decreased. It can be seen from the above analysis that the lithium titanate battery will have partial capacity loss when floating at a high temperature. In contrast to the 20Ah lithium titanate battery, the loss of the lithium cobalt oxide material is even more obvious, near the solid solution zone will generate more capacity.

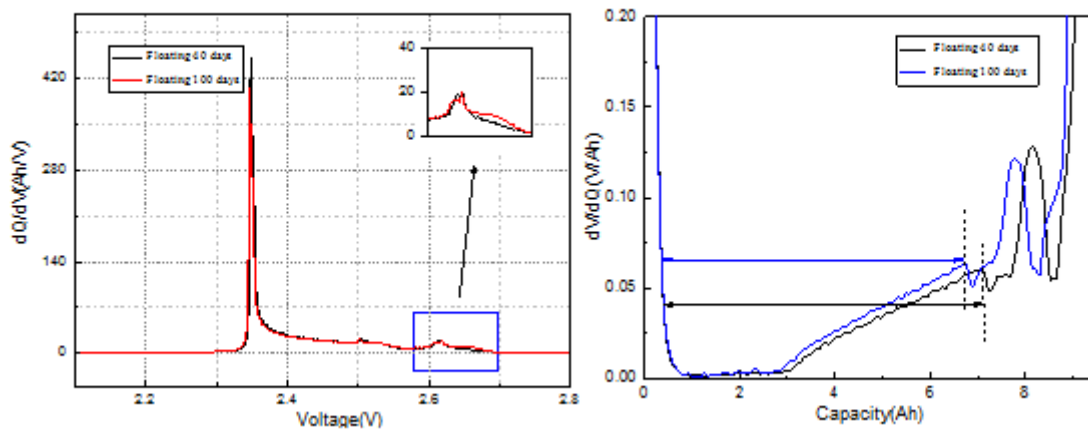


Figure 7. IC curve (left) and DV curve (right) of # 1 battery

Figure 8 shows the battery characteristics curve after floating at low temperature. In the IC curve, the first IC peak shows a slight decrease, corresponding to the reduction and offset of the DV curve. The corresponding capacity loss is 0.33Ah. The change of the second IC peak is not obvious; the change of DV curve is less, increasing 0.02Ah. Battery capacity near the solid solution zone increased with an increment of 0.37Ah, the final battery capacity change is less, indicating that the increased capacity of the solid solution make up for the capacity of corresponding loss of lithium cobalt oxide, compare to high temperature floating IC curve and find the capacity loss of lithium cobaltate decreases, which may be related to the activity at different temperatures. At the same time, the capacity of the solid solution zone increases less in the high temperature environment and different from the elevated position in the low temperature solid solution zone.

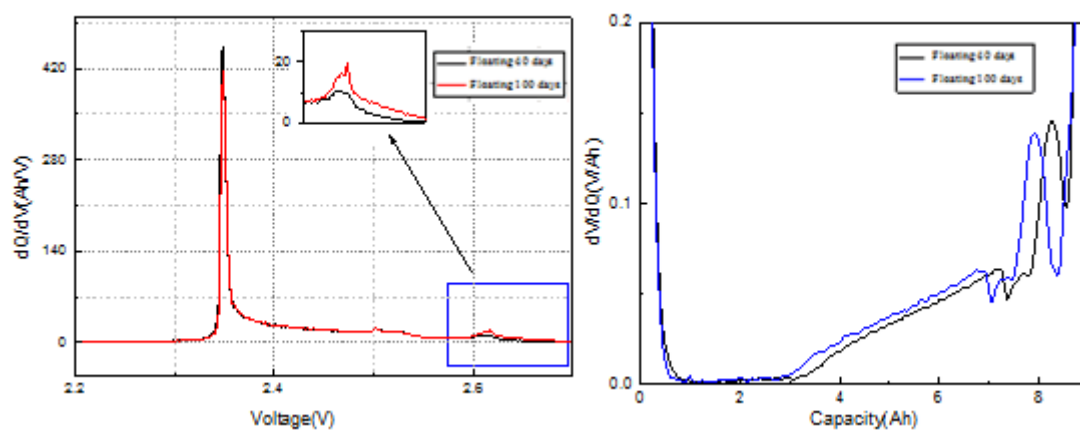


Figure 8. IC curve (left) and DV curve (right) of # 2 battery

Figure 9 shows the battery characteristics curve of # 3 battery after floating at room temperature. The height of the first IC significantly decreases, corresponding to the attenuation of capacity in the DV curve; however, the capacity decreases only by 0.09Ah. The corresponding capacity of the second IC peak increases by 0.05 Ah, and the battery capacity near the third peak significantly increase by 0.24Ah. Float charging at room temperature, the loss of lithium cobalt oxide material is less, and near the solid solution zone the capacity also increases.

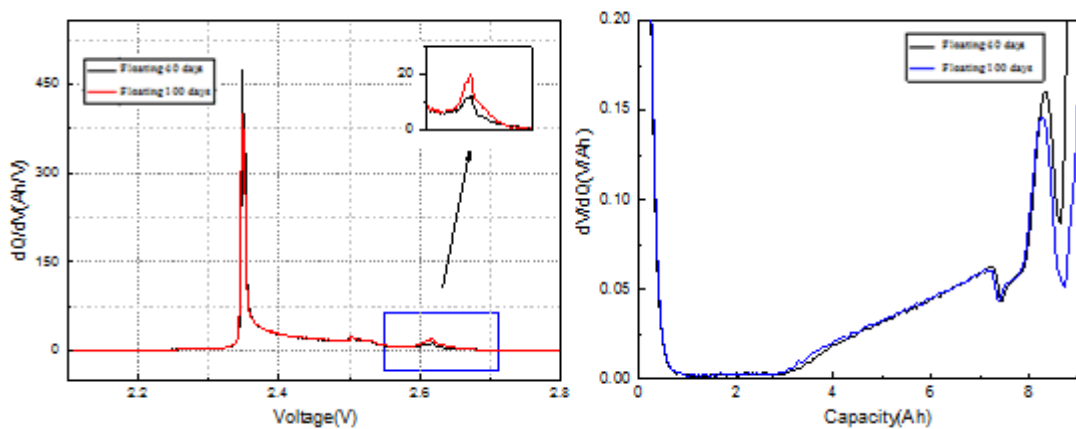


Figure 9. IC curve (left) and DV curve (right) of # 3 battery

In the floating test, the capacities of the lithium titanate batteries floated at various temperatures were significantly changed, the corresponding capacity changes of the three groups of battery materials are shown in Table 3, it is seen from the capacities of peak values, significant capacity attenuation occurred in the lithium cobalt oxide platform, the amount of attenuation is less at room temperature, which is the same as corresponds to phenomenon of 20Ah battery, indicating that the float process forms a significant capacity loss to lithium cobalt oxide material. Near the solid solution zone ②, the batteries capacity change is less at different temperatures, the role of float charging on the material is less, and the corresponding capacity change is not more. Near the solid solution zone ③, the floated capacities all increased at different temperatures.

Table 3. Capacity changes of each part of the battery anode material

	Lithium cobalt oxide (Ah)	Solid solution ②(Ah)	Solid solution ③ (Ah)	Total capacity (Ah)
High temperature				
2.8V floating	-0.32	-0.04	0.14	-0.22
Low temperature				
2.8V floating	-0.33	0.02	0.37	0.05
Room temperature				
2.8V floating	-0.09	0.05	0.24	0.20

It may be found by full charge state floating at various temperatures that the batteries can form significant capacity loss on the lithium cobalt oxide material and the results of the material loss are also verified by the 20Ah battery. Float charging has little effect on the battery material in the solid solution zone ②, but float charging leads to the increase of capacity on the platform of solid solution zone ③, indicating that temperature is an important factor affecting the float aging. Excessive temperature may cause the battery material side reaction intensified, while accelerating the reaction of high-potential platform, resulting in the battery to form more capacity at the end of charging. During use, the temperature balance in battery box of the rail vehicle should be kept as far as possible, not too high, so as to ensure the floating life of the battery pack.

5. Effect on float charging and aging of lithium titanate battery by different voltages

It is known from the above analysis that full charge state floating of lithium titanate battery will cause changes between different materials of the battery, in which the corresponding capacity of lithium cobalt oxide material reduces, the capacity increases near the solid solution zone. Due to the voltage platform of the solid solution zone is near charging ends while continuing charge at a low current under full charge state may cause the material's reaction. Therefore, the floating test comparison shall be conducted for 20Ah lithium titanate batteries under different voltage points and at both high and low temperatures. The battery, as a backup power supply in the rail vehicle, its too low electricity cannot guarantee reliable power supply, so the floating voltage is set to 2.65V, floating time is 60 days, analyze effect of floating constant voltage point on the battery capacity decline.

Figure 10 shows the battery characteristics curve of the # 3 battery before and after floating at a high temperature 50°C. The float voltage is 2.65V. It can be seen that after the battery is floated at 2.65V, the loss of corresponding capacity of the ternary material does not appear, but at full charge state, the corresponding capacity of the ternary material decays, indicating that the partial reaction is related to the voltage level. Due to the fact that the capacity of the full charge state float at low temperature is not obvious, temperature is less effect on it. Battery floating at 2.65V voltage also caused the lithium cobalt oxide material capacity reduction. Comparison of the capacity between the anode materials in the composite Table 4 with different constant voltage points floating, we can see there is no difference between the loss of lithium cobalt oxide material and the full charge state of the float charging; it is caused by the high temperature conditions. Near the solid solution zone battery did not produce a significant increase in capacity, only increased by 0.04Ah, which is different with the full charge state floating. In full charge state, the battery internal reaction tends to saturation under the action of the float current; some materials of battery solid solution zone are involved in the reaction, resulting in an increase in capacity. However, when floating at 2.65V, the battery has not yet reached the full charge state, and there is still room for voltage increase, so that no capacity increase is formed near the solid solution zone.

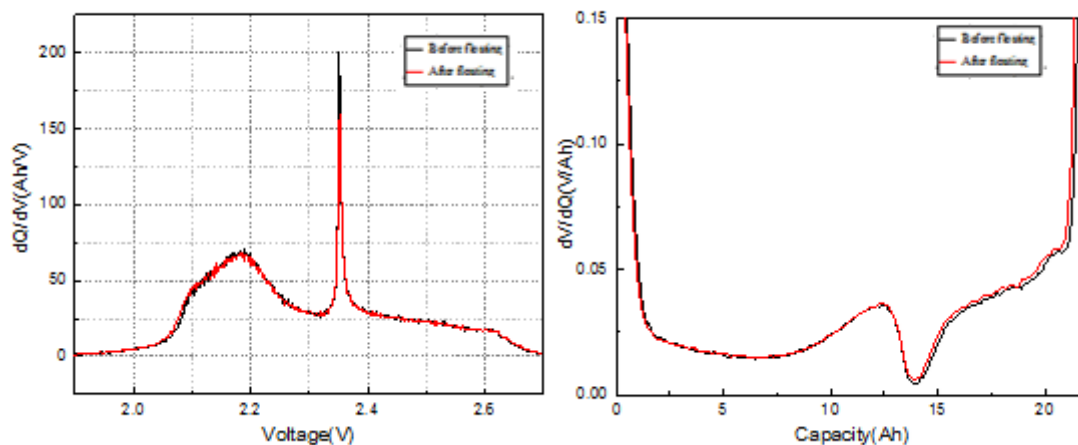


Figure 10. IC curve (left) and DV curve (right) of # 3 battery

Table 4. The corresponding capacity change of each part of materials after batteries floating at different voltage points

	Ternary material (Ah)	Lithium cobalt oxide (Ah)	Solid solution zone (Ah)	Total capacity (Ah)
High temperature 2.7V floating	-0.23	-0.27	0.80	0.30
High temperature 2.65V floating	0.03	-0.24	0.04	-0.17

Figure 11 shows the battery characteristics curve of the # 4 battery before and after floating at a low temperature, the float voltage is 2.65V, the test results are similar to those of full-charge state floating. Table 5 shows the capacity change of # 4 battery floated at different voltage points and at low temperature, it can be seen that the corresponding capacities of ternary materials all show an increase, indicating that the effect on ternary materials is less from low temperature floating at different voltage points. The conclusion of high temperature floating test shows that the loss of ternary material is the result of float charging at high temperature and full charge state and is affected by the common stress of temperature and voltage. For the lithium cobalt oxide voltage platform, the corresponding capacity is always loss when being floated under the high temperature environment. On the contrary, the capacity slightly increases at low SOC state when float charging at low temperature, which shows that high temperature environment is an important factor of lithium cobalt oxide material loss. Finally, in the solid solution zone, the full charge state floating in both high and low temperature environments increase in capacity, that is, the capacity increases slightly when floating at 2.65 V high temperature, while the corresponding capacity decreases when floating at 2.65 V low temperature, indicating that different voltage points are important factors that affect reaction in solid solution reaction zone, followed by the temperature.

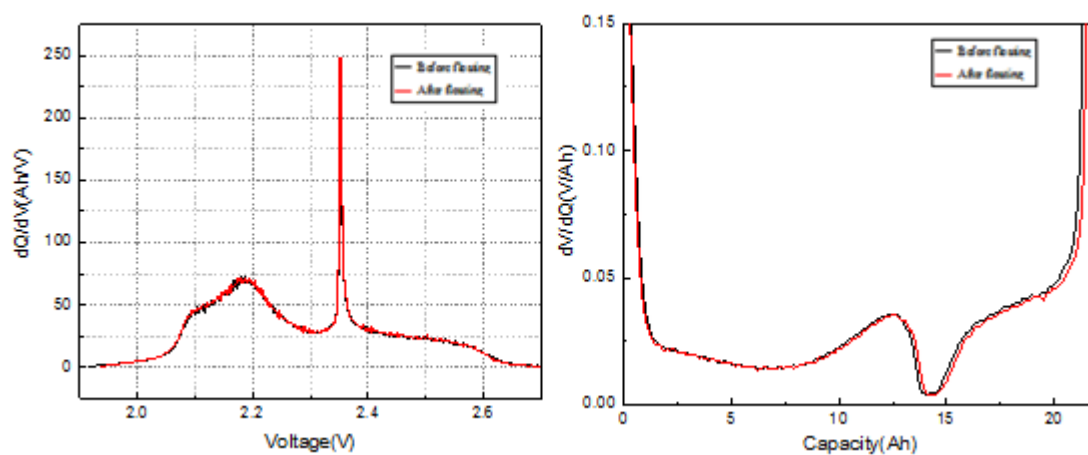


Figure 11. IC curve (left) and DV curve (right) of # 4 battery

Table 5. The corresponding capacity changes of each part of materials after battery floating at different voltage points

	Ternary material (Ah)	Lithium cobalt oxide (Ah)	Solid solution zone (Ah)	Total capacity (Ah)
Low temperature 2.7V floating	0.07	-0.01	0.16	0.21
Low temperature 2.65V floating	0.13	0.08	-0.05	0.16

Through the floating contrast of different voltage platform, we can draw the following conclusion: for 20Ah lithium titanate battery, different phase voltage platform will change; for the ternary material platform, at high temperature full charge state floating, there will be a small amount of attenuation of capacity, The rest of the environment is less impact on capacity; On the lithium cobalt oxide platform, high temperature is an important factor affecting the material, the impact of the constant voltage point of the float on the reaction is less; near the solid solution zone, the increase of capacity is synthetically affected by temperature and voltage, in which, the voltage point is the main affecting factor. When the

float voltage is increased, the capacity of the solid solution zone will change obviously. The temperature is the secondary affecting factor; the increasing temperature will accelerate the reaction process, resulting in increased capacity. Therefore, in the actual use of rail vehicles, we shall appropriately reduce the constant voltage point and maintain the appropriate temperature to reduce the battery side reactions.

6. Effect on float charging and aging of lithium titanate battery by different temperatures

This paper has conducted decomposition and description for proportion of the actual vehicle data in the rail vehicle auxiliary battery system in different operating conditions, focusing on affect of the float charging conditions on the battery life. Two lithium titanate batteries made of different materials are carried out for floating test, have researched the recession mechanism of aging life of lithium titanate battery, coupled with the impact of ambient temperature and voltage points, analyzed the battery recession under different factors, provided theoretical and data support for formulating control strategy of the auxiliary battery system.

References

- [1] Wang Zhanguo, Gong Minming. Lithium Titanate Battery Management System for EMU[J]. Chinese Railways, 2011, (12): 64-66.
- [2] Su Jian, Li Hongbing. Lithium Titanate Battery in the Application of EMU [J]. Electric Drive for Locomotives, 2011, (4): 38-40.
- [3] Yuan Fengbiao, Yang Jun. Lithium-ion Battery in the Application of the Railway Passenger Car [J]. Electric Drive for Locomotives, 2011, (3): 23-27.
- [4] Gong Minming, Wang Zhanguo, Ma Zeyu. Design of Lithium-ion Battery System for Dual-powered Metro Metro [J]. Urban Rapid Rail Transit, 2013, 26(5): 69-73.
- [5] Wang liqiang, Wang Wei, Wang Zhanguo, Zhang Zhiru, Liu Sijia. Study on the Inconsistency of Lithium Titanate Battery in Rail Transit [J]. Journal of Power Sources, 2017, 41(2): 195-197, 218.