

Experimental study on relationship between SOC and OCV of lithium-ion batteries

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Abstract

Electric Vehicles (EVs) are developed rapidly due to the energy and the environment problem. Lithium-ion batteries play an important role in energy storage system of EVs or other devices. The characteristics of power lithium-ion batteries are closely connected to ambient temperature. A battery testing system, including the charge/discharge device, the thermal chamber, DAQ card and etc, was constructed. With which, the experiments of 18650 cells and packs are carried out for the laws between SOC and OCV, also for the discharge capacity with different rates and ambient temperatures. These results can be used in battery management system (BMS) design for electric vehicles..

Keywords: Lithium-ion battery, state of charge (SOC), charge-open circuit voltage (OCV), temperature characteristics

1. Introduction

The rapid developments of automobile industry have brought people enormous convenience. However, automotive exhausts have been the main culprit of the air pollution in the urban area. On the other hand, as a kind of non-renewable energy, the petroleum and natural gas will be eventually exhausted in the near future with the consumption of them are rising. Energy saving and environmental protection have become the extremely prominent social problems [1]-[4].

The advent of the Electric Vehicles (EVs) and the Hybrid Electric Vehicles (HEVs) is to reduce energy consumption and environmental pollution caused by general vehicles. The adoptions of advanced power battery in electric vehicle are mainly Ni-Mh battery and lithium-ion battery [5]-[7]. Lithium-ion battery is characterize by high capacity, long life, high power density, and it will replace the present Ni-Mh battery to be the main energy storage system of the electric vehicle going with the declining costs [8], [9]. The economy is another very important aspect which will determine whether they can survive in the market competition. Meanwhile, the real-time and accurate estimation for the state of charge (state of charge, SOC) of the battery would have an impact on the economy of the hybrid electric vehicle [10], [11]. The estimation of SOC generally requires modeling of the battery cell and packs [12], the structure of the battery model and parameters identification should based on characteristics of charge-discharge test under different temperatures, which need sufficient test data of batteries. Equivalent circuit models in common use for lithium-ion battery are Thevenin model, RC model, and etc [13], as shown in Fig. 1.

The anode materials of lithium-ion batteries are mainly LiMnO₂, LiFePO₄ and LiCo_{1/3}Ni_{1/3}Mn_{1/3}O₂ [14]-[16] ternary materials. These materials are compared as shown in Table 1.

Ternary materials possess better performance in discharge voltage platform, specific capacity and compacted density compared with other two anode materials, which determine the energy density of the anode materials. Ternary material will own wider applications in power energy storage system of the HEV if the security performance of ternary lithium-ion batteries can be improved to a certain extent.

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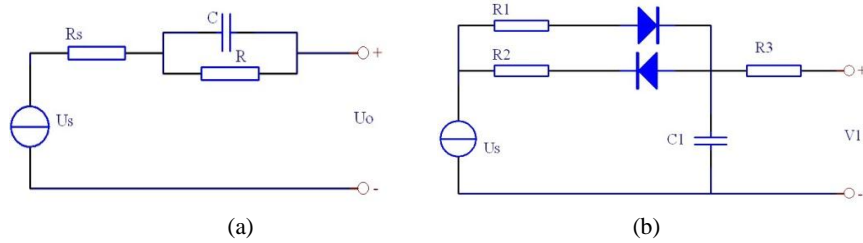


Fig. 1. Two common battery equivalent circuit models: (a) Thevenin model (b) RC model.

Table 1. Performance comparison for power batteries with different cathode materials

Materials	Security performance	Circle life	Discharge voltage platform	Specific capacity (mAh/g)	Compacted density (g/cm ³)	Prices (dollar/kg)
LiCo1/3 Ni1/3Mn1/3O2	Good	Good	3.6	145~155	3.2~3.7	≤26
LiMnO2	Better	Good	3.7	90~100	2.7~3.0	≤17
LiFePO4	Better	Better	3.2	120~140	2.0~2.3	≤26

2. Test Objects and Platform

This paper uses the cylindrical 18650 ternary lithium-ion power battery, manufactured by Sinowatt Dongguan Co., Ltd, as the experimental objects to get the basic characteristics. Specifications of cells are as following: nominal capacity 2.0 Amper-hour, nominal voltage 3.7V and mass 41 grams. Cells and packs experiment platform should simulate the vehicle working condition, which we can get the experimental data in charge-discharge process to verify module's structure design and the validity of the design. The sketch of the experimental platform was shown in Fig. 2.

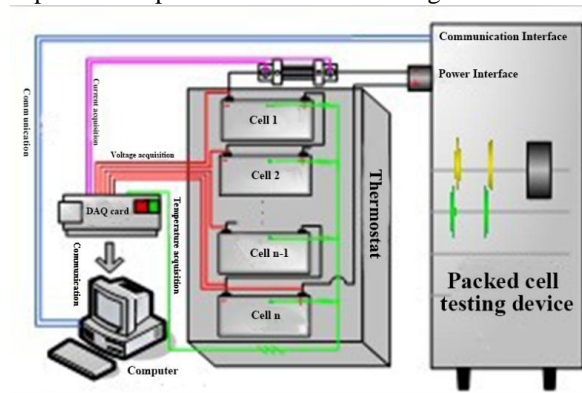


Fig. 2. The sketch of battery testing platform.

The experimental platform consists of five parts, including charge-discharge device of the battery, thermostat, data acquisition card, battery data record analysis and control computer, battery module. Computer can get and memorize the information (voltage, temperature and current) of batteries through the interaction with data acquisition card, we can analyze the state of battery, adjust charging method with data analysis software in computer and control the output of the charging-discharging device. The thermostat can hold temperature conditions for the test of the battery. The charging-discharging device provides the power source and the load for battery.

3. Relationship between SOC and Open-Circuit Voltage

3.1. Battery cells test

Open-circuit voltage is used to correct the estimated SOC, and this obviously play an important role in improving the estimate precision. Nine cylindrical 18650 power Li-ion battery cells were selected in the

SOC and OCV relationship test. The test procedure is as follows: First, cells were fully charged and put them statically for about one hour for the steady state; then, cells were discharged with constant current and ensure to decrease SOC with 0.05, measure the OCV after one hour, and discharge to decrease SOC with 0.05. Thus we can get 21 OCV values corresponding to SOC state from 1, 0.95, 0.90, 0.85, 0.80, ..., 0.10, 0.05. The test curve of single cell was shown in Fig. 3. We can obtain the relation curve of SOC-OCV, shown in Fig. 4 with nine cylindrical batteries respectively.

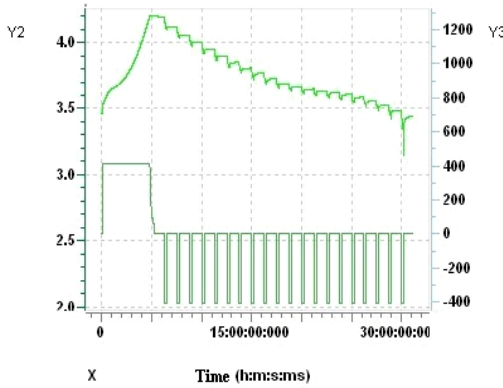


Fig. 3. SOC and OCV test.

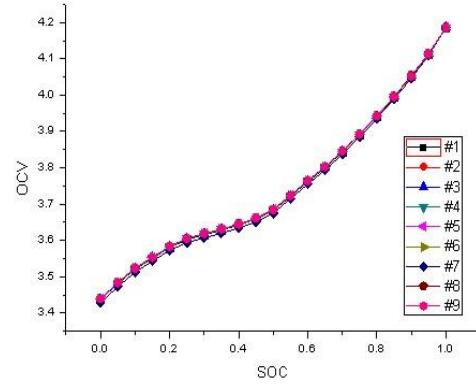


Fig. 4. Test results of 9 batteries's SOC and OCV.

The relationship between the SOC and OCV of the 18650 cells are nonlinear and we can use the OCV to estimate the SOC of battery. It is an appropriate method for using the OCV to estimate the initial SOC of battery especially after the EV stopped for an enough long time.

3.2. Battery packs test

18650 cells were selected for constructing two 5P10S packs to test the relationship between SOC and OCV. The testing procedure is the same as the above mentioned test procedure for cells and the test results were shown in Fig. 5. The battery packs can also keep a better consistency owing to the specified cells selection for packs.

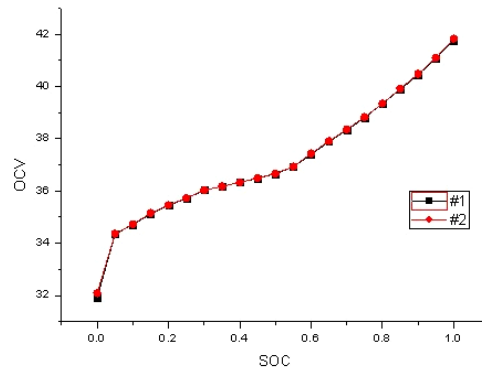


Fig. 5. Relationship between SOC and OCV of 5P10S packs.

4. Capacity with Different Discharge Rate

Battery system need to provide sufficient power when the EV is in climbing, launching, and accelerating, which means that high rate discharge current should be provided from battery system. To spy on characteristics of lithium-ion battery, we carried out the discharge tests with 0.1C, 0.5C, 1C discharge rate. Test results were shown in Table 2, the unit of the discharge capacity is mAh, and the discharge time is second.

Table 2. Battery capacity with different discharge rate

Cell number	0.1C=207.5 mA		0.5C=1037.5 mA		1C=2075 mA	
	Discharge capacity	Discharge time	Discharge capacity	Discharge time	Discharge capacity	Discharge time
#1	2093.5	608	1964.8	113	1898.9	54
#2	2077.7	603	1956.1	113	1894.8	54
#3	2096.5	608	1980.5	114	1925.3	55
#4	2077.4	602	1967.7	113	1908.9	55
#5	2097.2	611	1975.5	114	1914.2	55
#6	2082.6	601	1976.2	114	1921.3	55
#7	2113.5	615	1994	115	1932.9	55
#8	2100.7	614	1976.9	114	1918.5	55
#9	2077	602	1966.5	113	1910.2	55
Average values	2090.68	607.11	1973.13	113.67	1913.89	54.78

From these data, one can know, with the increase of discharge current from the battery, the capacity of the battery are decreased, because of the concentration polarization increases, the voltage drop caused by internal resistance increases, the lithium also increase with the increase of the discharge current ,thereby result in the decrease of capacity.

5. Capacity under Different Temperature

Due to the working condition of the vehicle changes dramatically, we test the lithium-ion battery at 0.5C discharged rate in the following temperature: -30°C , -20°C , -10°C , 0°C , 10°C , 30°C , 45°C and 55°C . As shown in Table 3 and Fig. 6, the discharge capacity has an obvious increase with the rising temperature. It is because that the diffusion rate of lithium-ion in the battery is slow at low temperature, with the rising temperature the diffusion rate increased and the activity of cells will be enhanced. However, the high temperature will disorder the activity of lithium-ion, which will result in the increase of the internal resistance and the decrease of the discharge capacity.

Table 3. Battery Capacity with different temperature

Cell number	#1	#2	#3	Average values
0.5C discharge capacity mAh	55°C	2163.6	2163.6	2172.3
	45°C	2127.4	2123.3	2122.3
	30°C	2048.9	2060.2	2069.8
	10°C	1816.9	1814.3	1832.2
	0°C	1590.7	1602.2	1591.0
	-10°C	1378.9	1393.9	1398.9
	-20°C	1030.4	1009.4	1027.7
	-30°C	335.6	377.6	332.2
Average values				

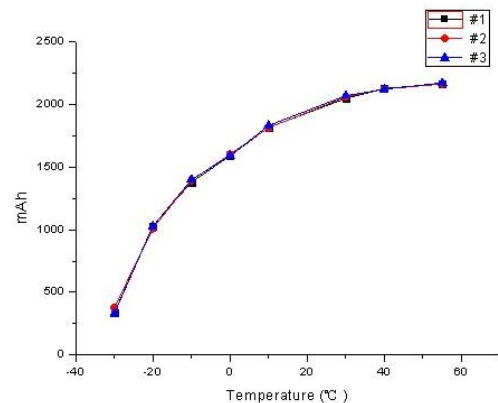


Fig. 6. Battery Capacity with different temperature.

6. Conclusions

In this paper, the relationship between SOC of Li-ion battery and OCV, discharge rate and capacity, capacity and temperature were investigated. The laws between SOC and OCV, the cell capacity with different discharge rate, the laws between capacity and temperature were proposed.

- The relationship between the SOC and OCV is nonlinear, we can use the OCV to estimate SOC, which can improve the estimated precision if we use the OCV to estimate SOC when in the downtime and adopt others estimations (Ampere-hour integral, Kalman filtering, and etc) when in the charge-discharge process.

- With the increase of the discharge current and the concentration polarization in the cell, the voltage drop caused by the increasing internal resistance of the lithium-ion battery, thus, the discharge capacity of the battery will decrease with the increase of the discharge rate.
- The diffusion rate of lithium-ion in the cell is slow at low temperature. The activity of cells and the discharge capacity will increase with the rising temperatures.

Generally, one can use the equivalent circuit model to estimate the SOC of the power battery after identification parameters in the model. In this paper, performance data of the ternary lithium-ion power battery was obtained, with which, the unknown parameters of its equivalent circuit model can be identified, and these results can be used in battery management system design for electric vehicles.

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