Investigation of the Internal Resistance in $LiFePO_4$ Cells for Battery Energy Storage System

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***Abstract*—Internal resistance is an important element for lithium-ion batteries in battery management system (BMS) for battery energy storage system (BESS). The internal resistance consists of ohmic resistance and polarization resistance. Neither of them can be measured directly and they are identified by some algorithms with battery charging/discharging experiment data. In this paper, several 10Ah $LiFePO_4$ cells were used for the investigation of the internal resistance. Based on an electric model for the $LiFePO_4$ cells, methods on estimation of ohmic resistance and polarization resistance were introduced. The cell characteristics were analyzed by pulse charge and discharge experiment data, especially when the state-of-charge (SOC) was neither too high nor too low. Results show that the ohmic resistance and polarization resistance stay at the same order of magnitude. Further, the ohmic resistance changes relatively little with the current and current variation. Meanwhile, the ohmic resistance keeps consistent in charge at different SOC. However, it increases gradually in discharge with the decreasing SOC. Generally, the polarization resistance increased both in charge and in discharge, while there is a reverse change at the SOC about 70%. This result is useful in developing accurate resistance for certain issues, especially for SOC or state-of health (SOH) estimation.**

Keywords—internal resistance; resistance estimation; $LiFePO_4$ cell; battery energy storage system (BESS)

I. INTRODUCTION

Lithium-ion batteries, especially $LiFePO_4$ batteries, are more and more popular in battery energy storage systems (BESS) [1]. To ensure the safety, efficiency and availability of the BESS operation, the performance of the battery is needed to track. However, the electrical characters are closely related to the chemical reactions of the battery. The mechanism of chemical reactions is so complicated that it is difficult to determine all of the characteristics for the full life cycle. Only a few important elements are selected for checking batteries. One of them is the internal resistance [2, 3].

In most electrical models of lithium batteries, the internal resistance includes the ohmic one, which causes the instantaneous voltage variation as soon as the current changes, and the polarization one, which leads to gradual voltage increasing/decreasing after the current changes. In the most simplified electrical model, composed of an ideal voltage source and a resistance in series, the internal resistance contains only the ohmic one. In other models, the polarization resistance is the resistance of the RC parallel network.

The most common way to measure the internal resistance is the electrochemical impedance spectroscopy (EIS) method, which has been known in the electrochemistry community over a century [4]. The measurement of EIS is so complicated that it is impossible to apply in BESS. In this paper, another method to measure the internal resistance by pulse charge/discharge experiment data is introduced [5].

The internal resistance is usually used for detecting hidden trouble spots, diagnosing ageing degree and estimating state-of-charge (SOC). When a battery suffers a fault, the performance such as the electromotive force and the internal resistance will take obvious variations suddenly compared to that of the normal one. There is a notion that the resistance increases as batteries recycling, while the resistance keeps a nonlinear relation with the cycle life. Though a triggering point to replace an ageing battery can be set, a function to calculate remaining cycle life by resistance is difficult to formulate. Because the resistance keeps consistent at the middle SOC stage for most lithium batteries, the SOC estimation algorithm by resistance is commonly taking when the SOC is either very high or very low.

This paper proposes an investigation on the performance of the internal resistance for $LiFePO_4$ cells. The second section presents an electrical model for the cells. Then, a method for resistance estimation by pulse charge/discharge experiment data is discussed. Finally, resistances under different conditions are measured and the analysis of resistances comparison is presented.

II. CELL MODELING

One of the most popular electrical models for lithium batteries is the Thevenin equivalent circuit model [6], as shown in Fig.1. In this model, the OCV is the close-to-equilibrium open-circuit voltage which can only be measured as the circuit current is zero and the polarization voltage u_p is zero. R_s is the ohmic resistance and R_p is the polarization resistance. Both of them are the study objects in this paper.

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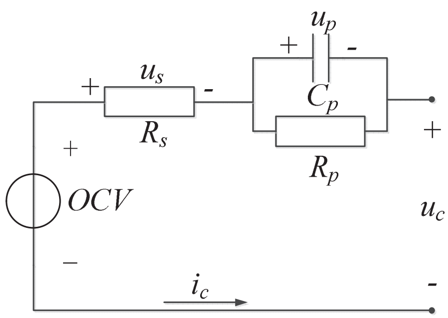

Fig. 1. Thevenin equivalent circuit model

Based on the model, the R_s can be calculated by the voltage us and the current i_c. It is impossible to measure us, while the variation of us can be achieved when the current i_c changes. Furthermore, R_s cannot be calculated in a constant current state or when the current changes slowly. The factors which affect the ohmic resistance include SOC, temperature and the ageing degree. Whether the current influences the ohmic resistance is discussed in section IV.

The polarization effect is performed by the RC parallel network and the Rp is the polarization resistance. Two or more serial-connected RC networks improve the fitting performance of the polarization effect. However, more RC networks will make parameters identification more difficult.

III. Resistance Estimation

To estimate the internal resistance, cell experiment data are needed. For batteries are electrochemical components and not real electrical devices, circuit model parameters depend on the defined stimulus [7]. Thus cell tests should be conducted according to the BESS application. A BESS is connected to the power grid by a power conversion system (PCS). The main function of a BESS is peak load shifting. On the operating mode, the power or current of the batteries is constant for several minutes and then changes to another power or current controlled by the PCS. Therefore, the resistance can be estimated by the pulse charge/discharge tests with period of several minutes [8].

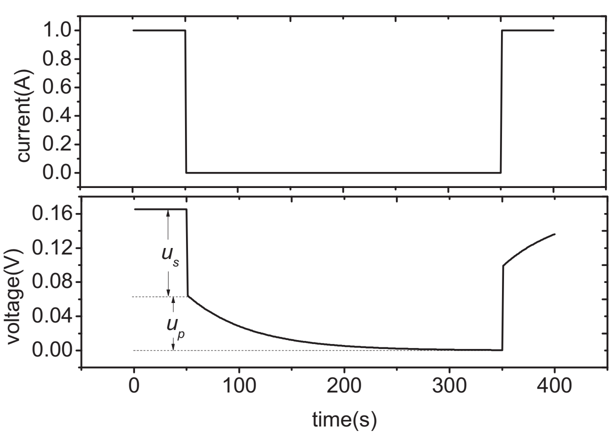

Fig. 2. Pulse charge test

A. Ohmic Resistance Estimation

As described above, the ohmic resistance is calculated when the current changes. Thus R_s can be calculated as the following equation:

$$R_s = \frac{\Delta u_s}{\Delta i_c} \tag{1}$$

A pulse charge test is shown in Fig.2. The cell charges for a moment and then stays still for several minutes. As soon as the state of the cell changes from charge to relaxation, the voltage on R_s drops from u_s to 0. Since the voltage of RC network doesn't change immediately, the variation of the cell voltage Δu_c equals to Δu_s. Although R_s can be estimated whenever the current changes, large current variation is preferred for improvement of estimation accuracy.

B. Polarization Resistance Estimation

According to the pulse charge test, the polarization voltage u_p decreases when the cell relaxes. Assuming the current keeps 0 from time t_1 to t_2, the u_p changes as the following equation:

$$u_p(t-t_1) = u_p(t_1)\cdot \exp(-\frac{t-t_1}{\tau}), t_1 < t < t_2 \tag{2}$$

And the time constant is:

$$\tau = R_p \cdot C_p \tag{3}$$

Since the current is zero and stays the same, the variation of u_p equals to that of u_c. R_p and C_p can be estimated with the relaxation data by MATLAB/Curve Fitting Tool.

Theoretically, any experiment data can be used for the polarization resistance estimation if the open circuit voltage (OCV) and R_s is known. An equation of state based on the cell model is shown as followed:

$$\begin{aligned} u_c(t) &= OCV - u_s(t) - u_p(t) = OCV - R_s \cdot i_c(t) \\ &- u_p(t')\exp(-\frac{t-t'}{\tau}) - R_p \cdot i_c(t)\cdot(1-\exp(-\frac{t-t'}{\tau})) \end{aligned} \tag{4}$$

Time t' is ahead of time t. OCV is a function of SOC, temperature, ageing degree and so on. It cannot be measured directly if the current is not zero. In fact, OCV is usually measured after the current stays zero for a long time. Another method to achieve OCV is solving the OCV describing function, whereas the estimation error of OCV can be large. So when the current is not zero, calculating R_p by the equation of state is influenced by the error of OCV. What's more, the error of R_s does affect the u_c, especially under a large current.

IV. Results Discussing

In this paper, the application of resistance focuses on SOC estimation. As shown in Fig.3, the relation between OCV and SOC is nonlinear. When SOC is low to 10% or up to 95%, the

OCV is very sensitive to SOC. However, in the other area, SOC = 10% to 95%, the curve is so flat that a little error in OCV estimation may lead to a significant difference in SOC. Meanwhile, the SOC always ranges from about 10% to 90% to keep the BESS operate safely. So the emphasis of resistance investigation is placed on the middle SOC range.

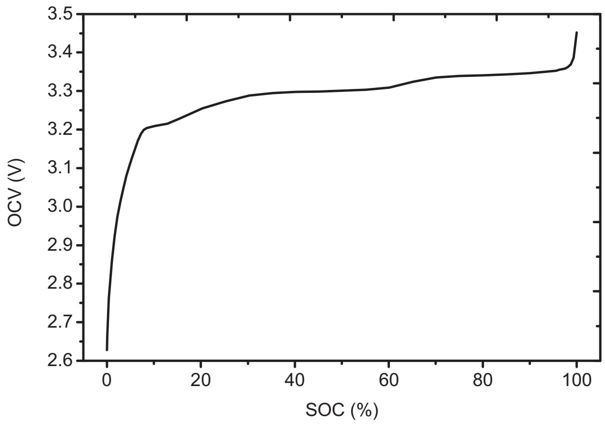

Fig. 3. OCV-SOC curve for $LiFePO_4$ cell

A. Ohmic Resistance

Various pulse current charge/discharge experiments have been conducted to measure ohmic resistance under different situations. The changing current is shown in Fig.4, so is the relative ohmic resistance, which is measured as soon as the current changes.

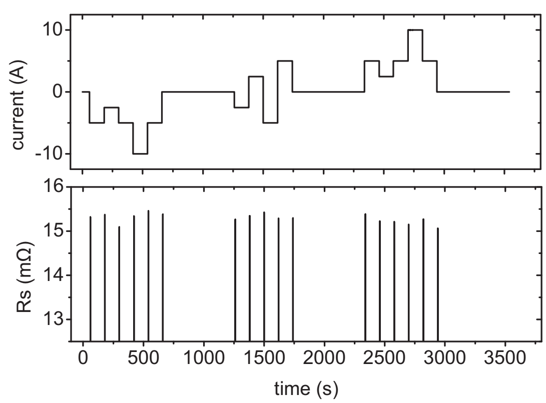

Fig. 4. Ohmic resistance under different current variations

The current varies from -1C to 1C, including -1C, -0.5C, -0.25C, 0C, 0.25C, 0.5C and 1C. Higher current seldom appears in BESS. The SOC ranges from 40% to 50%. The ohmic resistance R_s = 15.287±0.227mΩ and the error is about 1.49%, which indicates the current or current variation makes a little difference on the ohmic resistance measurement.

Another experiment is shown in Fig.5 to study the relationship between SOC and the ohmic resistance.

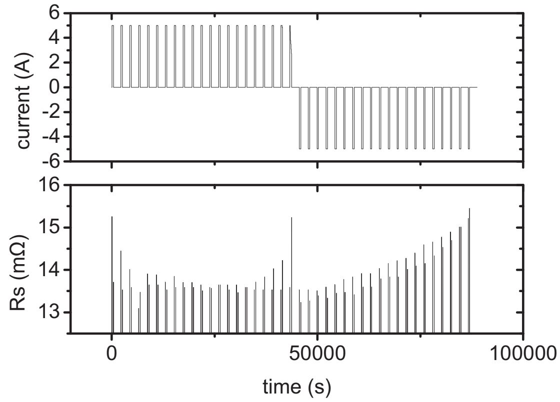

Fig. 5. Ohmic resistance under different SOC

The pulse current is from 0C to 0.5C or from 0.5C to 0C in charge and from 0C to -0.5C or from -0.5C to 0C in discharge. The SOC increases from 0% to 100% in charge and from 100% to 0% in discharge. There are 82 ohmic resistance measured in the experiment, including 42 in charge and the other 40 in discharge. The ohmic resistance R_s = 13.894±1.562mΩ and the error is about 11.25%

As the SOC increases, the ohmic resistance decreases at first and then increases in charge. However, different measurements lead to different resistances, especially when the SOC is high or low. In low SOC stage, the resistance measured by the current variation from 0C to 0.5C is larger than that from 0.5C to 0C. For example, the first ohmic resistance is 15.255mΩ, which is measured in current variation of (0.5C-0C) and the voltage is about 2.75V. The second one is 13.710mΩ, which is measured in current variation of (0C-0.5C). The difference between the two ohmic resistances is about 11.27%. In high SOC stage, the resistance measured by the current variation from 0C to 0.5C is smaller than that from 0.5C to 0C. The resistance keeps steady in both of the current variations in middle SOC stage, the same as that shown in Fig.4. The maximum difference of ohmic resistance measurement in a fixed SOC is caused by that when the cell voltage is 3.50V and SOC is about 100%. One is 13.590 mΩ, and the other is 15.233 mΩ with a difference of 12.09%.

As the SOC decreases, the ohmic resistance increases in discharge. The difference is 16.79% between the maximum ohmic resistance and the minimum one. At a fixed SOC, the ohmic resistances measured by stand to discharge and discharge to stand are almost the same.

In some research, the ohmic resistance is used to study the aging characteristics of lithium cells [9-11]. However, if the cell is not ‘old’ enough, the measurement error of the ohmic resistance is much larger than the difference caused by ageing. Therefore, the ohmic resistance can do little help for aging prediction. Measuring the ohmic resistance by a fixed current variation in the middle SOC stage is a good choice for limiting the measurement error.

B. Polarization Resistance

The polarization resistance cannot be measured by the method taken on the ohmic resistance for the voltage on the polarization capacitor stands the same at the moment the current changes. In a general way, the measurement is based on the changing data of the cell voltage after that the current turns to zero. The least square method is used for polarization parameters identification.

The experiment contains pulse charge and discharge, as shown in Fig.5. The charging/discharging time for a cycle is 6min, and the relaxation time is 30min. Therefore, the voltage of the polarization capacitor is considered to be zero at the end of each relaxation. As shown in Fig.6, the cell voltage almost remains unchanged before the relaxing process finishes.

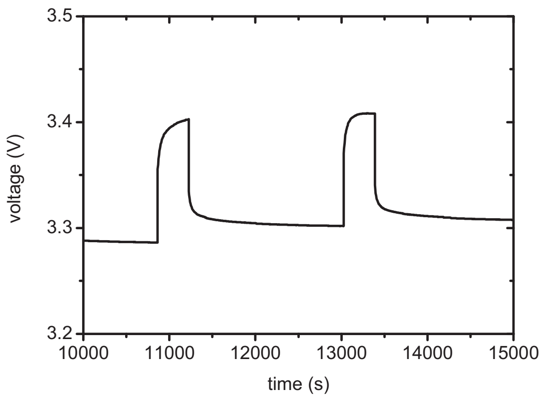

Fig. 6. Changing voltage in pulse charge experiment

Fig.7 shows the changing voltage of the polarization resistance in relaxation. When the cell changes from charge to relaxation, the cell voltage or the voltage on the polarization resistance decreases as time goes on. While the cell voltage or the voltage on the polarization resistance increases as the cell changes from discharge to relaxation. During the whole relaxation process, the rate of the voltage increasing or decreasing changes with the SOC.

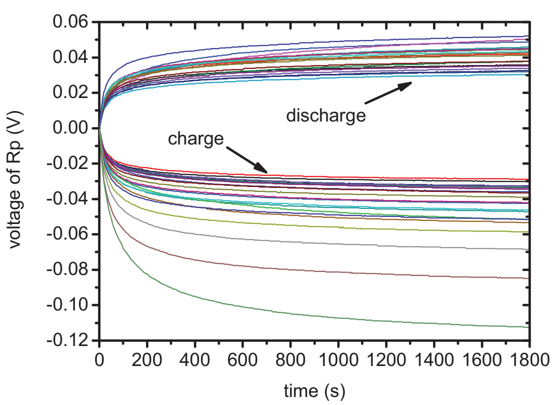

Fig. 7. The voltage of the polarization resistance in relaxation

Assume that the voltage of the polarization resistance is steady at the end of the charge/discharge process. That means the voltage of the polarization resistance is proportional to the polarization resistance at the beginning of the relaxation. At the end of the relaxation, the voltage of the polarization resistance decreases to zero and the variation of the cell voltage during the relaxation process is the voltage of the polarization resistance corresponding to the charge/discharge current. Therefore, the larger cell voltage variation means the larger polarization resistance.

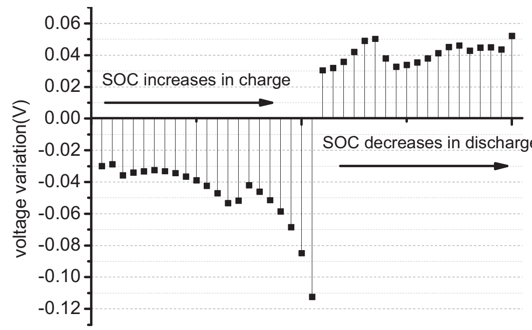

Fig. 8. The cell voltage variation in relaxation under different SOC

As shown in Fig.8, the cell voltage variation in relaxation increases as the SOC increases in charge. The polarization effect enhances and the polarization resistance increases. However, a change in the opposite direction occurs at the SOC about 70%. The change is caused by the chemical reaction in the cell and other batteries may not have the same feature. The phenomenon is similar to the incremental capacity, which differs in different batteries [12]. Besides, a hump is obvious in the polarization resistance at the SOC about 70% when the SOC decreases in discharge.

Several polarization resistances at different SOC are listed in Table I.

TABLE I. THE POLARIZATION RESISTANCE AT DIFFERENT SOC

SOC(%)	Polarization Resistance (mΩ)	
	Charge	Discharge
9.53	5.76	10.42
28.57	6.50	8.56
52.39	8.50	7.06
66.66	10.36	7.56
71.45	8.42	10.04
80.95	10.30	8.38
90.50	13.70	6.38
95.26	17.00	6.08

The variation trend of the polarization resistance is more complex than the ohmic resistance. Few researches on technical application of the polarization resistance have been carried on. However, identification of the polarization resistance at different SOC can help to estimate SOC. As shown in Table I, the polarization resistance gets to an extreme value at the SOC of 70%. By tracking the extreme value, we can modify the SOC around 70%, which the OCV-the SOC curve is flat and hard to achieve a precise SOC estimation result.

V. CONCLUSION

In this paper, the characteristic of the ohmic resistance and the polarization resistance of $LiFePO_4$/C cells has been investigated. Methods of resistance estimation are proposed, so are the experiments for parameters identification. According to the resistance measurement result, the ohmic resistance is steady in middle SOC stage no matter what current variation is used for calculation, but it changes with the SOC and the charge/discharge process. The performance of the polarization resistance is more complicated than that of the ohmic one. However, an important result that the polarization resistance takes a reverse change in variation trend at about SOC of 70% is discovered. The phenomenon is applied to $LiFePO_4$/C battery, but not for other batteries. For other batteries, the research method is also available. The result is available for SOC estimation. Intensive study on cell resistance is needed to conduct to get more usable information for lithium battery technical application such as BESS.

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