Research on Active Equalization of Lithium Battery via SOC

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Abstract. This paper presents an active equalization method for lithium battery via SOC. The high accuracy of SOC is promised by extended Kalman filter algorithm (EKF) based on the adaptive parameters equivalent-circuit model at all SOC region. Then a small size, low loss resonant soft-switching active equalization circuit is presented. That circuit combined with SOC do precisely balance the battery pack during charge and discharge processes, which can effectively improve the battery pack’s using life.

Introduction

The lithium ion battery is more widely used for the advantages of large capacity, small size, safety and environmental friendly, etc. Since capacity of single lithium battery is limited, many practical engineering applications require multiple batteries in series to increase capacity and voltage. However, due to the poor consistency of lithium batteries, battery pack connected in series tend to be lower than the single-cell life, and therefore we need to make balance \[1\]. Active equalization is research focus, but there are many areas to improve, such as the large volume circuit. This paper presents an active balanced approach via SOC, which get little equilibrium error during the charged and discharged process with smaller circuit size.

SOC Estimation

To ensure a balanced small error, it is necessary to accurately estimate the SOC of lithium battery. We reach the high precision of lithium battery SOC by using Kalman filter with adaptive parameters equivalent-circuit model(AP).

Since the parameters of battery are time-varying with different temperature and remaining state of charge, the adaptive parameter model is proposed to simulate internal battery to ensure high accuracy of SOC. The block diagram of AP model shows as figure 1. As we can see from the block diagram, the equivalent circuit model of lithium battery is constantly revised through the differences of output between battery and model. The parameters reconfiguration mechanism could be based on fuzzy regulator for the parameters vary non-linear\[2\]. Thus, the model closest to the true state of internal battery is being built, which provided a basis for high accuracy of estimating SOC.

Using the extended Kalman filter(EKF) estimates state of charge of lithium battery can achieve high accuracy on the basis of AP model, which leads the parameters varying with state of battery. So the AP equivalent-circuit model can be drawn into Fig2 that every parameter is non-fixed. According to Kirchhoff's laws and ampere-hour integration, we can get the state-space equation bellow.

\[
\begin{align*}
SOC_{k+1} &= A \cdot SOC_k + B_k \cdot i_k + \omega_k \\
U_k &= C_k \cdot U_{oc} - i_k R_0 - i_k R_1 \left(1 - e^{-\frac{\Delta t}{\tau}}\right) \\
&\quad - k_i k + v_k
\end{align*}
\] (1)
Lithium battery

Prototype model based PNGV

Parameters Reconfiguration Mechanism
d/dt SOC Estimation

Fig1 Block diagram of AP model

Where, \( A=[1], B_k=[-\beta \frac{\Delta t}{C}], C_k=[\frac{\partial u_k}{\partial SOC}], \quad \tau = R_1 C_1, \quad k = 1/C_b, \quad w_k \) and \( v_k \) is zero-mean Gaussian noise sequence with covariance \( E\omega_k \) and \( E\nu_k \). And the \( R_0, C_0, R_1, C_1 \) will change with the state of battery.

Fig2 AP equivalent-circuit model

Fig3 SOC estimation Error

We define the state \( X_k \) is \( SOC_k \), and initialize the state \( X_0 \) and covariance \( P(0) \) with \( SOC_0 \) and 0. Then the process of estimating SOC using EKF [3] is as follows.

Time update,
\[
\hat{x}_k = \hat{x}_{k-1} - B i_{k-1}
\]
\[
P_{k+1} = A_{k-1} P_{(k-1)} A_{k-1}^T + E\omega_k
\]

Gain update,
\[
K_f(k) = P_{(k)} C_k^T [C_k P_{(k)} C_k^T + E\nu_k]^{-1}
\]

State update,
\[
\hat{x}_k = \hat{x}_k + K_f(k)[U_k - g (\hat{x}_k, U_k)]
\]
\[
P_{k} = (1 - K_f(k)C_k)P_{(k)}
\]

Where, \( K_f(k) \) is Kalman gain matrix, \( g(x, U) \) is the output math function of model, \( P(k) \) is covariance of state estimation error. The estimating error of SOC using the former method is shown in Fig3. As can be seen from the figure, the above method can ensure error of SOC less than 5% even in the region of SOC blow to 20%. Therefore, the method of EKF based FAP model is effective.

Active Equalization circuit

Active equalization, also called energy-recovery balance, will be designed by the principle of resonant soft-switching. As we all know, LC series circuit whose terminal voltage is inconsistent will make resonant, and the frequent is going to be
\[
f = \frac{1}{2\pi \sqrt{L_1C}}
\]

By that principle, we can design the schematics of active equalization circuit, shown in Fig4. The frequency of PWM is half of resonant, and its duty cycle is 50 percent. Hypothesis that voltage of battery B1 is 3.6V, and B2 is 3.4V, the switch s1, s2 is going to close, and the other two is opposite. At the first half of cycle, LC circuit parallel across the battery of high SOC to make resonance, and the LC circuit is charged by the battery. The resonant current trends to zero when the time elapsed a half of resonant cycle, then switch state is about to be turned around to make the LC
circuit parallels to another cell of lower SOC. Then the low SOC battery is charged by LC circuit at the left half cycle phase. By this way, the energy transfer from one cell to another is achieved, and the cells will get balance after several cycles. At the same time, soft-switching come true for the current at the moment of switching tends to zero, and switching loss is small [3].

The Fig5 shows the current and voltage of LC circuit. We can recognize that a half of cycle storage power, and the other transfer out power, which combined the control of PWM would achieve balancing cells.

![Fig4 Resonant soft-switching balancing circuit](image)

![Fig5 Current and voltage of LC](image)

This method can get balance by inductors with microhenry level and capacitors with microfarads level, which overcomes the disadvantage that active balance needs large size circuit.

**Equalization via SOC**

The danger of lithium battery “out of balance” is that one or more cells may limit the discharge ability of the pack if their SOC is much more different. Over time, balanced evaluation is usually difference of battery terminal voltage. However, since the sampling error and other factors, the evaluation with voltage value often do not guarantee little difference of SOC between different batteries. Equalization via SOC not only can improve the balancing accuracy, but also can adopt different balancing strategy based on characteristics at charge or discharge process[5].

Consider the battery characteristic that cell SOC\textsubscript{k} must reside in a range \( \text{SOC}_{\text{min}} < \text{SOC}_{\text{k}} < \text{SOC}_{\text{max}} \) to improve the battery life [1]. For the cell \( i \) at SOC\textsubscript{k}, we can calculate that the capacity of ampere-hours left for charge is

\[
C_{\text{charge}}^{\text{charge}} = (\text{SOC}_{\text{max}} - \text{SOC}_{\text{k}})C_i \tag{8}
\]

and the capacity of ampere-hours left for discharge is

\[
C_{\text{discharge}}^{\text{discharge}} = (\text{SOC}_{\text{k}} - \text{SOC}_{\text{min}})C_i \tag{9}
\]

Where \( C_i \) is capacity of cell \( i \). Based on equations (8) and (9), the balancing procedure which can equalize both charge and discharge process is designed shown in Fig6. By using the method here the pack will provide better performance in the long run since all cell dynamic characteristics can be equaled.

![Fig6 Flow chart of equalization via SOC](image)
Conclusion

This paper presents an effectively method of active equalization during both charge and discharge process. Based on the adaptive parameters model, the EKF algorithm can reach high state estimating accuracy at all SOC region. The active balancing circuit is cleverly use of resonance reaching switching losses minimal by taking advantage of the instant zero resonant current while energy transfer.

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