Research on State-of-Charge (SOC) estimation using current integration based on temperature compensation

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Abstract: The traditional current integral method for the state-of-charge (SOC) estimation has an unusable estimation accuracy because of the current measuring error. This paper proposed a closed-loop temperature compensation method to improve the SOC estimation accuracy of current integral method by eliminating temperature drift. Through circuit simulation result in Multisim, the stability of current measuring accuracy is improved by more than 10 times. In a designed 70 charge-discharge experimental circle, the SOC estimation error with temperature compensation had 30 times less than error in normal situation without compensation.

1. Introduction
With the enhancement of environmental consciousness, the electric vehicle industry develops vigorously. As the power of electric vehicle, the state of charge (SOC) of the Li-ion battery is the key parameter to indicate its residual capacity. Accurate SOC estimation is the foundation of utilizing Li-ion battery with more safety and efficiency, and gives an important reference to predict the remaining driving mileage. Furthermore, it is conducive to maximum the charge-discharge circle of the battery capacity.

In recent years, many methods have been proposed to improve the performance of the SOC estimation, containing the current integral method, open-circuit voltage method, Kalman filter series algorithm, neural network algorithm and multi-model switch estimation algorithm based on the information fusion\textsuperscript{[1,2,3]}. The open-circuit voltage method estimates the SOC via the open-circuit voltage of the battery, but it requires the battery in non-working state and is not suitable for real-time estimation. Furthermore, the SOC estimation varies greatly from 20% to 90% while the open-circuit voltage changes only tens of millivolt which may bring severe measurement error. Kalman filter series algorithm generally using the battery load voltage as the observation parameter, which will becomes complex with many factors considered in the system state-space equations\textsuperscript{[3,4]}. Neural network method works based on a large number of system parameters, obtain a relatively accurate SOC estimation model through training, amount of calculation is needed and it is not suitable for the real-time embedded system of the electric vehicle. As the most popular SOC estimation method in practical, whether it is a single battery or a group of batteries, the current integral method can accurately calculate the available capacity. However, as an open-loop estimation method, limited to the
integrating time error, current detection error and non-Gaussian distribution noise, the accuracy of the current integral method is not enough[5].

In this paper, a closed-loop temperature compensation system is proposed. Because the resistance of negative temperature coefficient (NTC) thermistor varies uniformly with temperature, which is similar to the temperature drift of hall current sensor. A temperature compensation circuit is designed to eliminate the temperature drift of hall current sensor, and it’s verified by theoretical analysis and experiment that can remarkably improve the accuracy of the SOC estimation by current integral method.

2. Current Integral Method and Error Analysis
SOC defined as the radio of residual capacity and available capacity[3], changes continuously by time. Defining the SOC formula at time \( t \) as

\[
SOC(t) = SOC(0) + \frac{\int_0^t i(\tau) d\tau}{C_N}
\]

Where \( SOC(0) \) is the initial value at time 0, \( \eta \) is the Coulombic efficiency (generally taken as 1), \( i(\tau) \) is the current value (defined to be positive for charge and negative for discharge), \( C_N \) is the total available capacity of the battery.

The current integral method is the integral of the charging or discharging current times the time, the SOC estimation accuracy influenced by several factors[6], like

1) Inaccuracy of \( SOC(0) \). It influences the accuracy of the \( SOC(t) \). In particular, in the first working cycle, \( SOC(0) \) of the battery is usually unknown, generally is taken as zero. It can be calibrated in the subsequent working cycle based on the record of a complete charge and discharge cycle.

2) Inaccuracy of \( C_N \). \( C_N \) varies with external environment and the number of times that the battery is charged and discharged. Generally, \( C_N \), equal to the nominal capacity of the battery at room temperature in the first working cycle, is calibrated by real capacity in the subsequent working cycle.

3) Imprecision of \( i(\tau) \). The charge-discharge current on the electric vehicles can be regarded as the transient DC current with time, especially in the actual working condition, the discharge current mutation is frequent. The error of real-time current mainly comes from the sensor sensitivity error and measurement error. At present, electric vehicles often use high-precision hall current sensor to measure the current. It has advantages of good linearity, wide measurement frequency bandwidth, and excellent dynamic performance and so on. However, hall current sensor is vulnerable to the ambient temperature resulting in serious temperature drift, which is not easy to eliminate by calibration in real-time system.

In addition, the error of the integration time also brings the error to the current integral method. In the actual embedded system, a more accurate clock source is usually used to reduce this error.

In this paper, a closed-loop current detection system is adopted to eliminate the temperature drift of hall current sensor to improve the SOC estimation accuracy.

3. Principle of Temperature Compensation
For the temperature drift of hall current sensor, the existing temperature compensation method has two main categories: one is the hardware compensation method, divided into open-loop compensation method and closed-loop compensation method[7,8,9]. The other is software compensation, such as the use of two-dimensional regression analysis of numerical processing to achieve compensation[10].

Hardware open-loop compensation method requires high power stability, and ignoring the square term of temperature change (\( \Delta T^2 \)) which is far less than the influence brought by \( \Delta T \), is kind of incomplete temperature compensation method. The software compensation method is not suitable for real-time system with large data volumes.

3.1 Principle of Closed-loop Control System
Accurate current measurement is the foundation of the current integral method. Block diagram of closed-loop current detection system is shown in Figure 1, the product of the output signal $V_O$ and the temperature compensation signal $V_T$ as feedback signal is superimposed on the input signal $V_{IN}$ (current sensor output), the system transfer function defined as

$$\frac{V_O}{V_{IN}} = \frac{I}{I - KV_T}$$  \hspace{1cm} (2)

Where K is amplification factor of proportional element. For the hall current sensor,

$$V_{IN} = [I + a(T - T_0)]V_{IN0}$$ \hspace{1cm} (3)

$$V_T = b(T - T_0)$$ \hspace{1cm} (4)

Where $V_{IN}$ is the Laplace transformation of the current sensor output at $T$ °C, $V_{IN0}$ is the current sensor output at $T_0$ °C, $\alpha$ is temperature coefficient of hall current sensor. $V_T$ is the output voltage of temperature compensation circuit, $\beta$ is the corresponding sensitivity. Generally taking $T_0=25$ °C.

![Figure 1. Block diagram of closed-loop detection system](image)

Put formula (3) and formula (4) into formula (2), then

$$\frac{V_O}{V_{IN0}} = \frac{I + a(T - T_0)}{I - Kb(T - T_0)}$$ \hspace{1cm} (5)

Where $V_O$ is the output voltage of current sensor with temperature compensation. When $\alpha = -K\beta$, the ratio $V_O/V_{IN}$ is constant, thus the sensor output is not related to the ambient temperature, and temperature drift of hall current sensor is eliminated.

### 3.2 Circuit

The realization of the circuit consists of three parts: adder circuit, temperature compensation circuit and gain compensation circuit, as shown in Figure 2. In Figure 2, operational amplifier OP1, OP2 and OP3, resistors R1-R11, thermistor RNTC build the circuit. The output signal $V_O$ is only related to the input signal $V_{IN}$, regardless of temperature.

![Figure 2. Closed-loop temperature compensation circuit](image)

Adder circuit consists of operational amplifier OP1 and resistors, achieves the accumulation of input signal $V_{IN}$ and feedback circuit signal in Figure 1. Temperature compensation circuit consists of operational amplifier OP2, resistors and thermistor, achieves temperature. Thermistor RNTC with
negative temperature coefficient (NTC), the corresponding resistance with the temperature changes can be expressed as

$$R_{NTC} = R_0 e^{\frac{B}{T_0 + T}}$$

(6)

Where $R_{NTC}$ is the resistance of thermistor at $T$ °C, $R_0$ is the resistance of thermistor at reference temperature $T_0$. $B$ is a constant related to thermistor material. Generally taking $T_0=25$ °C.

4. Simulation and Results Analysis

In order to verify the validity of the proposed method, a simulation circuit in the Multisim software was designed. A muRata 47± 0.5% KΩ NTC thermistor NCP18WB473D03RB was selected to approximate the thermistor in circuit. The detailed circuit resistance is shown in Table 1.

Table 1. Parameters of circuit.

| RNTC | R1 (KΩ) | R2 (KΩ) | R3 (KΩ) | R4 (KΩ) | R5 (KΩ) | R6 (KΩ) | R7 (KΩ) |
|------|---------|---------|---------|---------|---------|---------|---------|
| R0(KΩ) | B      | 47      | 4101    | 100     | 100     | 378.04  | 359.21  | 20.1    | 100     | 100     |

Setting LEM Company DHAB S/04 hall current sensor for example, according to the datasheet, it could approximate the temperature drift and the ambient temperature into a linear relationship within ±20A range. When the ambient temperature reaches 100 °C, the corresponding temperature drift is ±1.2 A while reference point is ± 0.5 A at 25 °C, the slope of temperature drift curve is 0.7/(20×75) °C, as curve shown in Figure 3 in dot line.

Figure 3. Current detection error with and without temperature compensation

The operating temperature range of the automobile electronics is chosen as the observation interval, and the current detection error curve after temperature compensation as show in Figure 3 in solid line. In Figure 3, the current detection error without temperature compensation at 65°C is 4.37%, whereas the current detection error with temperature compensation is limited to a range of ±0.16% among $T \in [-30°C, 65°C]$. The curve of current detection error is enlarged as shown in Figure 4. It can be concluded that the accuracy of the current detection is increased by an order of magnitude, the current detection error caused by the temperature drift is greatly reduced.

The experiment, which was based on a Li-ion battery with the nominal voltage of 3.2V and the nominal capacity of 10AH, was designed to verify the theory mentioned above. According to "Technical specification of battery management system for electric vehicles" standardized charge and discharge condition 4 [11], as shown in Figure 5. 70 times charge and discharge experimental cycles were implemented when the ambient temperature rose continuously from -30°C at 1°C/min speed.

The experimental data were simulated by MATLAB, and the SOC estimation error were compared between results with temperature compensation and without temperature compensation, as shown in Figure 6. It can be seen that with the increase of the number of charge and discharge cycles, the
temperature drift error of the current sensor accumulates. The SOC estimation error without temperature compensation is as high as 45.68% after 70 cycles, whereas the corresponding SOC estimation error with temperature compensation is only -1.54%. The results show that the temperature compensation method greatly eliminates the temperature drift of the current sensor and improves the SOC estimation accuracy.

![Figure 5. Current of one charge and discharge cycle (Conditions 4)](image)

![Figure 6. SOC estimation error](image)

5. Conclusions

As the most widely used engineering estimation SOC method, the current integral method has the advantages of simple and easy to implement. However, due to the detection of hall current sensor limited by the temperature characteristics of semiconductor materials, the temperature drift problem is inevitable, and seriously affects the SOC estimation accuracy of the current integral method.

In this paper, by using the negative temperature effect of the NTC thermistor, a closed-loop control system is proposed to realize the temperature compensation of hall current sensor so that the tested current is not influenced by the ambient temperature. The control flow of the closed-loop control system is analysed in principle, which solves the temperature drift error caused by the square of the temperature change $\Delta T^2$, improving the measurement accuracy of hall current sensor in a large range. Meanwhile the implement circuit is simple with high reliability. And the theoretical validity is verified by circuit simulation experiment and working condition experiment.

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