A mechanical-electronic coupling model based state of charge estimation method for Lithium-ion pouch battery module

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Summary

The estimation of battery state of charge (SOC) is one of the core functions of battery management system. In recent years, the battery SOC estimation based on battery mechanical characteristics has attracted extensive attention. Battery SOC estimation by stack pressure is achieved by using cell thickness as an intermediate variable. In this paper, a mechanical-electronic coupling model of the Lithium-ion pouch battery module is established with the variation of battery thickness as the intermediate variable. Based on the identification of model parameters, the estimation algorithm of SOC based on EKF is proposed and verified by experiments.

Keywords: mechanical-electronic coupling model, stack pressure, battery thickness, state of charge estimation, li-ion battery

1 Model development

1.1 Proposed mechanical-electronic coupling model of the Lithium-ion pouch battery module

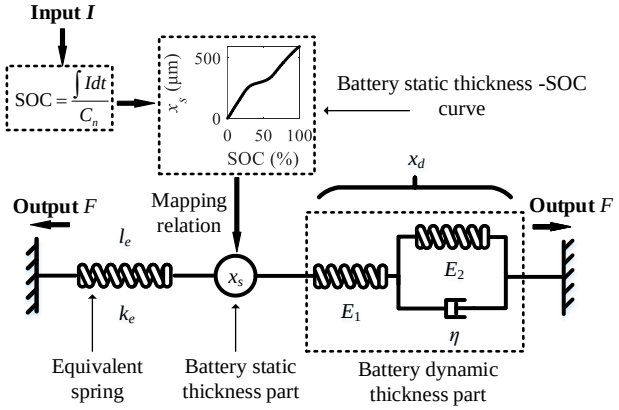

Figure1: The mechanical-electronic coupling model of the Lithium-ion pouch battery module

The core of the coupling relationship between the electrical and mechanical characteristics of the battery is the battery thickness. There is a stable relationship between battery SOC and the variation of battery static thickness. At the same time, the battery dynamic thickness change caused by the force change can be characterized by the equivalent mechanical model. So the mechanical-electronic coupling model of the Lithium-ion pouch battery module was proposed in Figure 1. The input and output of the model is the current and stack pressure, respectively. The intermediate variable of the model is the thickness change of each component. According to the model, the state space expression is as follows:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

其 中 ： $u = I$ $y = F - \dfrac{a_i E_1 E_2}{E_1 E_2 k_e + P(E_1 + E_2)}$ $x = \left[z \quad x_d - \dfrac{P a_i (E_1 + E_2)}{E_1 E_2 k_e + P(E_1 + E_2)} \right]^T$

$$A = \begin{bmatrix} 0 & 0 \\ \dfrac{P k_i (E_1 + E_2)}{k_e E_1 \eta + P\eta} & -\dfrac{k_e E_1 E_2 + P(E_1 + E_2)}{k_e E_1 \eta + P\eta} \end{bmatrix} \quad B = \begin{bmatrix} \dfrac{1}{C_n} \\ \dfrac{P k_i}{C_n (k_e E_1 + P)} \end{bmatrix} \quad C = \begin{bmatrix} \dfrac{k_i}{k_e} & -\dfrac{1}{k_e} \end{bmatrix} \quad D = 0$$

1.2 Observability of the battery model

In order to ensure that the battery state can be estimated by the established model, it is necessary to analyze the observability of the model. The observability matrix of the model is as follows:

$$O = \begin{bmatrix} C \\ CA \end{bmatrix} = \begin{bmatrix} \dfrac{k_i}{k_e} & -\dfrac{1}{k_e} \\ -\dfrac{P k_i (E_1 + E_2)}{k_e^2 E_1 \eta + k_e P \eta} & \dfrac{k_e E_1 E_2 + P(E_1 + E_2)}{k_e^2 E_1 \eta + k_e P \eta} \end{bmatrix} \tag{2}$$

In order to judge whether matrix O is full rank, the value of its determinant is calculated as follows:

$$|O| = \frac{k_i E_1 E_2}{k_e \eta (k_e E_1 + P)} \tag{3}$$

Since the numerator and denominator of the above equation will not be zero in actual operation, the observability matrix is full rank. The state variables of the model are observable.

2 Experimental verification

2.1 Experiment equipment and the configuration

In order to ensure the reliability of SOC estimation experimental results, a battery mechanical-electronic coupling characteristic testing system was built to simulate the state of battery modules under actual working conditions, as shown in Figure 2.

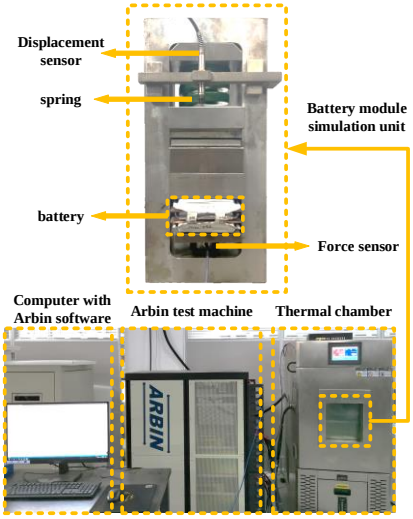

Figure2: Battery mechanical-electronic coupling characteristic testing system

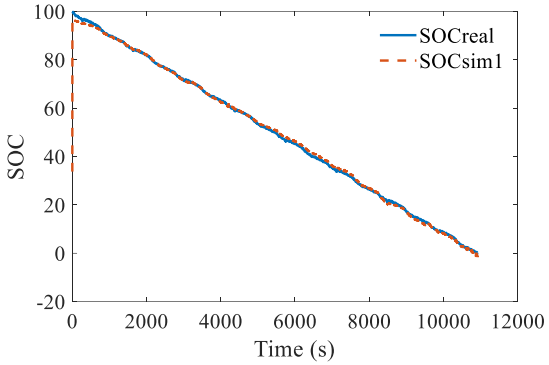

Figure3: Verification results of SOC estimation experiments

2.2 Experimental test procedure

Commercial pouch cells with a nominal capacity of 10 Ah were used in this study. The chemistry of the pouch cell was graphite/NMC with 3.7 V nominal voltage. The battery module simulation unit was placed inside the thermal chamber. The charging and discharging of the cells was performed with the Arbin test machine. Firstly, the New European Driving Cycle (NEDC) was utilized. The battery was charged by CCCV with a charge rate of 0.4C. After that, the battery was discharged with the NEDC drive cycle. The data from this experiment were used for parameter identification. Then the urban dynamometer driving schedule (UDDS) drive cycle was utilized in same procedure. The data from this experiment were used for experimental verification.

2.3 Identification method and the results

In the actual battery system, the measured current and voltage data are discrete data with a certain time interval. At the same time, the model is required to be linear and discrete when the SOC is estimated by the subsequent algorithm. Therefore, the above state space model needs to be discretized. The substitution formula for the first derivative is as follows:

$$\frac{\mathrm{d}\boldsymbol{x}(k)}{\mathrm{d}t}=\frac{\boldsymbol{x}(k+T)-\boldsymbol{x}(k)}{T} \tag{4}$$

The sampling period in this paper is 1 second, and the linear discrete battery model is obtained as follows:

$$\begin{cases}\boldsymbol{x}_{k+1}=(\boldsymbol{A}+\boldsymbol{E})\boldsymbol{x}_k+\boldsymbol{B}u_k\\ y_k=\boldsymbol{C}\boldsymbol{x}_k+\boldsymbol{D}u_k\end{cases} \tag{5}$$

The absolute value of the difference between the model output and the actual measured output was set as the objective function, and the model parameters were identified through the genetic algorithm toolbox in Matlab.

2.4 Experiments and results of SOC estimation based on Extended Kalman Filter

Experimental results show that the estimation accuracy of battery SOC is within ±2%, as shown in Fig. 3