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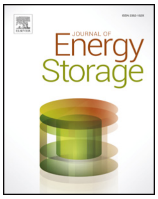

Detecting the internal short circuit in large-format lithium-ion battery using model-based fault-diagnosis algorithm

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ABSTRACT

The spontaneous internal short circuit that sporadically occurs during operation is an unsolved safety problem that hinders the widespread application of lithium ion batteries. An online fault-diagnosis algorithm is an urgent requirement for early detection of the spontaneous internal short circuit of lithium-ion batteries to guarantee safe operation. This paper presents a model-based fault-diagnosis algorithm for online internal-short-circuit detection. Relying on the theory of model-based control, the algorithm transforms the measured voltage and temperature to the intrinsic electrochemical status that can reflect typical internal-short-circuit features, i.e. the excessive depletion of capacity and abnormal heat generation. The estimated status of the suspicious cell deviates from the average value of the battery pack, therefore the algorithm can capture the internal-short-circuit fault by evaluating the levels of deviation. Simultaneously considering the diagnosis result calculated from both the voltage and temperature signal helps enhance the robustness of the algorithm with few false alarms. Substitute internal-short-circuit tests confirm that the algorithm is capable of identifying the internal-short-circuit fault before it develops into a severe hazard, e.g., thermal runaway. The equivalent short resistance, which can reflect the level of the internal short circuit, can be estimated with small error by the online fault-diagnosis algorithm.

1. Introduction

The new energy vehicle market is thriving, owing to breakthroughs in the energy density and cycle life of lithium-ion batteries [1,2]. However, safety problems have appeared as the industry is pursuing higher energy densities for lithium-ion batteries [3–5]. Cramming more active materials within a battery package is an intuitive solution to enhance the energy density, but this causes a higher potential for an internal short circuit (ISC) [6], e.g., the accidents in the Boeing Dreamliner [7] and Samsung Galaxy S7 [8].

The actual formation mechanism of a spontaneous ISC during onboard operation still requires further study; while researchers have not ceased to explore the “truth.” A lithium dendrite that pierces the separator and connects the cathode with the anode is thought to be one of the causes for the spontaneous ISC [9]. The growth of a lithium dendrite has been confirmed by microscopy [10–12], whereas the growth behavior can be predicted by electrochemical models [13]. Current models cannot simulate the full growing process of a lithium dendrite including all the interactions at the interface between the anode, electrolyte, and the separator [14,15]. Therefore modeling the formation of the full electric circuit for ISC still requires further study. Evidences indicate that once an electric circuit that discharges the cell is formed, the ISC will influence the thermal runaway behavior of lithium-ion batteries [16–18]. However, the mechanism of thermal runaway induced by an ISC is still unclear [19], and new interpretations are emerging sporadically [20,21].

To secure the battery pack from an ISC hazard, an online fault-diagnosis algorithm that can early detect an ISC is essential [6]. Fig. 1 shows the scheme of developing an online fault-diagnosis algorithm for ISC detection, including three correlated levels. Level I is for data generation, which can be used for model calibration, knowledge (of the ISC characteristics) accumulation, and algorithm validation. Level II is for the ISC characterization, which indicates the key features that can be used for fault diagnosis. Level III is for algorithm development, which utilizes all types of fault-diagnosis algorithms.

The objective of Level I is to generate sufficient data for the researchers/engineers to characterize the ISC behavior, and to validate the fault-diagnosis algorithm. Researchers are attempting to develop a proper substitute ISC test approaches to simulate the real failure of an ISC and to facilitate the characterization of the ISC features [22].

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Nomenclature

A_k, C_k	Matrix for the state-space model of battery (/)
A_S	The surface area of the battery (m^2)
C_1	The first-order capacitance in the battery model (F)
C_p	The heat capacity of the battery (J·kg-1·K-1)
E	The error between the measured voltage and the predicted voltage (V)
h	The heat convection coefficient (W·m-2·K-1)
I	The current (A)
I_{heat}	The heat current in the test for the determination of thermal runaway boundary in an ISC case (A)
i_T	The index number of the cell that has the minimum temperature ((1))
i_V	The index number of the cell that has the minimum voltage ((1))
L	The feedback gain for state update ((1))
M	The mass of the battery (kg)
P	The covariance matrix for the parameter identification algorithm (/)
P_{heat}	The heat power in the test for the determination of thermal runaway boundary in an ISC case (W)
Q_{st}	The standard capacity of the battery (Ah)
R_0	The direct-current resistance in the battery model (Ω)
R_1	The first-order resistance in the battery model (Ω)
R_{heat}	An embedded resistance to generate ohmic heat to heat the battery to thermal runaway (Ω)
R_{ISC}	The equivalent short resistance at the ISC point (Ω)
R_Ω	The ohmic resistance that reflects the average ohmic heat generation power considering the current (Ω)
$\overline{R_\Omega}$	The average R_Ω in the battery pack (Ω)
$R_{\Omega,W}$	The R_Ω for the “worst cell” that has the highest temperature (Ω)
SOC	The state of charge (1)
$\overline{SOC}$	The average *SOC* in the battery pack (1)
SOC_W	The *SOC* for the “worst cell” that has the lowest voltage (1)
T	The temperature (°C)
$\overline{T}$	The average temperature in the battery pack (°C)
T	The temperature rise rate (°C·s − 1)
T_{IN}	The internal temperature of the battery (°C)
T_{lim}	The temperature limit for safe operation (°C)
T_{OUT}	The temperature measured on the surface of the battery (°C)
T_W	The maximum temperature in the battery pack (°C)
T_∞	The ambient temperature (°C)
t_{DT}	The time when the internal short circuit is detected by the algorithm (s)
t_{ISC}	The triggering time of internal short circuit (s)
$t_{Lev,1}$, $t_{Lev,2}$, $t_{Lev,3}$	The moment when the algorithm returns fault flag $\Psi_1 = 1$, $\Psi_1 = 2$, $\Psi_1 = 3$ (s)
t_{TR}	The time when thermal runaway occurs (s)
U_1	The voltage at the first-order resistance in the battery model (V)
V	The voltage (V)
$\overline{V}$	The average voltage in the battery pack (V)
V_{exp}	The real voltage measures in experiment (V)
V_{lim}	The voltage limit for safe operation (V)
V_{mdl}	The voltage predicted by the model (V)
V_W	The minimum voltage in the battery pack (V)
$\overline{V_{1-3}}$	The average voltage between the time from $\Psi_1 = 1$ to $\Psi_1 = 3$ (V)
$y^0_{1,k}$, $y^0_{2,k}$	The intermediate vector for temperature filtering, the superscript “0” means “before filtering” (°C)
$y^F_{1,k}$, $y^F_{2,k}$	The intermediate vector for temperature filtering, the superscript “F” means “after filtering” (°C)
Z	The data observation in the algorithm of parameter identification using recursive least squares (V)
$z^F_{1,k}$, $z^F_{2,k}$	The intermediate *Z* vector for temperature filtering, the superscript “F” means “after filtering” (W)
α	The first-order time constant for the battery model (s)
β	The forgetting factor in the parameter identification algorithm (1)
γ	The forgetting factor in temperature filtering (1)
ΔR_Ω	The level of abnormal heat generation, defined as the quotient of the worst R_Ω and the average R_Ω (Ω)
ΔSOC	The difference between the average value and the worst value of the *SOC* of the battery pack (1)
ΔT	The difference between the average temperature and the maximum temperature in the battery pack (°C)
Δt	The sampling interval of time (s)
ΔV	The difference between the average voltage and the minimum voltage in the battery pack (V)
ε	The estimation error in the parameter identification algorithm (W)
η_C	The columbic efficiency (1)
Θ	The vector for the parameters to be identified in the algorithm of parameter identification using recursive least squares (/)
Λ_S	The preset threshold for judging ISC relying on the value of Ψ_Σ (1)
Σ^-	The priori covariance matrix (1)
Σ^+	The posteriori covariance matrix (1)
Σ_w	The error covariance matrix for the state update (1)
Σ_v	The covariance matrix for the measurement noise (1)
Φ	The vector for the data input in the algorithm of parameter identification using recursive least squares (/)
φ	The intermediate Φ vector for temperature filtering (A^2)
Ψ_1	The fault level indicating excessive capacity depletion (1)
Ψ_2	The fault level indicating abnormal heat generation (1)
Ψ_3	The fault level indicating large voltage deviation (1)
Ψ_4	The fault level indicating large temperature deviation (1)
Ψ_T	The fault level calculated from the temperature signal (1)
Ψ_V	The fault level calculated from the voltage signal (1)
Ψ_Σ	The overall fault level for ISC detection (1)

Subscript

i, j	Index number for batter cell, or thermocouples.
k	Time index.
V	For the voltage.
T	For the temperature.

Superscript

-	The priori state estimates.
+	The posteriori state estimates.

Abbreviations

BMS	Battery management system
FUDS	Federal urban driving schedule
ISC	Internal short circuit
OCV	Open circuit voltage
SOC	State of charge
TC	Thermocouple
USABC	U.S. advanced battery consortium