Journal of Power Sources 396 (2018) 715–724

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Online estimation of thermal parameters based on a reduced wide-temperature-range electro-thermal coupled model for lithium-ion batteries

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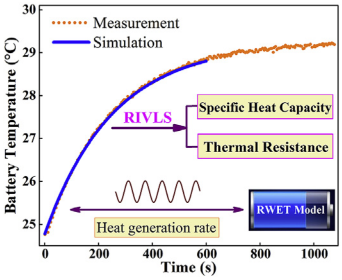
HIGHLIGHTS

- An online and simultaneous estimation method for thermal parameters with less time.
- Heat generation calculation using the RWET model without inherent errors.
- High estimation accuracy of thermal parameters validated with traditional methods.
- Good robustness with respect to the uncertainty of measurement data.
- A generic method with high adaptability verified by sufficient experiments.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Lithium-ion battery
Thermal parameters estimation
Recursive instrument variable least square method
Electro-thermal coupled model
Sinusoidal alternating current

ABSTRACT

To improve the accuracy of thermal model, optimize the design of heat dissipation system and evaluate online the thermal management system, an online estimation method of key thermal parameters is developed from carefully designed experiments, rather than being taken from the literature or the empirical value. The accurate prediction of heat generation, which is based on a reduced wide-temperature-range electro-thermal coupled model, is presented under easily obtainable alternating current excitation at different temperatures. To circumvent some inherent errors, a combined experimental/computational approach to simultaneously estimate the specific heat capacity and thermal resistance is proposed using quasi step power, with which the identification time is significantly reduced. The identified values of specific heat capacity and thermal resistance are validated with high accuracy. The adaptability validation is carried out under different temperatures and cooling conditions, as well as using different battery chemistries, indicating that the proposed method is generic. The in-situ methodology, thanks to good robustness on the colored noise, is capable of providing a promising candidate for accurate thermal modeling, on-board evaluation of battery thermal safety, and advanced design of thermal management system for electric vehicles.

1. Introduction

Lithium-ion batteries (LIBs) have extensively emerged as an important power source for electric vehicles (EVs) due to its superiority, such as good performance, high energy density and long cycle life. However, thermal issues of LIBs, such as the accelerated degradation

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https://doi.org/10.1016/j.jpowsour.2018.03.075
Received 11 January 2018; Received in revised form 8 March 2018; Accepted 27 March 2018
0378-7753/

Nomenclature

Q_b	Heat generation rate (W)
T_a	Ambient temperature (°C)
T	Battery temperature (°C)
u_o	Battery terminal voltage (V)
u_{ocv}	Open circuit voltage (V)
i	Current (A)
U_{ocv}	Equilibrium potential (V)
k	Computational time (s)
Δt	Time interval (s)
n_d	Order of error transfer function
K	Modified gain matrix
I_1	Identity matrix
f	Frequency (Hz)
$R_p(T, f)$	Polarization resistance (Ω)
$C_p(T, f)$	Polarization capacitance (F)
$R_b(T)$	Ohm resistance (Ω)
$R_x(T, s)$	Resistance (Ω)
$C_x(T, s)$	Capacitance (F)
E_{arx}	Activation energy of R_x (kJ·mol^{-1})
E_{acx}	Activation energy of C_x (kJ·mol^{-1})
b_{rx}	Proportional coefficient for resistance
b_{cx}	Proportional coefficient for capacitance
I	Peak value of alternating current (A)
T_o	Initial temperature difference (K)
A_1	Amplitude of the colored noise (°C)
L	Inductance (H)
R	Gas constant (J·mol^{-1}·K^{-1})
m	Battery mass (g)
R_T	Thermal resistance (K·W^{-1})
C_b	Thermal capacity (J·K^{-1})
C_p'	Specific heat capacity (J·g^{-1}·K^{-1})
C_{p0}'	Specific heat capacity (J·g^{-1}·K^{-1})

Greek symbols

V_ε	Noise (W)
$R_\alpha(T)$	Parameter of polarization resistance (Ω)
$R_\beta(T)$	Parameter of polarization resistance (Ω)
$C_\alpha(T)$	Parameter of polarization capacitance (F)
$C_\beta(T)$	Parameter of polarization capacitance (F)
$C_\gamma(T)$	Parameter of polarization capacitance (F)
$\lvert\varepsilon\rvert_{\mathrm{avg}}$	Mean value of the absolute error (°C)
$\lvert\varepsilon\rvert_{\mathrm{max}}$	Maximum relative error (°C)
τ_T	Thermal time constant (s)
e_γ	Gauss white noise (°C)
V_γ	Colored noise (°C)
$V_{\gamma 1}$	Colored noise (°C)

Subscripts

X	α or β or γ or b

Acronyms

ARC	Accelerating rate calorimeter
DC	Direct current
DST	Dynamic stress test
EIS	Electrochemical impedance spectroscopy
EV	Electric vehicle
EW	Electrochemical workstation
FD	Frequency-dependent
LFP	$LiFePO_4$
LIB	Lithium-ion battery
MAE	Maximum absolute error
MRSS	Mean residual sum of squares
NCA	$LiNi_xCo_xAl_xO_2$
RIVLS	Recursive instrument variable least square
RMSE	Root mean square error
RWET	Reduced wide-temperature-range electro-thermal
SAC	Sinusoidal alternating current
SAP	Sinusoidal alternating power
SOC	State of charge
TMS	Thermal management system

and thermal runaway at the elevated temperature, are still the main barriers to the wide spread deployment of LIBs in EVs [1,2]. Consequently, a well-designed thermal management system (TMS) is crucial to prevent overheating [3]. Thermal modeling, which elucidates the mechanism underlying the temperature rise of LIBs, is of great importance during the design phase of a TMS.

Thermal modeling of LIBs using partial differential equation [4], or finite element method [5] can be adopted to obtain the analytical solution of temperature distribution. However, these models are computationally intensive and difficult to parameterize, which limit their applicability in TMS. Due to its inherent simplicity, the lumped thermal model has been widely adopted for on-board temperature control for EVs. In addition, it is found that the main cause for the temperature non-uniformity is the heat flux from the battery surface, rather than the heat generation within the core [6]. To improve the accuracy of the lumped thermal model and optimize the design of heat dissipation system, key parameters such as specific heat capacity of LIBs and thermal resistance between LIBs and surroundings need to be carefully determined and should not be simply taken from the literature [7–9] or the empirical value [10].

Generally, three approaches can be employed to obtain the specific heat capacity. The adiabatic heating using an accelerating rate calorimeter (ARC) [11,12] or the polyurethane foam [13] allows determination of the specific heat capacity. However, these methods suffer from expensive thermal equipment, such as calorimeters, and challenges associated with their installations [14]. Most seriously, these adiabatic heating is not easy to be realized under practical operating conditions and the non-ideal thermal insulation inevitably results in the inherent error. The physics-based thermal parameter determination [15] is attractive but hardly applicable [16], because the details of battery design and battery materials are normally not provided by battery manufacturers. The transient state of temperature-rise of LIBs can be used to estimate the specific heat capacity only when the thermal resistance is previously known [17]. Nevertheless, the estimation of thermal resistance requires quasi-steady-state and thus it is time-consuming.

There are several previous efforts, such as the heat flux measurement, the quasi-thermal-equilibrium estimation and the stationary method without current injection, to determine the thermal resistance between LIBs and surroundings. The heat flux measurement with a gradient heat flux sensor [18], which allows determination of the thermal resistance, suffers from challenges associated with the especial equipment and their installations. The quasi thermal equilibrium between heat generation and dissipation of LIBs is time-consuming because the thermal time constant is normally large, such as 3 h [19]. The thermal resistance estimated from the stationary method [20,21] without current injection is strongly associated with the specific heat capacity. Consequently it results in great uncertainty and is time-consuming.

Some methods are developed to simultaneously determine the