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Butler-Volmer equation-based model and its implementation on state of power prediction of high-power lithium titanate batteries considering temperature effects

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ABSTRACT

This paper provides a further step towards popularizing the proposed Butler-Volmer (BV) equation-based model and its implementation on state of power (SOP) prediction at various temperatures, which is based on the relationship between state of charge and state of useful charge. The actual 10 s SOP of battery is obtained using the constant current pulse when the restriction of voltage is exactly managed. The COMPLEX method is taken to determine the coefficients of the simplified form of BV equation, enabling online estimation of battery states. Robustness analysis of the proposed model and algorithm on SOP prediction over a large temperature range is analyzed and verified, showing their reliability and accuracy in estimating the terminal voltage and predicting power capability.
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1. Introduction

Lithium-ion batteries are favored as a preferred candidate for a large variety of electrical devices and systems such as cell phones, electric vehicles and renewable energy storage applications, owing to their superior performance in power density, energy density and reliability to other energy storage devices [1–3]. In particular, the lithium-ion batteries using $Li_4Ti_5O_{12}$ (LTO) as its anode instead of graphite, which is also known as lithium titanate battery, has been recognized as a leading selection for electric-powered transportation in the future due to its attractive performance in rate characteristics and chemical stability [4,5]. Moreover, such a kind of battery has been widely utilized as an energy source in many frequent start-stop applications, since it has higher power capability and longer life than the lead-acid battery [6].

In order to guarantee the economic efficiency and reliability of the whole system, a well-designed battery management system (BMS), which is capable of monitoring and predicting battery states such as state of charge (SOC), state of health (SOH), state of energy (SOE), and state of power (SOP), is essential [7,8]. Overly optimistic or pessimistic values of battery states, leading to abuse or waste of battery available capability, will eventually generate permanent degradation or an inefficient use of the battery. Therefore, several accurate and reliable algorithms of SOC estimation have been reported to meet critical requirements of diversified circumstances over the past decades [9–11]. The SOH reflects the capability of a battery to store energy and provide certain power compared to its initial condition, and it was typically analyzed and quantified based on the battery parameters evolution (in terms of capacity and power) with aging [12,13]. As two critical variables in BMS for supporting optimal battery operation, SOE and SOP, corresponding to energy and power capability of the battery in a given task, determine both how long the battery will last and the potential of it during acceleration and regenerative braking events. Unlike SOC

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Nomenclature

a_1	Coefficient of SOU dependency of OCV expression at T_1
a_2	Coefficient of SOU dependency of OCV expression at T_1
a_3	Coefficient of SOC dependency of OCV expression at T_1
a_4	Coefficient of SOC dependency of OCV expression at T_1
a_5	Coefficient of SOC dependency of OCV expression at T_2
a_6	Coefficient of SOC dependency of OCV expression at T_2
b_1	Coefficient of SOU dependency of internal resistance expression at T_1
b_2	Coefficient of SOU dependency of internal resistance expression at T_1
b_3	Coefficient of SOC dependency of internal resistance expression at T_1
b_4	Coefficient of SOC dependency of internal resistance expression at T_1
b_5	Coefficient of SOC dependency of internal resistance expression at T_2
b_6	Coefficient of SOC dependency of internal resistance expression at T_2
c_1	Coefficient of SOU dependency of polarization capacitor expression at T_1
c_2	Coefficient of SOU dependency of polarization capacitor expression at T_1
c_3	Coefficient of SOC dependency of polarization capacitor expression at T_1
c_4	Coefficient of SOC dependency of polarization capacitor expression at T_1
c_5	Coefficient of SOC dependency of polarization capacitor expression at T_2
c_6	Coefficient of SOC dependency of polarization capacitor expression at T_2
C_M	Maximum available capacity of battery measured at room temperature
$C_M(T)$	Maximum available capacity of battery measured at T
C_p	Polarization capacitor of battery
F	Faraday constant
$f_1(\cdot)$	Coefficient of the simplified form of BV equation
$f_2(\cdot)$	Coefficient of the simplified form of BV equation
I_{ch_maxc}	Maximum charge current usingR_{pc}
I_{ch_max1}	Maximum charge current under the limit of U_{ch_lim1}
I_{ch_max2}	Maximum charge current under the limit of U_{ch_lim2}
I_{dch_maxc}	Maximum discharge current usingR_{pc}
I_{dch_max1}	Maximum discharge current under the limit of U_{dch_lim1}
I_{dch_max2}	Maximum discharge current under the limit of U_{dch_lim2}
I_o	Current flowing through battery
I_{pc}	Current amplitude of reference rate by manufacturers, namely 1 C in our discussion
J_0	Exchange current density
P_{ch_max1}	Maximum charge power under the limit of U_{ch_lim1}
P_{ch_max2}	Maximum charge power under the limit of U_{ch_lim2}
P_{dch_max1}	Maximum discharge power under the limit of U_{dch_lim1}
P_{dch_max2}	Maximum discharge power under the limit of U_{dch_lim2}
$Q_{ch\_T_L}$	Charge capacity at T_L
$Q_{ch\_T_N}$	Charge capacity at T_N
$Q_{dch\_T_L}$	Discharge capacity at T_L
$Q_{dch\_T_N}$	Discharge capacity at T_N
Q_{LOC}	Capacity of loss of charge
Q_{LOD}	Capacity of loss of discharge
R	Gas constant
R_p	Polarization resistance of battery
R_{pc}	Polarization resistance measured at the current of 1C
R_Ω	Internal resistance of battery
S	Effective area
T	Temperature (K)
T_L	Low temperature (°C)
T_N	Room temperature (°C)
t_0	The initial time when battery begins to be discharged
t_1	The time when battery begins to rest after being discharged
t_2	The end time of battery operation
t_3	The initial time of constant current pulse
t_4	The end time of constant current pulse
U_{ch_lim}	Constraint of voltage when battery is charged
U_{ch_lim1}	The former of two proposed constraints of voltage when battery is charged
U_{ch_lim2}	The lattery of two proposed constraints of voltage when battery is charged
U_{dch_lim}	Constraint of voltage when battery is discharged
U_{dch_lim1}	The former of two proposed constraints of voltage when battery is discharged
U_{dch_lim2}	The lattery of two proposed constraints of voltage when battery is discharged
U_o	Battery terminal voltage
U_{ocv}	Open circuit voltage (OCV)
U_p	Voltage of a RC parallel network
$U_{p_{max}}$	Static value of battery polarization after a finite operation time that is much longer than τ
Δt	Time variation
α	Reflection ratio
β	Contraction ratio
γ	Expansion ratio
μ	Shrink ratio
δ	Limit of reflection ratio
ε	Defined error tolerance
$\eta(\cdot)$	Battery overpotential

which indicates the state of electrical charge/capacity rather than the energy of battery, SOE defines the ratio of the residual energy to the total energy inside the battery, and can be further employed as a replacement for a fuel gauge utilized in conventional vehicles. He et al. [14] presented an improved SOE estimation of lithium-ion battery based on the Gaussian model and central difference Kalman filter. Zhang et al. [15] developed a new approach to jointly estimate battery SOE and SOP under different temperatures. On the other hand, reliable SOP predicting methods, although plenty of related researches have been conducted [16–20], remain a vital task for a BMS designer. Because the cycle life of LTO battery is predicted to be at least 10000 times [4], the SOH can be marginalized in our work. In this study, we focus on how to predict SOP of a high-power LTO battery under different operating temperatures.

Generally, the SOP is defined as the maximum charge and discharge power within a certain time horizon but without crossing the safe region of battery. Due to high complexity in battery's operating environments, power capability of a battery is limited by the multiple constraints of current, voltage, SOC and temperature. Commonly used techniques for prediction of SOP fall into two

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