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Online peak power prediction based on a parameter and state estimator for lithium-ion batteries in electric vehicles

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A B S T R A C T

The goal of this study is to realize real-time predictions of the peak power/state of power (SOP) for lithium-ion batteries in electric vehicles (EVs). To allow the proposed method to be applicable to different temperature and aging conditions, a training-free battery parameter/state estimator is presented based on an equivalent circuit model using a dual extended Kalman filter (DEKF). In this estimator, the model parameters are no longer taken as functions of factors such as SOC (state of charge), temperature, and aging; instead, all parameters will be directly estimated under the present conditions, and the impact of the temperature and aging on the battery model will be included in the parameter identification results. Then, the peak power/SOP will be calculated using the estimated results under the given limits. As an improvement to the calculation method, a combined limit of current and voltage is proposed to obtain results that are more reasonable. Additionally, novel verification experiments are designed to provide the true values of the cells' peak power under various operating conditions. The proposed methods are implemented in experiments with $LiFePO_4$/graphite cells. The validating results demonstrate that the proposed methods have good accuracy and high adaptability.

1. Introduction

Lithium-ion batteries have become the optimal energy-storage choice in current electrical equipments because of their high energy density and excellent cycling performance [1,2]. As significant alternatives to traditional fossil energy resources, high-power lithium-ion batteries, including $LiFePO_4$/graphite cells, have been widely applied in many portable energy-storage applications, e.g., electric vehicles (EVs) [3–6]. To guarantee the safety of electric vehicle users, the EVs, and the batteries, a battery management system (BMS) is needed to provide accurate and real-time estimates of the performance characteristics of the battery, such as peak power/state of power (SOP), state of charge (SOC), and state of health (SOH) [7–9]. In this study, we focus on how to predict the peak power/SOP of a $LiFePO_4$/graphite battery in real time under various operating temperatures and aging conditions.

The definition of peak power used in this paper is based on Ref. [7]. For simplicity, the discharge and charge peak power are collectively taken as the peak power in this study, as specifically described below.

Peak power: based on the present battery conditions, the maximum power that can be maintained continuously for T seconds without violating the preset operational design limits on the cell's current, voltage, SOC, or power. And SOP is defined as the percentage of the peak power relative to a nominal power (P_N).

As the basic dynamic performance state of an energy-storage system, the battery's peak power determines the instantaneous acceleration ability of vehicles, the absorption capability of the feedback-braking energy and the power distribution between the vehicle engine, and the electric motor in plug-in hybrid electric vehicles (PHEVs) as well as hybrid electric vehicles (HEVs). However, the battery's peak power changes with the various operating temperatures, loads, and aging states, especially when the vehicle is running at low temperature, under a continuously heavy load, or at a low SOH. Thus, if a single constant peak power is used as the power limit, certain abnormal situations, such as over-voltage and over-current conditions, may occur to the battery, or the battery may not be able to provide the vehicle with the expected power because of the self-protection of the battery system. Both of these cases can result in danger to the vehicles or passengers; thus, we

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Nomenclature

Symbols

OCV	open-circuit voltage, V
R_O	ohmic resistance, Ω
R_P	polarization resistance, Ω
C_P	polarization capacitance, F
τ_P	time constant of a parallel resistance–capacitance circuit, s
U_L	terminal voltage of a cell (i.e., load voltage), V
I_L	total current through a cell (i.e., load current), A
I_P	polarization current through polarization resistance, A
Δt	a time horizon, s
K	total number of sampling points corresponding to Δt
ΔU_P	voltage variation of polarization link during Δt, V
ΔQ_P	charge variation of polarization link during Δt, As
T	duration of entire pulse, s
K_T	total number of sampling points corresponding to T
T_C (T_V)	duration of pulse under constant current (voltage) mode, s
K_C (K_V)	total number of sampling points corresponding to T_C (T_V)
λ	a variable used to determine operating duration under constant current or constant voltage mode
ΔT_S	sampling period, s
P	power, W
P_N	nominal power, W
PP	peak power, W
Q_C	present capacity of a cell, Ah
Q_N	nominal capacity of a cell, Ah

Subscripts, superscripts

k	time step index
chg	charge
dis	discharge
init	initial value
lim	limit value
max	upper limit value
min	lower limit value
$\hat{}$	an estimation value
$\hat{}-$	a posteriori estimation value

Abbreviations

BMS	battery management system
EKF	extended Kalman filter
AEKF	adaptive extended Kalman filter
DEKF	dual extended Kalman filter
EV	electric vehicle
HEV	hybrid electric vehicle
PHEV	plug-in hybrid electric vehicle
EP	electrochemical polarization
FUDS	federal urban driving schedule
HPPC	hybrid pulse power characterization
PNGV	partnership for a new generation of vehicles
RMS	root mean square
R-RC	a resistance in series with a parallel resistance and capacitance
SOC	state of charge
SOH	state of health
SOP	state of power

should be able to dynamically predict the peak power during actual operating processes under the constraint of all limiting conditions of the battery, including voltage, current, and SOC.

A peak power measurement method based on hybrid pulse power characterization (HPPC) tests is detailed in the PNGV (partnership for a new generation of vehicles) battery test manual [10]. However, it only considers the voltage limit in power estimation and applies an approximate prediction horizon T to the estimation based on the Rint model.

In Ref. [7], a new model-based method that uses a dynamic cell model to predict the cell and battery-pack power is described. The author clarifies that the limits of battery voltage, current, and SOC should be enforced when estimating power. In this method, the parameters of the model are functions of SOC, temperature, capacity, aging, and other factors. As more factors are considered, a more accurate dynamic characteristic of a battery will be simulated and a higher precise estimation result of power estimation can be obtained; however, more off-line targeted experiments need to be performed to develop the function expressions. Based on Ref. [7], a dynamic electrochemical polarization (EP) battery model and an adaptive extended Kalman filter (AEKF) were used in Refs. [11,12] for more convergent estimation results; however, the off-line targeted experiments still need to be performed.

Additionally, another method is presented in Refs. [13,14]. In this method, the battery model considers diffusion resistance and is represented by the direct differential (DD) expression, which allows the model parameters to be identified without prior off-line experiments. However, in this expression, dV/dt and dI/dt need to be obtained during the computational process; thus, the method requires that sensors and programs operate on higher sampling rates than the state of arts.

In this paper, a novel model-based peak power/SOP prediction method is presented with three significant improvements.

1. The proposed method can be applied to different temperature and aging conditions.
2. The calculation of peak power under the current and voltage limits is improved.
3. Validation experiments are first designed to verify the accuracy of the prediction results.

The following sections of this paper are arranged as follows. Section 2 presents an online estimator method for all of the parameters and states of a battery model, which is the basis for the peak power/SOP prediction method. The new estimator is based on new state-space equations in the framework of the dual extended Kalman filter (DEKF) and takes the parameters as independent variables rather than functions of SOC, temperature, aging, or other factors. Section 3 introduces using the obtained parameters and states to achieve accurate online predictions of the peak power and SOP under a combined limit condition. In Section 4, validation experiments, which can provide the true values of peak power, are designed and described. Then, the proposed prediction methods are implemented in the validation experiments on $LiFePO_4$/graphite cells with different temperature and aging conditions, and the accuracy and stability of the method are verified in Section 5. Finally, the procedure for the entire prediction algorithm and suggestions for future research in this field are provided.