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Power capability prediction for lithium-ion batteries based on multiple constraints analysis

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ABSTRACT

The power capability of the lithium-ion battery is a key performance indicator for electric vehicle, and it is intimately correlated with the acceleration, regenerative braking and gradient climbing power requirements. Therefore, an accurate power capability or state-of-power prediction is critical to a battery management system, which can help the battery to work in suitable area and prevent the battery from over-charging and over-discharging. However, the power capability is easily affected by dynamic load, voltage variation and temperature. In this paper, three different constraints in power capability prediction are introduced, and the advantages and disadvantages of the three methods are deeply analyzed. Furthermore, a multi-limited approach for the power capability prediction is proposed, which can overcome the drawbacks of the three methods. Subsequently, the extended Kalman filter algorithm is employed for model based state-of-power prediction. In order to verify the proposed method, diverse experiments are executed to explore the efficiency, robustness, and precision. The results indicate that the proposed method can improve the precision and robustness obviously.

1. Introduction

Green energy and sustainable development have become the focus of research in many countries because of energy crises and environmental issues. In this case, new energy vehicles, especially electric vehicles (EVs), which contain battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), are considered as important directions for future transportations and attract the attention of governments and automobile manufacturers all over the world [1]. For EVs, the power battery is a critical component used to provide power source of EVs in the process of operation. The lithium-ion batteries (LIBs) have been more attractive for the EV applications due to their higher specific or volumetric power and energy density, higher cycle lifetime, decreasing costs and environmental friendliness.

However, there exist some problems in LIBs, such as security, stability and consistency of the battery cells. Therefore, EVs are always equipped with a battery management system (BMS) in order to ensure the batteries operate with safety and reliability during its entire lifetime [2,3]. The BMS is an intelligent supervisory system which can complete the battery parameters collection, battery states estimation, battery equalization, real-time fault diagnosis and intelligent management and control [4]. Among them, battery states estimation include state-of-charge (SOC), state-of-energy (SOE), state-of-power (SOP) and state-of-health (SOH) [5–9]. In particular, SOP indicates the maximum power capability of the LIBs, which is intimately correlated with the acceleration, regenerative braking and gradient climbing power requirements [10]. In addition, accurate SOP prediction can not only guarantee the safety but also regulate EV's performance and optimize battery energy usage.

The definitions of power capability are not the same in literatures, such as SOP [8], state-of-available-power (SOAP) [11], state-of-function (SOF) [12–14]. The SOP is the ratio of peak power to rated power, where peak power indicates quantity of maximum power that can be maintained continuously for a short period of time without exceeding the set threshold [15]. The SOAP is mainly related to the amount of power which the battery can deliver to or accept from the vehicle powertrain over a certain time horizon [11]. However, SOF describes a logical symbol (1 or 0) whether there is sufficient power capability to achieve a specified

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function (e.g., cranking capability) [13]. In this paper, the SOP definition is employed to reflect the power capability. The SOP needs to be deduced through measurable parameters, since it cannot be measured directly by any sensors. Moreover, SOP is difficult to be obtained by simple calculations because of the complex electrochemical reactions inside the cell. Therefore, the SOP prediction has become an important branch of the internal state estimation of the battery, which attracts many scientific research institutions and scholars into this study.

According to the domestic and research, the commonly used peak power computational methods can be divided into four types: (1) Hybrid pulse power characterization (HPPC) method [16]: estimate the instantaneously available power based on the operational design maximum and minimum voltage limits. (2) Voltage-limited method [3,8,15,17–19]: estimate the continuously available power based on the operational design maximum and minimum voltage limits. (3)Current-limited method [3,15,17–19]: estimate available power based on the operational design maximum and minimum current limits. (4)SOC-limited method [3,8,16,17]: estimate available power based on peak current which is calculated by current SOC and the maximum and minimum SOC limits. The HPPC method is one of the state-of-the-art approaches used for static peak power capability in laboratory environments, where there are some drawbacks that it cannot be employed to continuous peak power prediction case and the method neglects the current-limit, power-limit, SOC-limit, etc. In order to improve the HPPC method, Plett in Ref. [8] proposed the voltage-limited method which can have continuously SOP estimation. However, the problem is that the proposed method is based on a simply battery model, which ignore the dynamic effect of the LIBs. In Ref. [10], Sun et al. presented a model-based dynamic multi-parameter method for peak power capability estimation, and the multi-parameter method takes dynamic effect into consideration, which use RC network to simulate the dynamic performance of transient phenomenon of LIBs. In terms of SOC-limited method, it is easy to lead over-charge or over-discharge of the LIBs without SOC as a constraint when the LIBs are near fully charged or discharged. However, the method that uses SOC to estimate SOP of the LIBs will give over-optimistic power estimation, due to the peak current cannot be allowed to be discharged or charged over a wide range of SOC [16]. Hence, a multi-limited (voltage-limit, current-limit, power-limit, SOC-limit, etc) SOP prediction method is proposed for obtaining more accurate results in Ref. [17].

In addition, as one of the multiple constraints, an accurate SOC value has great impact on the SOP prediction accuracy, hence an accurate SOC estimation method is necessary. Over the past few years, a number of SOC estimation algorithms have been proposed including coulomb-counting algorithm [20], extended Kalman filter (EKF) [21], unscented Kalman filter (UKF) [22], particle filter (PF) [23], unscented particle filter (UPF) [24], slide mode observer (SMO) [25] and other intelligent algorithms [26,27]. On this basis, Xiong et al. proposed a SOC and peak power capability joint estimation approach in Ref. [17]. Adaptive extended Kalman filter (AEKF) based method is employed to achieve an accurate and robust SOC estimation, where results show that the proposed method can not only achieve an accurate SOC estimate but also gives reliable and robust peak power capability estimate. To improve the estimation accuracy and reliability for battery state, an adaptive unscented Kalman filter (AUKF) has been proposed to develop a joint SOE and SOP estimator in Ref. [19]. The unscented transformation (UT) and adaptive error covariance matching technology as crucial parts of the AUKF, are employed to improve the state estimation accuracy. The results imply that the associated errors are less than around 2% even if given a large erroneous initial value. In Ref. [28], the authors presented a novel approach to the estimation of state of maximum available power in LIBs, which utilizes PF algorithms to estimate SOC. This method formulates an optimization problem for the battery power based on a non-linear dynamic model, where the resulting solutions are functions of the SOC. The results show that both estimation algorithms converge to the true value of the state even if there is an erroneous initialization.

In this paper, three different constraints in peak power capability prediction are introduced, and the advantages and disadvantages of the three methods are deeply analyzed. Furthermore, a multi-limited approach for the peak power capability prediction is proposed, which can overcome the drawbacks of the three methods. Subsequently, the extended Kalman filter algorithm is employed for model based state-of-power prediction. The remainder of the paper is organized as follows: Section 2 describes the multi-limited method for peak power capability prediction. The methodology of SOP estimator based on the proposed method is presented in Section 3. To evaluate the proposed approach, the experiment and evaluation of the proposed method are reported in Section 4. Finally, conclusions are drawn in Section 5.

2. Analysis of multiple constraints in power capability prediction

As mentioned above, the peak power capability of LIBs is affected by the maximum charge and discharge current, the maximum and minimum cut-off voltage, the remaining available capacity of the battery, etc. In order to estimate the peak power capability accurately, there are multiple constraints (voltage, current, SOC, rated power) that should be taken into consideration, which can be expressed as follows:

$$\left\{\begin{array}{l} U_{\min} < U < U_{\max} \\ I_{\min}^{\mathrm{chg}} < I < I_{\max}^{\mathrm{dis}} \\ SOC_{\min} < SOC < SOC_{\max} \\ P_{\min}^{\mathrm{chg}} < P < P_{\max}^{\mathrm{dis}} \end{array}\right) \tag{1}$$

where U, I, SOC, P represent the battery's terminal voltage, current, SOC, and power, respectively; $U_{\max}$, $U_{\min}$ represent maximum charge cut-off voltage and minimum discharge cut-off voltage, respectively; $I_{\max}^{\mathrm{dis}}, I_{\min}^{\mathrm{chg}}$ represent maximum discharge current and minimum charge current(assumed positive for discharge, negative for charge), respectively; $SOC_{\max}$, $SOC_{\min}$ represent maximum and minimum SOC, respectively; $P_{\max}^{\mathrm{dis}}, P_{\min}^{\mathrm{chg}}$ represent maximum discharge power and minimum charge power, respectively. $U_{\max}$, $U_{\min}$, $I_{\max}^{\mathrm{dis}}, I_{\min}^{\mathrm{chg}}$, $SOC_{\max}$, $SOC_{\min}$, $P_{\max}^{\mathrm{dis}}, P_{\min}^{\mathrm{chg}}$ constraints are dependent on the battery type, working condition and other factors.

For the battery charge and discharge process, the peak power capability of LIBs can be calculated by Eq. (2):

$$\left\{\begin{array}{l} P_{\min}^{\mathrm{chg}} = \max(P_{\min}, UI) \\ P_{\max}^{\mathrm{dis}} = \min(P_{\max}, UI) \end{array}\right) \tag{2}$$

where $P_{\max}$, $P_{\min}$ denote design limits of the battery.

In order to easily understand the meaning of Eq. (2), a more intuitive description is shown in Fig. 1. The discharge process and charge process are shown in Fig. 1 (a) and (b), respectively.

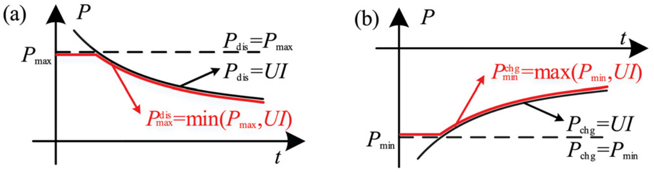

Fig. 1. The schematic diagram of the peak power capability calculation: (a) Discharge process; (b)Charge process.