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Multi-timescale power and energy assessment of lithium-ion battery and supercapacitor hybrid system using extended Kalman filter

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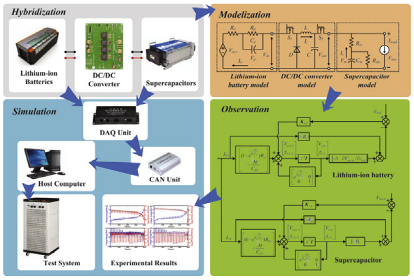
HIGHLIGHTS

- Explicit analyses of power capability with multiple constraints are elaborated.
- The extended Kalman filter is employed for on-board power capability prediction.
- The detailed prediction process and implementations are graphically displayed.
- The power capability is quantitatively assessed under dynamic loading schedules.
- The maximum charge/discharge energy with different time scales is explored.

GRAPHICAL ABSTRACT



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ABSTRACT

The power capability and maximum charge and discharge energy are key indicators for energy management systems, which can help the energy storage devices work in a suitable area and prevent them from over-charging and over-discharging. In this work, a model based power and energy assessment approach is proposed for the lithium-ion battery and supercapacitor hybrid system. The model framework of the lithium-ion battery and supercapacitor hybrid system is developed based on the equivalent circuit model, and the model parameters are identified by regression method. Explicit analyses of the power capability and maximum charge and discharge energy prediction with multiple constraints are elaborated. Subsequently, the extended Kalman filter is employed for on-board power capability and maximum charge and discharge energy prediction to overcome estimation error caused by system disturbance and sensor noise. The charge and discharge power capability, and the maximum charge and discharge energy are quantitatively assessed under both the dynamic stress test and the urban dynamometer driving schedule. The maximum charge and discharge energy prediction of the lithium-ion battery and supercapacitor hybrid system with different time scales are explored and discussed.

1. Introduction

The lithium-ion battery has become one of the optimal choices for energy storage in many fields because of its high energy density and long cycling life [1]- [2]. Several strategies have been proposed for the energy management of the batteries, especially for the applications in electric vehicles and micro grids [3]- [4]. To guarantee the safety operation of the batteries, a battery management system is necessary in order to provide intelligent functions including: accurate estimation of battery states such as the state-of-charge (SOC) [5–10], state-of-energy

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(SOE) [11]- [12], state-of-power (SOP) [13–16] and state-of-health (SOH) [17]- [18], battery equalization [19]- [20], thermal management [21], fault diagnosis [22–24], etc. To ensure the batteries work in suitable area and prevent them from over-charging and over-discharging, accurate and real-time estimation of power capability and maximum charge and discharge energy is crucial and necessary.

A conventional method to estimate the charge and discharge power capability is the hybrid pulse power characterization (HPPC) method [25]. However, the power capability predicted by this approach is over optimistic, which neglects the design constraints such as current, power, and SOC. As an improvement of the HPPC method, the voltage constraint method has been proposed which can estimate the continuously peak power based on the design voltage constraint [26]. However for the lithium-ion batteries, this approach is easy to cause over-charge or over-discharge when the voltage is near fully charged or discharged workspace. Another constraint should be considered is the SOC. However, this approach will obtain over optimistic power prediction, since the peak current cannot be allowed to be charged or discharged over a wide range of SOC. Therefore a multiple constraints power capability prediction which considers the voltage, SOC, as well as the designed current and power is reasonable for real applications. In Ref. [14], a multi-parameter constraints dynamic estimation method is proposed to predict the battery continuous period power capability. In this work the SOE is first considered as one of the constraints for power capability estimation in order to obtain more accurate results for power capability assessment.

As one of the important constraints, an accurate and real-time SOC estimation has great impact on the power capability estimation. There are many existing methods for SOC estimation such as the coulomb-counting algorithm [27], the open-circuit voltage method [28]- [29], the Kalman filter method [30], the particle filter method [7], the neural network method [31], etc. The coulomb counting algorithm is simple to realize, however it suffers from problems like uncertainty of initial state, and accumulated error from current drift. The open-circuit voltage approach takes long time of experiments and it is not suitable for on-line estimation. The above two methods are restricted to operating conditions without adequately considering the reliability and real-time performance. To overcome the drawbacks of the above methods, the model based approach such as the Kalman filter and particle filter has be investigated and applied on SOC estimation which performs accurate and robust estimation results.

In recent years, more and more people start to concern the hybridization of the batteries and supercapacitors which is considered as a better use than the individual use of batteries or supercapacitors [32]. The lithium-ion batteries have complementary characteristics with high energy density but low power density. However the supercapacitors provide fast and effective output because of its high power density and high efficiency. In order to enhance the operation of lithium-ion batteries, supercapacitors are used to integrate with batteries as buffers and compose hybrid energy storage systems [33]- [34]. Diverse studies of configuration, control, and integration of the battery and supercapacitor have been reported in literature. In Ref. [35], Hu et al. reported a survey of principal roles, types, and management needs for the batteries. A multi-objective optimization approach, with the goal of reducing the hybridization cost while prolonging battery life is reported in Ref. [36]. In Ref. [37], Zhang et al. presented an overview of modeling, state estimation, and applications of the supercapacitor. This work indicates that co-working with high energy-density devices can sufficiently reap synergistic benefits of multiple energy-storage units.

The assessment of power and energy capability is crucial to the efficiency and security of the battery and supercapacitor hybrid system. However, few literature focus on the estimation of power and energy assessment for both the lithium-ion batteries and the supercapacitors. In this work, a model based multi-timescale power capability and maximum charge/discharge energy prediction approach is presented for the lithium-ion battery and supercapacitor hybrid system. An explicit analysis of power capability and maximum charge and discharge energy prediction with multiple constraints of current, voltage, and SOC is elaborated. In order to overcome estimation errors caused by sensor noises, the extended Kalman filter is employed for power capability and energy prediction. The charge and discharge power capability and the maximum charge and discharge energy are quantitatively assessed under different dynamic characterization schedules. The maximum charge and discharge energy with different time scales for both the lithium-ion battery and supercapacitor are explored and discussed.

The remainder of the paper is organized as follows: In section 2, the models of the lithium-ion battery and supercapacitor are developed and the main steps of the model parameter identification algorithm are illuminated. In section 3, the continuous charging and discharging current and power prediction is analyzed based on multiple constraints. The maximum charge/discharge energy prediction with different time scales is presented. In section 4, the charge and discharge power capability and maximum charge and discharge energy are quantitatively assessed under both the dynamic stress test and the urban dynamometer driving schedule. The maximum charge and discharge energy prediction of the lithium-ion battery and supercapacitor hybrid system with different time scales are explored and discussed. Finally, the conclusions are drawn in Section 5.

2. Model development and parameter identification

Accurate battery and supercapacitor models are required to ensure accuracy in power capability and energy prediction. Therefore, the battery and supercapacitor model structures, and the model parameter determination approach will be introduced in this section.

2.1. Model framework

The lithium-ion batteries have complementary characteristics with high energy density but low power density. However the supercapacitors provide fast and effective output because of its high power density and high efficiency. In order to enhance the operation of lithium-ion batteries, supercapacitors are used to integrate with batteries as buffers and compose hybrid energy storage systems. There are many kinds of topologies for the hybrid energy storage systems. The structure in this work consists of three parts: the lithium-ion battery, the supercapacitor and the DC/DC converter. In order to simulate the dynamic behavior of the lithium-ion battery and supercapacitor hybrids, an equivalent circuit model is developed as shown in Fig. 1.

2.1.1. Model of lithium-ion battery

To simulate the dynamic behavior of the lithium-ion battery, the resistor-capacitor network based equivalent circuit model is developed as shown in Fig. 1. The model structure can be divided into three parts: (1) the open-circuit voltage source V_{ocv} is used to represent the equilibrium potential of the lithium-ion battery. (2) the series resistance R_o is used to model the internal ohmic resistance of the lithium-ion battery due to its fast dynamic. (3) the parallel resistor-capacitor network is used to represent the polarization phenomenon of the lithium-ion battery for the slow dynamic.

The observation equations for the lithium-ion battery model can be derived as:

$$\dot{V}_p = -\frac{1}{R_pC_p}V_p + \frac{1}{C_p}I_b \tag{1}$$

$$V_{in} = V_{ocv} - R_oI_b - V_p \tag{2}$$

where R_o represents the internal omhic resistance, R_p and C_p represent the internal polarization resistance and capacitance, I_b represents the current flowing from the battery, V_{in} represents the terminal voltage of the lithium-ion battery, V_{ocv} represents the open-circuit voltage (OCV),