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Energy awareness for supercapacitors using Kalman filter state-of-charge tracking[☆,☆☆]

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HIGHLIGHTS

- The energy stored in a supercapacitor cannot be determined by terminal voltage alone.
- Kalman state tracking with a three branch model improves stored energy awareness.
- A novel estimation technique enables in-situ estimation of required model parameters.
- The proposed method accurately determines the energy buffered in a supercapacitor.

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ABSTRACT

Among energy buffering alternatives, supercapacitors can provide unmatched efficiency and durability. Additionally, the direct relation between a supercapacitor's terminal voltage and stored energy can improve energy awareness. However, a simple capacitive approximation cannot adequately represent the stored energy in a supercapacitor. It is shown that the three branch equivalent circuit model provides more accurate energy awareness. This equivalent circuit uses three capacitances and associated resistances to represent the supercapacitor's internal SOC (state-of-charge). However, the SOC cannot be determined from one observation of the terminal voltage, and must be tracked over time using inexact measurements. We present: 1) a Kalman filtering solution for tracking the SOC; 2) an on-line system identification procedure to efficiently estimate the equivalent circuit's parameters; and 3) experimental validation of both parameter estimation and SOC tracking for 5 F, 10 F, 50 F, and 350 F supercapacitors. Validation is done within the operating range of a solar powered application and the associated power variability due to energy harvesting. The proposed techniques are benchmarked against the simple capacitive model and prior parameter estimation techniques, and provide a 67% reduction in root-mean-square error for predicting usable buffered energy.

1. Introduction

Supercapacitors represent an emerging and rapidly developing energy storage technology that provides significant robustness and efficiency benefits over alternative energy storage technologies [2]. In particular, compared with electrochemical batteries, supercapacitors can typically survive 100 to 1000 times as many charge–discharge cycles before there is significant degradation of capacity or efficiency [3]. This is a substantial benefit for remote systems because it can reduce the frequency of maintenance visits to remotely deployed nodes and thereby achieve greater cost-effectiveness. Thus far, supercapacitors have been commonly applied for buffering energy over short durations, e. g. supercapacitor-battery hybrid storage [4,5], and regenerative breaking [6–8]. For these applications, peak power and short-term efficiency are supercapacitors' most important strengths.

The proposed work targets long-term energy storage applications where accurate energy awareness is important. For example, a remotely deployed system can rely on solar energy harvesting. Without a reliable connection to the electrical grid, accurate

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knowledge of a supercapacitor's SOC (state-of-charge) is critical to know how much energy remains available to the system [9,10]. Long-term energy storage applications are also motivated by the robustness and durability benefits of supercapacitors. These benefits have been used to prototype a supercapacitor-based, WSN (wireless sensor node) with 20 years of projected service-free lifetime [11].

Tracking SOC can also be important when supercapacitors are used in banks of multiple devices in series or parallel configurations. These configurations benefit from load balancing in order to prevent specific cells from over-charging and suffering premature capacity degradation [12]. However, if SOC is not accounted for it can be difficult to perform on-line measurements of capacity degradation for the individual cells, or make real-time load balancing decisions.

Kalman tracking for a supercapacitor's SOC is proposed to exploit the energy awareness benefits of supercapacitors. Compared to rechargeable batteries, the stored energy in a supercapacitor is more directly related to its terminal voltage, v_{sc}, via the capacitance, C. However, the simple model, $Cv_{sc}^2/2$, for stored energy neglects important non-ideal behavior: both charge redistribution and leakage affect storage capacity and the net portion of the energy that is available to a system after internal losses. It is shown that the total energy needed to fully charge a supercapacitor to its maximum voltage can vary up to 23% depending on the power level at which a supercapacitor is charged. This variation in capacity cannot be accounted for by the simple model. Extensive work has been done to model supercapacitor behavior [13–21], but this paper goes to the next step: translating these models into usable energy awareness. The proposed Kalman tracking technique uses the three branch equivalent circuit [15] to account for this non-ideal capacity variability. The Kalman filter balances uncertainty by weighting the correction due to each new observation on the estimate of the circuit's SOC.

A common difficulty of Kalman tracking is the accuracy of the model. The parameter estimation technique proposed here provides a novel method to fit the parameters of the three branch equivalent circuit. The proposed technique does not require specific tests to be performed in the field or before the device is deployed: fitting is able to utilize the actual current profiles encountered by the application, provided significant power variability occurs. Prior methods for parameter estimation have relied on electrochemical impedance spectroscopy (EIS), which requires specialized test equipment and cannot be performed in the field [22–24], or have been designed to only fit the capacitance and series resistance, but not the parameters for redistribution [25].

In addition to describing the proposed parameter estimation technique and Kalman tracking methodology, this paper also presents experimental validation of both techniques for 50 F supercapacitors and parameter estimation for 5 F, 10 F and 350 F supercapacitors.

This paper begins with background and modeling for supercapacitors in Section 2. Sections 3 and 4 then present the proposed parameter estimation and Kalman tracking techniques. Section 5 evaluates the performance of each technique as compared to the simple capacitive model. Results and discussion of the experiments are given in Section 6. Conclusions and contributions are summarized in Section 7.

2. Modeling

Charge storage in supercapacitors relies primarily on two phenomena: the EDL (electric double layer) and pseudocapacitance [13], that are illustrated in Fig. 1a. Voltage applied across the supercapacitor terminals pushes charge to the surface of the electrode material forming a surface layer. Oppositely charged ions in the electrolyte are, in turn, attracted by the surface charge forming a second layer. The two layers make up the EDL capacitance. Reversible chemical reactions store additional charge on the surface of the electrodes and contribute pseudocapacitance. Much higher capacitances than conventional electrolytic devices are obtained because of the small distance (comparable to atomic radii) between opposite charges and the large surface area of the porous electrodes.

A simple capacitive model fails to account for three sources of non-ideal behavior in supercapacitors: both the EDL and pseudocapacitance are voltage dependent; the diffusion of ions into the porous materials is not instantaneous; and there is spontaneous leakage of stored charge. Diffusion, or charge redistribution, is observable after a charging current into a supercapacitor is discontinued. Diffusion of ions in the electrolyte causes the terminal voltage, v_{sc}, to spontaneously decay. Diffusion push ions away from regions of high concentration near the readily accessible (and more quickly charged) portions of the porous surface. Modeling a supercapacitor's SOC accounts for charge redistribution as the penetration of stored charge into a string of resistive-capacitive (RC) transmission line storage elements [14] as in Fig. 1a, or simplified as an array of time constants in parallel RC branches [15] as in Fig. 1b. Leakage has been simply modeled as a fixed parallel resistance [15], or a variable resistance depending on factors such as the supercapacitor's voltage, temperature and internal state [16,26,17,18,27].

Prior work has shown that a simple capacitive model can provide adequate energy awareness for low powered solar-supercapacitor WSN (wireless sensor nodes) [28,29]. Online parameter estimation has also been demonstrated for a single branch model [30]. Although the simple model is preferable because of the limited computational capabilities of these systems, results in Ref. [29] show significant improvement when the fixed capacitance, C_{simple}, is tuned to the specific discharge speed, similar to the manner in which three branch equivalent circuit intrinsically accounts for the effect of charging speed on SOC. Modeling a supercapacitor using the three branch equivalent circuit is especially important for higher powered systems with greater power variability than WSN.

The impact of both redistribution and leakage when the charging current, i_{sc}, is varied over a wider range of power is shown in Fig. 2. The observed supercapacitor behavior is compared to the baseline, simple capacitive model for stored energy,

$$E = \frac{1}{2} C_{\text{simple}} v_{sc}^2, \tag{1}$$

where v_{sc} is the terminal voltage for the supercapacitor, and the capacitance, C_{simple}, is fitted to the average slope of the observed data,

$$C_{\text{simple}} = \left(\frac{1}{N} \sum_{n=1}^{N} \frac{dv_{sc}}{dq} \right)^{-1}. \tag{2}$$

For each of the N observations in (2), taken over the three durations of charging in Fig. 2, the differential charge, dq, is calculated as $i_{sc}dt$, where i_{sc} denotes the (constant) charging current and t denotes time. In terms of energy awareness, Fig. 2 shows that the total energy needed to charge the 50 F supercapacitor,

$$E_{\text{obs}} = \int v_{sc} i_{sc} dt = \int v_{sc} dq, \tag{3}$$

varies between 188 J and 231 J (23% variation) even though the