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Open circuit voltage characterization of lithium-ion batteries

B. Pattipati, B. Balasingam*, G.V. Avvari, K.R. Pattipati, Y. Bar-Shalom

Department of Electrical and Computer Engineering, University of Connecticut, 371 Fairfield Way, U-2157, Storrs, CT 06269, USA

HIGHLIGHTS

- A novel *normalized OCV modeling* approach is developed.
- The normalized OCV modeling is stable over temperature changes and battery aging.
- The importance of battery capacity in OCV modeling is demonstrated.
- The hysteresis is marginalized by having symmetric charging and discharging data.
- Proposed OCV modeling is validated for different chemistries, temperatures and aging.

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ABSTRACT

Several aspects of the open circuit voltage (OCV) characterization of Li-ion batteries as it applies to battery fuel gauging (BFG) in portable applications are considered in this paper. Accurate knowledge of the nonlinear relationship between the OCV and the state of charge (SOC) is required for adaptive SOC tracking during battery usage. BFG in portable applications requires this OCV–SOC characterization to meet additional constraints: (i) The OCV–SOC characterization has to be defined with a minimum number of parameters; (ii) It should be easily computable and invertible with few operations; and (iii) Computation of the model, its derivative and its inverse should be possible in a numerically stable way. With the help of OCV–SOC characterization data collected from 34 battery cells each at 16 different temperatures ranging from −25 °C to 50 °C, we present the following results in this paper: (a) A robust normalized OCV modeling approach that dramatically reduces the number of OCV–SOC parameters and as a result simplifies and generalizes the BFG across temperatures and aging, (b) Several novel functions for OCV modeling, (c) Efficient methods to simplify the computations of OCV functions, (d) Novel methods for OCV parameter estimation, and (e) A detailed performance analysis.

1. Introduction

Rechargeable Lithium-ion batteries are widely used in electric vehicles, personal/wearable electronic devices, household appliances, aerospace equipment, grid storage, and so on. Estimating the state of charge (SOC) and state of health (SOH), known as battery fuel gauging [1–3], is an important function in equipment powered by rechargeable batteries. The OCV is a measure of the electromotive force (EMF) of the battery, which is known to have a monotonic relationship with the SOC of the battery, hence, estimating SOC must have been a straightforward, voltage-look-up process. However, due to the variable internal resistance, capacity, hysteresis and relaxation effects of the battery, the BFG involves many components as outlined in Fig. 1; please see Ref. [2] for a detailed description of the function of each block. The focus of the paper is on estimating the parameters of the OCV–SOC characterization.

Existing OCV modeling approaches can be broadly classified into chemistry-based and Current–Voltage based approaches. In chemistry-based approaches [4], the OCV of each electrode (anode and cathode w.r.t. some reference) is expressed as a function of the utilization of the electrode (the lithium concentration in the electrode normalized by the maximum possible concentration) or the SOC of each electrode. It is generally assumed that this anode and cathode SOC varies linearly with the cell SOC [5]. Subsequently, the difference between the OCV of the anode and cathode gives the OCV of the complete cell. High current rates (i.e., near the rated maximum) have been shown to affect the macroscopic processes in

* Corresponding author.
E-mail addresses: bharath@engr.uconn.edu (B. Pattipati), bala@engr.uconn.edu, bhalakumar@gmail.com (B. Balasingam), vinod@engr.uconn.edu (G.V. Avvari), krishna@engr.uconn.edu (K.R. Pattipati), ybs@engr.uconn.edu (Y. Bar-Shalom).

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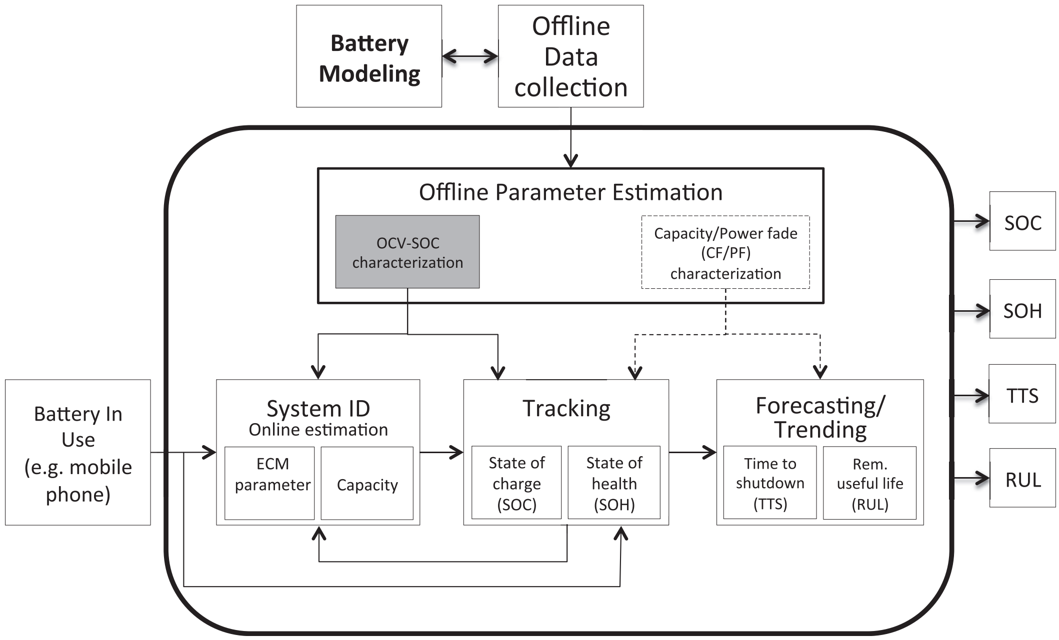

Fig. 1. Elements of a BFG. The focus of this paper, OCV–SOC characterization is shaded in gray. Details of System ID block can be found in Refs. [1,2] and the details of SOC tracking block can be found in Ref. [3].

a way that the OCV hysteresis vanishes for Li-ion cells, which regularly show OCV hysteresis after low current application [6]. Roscher et al. [7] conducted OCV (full and partial charge–discharge cycle) tests on Lithium ion phosphate ($LiFePO_4$) batteries to characterize the hysteresis and recovery effects. The final OCV model is constructed by concatenating the actual SOC, the recovery factor and the hysteresis factor. Our focus in this paper is on Current–Voltage based OCV–SOC characterization.

The Current–Voltage based OCV–SOC characterization can be summed by two simple steps:

(i) Collect pairs of {OCV, SOC} values, spanning the entire range of SOC$\triangleq[0, 1]$
(ii) Use the above data to estimate the parameters of the function OCV $= f$(SOC) for a hypothesized function f.

There are challenges in both of the above steps. The objective of this paper is to detail them and discuss ways to address them.

Fig. 2 shows the equivalent circuits of a battery when it is experiencing dynamic current versus when it is rested [1]. When the battery is experiencing dynamic current, the voltage difference between OCV, $V_\circ(s[k])$, where, $s[k]$ is the SOC at the discrete time k, and the measured terminal voltage $v[k]$ becomes higher. When the current $i[k]$ becomes zero, the battery starts to "relax", i.e., the capacitors $C_1,\ldots,C_N$ start to discharge through $R_1, \ldots, R_N$, respectively. The battery is said to be in a "rest state" when $i[k] = 0$ for longer than the multiple (typically ≥ 5) of the largest time constant R_iC_i in the equivalent circuit model, i.e., until all the capacitors $C_1,\ldots,C_N$ are fully discharged. However, the OCV is still unreachable at the terminal even after the battery is rested, due to the hysteresis voltage $h[k]$.

The hysteresis, also known as "voltage pull" – a derivative expression, depends on the direction, magnitude and duration of the preceding current as well as on the SOC. Hysteresis is known to result from thermodynamical entropic effects, mechanical stress, and microscopic distortions within the active electrode materials, which perform a two-phase transition during lithium insertion/extraction [6]. Thus, knowing the exact value of hysteresis is impractical. However, since the direction of the hysteresis voltage is opposite during charging and discharging,[1] the OCV (at a certain SOC) can be approximately estimated by averaging the measured terminal voltage during charging and discharging when the entire experiment is performed using the same magnitude of current. Usually, a smaller current[2] is required in order to reach the OCV at both ends, i.e., to measure OCV from $V_\circ(0)$ to $V_\circ(1)$.

The SOC of the battery for OCV–SOC characterization is computed through Coulomb counting, which keeps track of the amount of Coulombs extracted from/inserted into the battery and computes the SOC as a ratio of remaining Coulombs and battery capacity. Hence, the knowledge of battery capacity is crucial for accurate OCV–SOC characterization. Usually, the OCV–SOC characterization is performed on a new battery, hence, manufacturer specified capacity (also known as "rated capacity") or Coulomb counting from a fully charged battery to a fully empty battery at very low current values will serve as a fairly accurate estimate of the initial battery capacity.

However, the battery capacity is known to fade over time; hence, the BFG[3] needs to account for the capacity fade over time. At this point, the OCV–SOC characterization made using incorrect capacity will become more and more unsuitable. We will elaborate on this point later in this paper.

The conclusion from the existing literature is that the OCV–SOC characterization changes with battery temperature. Hence, many existing approaches suggested computing OCV parameters at

[1] It must be noted that the hysteresis voltage reversal is delayed, i.e., when the current reversal occurs, the hysteresis reversal follows with a delay.

[2] Using high current in OCV experiments will prevent reaching full battery (SOC = 1) or empty battery (SOC = 0).

[3] A BFG needs the battery capacity information in the "Coulomb counting equation" or process model, see Ref. [3].