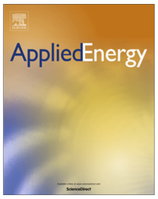
Applied Energy 143 (2015) 200–210

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Accurate and versatile simulation of transient voltage profile of lithium-ion secondary battery employing internal equivalent electric circuit

T. Tanaka [a,*,1], S. Ito [a], M. Muramatsu [a], T. Yamada [a], H. Kamiko [a], N. Kakimoto [a], Y. Inui [b]

[a] *Department of Electrical and Electronic Engineering, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi 316-8511, Japan*
[b] *Department of Electronic Systems Engineering, The University of Shiga Prefecture, 2500 Hassaka-cho, Hikone 522-8533, Japan*

HIGHLIGHTS

- Simulation method for voltage profile of lithium-ion secondary battery is proposed.
- Three test batteries with different output power density are prepared.
- Accuracy of the proposed method is confirmed for all test cases.
- The proposed method is very helpful to establish various battery control systems.

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 7 January 2015
Accepted 7 January 2015

Keywords:
Lithium-ion secondary battery
Transient voltage profile
Electromotive force
AC impedance

ABSTRACT

This paper presents a new numerical simulation method to calculate transient voltage profiles of lithium-ion secondary batteries. The method employs circuit analysis of an internal equivalent electric circuit composed of an electromotive force, an *LR* parallel circuit, and eight *CR* parallel circuits. To demonstrate the accuracy and versatility of this approach, the authors measured the transient voltage responses of three types of test batteries with different output power densities, and compared these experimental data with simulation results. Battery performance was tested using different charge/discharge current patterns and a range of values for state of charge (SOC) and operating temperature. The accuracy of the proposed simulation method was confirmed for all test cases using the three different batteries and charge/discharge current patterns, demonstrating that the method is versatile and applicable to various lithium-ion secondary batteries regardless of type. Since the employed internal equivalent electric circuit is composed of only DC voltage source and linear R, L and C elements, all of general purpose software for electric circuit simulations can easily deal with the circuit. This advantage and the obtained results indicate that the proposed simulation method is a useful technique and offers a powerful tool to develop sophisticated battery control systems for various applications.

1. Introduction

Lithium-ion secondary batteries are already widely used as power sources for mobile devices [1]. These types of batteries are now becoming popular for other applications, particularly as energy storage devices for hybrid and electric vehicles [2–5]. In addition, lithium-ion secondary batteries are expected to be used as storage batteries for photovoltaic power generation systems [6].

Since battery performance requirements differ depending on the application, a wide range of battery types have been developed with different performance specifications, e.g., nominal capacity and highest applicable current rate [7–10]. Much of this variation is due to the materials used [11–13]. However, the usable voltage range of lithium-ion secondary batteries is roughly the same regardless of battery type. The battery terminal voltage is required to be kept within the proper range, between 2.7 V and 4.2 V, to prevent breakdown due to over-discharge or over-charge.

These facts suggest that, as lithium-ion secondary batteries are applied to a larger array of commercial products, control systems that maintain terminal voltage in its proper range will become more and more important. To shorten the development period of such systems, simulation code is used and has been very effective. Simulation methods that can accurately calculate battery voltage

---

* Corresponding author. Tel.: +81 294385185; fax: +81 294385275.
E-mail address: tadasi_t@mx.ibaraki.ac.jp (T. Tanaka).
URL: http://www.ee.ibaraki.ac.jp/enepow (T. Tanaka).

[1] T. Tanaka is permanently working in Ibaraki University as an Assistant Professor. His research interests include electrical behavior of lithium-ion secondary battery and also numerical simulation and system design with respect to solid oxide fuel cell.

http://dx.doi.org/10.1016/j.apenergy.2015.01.028
0306-2619/

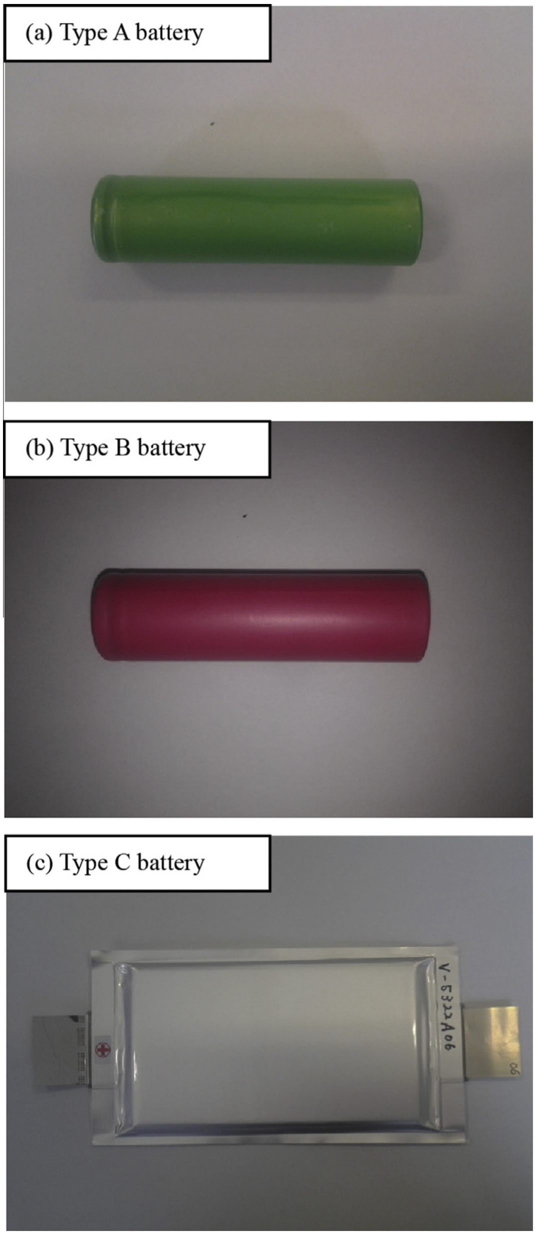


Fig. 1. Photographs of three test batteries.

profiles are, therefore, very useful techniques and serve as very powerful tools to develop sophisticated battery control systems. Considering these facts, many computing methods for battery voltage profiles have been proposed and developed.

One common and popular approach for performance simulations of lithium-ion secondary batteries is to develop governing equations for specific electrochemical and physical processes occurring in the battery, and to numerically solve these equations simultaneously, using the appropriate set of initial and boundary conditions [14–16]. This approach is desirable because battery electrochemical and physical processes are directly taken into consideration. To put this kind of simulation into practice, however, detailed information about battery materials and microstructures is necessary. In particular, a detailed understanding of the materials used in the electrodes, electrolyte, and separator is needed to establish the electrochemical and physical properties of each battery component. Detailed information about battery microstructures, such as the grain size of the electrode active materials and the separator thickness, is needed to determine boundary conditions of each process modelled in the battery. These stringent requirements mean that only battery manufacturer engineers can make sufficient use of this kind of simulation. On the other hand, engineers developing battery-based applications usually cannot use such an approach, because there is no way for them to get the above information.

Another approach to simulate the transient behavior of lithium-ion secondary batteries is by using an internal equivalent electric circuit [17,18]. This approach belongs to the category of black-box methods, where parameters of the internal equivalent electric circuit are determined through fitting calculations using measurements of AC impedance characteristics and/or voltage responses to stepwise current change. Simulation methods based on this approach are, therefore, user-oriented techniques and can be easily applied to practical calculations by battery applications engineers, because information about battery materials and microstructures is not required in this approach. Previously developed simulation methods based on this approach, however, employ a very simple equivalent electric circuit that contains only one or two *CR* parallel or similar circuits to calculate transient behavior, and the accuracy of these methods leaves much to be desired. Specifically, simulation methods specialized for long term (one hour or longer) transient behavior [17,19] cannot accurately calculate the transient behavior due to pulse charge/discharge cycles with periods of several seconds, and vice versa. In addition, the literature lacks studies showing that simulation methods based on this approach are applicable to various lithium-ion secondary batteries regardless of type. In other words, the true versatility of this approach is an important problem to be clarified.

In the present study, the authors use an internal equivalent electric circuit composed of an electromotive force, an *LR* parallel circuit, and eight *CR* parallel circuits to more fully express the transient behavior of a lithium-ion secondary battery, and develop a numerical simulation method to calculate transient voltage profiles of such batteries. The proposed method, with its use of a more detailed internal equivalent electric circuit compared with previously reported methods, should enable more accurate and versatile calculations.

To demonstrate the advantages of the proposed approach for calculation of transient voltage profiles of lithium-ion secondary batteries, the authors prepared three types of test batteries with different output power densities, and compared the calculated transient voltage responses of the batteries with the corresponding measured responses. The simulation and the experimental tests used various charge/discharge current patterns with different duration times, different values of the state of charge (SOC) changes, and a range of battery temperatures.

2. Test batteries

Three kinds of batteries with different performance characteristics (designated Types A, B, and C) were prepared for this study. The Type A battery is a low power density type 18650 cylindrical battery (SONY US18650GR with 18 mm diameter and 65 mm length) used for digital camcorders. This battery was extracted from a commercially available battery pack and, therefore, the

Table 1
Nominal voltage range and capacity of three test batteries.

Battery type	Nominal voltage range (V)	Nominal capacity (Ah)
Type A	2.7–4.2	2.20
Type B	2.7–4.2	2.27
Type C	2.7–4.2	2.00