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# Bandwidth based electrical-analogue battery modeling for battery modules

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## HIGHLIGHTS

► Recognize the bandwidth characteristics of a commonly accepted battery model.
► Build model based on the bandwidth of the stimulus by assigning time constants.
► Model at the module level (vs. cell level), taking advantage of cell averaging.
► High fidelity has been proved for a Li-ion battery module on performance test.

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## ABSTRACT

A technique for building a high fidelity electrical-analogue battery model by identifying the model parameters at the module level, as opposed to the cell level, is proposed in this paper. The battery model, which is represented by electrical circuit components, can be easily integrated into popular simulation environments for system level design and predictive analysis. A novel bandwidth based time-domain procedure is introduced for identifying the model parameters by selective assignment of the limited bandwidth of the battery model approximation according to the natural bandwidth of the system that uses the battery. The aim of this paper is to provide an accurate off-line electrical-analogue battery model for simulation of larger systems containing large-format batteries, as opposed to a detailed electrochemical model suitable for simulation of internal battery processes. The proposed procedure has been experimentally verified on a 6.8 Ah Ultralife UBBL10 Li-ion battery module which is a “microcosm” for a modern large-format battery pack. A maximum 0.25% error was observed during a performance test with arbitrary but bandwidth-limited charging and discharging intervals characteristic of a typical battery application.



## 1. Introduction

Driven by the fast growing hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) market, batteries are gaining greater attention because the battery pack is a key component [1,2]. High fidelity battery models that are applicable to high power and energy batteries and that are computationally tractable are needed by system designers, as they need a battery model which can be easily integrated into popular simulation environments for system level design and predictive analysis.

There are two main kinds of battery models available in the literature: physical models which are mainly electrochemical battery models, and behavior models, including mathematical models and electrical-analogue battery models. The term of “electrical-analogue battery model” was introduced, as opposed to “electrical battery model”, to emphasize the fact that the model is actually an “analogue” of an electrical system rather than a model of specific electrical components (such as series internal resistance). In other words, the model is a state-space dynamical model represented by electrical components. The distinction is necessary because for the electrical-analogue battery models typically reported in the literature, the circuit components rarely represent the components of a real battery.

There are direct relationships between the battery electrochemistry and the parameters in the electrochemical models, which usually involve a number of coupled partial differential equations [3,4]. These models are complicated and comprehensive, which yield better accuracy than other types of battery models; but they are mostly used by battery designers for battery structure and material design. A disadvantage of the electrochemical models are

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that they are computationally intensive often making them too slow to execute for system level simulation [5–8]. For the behavioral models there are not necessarily direct correlations between the battery physical parameters and the model parameters. The scope of this work is to report on improvements in the procedures for estimating parameters of behavioral models. Modeling of detailed electrochemical processes internal to the battery is not treated in this work.

The mathematical battery models usually come from empirical or stochastic equations [9,10] drawn largely from static features of the battery terminal characteristics. These models are simple and fast in simulation, but when used in dynamic system simulation they are generally less accurate compared with other types of battery models [5,7]. In some circumstances they may be acceptable for low-power battery applications with slow dynamics, or where simulation accuracy is not strictly enforced. These models are not often used where batteries can be expected to experience strong dynamics, such as for the case of a battery pack in HEVs/PHEVs.

The electric circuit analogue battery model uses electric circuit elements such as voltage sources, current sources, resistors, capacitors and inductors to represent a real battery, although the procedure for identifying parameters and assigning them to the circuit elements often does not correlate with a specific equivalent physical element. In fact, the model is more accurately described as a truncated approximation of a non-linear system. The complexity of electrical-analogue battery models lies between the electrochemical models and the mathematical models [5,7]. Comparing the mathematical models and the electrical-analogue battery models, the mathematical models typically code equations curve fit to data that do not have the two-stage coupled form of the electrical-analogue battery model. The electrical-analogue model combines a separate estimator of the true open-circuit voltage (OCV) with state equations (RC networks) that model the dynamic series voltage obscuring the true OCV at the battery terminals. The former can be separately estimated using the state of charge (SOC)-OCV method described here. The fidelity of the latter can be improved as needed by increasing the order of the state equations (i.e., adding RC networks). Since these electrical-analogue models are represented by electrical circuit elements, they are inherently suitable for simulation software with circuit solvers for network analysis and thus are easily implemented into high-level power system design and simulation.

Various electrical-analogue battery models have been built and reported in the literature [5–8,11–18], however, the accuracy of most of the models are not acceptable for high fidelity system level modeling [11,14,18], or the procedure to extract the model parameters is challenging [8], or the modeling requires information about the physical parameters that may not be available to the general user [19]. The object of the modeling is usually a single battery cell instead of a battery assembly containing many battery cells, and more importantly is that much of the behavioral battery model research has taken the circuit components in the battery model as a representation of battery physical parameters, rather than as a behavioral representation of battery current-voltage ($I$–$V$) characteristics.

Since a real-world battery is a non-linear system [5,17,20], there should be no natural exponential moments if a finite number of exponential terms are used to approximate the battery behavior. The number of RC networks used in the electrical-analogue battery model is inherently limited and is equivalent to a truncated exponential representation of a non-linear system – a real-world battery. Thus when facing this inherent need to reconcile the practical limits of the approximation, preference should be given to the time constants of the exponential moments (RC networks in the battery model) that accommodate the desired battery stimulus or battery application. In other words, the time constants of the RC networks in the electrical-analogue battery model should be systematically chosen based on a specific battery stimulus or battery application bandwidth, rather than pursuing natural characteristics of the battery that may not be relevant to the system modeling objectives. Limiting the approximation to the relevant system-driven characteristics is the inherent reason for the improved accuracy reported here as verified by experimental observation.

In this paper, we examine constructing the dynamical representation of the electrical-analogue model based on the dynamical needs of the larger simulation. The temporal resolution of the larger simulation is constrained for many potential reasons. One will be the limitations of models other than the battery model. Another is temporal characteristics of the application. For example, an automobile powertrain will be operated within characteristic temporal limits that are natural to the application. A finite resolution battery model such as the one used in this paper can be "tuned" to this characteristic time scale. The procedures described in this paper are suitable for this process.

The proposed battery modeling aims at battery modules, especially large-format battery assemblies, and delivers high fidelity results. The advantage of this module level procedure is that non-idealities known to exist in battery modules consisting of many cells, such as weak cells, unbalanced cell state of charge and interconnection impedances, is captured self-consistently at the time the battery parameters are identified. In addition, module-to-module variation is less pronounced than cell-to-cell variation due to the cumulative effects of cell averaging. It is likely, then, that a battery model of the module will be more robust against such variation than a module model "built up" in a virtual sense by forming networks of an inherently idealized single cell model. To put it another way, to capture the same confidence in the terminal behavior of a large-format battery pack as gained by doing an actual experimental observation of the battery terminal characteristics it would be necessary to build statistical models of individual cells.

This paper identifies the electrical-analogue battery model parameters based on the bandwidth characteristics of the model with measurements of battery terminal voltage and current. The open-circuit voltage versus state of charge profile is initially estimated with a rapid test method [20], and then improved based on a test profile designed for the purpose. The proposed parameter identification technique is experimentally verified on a 6.8 Ah Ultralife UBBL10 Li-ion battery with a maximum error of 0.25%.

This paper is organized as follows. Section 2 describes the electrical-analogue battery model. Section 3 presents the parameter identification algorithm for the electrical-analogue battery model. Section 4 details the procedure to extract the SOC–OCV profile. Section 5 explains the experimental test apparatus. Section 6 discusses the verification of the battery model. Section 7 concludes this paper.

## 2. The electrical-analogue battery model

A well-recognized electrical-analogue battery model of Lithium-ion batteries [5,7,8,16,17] is shown in Fig. 1. It includes two parts: the left part is the state of charge estimator, which estimates battery SOC based on coulomb-counting as shown in Eq. (1) (DOD: depth of discharge); the right part is an electrical network that is a circuit representation of a truncated approximation of the dynamic response of the electrochemical battery system. A circuit representation is easily integrated into circuit simulation software for self-consistent electrical analysis within a larger system simulation. The bridge between these two parts is the SOC–OCV