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Overview of Battery Models for Sustainable Power and Transport Applications

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Abstract

Battery modeling is an excellent way to predict and optimize some batteries' basic parameters like state of charge, battery lifetime and charge/discharge characteristic. Over the years, many different types of battery models have been developed for different application areas. Individual models differ in complexity, input parameters, available outputs and overall accuracy. This paper categorizes battery models according to various criteria such as approach methods, timescale of modeling or modeling levels. The overview is focused on practical use of individual models and their suitability for different areas of industries, like e-mobility, power engineering or information and communications technology. Finally, the criteria for choosing a suitable battery simulation model for various practical applications are summarized.

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Keywords: Batteries; Battery modeling; Electrochemical model; Analytical model; Stochastic model; Equivalent circuit model

1. Introduction

The battery technology has been integrated into wide range of applications in the past years. Today, batteries are inseparable part of ordinary life, as well as important technology in various industries. Different needs of different areas of industries led to development of various types of batteries with required characteristics. For example, the

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electromobility needs light weight batteries capable of producing fast energy under dynamic charge/discharge profiles, as well as under the influence of variable external conditions. Sustainable power applications require batteries with high capacity, which can absorb energy in time of overproduction and are ready to fully substitute the sustainable source in time of non-generation.

Along with the development of batteries various battery models have been developed as well. These models serve for demonstration and better understanding of basic features of batteries. Nevertheless, they can represent physical limits and are able to predict behavior under different conditions. Numerous models have been developed for various purposes. For example, electrochemical models are very accurate and complex, they are used by manufacturers for development and research purposes. For simulation of electric systems, more simple but less accurate equivalent circuit models are used. Each model has its advantages and disadvantages and is suitable for a specific application.

The paper is organized as follows. Section 2 provides classification of battery models based on different criteria. Section 3 gives example of an electrochemical model. In section 4, an analytic model is discussed. Introduction into stochastic models is stated in section 5. Section 6 takes closer look at simple examples of electric circuit models. Finally, the conclusions are provided in section 7.

2. Classification of battery models

One of the first steps of battery modeling is to decide, what is the purpose of the modeling. Every application of the model requires slightly different approaches and parameters. There is no strict rule, how to categorize battery models, same models can belong to more than one class.

Battery models can be classified by different criteria, in general we can divide battery models by:

- different perspectives of modeling, to:
  - electrochemical models,
  - electrical models,
  - thermal models,
  - mechanical models,
  - molecular models,
  - combinations of interdisciplinary models (electro-thermal, etc.),
- different level (depth) of modeling:
  - system level,
  - pack level,
  - stack and module level,
  - full cell level,
  - half cell level,
  - material level,
- different techniques or approaches of modeling:
  - physical based models (Electrochemical),
  - empirical models,
  - analytical or mathematical model,
  - equivalent electrical circuit models,
  - stochastic models,
  - hybrid models,
- different time scales of the models:
  - short term (dynamic behavior, partial charge, discharge),
  - medium term (full cycle),
  - long term (multiple cycles, complete lifetime) [1].

Material level physically based models are the most accurate and are often used for a comparison with others. These models are too complex and require many input parameters for simulations. They are used for precise prediction of parameters and long-term behavior analyses. Computational efficiency is poor, due the complex sets of partial differential equations, thus not suitable for online applications.

On the other hand, empiric models are simple and effective but at cost of low accuracy caused by the approximations in battery operation. They are based on fitting certain functions to experimental data without making use of any physicochemical principles. Due to relatively small number of input parameters and high computational efficiency, these models are used in real-time prediction of basic values, for example state of charge (SOC) and state of health (SOH).

Generally, analytical and equivalent electrical circuit models are adequately accurate and simple. Main advantage of these models is an availability of input parameters. For simpler models, inputs can be directly extracted from manufacturers datasheet. The equivalent electric circuit model is easy to understand and is capable of capturing I-V characteristic, thus it is suitable for simulation with other electrical circuits and systems. To increase accuracy without significant loss in computing time, it is possible to partially combine approaches into hybrid model. This kind of model is basically made to fit the specific application.

3. Electrochemical models

To monitor the battery SOC and SOH, an accurate, high-fidelity battery mathematical model has to work collaboratively with an accurate and robust estimation strategy. For EV applications, battery SOC and SOH monitoring is an extremely challenging task; because there are numerous parameters that interact together and affect battery performance. Batteries run under dynamic environment of acceleration and deceleration depending on the driving cycle. Many factors affect the battery models and estimations accuracy such as imbalance between cells, self-discharge, aging effects, capacity fade, and temperature effects not provided by battery manufacturers. Electrochemical model's parameters can be experimentally measured by examining the cells, but this approach is costly, time consuming, and often all parameters cannot be obtained [2], [3].

SOC estimation based on electrochemical models has been investigated in [4], [5], [6], [7]. These models are preferred to the equivalent circuit ones, or to other kinds of simplified models, thanks to their ability to predict the physical cells limitations, which have a relevant effect in the automotive application [8]. In [4] and [5], the authors have revised a full order electrochemical model in order to obtain an average model, which reduces the battery model complexity [9].

3.1. Dualfoil model

Dualfoil model is a powerful macro homogeneous battery model that can be used to treat the coupled phenomenon in a porous electrode battery system (including Ni-H and Li-ion battery) [6], [10]. Dualfoil program based on Fortran programming language was originally developed by Marc Doyle and John Newman in 1992. Dualfoil can be used to simulate the electrochemical and thermal phenomena under various operating conditions for Li-ion battery and can help researchers understand deeply battery performance in order to improve them.

The simulation parameters can be divided into two categories. The first category includes design-adjustable parameters such as electrode thickness and volume fractions, particle sizes, separator thickness, and initial salt concentration. The other includes the intrinsic parameters of material (e.g. lithium diffusion coefficient, material density, and heat capacity) and some thermodynamic and kinetic data for the electrochemical reactions [11].

4. Analytic models

The analytical models are the simplified electrochemical models that include nonlinear capacity effects and are able to predict runtime of the batteries with reduced order of equations [12]. This makes this type of models much easier to use. The analytical models describe the battery at a higher level of abstraction than the electrochemical and electrical circuit models [13]. These models perform well for the SOC tracking and runtime prediction under specific discharge profiles. The simplest analytical model is called Peukert's law [14]. It represents the nonlinear relationship between the runtime of the battery and the rate of discharge, but the recovery effect is not taken into account. Another analytical model is the kinetic battery model (KiBaM).

4.1. Kinetic Battery Model

Kinetic Battery Model was developed by Manwell and McGowan [15], [16], [17]. The KiBaM is a very intuitive battery model. It is called kinetic because it uses a chemical kinetics process as its basis [18]. It was originally developed to model chemical processes of large lead-acid batteries [15], [12].

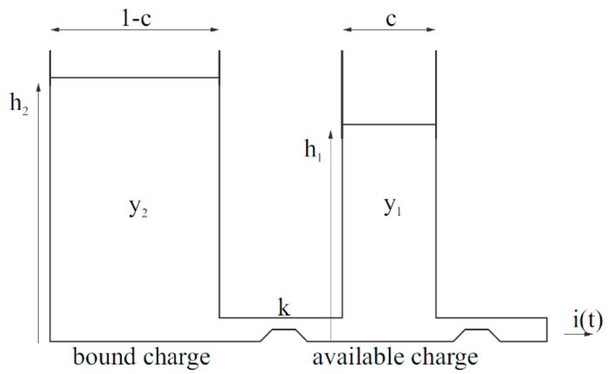

Fig. 1. Two-well-model of the Kinetic Battery Model

In the model, the battery charge is distributed over two wells: the available-charge well and the bound-charge well (Fig. 1). A fraction c of the total capacity is put in the available charge well ($y_1(t)$), and a fraction $1 - c$ in the bound charge well ($y_2(t)$). The available charge well supplies electrons directly to the load ($i\,(t)$), whereas the bound-charge well supplies electrons only to the available-charge well. The charge flows from the bound charge well to the available charge well through a "valve" with fixed conductance, k. Along with this parameter, the rate at which charge flows between the wells depends on the height difference between the two wells. The heights of the two wells are given by:

$$h_1 = y_1/c;\ h_2 = y_2/(1 - c). \tag{1}$$

The battery is considered empty when there is no charge left in the available charge well. When a load is applied to the battery, the available charge reduces, and the height difference between the two wells grows. When the load is disconnected, charge flows from the bound-charge well to the available-charge well until h_1 and h_2 are equal again. So, during an idle period, more charge becomes available and the battery lasts longer, as when the load is applied continuously. In this way, the recovery effect is taken into account. Nevertheless, the rate capacity effect is covered, since for a higher discharge current the available charge well will be drained faster, less time will be available for the bound charge to flow to the available charge. Therefore, more charge will remain unused, the lower is effective capacity [18].

Equations (1) do not represent the modern batteries used in mobile devices, like Li-ion batteries, which have different discharge profile. However, if one is only interested in the battery lifetime, and not so much in its actual voltage during discharge, the two-well model of the KiBaM can still be used, because the two-well model describes both the rate capacity and the recovery effect [13].

The KiBaM model is capable of describing the capacity variation of the battery due to the nonlinear capacity effects. However, it cannot represent the dynamic characteristics of the battery required for codesign and cosimulation with other electrical circuits and systems [12].

5. Stochastic models

Stochastic models describe the battery in an abstract manner like the analytical models. However, the discharging and the recovery effect are described as stochastic processes [13]. The stochastic model focuses on modeling recovery effect and describes the battery behavior as a Markov process with probabilities in terms of parameters that are related to the physical characteristics of an electrochemical cell [21].

5.1. Chiasserini and Rao stochastic model

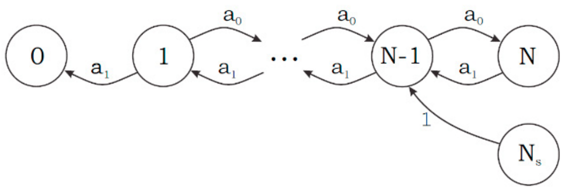

Fig. 2. The basic Markov chain

The first stochastic battery models were developed by Chiasserini and Rao. They published a series of papers on battery modeling based on discrete-time Markov chains between 1999 and 2001 [19]-[24]. In [19], the models of a battery of a mobile communication device for transmitting packets are described. In the simplest model, the battery is described by a discrete-time Markov chain with $N + 1$ states, numbered from 0 to N (Fig. 2). The state number corresponds to the number of charge units available in the battery. One charge unit corresponds to the amount of energy required to transmit a single packet. N is the number of charge units directly available based on continuous use. In this simple model, every time step either a charge unit is consumed with probability $a_1 = q$ or recovery of one unit of charge takes place with probability $a_0 = 1 - q$. The battery is considered empty when the absorbing state 0 is reached or when a maximum of T charge units have been consumed. The number of T charge units is equal to the theoretical capacity of the battery ($T > N$) [13].

6. Electrical-circuit based models

The electrical circuit based models use equivalent electrical circuits to capture the characteristics of batteries by using the combination of voltage and current sources, capacitors, and resistors. Some of these models can also track the SOC and predict the runtime of the batteries by using sensed currents and/or voltages. The electrical circuit models are good for codesign and cosimulation with other electrical circuits and systems. However, the existing electrical circuit models do not integrate battery nonlinear capacity behaviors, leading to an inaccurate prediction of remaining battery capacity and operating time [25]. The rate capacity effect is considered in the electrical circuit model of [26] by using a rate factor in the SOC tracking. An enhanced circuit-based model was developed in [27] and [28] by mixing an electrical circuit model [25] with Rakhmatov’s diffusion analytical model [29] to include the battery recovery effect. However, due to the high complexity of the diffusion analytical model that enhanced model is highly complex and, therefore, is not feasible for real-time applications, such as real-time performance estimation/prediction for power management of batteries [12].

6.1. Ideal battery model

This model is the simplest and the most approximate equivalent circuit model. It consists of an ideal battery with open-circuit voltage E_0 and constant internal resistance R_{IN} (Fig. 3(a)). Both values can be obtained from open-circuit measurements and measurements with connected load, when battery is fully charged [30].

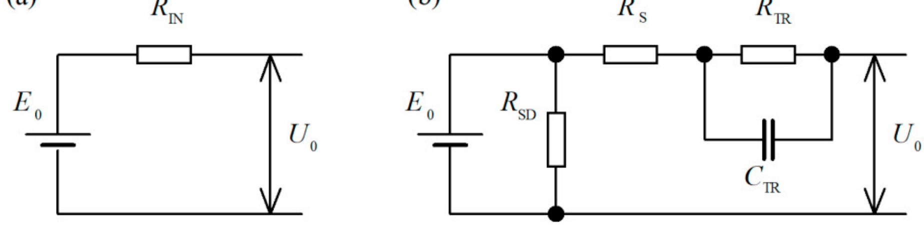

Fig. 3. (a) Ideal battery model; (b) Thevenin-based model

This model has several drawbacks. This model does not take into account the varying internal resistance because of varying state of charge, electrolyte concentration and sulfate formation. In this model, the energy drawn out of the battery is assumed to be limitless or where the SOC is of little importance [30].

6.2. Thevenin-based model

In its most basic form, a Thevenin-based model, shown in Fig. 3(b), uses a series resistor (R_S) and an RC parallel network (R_{TR} and C_{TR}) to predict battery response to transient load events at a particular state of charge, by assuming the constant open-circuit voltage E_0. Unfortunately, this assumption prevents it from capturing steady-state battery voltage variations as well as runtime information.

Its derivative models [31]-[37] gain improvements by adding additional components to predict runtime and DC response, but they still have several disadvantages. For example, the model in [31] uses a variable capacitor instead of E_0 to represent nonlinear open-circuit voltage and SOC, which complicates the capacitor parameter and needs the integral over voltage to obtain SOC. Authors in [32] model the nonlinear relation between the open-circuit voltage and SOC, but ignore the transient behavior. Models in [33], [34] and [36] need additional mathematical equations to obtain the SOC and estimate runtime, and they are not implemented in circuit simulators. Authors in [35] adopt two constant RC parallel networks, but only work at a particular SOC and temperature condition. The model in [37] employs a complicated electrical network extracted from physical process to model open-circuit voltage, which complicates the whole model [38].

7. Conclusion

An overview of the battery models has been presented in this paper. Models have been classified by different criteria significant for system simulation. Appropriate types of models have been presented along with simple examples. Literature references with more detailed description have also been stated.

Presented models can be used for simulation of all sort of batteries with certain accuracy. In fact, accuracy defines the suitability of different models for different kinds of batteries. High accurate models, for example electrochemical, can handle any kind of technology including its specific behavior. On the other hand, less accurate models may be a better fit for particular types. For example, KiBaM is well suited for Lead-Acid batteries due to their discharge characteristic, Ni-based batteries and their memory effect can be easily presented by the stochastic model. By using the least accurate models, a technology of modeled battery is actually neglected.

Based on the overview stated in this paper, it can be noted than the best suited for usage in transport applications are electrochemical based models as well as equivalent circuit ones. For accurate prediction and long-time estimations of behavior under various conditions, the low order electrochemical models are well equipped. They are capable of representing non-linear effects, due to their physical foundations. Thus, the accuracy is kept on high level even under dynamic environment of acceleration and deceleration of the driving cycle. The main disadvantage of electrochemical model is complexity and the resulting low computational efficiency and availability of numerous input parameters.

However, if it is more important to use battery model as a part of more complex simulation, equivalent circuit model can provide required results. Sufficient accuracy can be achieved by using high order circuit models, without greater impact on computational efficiency and availability of input parameters. Thus, they are suitable for online monitoring and real time applications.

Sustainable power applications often demand model capable of dynamic simulations and which can be easily embedded into complex environment of power grid. In this case we are looking for model with outputs in electric values which are properly accurate, computational efficient and do not require large number of experimental obtained input parameters. Well suited option is correctly chosen equivalent circuit model, due to its electric output characteristics and easy implementation to system simulation model.

Hybrid models are also appropriate for both mentioned applications. They are capable of combining both, accuracy and efficient computing time. The disadvantage is overall complexity of hybrid model.

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