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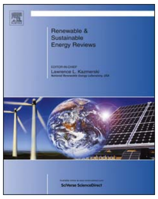

A review of stochastic battery models and health management

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ABSTRACT

Batteries are promising sources of green and sustainable energy that have been widely used in various applications. Battery modelling as the basis of battery management system is vital for both technology development and applications of batteries. Compared with other battery models, stochastic battery models feature high accuracy and low time consumption. Moreover, charging profile, battery behavior, and discharging profile can all be considered to optimize battery performance and usage, which is a key issue in battery usage in real life. Given the significance of stochastic modelling and the progress of battery health management, this paper reviews various aspects of related studies and developments from different fields, while identifying their corresponding merits and weaknesses. Remaining challenges are discussed, and several suggestions are offered as possible inspirations for further research.

1. Introduction

Energy produced by fossil fuels and by nuclear energy comes with shortages due to their negative impact on our health and our environment such as the carbon dioxide (CO2) emissions and waste products of nuclear [1]. In contrast, as a promising source of green and sustainable energy [2], batteries that store and provide electrical power have been widely used in various applications, such as in wireless sensor networks (PV-battery systems) [3–6], mobile devices [7], electric vehicles (EVs) [8,9], and hybrid EVs (HEVs) (transportation systems), which help to reduce CO2 emissions [10–12]. A report on battery technology and market conducted by BCC Research [13] indicates that the battery market is projected to reach US$30.9 billion by 2019, with an annual growth rate of 5.5%. This huge market has motivated various studies on batteries at different scales.

Battery health management (BHM), also known as a battery management system (BMS) [1], is a key element in battery utilization in complicated systems [14,15]. BMS does not only accurately estimate battery state based on state of charge (SoC) and state of health (SoH) [1] in energy management modules, it also generates the future operational policies of a battery to manage its usage, prolong its lifetime [16], reduce maintenance costs, and prevent safety hazards [15]. To achieve these tasks, several stages of BMS, including battery modelling, battery state monitoring, and battery management should be performed individually.

Battery modelling as the basis of BMS is vital for both technology development and applications of batteries [17]. In the past decades, a series of battery models have been developed [18–25]. In general, these models can be divided into several categories: physical chemistry models, such as the lithium–polymer insertion cell model [26,27]; empirical models, including Peukert's law model [28]; abstract models, such as electrical circuit models [29,30]; stochastic models [31,32]; and other hybrid models. Most of these models directly aim to 1) simulate battery behavior and interpret battery issues intuitively for designers and users; 2) accurately estimate capacity, available power, SoC, SoH, state of life (SoL), etc., which are critical for understanding the health of a battery in use. Furthermore, modelling can enable designers to gain complete insight into battery performance even during the design stage, i.e., researchers can identify which design will exhibit the best performance from various battery designs [33].

Compared to other existing battery models, stochastic models, particularly Markov chain processes, can model battery-powered systems as a whole [34,35]. Moreover, the stochastic model can model bursty aging processes and consider operational profiles and management, unlike in the case of other conventional models that can only

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illustrate battery behavior [36]. As mentioned in Ref. [37], stochastic models aim to describe batteries theoretically, similar to analytical models [33], with less time consumption than electrochemical models and better accuracy than other models. In practice, complex electrochemical reactions that occur within batteries while charging or discharging are significantly affected by random ambient temperature and random use profile [38–40]; stochastic models can be used to characterize the stochastic nature of battery-powered systems. In summary, all the aforementioned works validate the importance of research on stochastic models for batteries.

Several review papers on battery models, battery performance, and BMS systems have been published in the past years [14,15,17,33,37,41–44]; however, no publication has focused on stochastic BHM modelling [20]. Given the significance of stochastic modelling and the progress of BHM, this review aims to summarize existing research results on stochastic battery models and health management.

In general, the procedure to develop stochastic BHM for real applications can be summarized as an analysis of the requirements of battery management, aging mechanisms, battery usage patterns, stochastic battery modelling, health management, and parameter estimation. The rest of this paper is organized according to the general procedure to summarize all the main aspects of stochastic BHM comprehensively. Section 2 describes efficient battery health indicators, which are significant for understanding the state of a battery and for the health management of a battery by considering aging processes and usage patterns. Several closely related concepts and their relationships have been discussed. Section 3 systematically reviews existing stochastic models that have been applied to batteries; this section also presents stochastic-based management for batteries. Section 4 focuses on typical approaches for estimating the parameters of stochastic processes. Section 5 summarizes all previous works and discusses the identified challenges, while offering suggestions for further research in the field of stochastic BHM.

Given the different styles of rechargeable and nonrechargeable batteries, some notations are similar to one another but do not have the same name or have the same name instead of the same meanings. To unify all the concepts and provide a clear understanding of these concepts in this paper, we merge several concepts that are mainly related to rechargeable batteries.

1. **Charge recovery:** An effect in which charges can be recovered during a certain duration of relaxation time in the discharge process.
2. **Capacity recovery:** An effect in which available capacity can be recovered during a certain duration of relaxation time in the charge/discharge cycling process.
3. **Time slot:** A time step that is modeled from a Markov chain process.

2. Battery health indicators and aging processes

In this section, we investigate and establish the relationships among battery aging mechanisms, usage patterns, and health indicators, which will be critical for accurate stochastic battery modelling and BHM. The basic objectives of battery management are to ensure the safety, reliability, and efficiency of batteries and battery-powered systems even under extreme conditions. Direct and reasonable issues that require the considerable attention of designers are given as follows: 1) the type of information that should be delivered to users to simplify and improve understanding of the health state of a battery in use, and 2) the processes in which the aforementioned efforts are extended to various working conditions, i.e., finding ways to deliver accurate information to users even under different usage patterns. To realize the objectives, a BMS designer should generally consider efficient battery health indicators, battery aging mechanisms, and typical battery usage patterns.

2.1. Efficient battery health indicators

Complicated electrochemical processes in batteries hardly measure the inner chemical characteristics of a battery. In practice BMS designers should develop systems with indicators that can identify actual battery health state rather than with complicated and specialized electrochemical parameters for the easy understanding of users. Therefore, several battery health indicators, which can reflect the real performance and the internal aging state of a battery, are desired. In this paper, systematic and efficient battery health indicators have been proposed, along with the identified inner relations among these indicators, which can play important roles in guiding designers to choose an effective set of battery health indicators to satisfy design requirements while minimizing the size of an indicator set.

2.1.1. Capacity and impedance

The capacity of a battery is its capability to store energy. For a rechargeable battery, capacity decreases across its lifetime because of aging. Similar to capacity, the impedance parameters of a battery identify its internal state, but significantly change across its lifetime because of aging processes. The effect of aging on battery performance in terms of capacity loss and impedance rise has been estimated by Safari et al. [45,46] by establishing a phenomenological model, which has been extensively used as a reference in subsequent research.

2.1.2. SoC

The accurate SoC of a battery can provide significant information, such as the relative amount of energy remaining in a battery. SoC intuitively indicates how long a battery can last before recharging is required [41]. For battery packs, the accurate SoC values of each cell are critical for battery management, such as for balancing; these values affect the design of BMS [47,48]. One of the classic formulas for calculating SoC is the Coulomb counting (ampere–hour integral) equation, which is given as follows:

$$SoC\,(t) = \left(1 - \frac{\int_0^t \eta i \cdot d\tau}{C_{bat}}\right) \times 100\%, \tag{1}$$

where C_{bat} will either be the initial capacity or the current capacity of the battery for different applications. i is the current with positive and negative values for the discharging and charging processes, respectively. η denotes Coulombic efficiency, which has values less than 1.

2.1.3. Available power

In practice, sufficient power should be provided to replace a specific amount of charge drained from a battery. Available power is a direct indicator of battery performance and is limited by voltage, current, SoC, and temperature.

2.1.4. SoH

SoH is used to denote the specified health condition of a battery in use compared with its brand new state [49–53]. As indicated in [41], the definition of SoH varies for different applications. However, the value of SoH can be estimated and determined based on capacity and impedance rather than on measurement [41,54–56]. One of the frequently used versions is generally defined as $SoH\,(t) = \frac{C_t}{C_{bat}} \times 100\%$ [57,58], where C_{bat} is the initial capacity of the battery. C_t is the actual capacity at time t.

2.1.5. Remaining useful life (RUL) and SoL

RUL [59] and SoL have the same meaning to a certain extent. In general, two types of representations are available for battery life. The first is cycle life, and the second is lifetime in use (not calendar time). Both representations depend on battery type, usage pattern, and a predetermined end of life (EoL) criterion, such as normal usage of 80% remaining capacity.