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Dynamic battery cell model and state of charge estimation

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HIGHLIGHTS

- Accurate electro-thermal battery model that includes thermal balance equations.
- Dynamic cell model with potential corrections for electrode, electrolyte chemistry.
- Includes consistent parametric model of the dynamic aspects of unsteady temperature.
- Model includes the variable discharge/charge current during simulation time.
- Application to *SOC* estimation via decoupled extended Kalman filtering.

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ABSTRACT

Mathematical modelling and the dynamic simulation of battery storage systems can be challenging and demanding due to the nonlinear nature of the battery chemistry. This paper introduces a new dynamic battery model, with application to state of charge estimation, considering all possible aspects of environmental conditions and variables. The aim of this paper is to present a suitable convenient, generic dynamic representation of rechargeable battery dynamics that can be used to model any Lithium-ion rechargeable battery. The proposed representation is used to develop a dynamic model considering the thermal balance of heat generation mechanism of the battery cell and the ambient temperature effect including other variables such as storage effects, cyclic charging, battery internal resistance, state of charge etc. The results of the simulations have been used to study the characteristics of a Lithium-ion battery and the proposed battery model is shown to produce responses within 98% of known experimental measurements.

1. Introduction

Battery designs play an important role in the design of electric vehicles, and a wide variety of battery types are available in the market. A distinguishing feature of these batteries is the price per kilowatt-hour varies according to battery type as mentioned in Smith [1]. The Lithium-ion (Li-ion) batteries have attracted the popularity among many battery types to be used in hybrid electric vehicles due to high volumetric and gravimetric energy density and low self-discharge rate [2]. A Lithium-ion battery refers to a battery where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ions (Li+). Lithium ions move from the anode to the cathode during discharge process and they are inserted into the voids in the cathode. The reverse is true during charging. In the case of Li-ion batteries a particular concern is ageing effects such as plating. Plating (or deposition) of metallic lithium is an important battery degradation and failure mechanism which is a concern for Li-ion batteries because, it can lead to short circuits and uncontrollably high temperatures [3].

In this paper we consider the dynamic modelling and simulation that accounts for all aspects of the battery life cycle such as self-discharging, gassing effect, diffusion processes, acid stratification, state of charge, over voltage stabilization etc. which is quite an involved process as outlined by Zoroofi [4]. The application of the model to state of charge (*SOC*) estimation using an extended Kalman filter is also considered.

Broadly, battery models may be classified as circuit based models and electro-chemical models. However the distinction is only superficial, as all electro-chemical models can be represented by equivalent circuits, if one permits the circuit elements to be active or regenerative elements rather than just passive circuit

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elements. Furthermore, the circuit elements may be non-linear functions of the internal state of the battery. The basic circuit model is the Thevenin equivalent circuit of the battery and its extensions as discussed in Vepa [5]. In these approaches one establishes a linear model of the relationship between the terminal voltage and the current available to the application. The polarization losses are expressed as nonlinear voltage losses. An alternate approach is to assume a linear relationship between the rate of change of the terminal voltage and the rate of change of the *SOC*, which is usually the key metric of interest. The proportionality constant could be assumed to be locally linear or nonlinear. The *SOC* is defined as the percentage of the completely extractable charge capacity remaining in the battery. The*SOC* indicates the amount of electrical energy remaining in a battery. A key performance parameter is an accurate estimate of the *SOC* as and when it is being used and is important both for the battery application designers as well as for the battery users. An accurate indication of the battery *SOC* during the runtime allows the user to ensure that the battery is neither over-charged nor under-discharged, resulting not only in the optimum use of the power available but also in a longer battery life. The methods of estimating the battery *SOC* can be broadly classified as:

i) Discharge test under controlled conditions to determine the capacity remaining at any instant after a specific loss of capacity;
ii) Ampere-hour counting or charge counting (initial *SOC* must be known and involves estimation of the current loss);
iii) Based on the relation between the open-circuit voltage and*SOC*;
iv) Model based estimation;
v) Heuristic interpretation of measured data (electrolyte properties and other).

Several of the above methods rely on test data and the usual tests carried out on a battery are:

i) Open-circuit voltage test to determine the relationship between the terminal voltage, the terminal current and the*SOC*;
ii) Hybrid Pulse Test: Hybrid Pulse Power Characterisation (HPPC) profiles with constant current discharge and charge pulses with rest periods or pauses with no charging or discharging are used to measure battery performance characteristics;
iii) Federal Urban Driving Schedules Tests (FUDS): FUDS is a typical dynamic driving cycle and is usually used in the USA to verify the usefulness and the accuracy of the battery models.

Most measured data is characterised by uncertainties and there are usually five classes of uncertainties to consider: i) measurement uncertainty, ii) algorithmic uncertainty, iii) environmental uncertainty, iv) model parameter uncertainty and v) model dynamics uncertainty or un-modelled dynamics. Thus the first step is usually to extract the model parameters by applying suitable model identification and parameter estimation methods to the measured data as discussed by Birkl and Howey [6]. One can adopt either a time domain approach, such as the method of Alavi, Birkl and Howey [7] which can then be used directly to simulate the battery dynamics (see for example Thanagasundram et al. [8]) or a circuit based approach as in Howey et al. [9]. One could also adopt a direct approach and identify the *SOC* characteristic from the measured data as was done by Li, Chattopadhyay and Ray [10].

A novel approach to battery modelling can be found in Sepasi, Ghorbani and Liaw [11] and in Xia et al. [12]. Here, we investigate to present a cell level battery model which incorporates the most significant parameters that have been mentioned previously. As mentioned earlier, circuit based electrical models are very useful and complex enough to represent the electrochemical behaviour within the cells that describe the dynamics of the electron transfer and energy dissipation. Zhang et al. [13], Thanangasundram et al. [8] and MathWorks [14] used the open-circuit voltage to estimate the state of charge of the battery. Erdinc, Vural, Uzunoglu [15] employed the battery internal resistance as a function of *SOC* when modelling discharging/charging characteristics. Storage and cyclic effects also were added to the internal resistance. The dynamics of the*SOC*, is given by Erdinc, Vural, Uzunoglu [15] and is,

$$\frac{d\,SOC(T)}{dn} = k_1 n + k_2. \tag{1}$$

The temperature effect on the battery system was modelled along with the rate of change of *SOC*. In equation (1), n is the cycle number, k_1 and k_2 are constants. The variable T identifies the operating temperature of the battery. The equation (1) was based on a semi empirical formulation for variation of *SOC* at the negative electrode with the cycling effect confined to two specific temperatures of 25 °C and 50 °C.

When modelling the effect of battery temperature, experiments by Tan, Mao and Tseng [16] demonstrate that it is essential to consider both the change in the ambient temperatureT_{amb} due to environmental conditions and the rise in internal battery cell temperature T_{Cell} due to chemical reactions in the electrolyte and the electron transfer effect. Although most experiments are conducted at a constant temperature (see for example Chen and Rincon-Mora [17]), for electric vehicles (EV) especially, the rise in the ambient temperature due to a hot external environment as well as the heat emission from an automobile engine can affect the battery performance severely as mentioned by Kroeze and Krein [18]. To account for all the performance characteristics, the effects of both the ambient and internal battery cell temperature have to be explicitly considered. Though, the change is not substantial the ambient temperature above a critical temperature can affect the battery performance. Simulation tests were carried out to check this ambient temperature as a variable factor disregarding the thermal energy balance within the cell due to current flow and gradually increasing the operating temperature above room temperature (room temperature was taken as 25 °C) in steps of 5 °C above 25 °C. It was observed that when the temperature goes up slightly above 45 °C, the discharging curves start to fall back and coincided with the 45 °C curve. Further simulation tests with decreasing temperature of step size 2 °C, below 45 °C, confirmed that the maximum temperature beyond which the results are unusual and possibly unreliable, and is 42 °C. Similar tests (simulation) were carried out for temperatures below 0 °C and the lowest temperature below which the results are unusual is -10 °C. This model behaviour partially confirms the electrostatic capacitance variation of general purpose capacitors when the temperature is greater than 42 °C and when it is less than -10 °C. Further details and comments regarding simulations can be seen in section 7.

Batteries are designed for operation at normal temperatures (15-42 °C) as outside these temperatures ageing effects and thermal instability are often problematic resulting in safety problems. The ageing and thermal instability problems are briefly discussed in a latter section.

In this paper a new dynamic Li-ion battery model is proposed and validated. One of the key features of this paper is that, it presents a dynamic battery model that is accurate and consistent not only at a constant cell temperature but also at varying ambient and internal cell temperatures. The other contributions made in this