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An online framework for state of charge determination of battery systems using combined system identification approach

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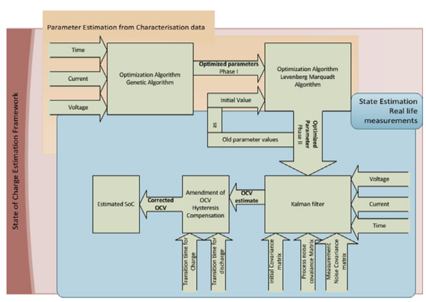
HIGHLIGHTS

- Use of two system identification optimization (Genetic Algorithm and Levenberg-Marquardt).
- Algorithms are adapted for extracting parameter of batteries.
- Use of novel error function based hysteresis compensation.
- Newly developed online state of charge estimation framework.
- Designed for most battery chemistries with minimal adaptation.

GRAPHICAL ABSTRACT



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ABSTRACT

In this article, an online state of charge (SoC) estimation framework is proposed, designed and implemented using the system identification approaches. The techniques are composed of cross combination between two modified nonlinear optimisation algorithms (modified Genetic Algorithm and modified Levenberg Marquardt) adapted for battery cell parameter estimation. Subsequently a linear recursive Kalman filter is employed to estimate the state parameters of the battery cell. Moreover, a newly statistical approach is developed to encounter hysteresis phenomena within the cell. The prerequisite for the SoC determination in the electrical vehicle (EV) is challenging as the battery can be composed of hundreds of cells while the load current changes dramatically inside the cells and the required elapsed time for SoC determination should be as short as possible to extend the expected lifetime of the battery pack. Thus, the accurate estimation of the SoC of the cells in a battery pack is one of the key factors for using them effectively. The framework is found to be robust, optimal and implementable in time constrained environment with acceptable accuracy.

1. Introduction

The state of charge (SoC) of a battery is a measure of the amount of electrical energy stored in the battery. An accurate SoC estimation depends on two aspects according the definition of SoC given by coulomb counting (Ah) equation: one is the initial SoC (S_0), coulombic efficiency (η), and the other is the calculation of SoC consumption,

$$S_t = S_0 - \int_0^t \frac{\eta I}{C_n} \mathrm{d}t \tag{1}$$

So in case that the initial state of charge and the actual true capacity (C_n) with coulombic efficiency is known, Eq. (1) provides

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the quickest and the most precise value of the state of charge of the battery cells. Table 1 provides an inventory of technical terms used in the article. In reality due to the variability among the cells and the limitation of real life sensor accuracy, it is impossible to determine the true capacities for each cell in a battery pack and the initial state of charge is also very difficult to determine confidently due to different real life battery cell characteristics e.g. coulombic over potential [1]. Furthermore, because of the nonlinear behaviour of the cells inside a battery pack and the absence of a definitive model to interpret the behaviour of each cell state of charge determination can be a challenging task. The problem is exacerbated in case of a battery pack operational in EVs or grid level that contains a number of cells (e.g. Opel Ampera: 288 cells, Nissan Leaf: 196 cells) and the load current is highly varying according to the driving profile. It is the intention to find the state of charge of different cells at once in an online[1] automated manner. Especially for the online battery state of charge determination system, the task requires a solution for a number of challenges in the field of modelling which consists of the identification of the parameters, (near) accurate mathematical representation, assessing deterministic or stochastic behaviour of the system, and ultimately translating all these pieces of the information into one integrated setting that can evolve with the change of the surroundings which can eventually validate the utility of the methodology.

The SoC of the battery is a complex non-linear function of parameters. Key factors affecting the SoC are the charge–discharge rates, hysteresis, temperature, cell age, and self-discharge [1]. The existing SoC estimation methods can generally be categorised into two types: direct kind and indirect kind schemes. One of the direct approaches simply indicates the remaining capacity by using current integration or coulomb counting technique. However, a large SoC estimation error exists caused by the inaccurate initial SoC and the low calculation accuracy of the coulomb (Ah) consumption due to some uncertain disturbances originating from the real life sensor characteristics. On the other hand, the indirect methods determine the SoC by using the battery's intrinsic relationship between the SoC and some electrical parameters such as open circuit voltage (OCV). OCV naturally declines proportionately with the energy expenditure and is widely used for SoC estimation. But the direct measurement of the OCV is difficult for online application due to the long waiting time for the batteries to reach a steady state condition [2,3]. A variety of techniques has been proposed to measure or monitor the SoC of a cell or battery each has its relative merits, as reviewed by Ref. [4]. Some methods are specific to particular cell chemistries. Most methods depend on measuring some convenient parameter, which varies with the SoC. [5] proposed a real-time SoC evaluation system for Li-ion batteries combining direct measurement of electromotive force (EMF) during the equilibrium state and coulomb counting during the charge–discharge states. [6] implemented a sliding-mode observer for robust tracking under nonlinear conditions based on a RC battery model. [7] proposed a SoC determination method based on an extended Kalman filter for observation of the parameters of the modified Randles circuit battery model. [8] used a recursive least square algorithm with an optimal forgetting factor for estimating OCV from the battery under test using an OCV–SoC look up table. [9] used a Kalman filter to find the state of charge of batteries and did not take account of hysteresis effect which diminishes the usage of the direct application of their system to estimate SoC for most of the batteries. [10] used two extended Kalman filter (EKF) loops to integrate the hysteresis phenomenon, one for SoC estimation and one to offset the hysteresis effect. The usage of two EKF makes the system computationally burdened. Also both of [9,10] use an experimental method to derive the parameters from the batteries without further optimisation and for that reason there is a chance of failure to represent the best dynamic battery behaviour as these values did not provide the best fit to the terminal values since parameter optimisation was not done to get the best fit.

Table 1
Different technical terms and respective definition.

Terms	Definition
C-rate	The rate at which a battery can deliver or accept current, stated in terms of the rated capacity of the cell in amp-hours. This may also be referred to as the hour rate, such as the 1-h rate.
Coulombic efficiency, η	Ratio of charge delivered by a rechargeable battery during discharge cycle to the charge stored during charge cycle.
Battery Management System (BMS)	An electronic device assembly or system that monitors and controls a rechargeable battery. Parameters measured by the system may include cell temperature, voltage, and current. From this data, the BMS can compute the state of charge of the battery and other necessary battery state. The BMS may also contain sensors and circuitry for protection such as over-current, over-temperature, or over-voltage.
Battery pack	Collection of batteries or individual cells electrically connected in series and/or parallel combinations along with the required electrical interconnections, mechanical packaging, thermal management, and sensing circuitry. Because it is a self-contained assembly, a battery pack can be easily swapped in and out of the application.
SoC	Defined as the capacity left in a battery expressed as a percentage of some reference. SoC of a battery is usually expressed as a percentage of the current battery capacity when it is fully charged.
Initial state of charge S_o	Battery Starting SoC condition for a defined application. Full battery means 100% SoC while 0% means Empty battery.
True capacity, C_n	True or nominal capacity is different from the physical or theoretical capacity of a cell, which is dependent upon the active material in the cell and is based upon the total amount of energy that can be stored or extracted from the cell when manufactured. It can be reached by discharging the cell with a very small current at the specified temperature.
Coulombic capacity, Ah	Unit of electric charge, the amount of current delivered for 1 h

This article proposes a new framework for the state of charge estimation considering the use of two different nonlinear optimisation algorithms namely modified Genetic Algorithm (Section 3.3.1) and modified Levenberg Marquardt method (Section 3.3.2) for parameter estimation and using Kalman filter (Section 3.4) for battery state estimation. This article addresses the hysteresis concern of the OCV curve of battery cells with the introduction of a probabilistic parameter (Section 3.5). Overall, this state of charge estimation method is designed for the required purpose of SoC determination in varying dynamic conditions of large battery packs, e.g., hybrid electric vehicle (HEV), Battery electric vehicle (BEV) or grid scale battery pack that operates in dynamic environments.

2. Methodology

The fundamental part of the proposed framework is a coupling of the estimation methodologies for the state and parameter estimation. The framework is illustrated in Fig. 1. A lumped parameter battery model is used to estimate different voltage levels and this

[1] Online: The processing of data piece-by-piece in a sequential manner without availability of the entire data from the start of estimation.