Implementation of an Improved Coulomb-Counting Algorithm Based on a Piecewise SOC-OCV Relationship for SOC Estimation of Lead-acid Battery

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***Abstract*—Considering the expanding use of embedded devices equipped with rechargeable batteries, especially Li-ion batteries that have higher power and energy density, the battery management system is becoming increasingly important. In fact, the estimation accuracy of the amount of the remaining charges is critical as it affects the device operational autonomy. Therefore, the battery State-Of-Charge (SOC) is defined to indicate its estimated available charge. In this paper, a solution is proposed for Li-ion battery SOC estimation based on an enhanced Coulomb-counting algorithm to be implemented for multimedia applications. However, the Coulomb-counting algorithm suffers from cumulative errors due to the initial SOC and the errors of measurements uncertainties, therefore to overcome these limitations, we use the Open-Circuit Voltage (OCV), thus having a piecewise linear SOC-OCV relationship and performing periodic re-calibration of the battery capacity. This solution is implemented and validated on a hardware platform based on the PIC18F MCU family. The measured results are correlated with the theoretical ones; they have shown a reliable estimation since accuracy is less than 2**

***Index Terms*—Keywords Li-ion battery, Monitoring, SOC, Coulomb-counting, Piecewise linear SOC-OCV, Hardware implementation**

I. Introduction

Currently, we are living in big developing in electronic applications, especially multimedia ones like smartphones, tablets and PCs, where portability remains the most important advantage. To strengthen the effectiveness of these mobile devices, a challenge of autonomy rises to make them reliable as long as possible. Hence, to ensure a permanent energy supply, we resort to rechargeable batteries. Actually, there are several kinds of rechargeable batteries used in industry: Lead-acid, Ni-MH, Ni-Cd, and Li-ion [1,2]. Nevertheless, the portable electronic devices tend to be more compact and lighter, so batteries based on the Li-ion technology seem to be more adequate than other batteries, thanks to their good characteristics; namely high energy density, high voltage, the important number of charge/discharge cycles, and safety, as reported in [2]. Besides, the state of the battery needs to be accurately controlled by algorithms designed to be embedded in the Battery Management System (BMS) in order to ensure a better use and a long battery life. Consequently, the concern of monitoring the remaining capacity is the most crucial task in BMS. Accuracy in State of Charge (SOC) estimation gives the precise energy available in the battery, easing the application control, avoiding irreversible damage to the battery's internal structure and ensuring optimal utilization. In literature, a great number of SOC estimation methods are available [3,4,5]: electrochemical [6], book-keeping [7,8,9,10], model-based [11,12] and black-box, also called data-oriented [13,14]. Each of these methods has strengths and weaknesses, and our goal is to develop a solution offering a compromise between accuracy and simplicity since we are targeting a hardware implementation on the BMS of a Li-ion battery. Indeed, in this paper, we propose an efficient SOC estimation algorithm based on the Coulomb-counting algorithm which is a book-keeping approach. Using a piecewise linear relationship mapping between SOC and the Open Circuit Voltage (OCV) we try to overcome the drawbacks of this approach so as to improve its accuracy.

II. Related work

It has always been a big concern to estimate the SOC for energy storage devices. The estimation accuracy of SOC does not only give an information about the remaining useful capacity, but also indicates the charge and discharge strategies, which have a significant impact on the battery. Thus, a Li-ion battery may have different capacities due to aging, ambient temperature and self-discharge effects. Several methods for

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estimating SOC have been introduced in the literature. In this paper four main categories of SOC estimation methods are identified as presented in Table 1. The electrochemical methods are reported as high accurate because they deal with the internal properties of the battery such as lithium ions dimensions and the electrolyte concentration [15], but they are difficult to implement since it is not evident to access to the chemical structure in on-line monitoring systems. The model-based methods use various models and algorithms to calculate the SOC. Actually, they require an equivalent model used to simulate the battery behaviors. Thus many models types were suggested in literature [16]. These methods also require an adaptive algorithm generally based on state observers such as Kalman filter [17,18,19,20], Luenberger observer [17,21] and others [12,22,23]. Accordingly, their accuracy depends on the efficiency of the battery model and the precision of its characterized parameters. The data-oriented methods, essentially based on artificial intelligence algorithms like neural network [13,20] and fuzzy logic [14,20,24], estimate the SOC accurately for all kinds of batteries considered as black-boxes without the need for any information about the internal behaviors. These methods require a large number of training data. Therefore, they need powerful and costly processing and their effectiveness depends on the accuracy of the learning data. The book-keeping methods also known as Coulomb-counting, consist of a temporal integrating of the battery current during charge and discharge. The accuracy of these methods [7,8,9] is strongly dependent on the precison of current sensors.These non-model-based methods may accumulate errors caused by measurements, possible embedded noise and an inaccurate initial SOC. Given that the aim of this work is to develop an

TABLE I
REVIEW OF SOC ESTIMATION METHODS

SOC estimation method	Characteristics
Impedance spectroscopy	High accuracy
Kalman filter, extended Kalman filter	Accuracy depends on the precision of the battery

embedded monitoring system, and considering that the data-oriented and the model-based methods are restrictive in terms of hardware implementation–since they require large data memory storage and heavy computation to describe the battery behaviors [5,28]– we opt for the Coulombmetric counting method. Indeed, Coulomb-counting is only based on direct measurement, so it is not hard to implement and gives enough precision of the SOC estimation in multimedia applications. Coulomb-counting based algorithms are often used as a core technology for battery SOC estimation in BMS. They express the SOC as the ratio of available capacity to the nominal one. The remaining capacity in a battery can be calculated by measuring the current flow rate (charging/discharging) and integrating it over the time interval. The common equation to calculate the SOC is given by Eq. (1), where the SOC0 represents the initial SOC, bat I represents the current across the battery and, Qrated is the nominal capacity of the battery.

$$SOC = SOC_0 + I_bat * 100/Q_r \qquad (1)$$

However, this book-keeping method suffers from cumulative errors problem and the inaccuracy of the initial SOC estimation. Several researchers have reported these limitations and have proposed some solutions to solve them. For example, in [7], to avoid cumulative errors, a coefficent of Coulombic efficiency was added to the Eq. (1). In the same vein, the accuracy of the initial SOC affects severely the estimated SOC since is an additive term according to the definition in Eq. (1). Subsequently, we need to estimate 0 SOC with rigor and make the access to the initial SOC easier, for that the OCV-SOC model is generally used; because knowing the OCV value leads to having the instantaneous SOC owing to a well-known mapping between OCV and SOC. For this reason, the OCV-SOC model is widely utilized in a lot of works for battery characterization and monitoring [6,4,29,30]. The OCV-SOC mapping function can be implemented either as lookup tables [31,32] or an analytical expression [33,34,35]. The latter solution gives a better computational efficiency and can be generalized for all types of Li-ion batteries, unlike the lookup tables which are specific to each battery and are still too heavy to be implemented [33]. The analytical expression of the OCV-SOC curve has been differently defined in literature [25]. Figure 1 displays the typical curve of a Li-ion OCV-SOC. model. Fig.1. Typical OCV-SOC curve for Li-ion batteries. Various works tried to give a fitting equation to this curve. In fact, in [5, 26] it was reported that the OCV-SOC relationship can be approximated to a linear segment which is not correlated with the reality but rather gives an acceptable accuracy and eases the implementation. Many other forms of OCV-SOC fitting were proposed which respect the nonlinear behavior of the battery and give a high accuracy. However, they have been considered to be unsuitable for hardware implementation [33]. In order to combine both accuracy and low complexity, the OCV-SOC curve was expressed as a piecewise linear system, as in [36], to have a reliable initial SOC estimation. In this paper we propose an efficient Coulomb-counting algorithm of a SOC estimation for Li-ion batteries within a hardware platform based on microcontroller which can be used as a real-time tool for multimedia applications. The accuracy of this algorithm is guaranteed by using a piecewise SOC-OCV model to identify the intial SOC, a periodical recalibration to overcome cumulative errors due to an eventual inaccuracy of sensors and a temperature monitoring using an adaptive coefficient. The experiments prove that the suggested method is reliable and stable, and they result in obtaining SOC with less than 2% of error.

III. Ease of Use

Coulomb-counting is based on exploiting the Eq. (1) by quantifying the charge delivered by the battery through sensing its input and output current [7,37]. Yet, there are some inefficiencies when using this method. First of all, the access to the initial SOC is not guaranteed. Secondly, selfdischarge may distort the real SOC value after a long storage period and finally the reference capacity Qrated must be updated in terms of battery ageing. Furthermore an SOC estimation is performed at varying ambient temperature which should be taken into account. The literature shows enhanced Coulomb-counting algorithms which allow the determination of the initial SOC using the SOC-OCV curve, takes into account self-discharge losses and performs a recalibration at fully and empty stages. Figure 2 gives the flowchart of the propopsed algorithm used to manage the battery monitoring by switching from a battery operating mode to another in accordance with transition conditions. The estimation of the SOC of a Li-ion battery by the developed method is based on monitoring the voltage V the current bat I and the temperature T°. The operation mode of the battery is recognized by the direction of the current through the battery system. When the battery is in an open circuit mode, , a compensation of self-discharge losses will be considered as will be explained in the subsection 3.4. The information needed to perform the monitoring are the measurement of the battery voltage and the current flowing through it. Coulomb counter is used to track the SOC when battery is charging, discharging and selfdischarging. The amount of charges in an operating period is obtained by a temporal integration of a measured charging/discharging current bat I as expressed in Eq. (2).

$$\delta Q = |_t I dt \tag{2}$$

This variation that will be used in Eq. (2) will be negative if the battery is in discharge and will be positive if in charge..

A. Initial SOC determination

Several studies have been conducted to remedy to the problem of accurate estimation of the initial SOC [36]. The most common technique is to use a bijective OCV-SOC function that relates the open circuit voltage to its corresponding SOC value as detailed in the in section 2. This curve is actually determined experimentally by the OCV test by applying a pulse load on the Li-ion battery, then the battery reach an equilibrium where the voltage is extracted in every 5In this proposed algorithm, we start by determining the 0 SOC from measuring the initial OCV, for that we consider the inverse function noted SOC-OCV relationship of Li-ion battery which can be approximated to piecewise linear curve. As demonstrated in Fig.3, the curve is divided into eight segments [25], and each segment can be expressed as a linear relation as in Eq. (3)

$$SOC = a * OCV - b \tag{3}$$

B. Charge Mode

The typical charge procedure of a Li-ion battery consists of constant-current constant voltage (CC-CV) process [29]. The Coulomb counter is presented by Qgained as expressed in .(4), which represents the quantity of charge accumulated during an operating period equal to .

$$Q_g(t+T) = Q(t) + \delta Q(t+T) \tag{4}$$

C. . Discharge mode

Figure 4 shows the typical voltage curves when a Li-ion battery is discharged by different C-rate When the current bat I is negative, then the battery is in the discharging mode. In this mode, the Coulomb counter is presented by Qlost, which represents the amount of charges losses in the operating period

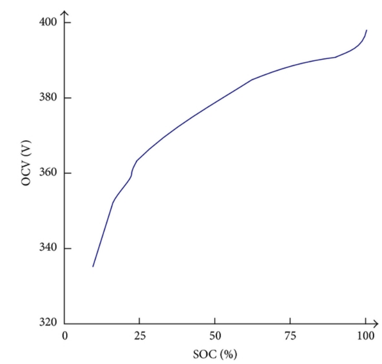

Fig. 1. The proposed piecewise linear relationship of SOC-OCV.

D. Self-Discharge Mode

At the battery storage periods, considering that Li-ion batteries reach 5amount of charge losses per hour is calculated; this amount is designed by the constant, per hour / q . Then, the quantity of charge dissipated in this phase Qoc is calculated by Eq. (10), representing the cumulative losses during the storage hours This value will be added to the amount of charges lost Qlost during discharge mode and subtracted from the amount of charge accumulated Qgained in the charge mode as expressed in Eq. (4)

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Thank you