Journal of Energy Storage 8 (2016) 160–167

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Fast-charging of lithium iron phosphate battery with ohmic-drop compensation method

M.H. Noh[a,b], P.X. Thivel[a,b], C. Lefrou[a,b], Y. Bultel[a,b,*]

[a] Univ. Grenoble Alpes, LEPMI, F-38000 Grenoble, France
[b] CNRS, LEPMI, F-38000 Grenoble, France

ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 14 October 2016
Accepted 15 October 2016
Available online 28 October 2016

Keywords:
Li-ion
Fast-charging
Ohmic-drop compensation
Temperature
Ageing

ABSTRACT

Developing fast-charging protocols for Li-ion batteries is a key issue for a wider deployment of electric vehicles and portable electrical devices. In this study, fast-charging of lithium iron phosphate batteries is investigated with different protocols. High charging rates are used with an extended constant current period thanks to a higher limit voltage based on the ohmic-drop compensation principle. This study shows that a compromise has to be found between the charging time and the durability of the battery. As an example a 6C charge with 57% ohmic-drop compensation allows to reach 95% of charge in 11 min and the full charge in half an hour. With this protocol, more than 1500 cycles are reached before getting below 80% of state of health.

1. Introduction

Currently, rechargeable batteries or secondary batteries are electrochemical storage systems that are frequently being used in various application fields. Portable applications are the main sector that depends on this type of energy storage, for example smartphones, tablets or laptops. For stationary applications, batteries to store electricity are identified as a potential solution to mitigate both the intermittency and limited predictability of alternative energies. However, the transportation sector has also become very dependent on rechargeable batteries over the past few years, as new electric vehicles or EVs have been commercialized throughout the world [1]. The transportation sector has marked a turning point in the increased demand for more robust, energy efficient and high capacity rechargeable batteries.

As a result, the Li-ion rechargeable battery has become the major technology to satisfy the increased demand. This type of battery possesses higher energy densities per mass and volume than other types of batteries such as nickel-cadmium or nickel-metal hydride system. In addition, Li-ion technology provides higher voltages than nickel based systems [2].

As for all other secondary battery types, the Li-ion type also needs to be recharged. Generally, the charging process of a Li-ion battery is divided into 2 charging stages, these are the constant current stage (CC) and constant voltage stage (CV). During the CC stage, the battery is charged at a chosen constant current (i.e. charging rate) until a certain upper voltage limit U_f. is reached before switching to CV stage. The upper voltage limit U_f. is predetermined by the manufacturer, it designed to ensure longer battery life-span by avoiding side reactions. During the CV stage, the battery is normally charged more slowly with a degrading current to maintain the battery at a constant voltage until the current limit called I cut-off, is attained. Even though the CV stage is slow, it allows the relaxation of the species concentrations inside the electrolyte and electrode materials. The duration of the total charging period depends on the charging rate applied.

In the context of EV applications, Li-ion batteries are faced with reliability and durability issues. Nevertheless, it is a mandatory requirement in EV applications to minimize the battery charging time; so, a fast-charging method must be developed properly. If fast-charging is applied, theoretically the battery can be recharged in a shorter period, which is not the case for current EVs. Unfortunately, the fast-charging process causes accelerated battery ageing [3] and high cell temperature increase [2]. This latter aspect may be dangerous because of the highly flammable substances used in lithium-ion batteries.

Different methods are proposed in the literature for fast-charging. The fast-charging process for the Li-ion battery can be performed by increasing the C-rate of the CC stage [2,4,5]. For example, Lopez et al. [2] observed that the total charging time is reduced by about 63% for a fast charge at 1.5C-rate compared to the

* Corresponding author at: LEPMI, 1130 rue de la piscine, BP75, 38402, Saint Martin d'Hères, France.
E-mail address: yann.bultel@lepmi.grenoble-inp.fr (Y. Bultel).

http://dx.doi.org/10.1016/j.est.2016.10.005
2352-152X/

nominal C-rate of C/2. Nevertheless, their results show that the energy efficiency of the charging process decreases greatly when the charging C-rate rises. On the other hand, Huang et al. improve their fast charging strategies by evaluating and characterizing Li-ion battery [4]. Brief current of charging and discharging current interrupts the charging process during constant current period to restrict the hysteresis effect. There's also a fast charging strategy of implying a multi stage charging process during the constant voltage (CV) period to reduce the charging time [6]. Other methods for fast-charging are also proposed in the literature based on pulsing current [7–9]. This latter method has shown good global performance, but an optimal configuration remains a challenge. For its part, the pulse charging is based on constant current steps of short duration followed by relaxation periods. The sequences can vary depending on the pulse amplitude and duration, as well as on the relaxation time. This method is highly recommended for fast-charging purpose as the current imposed is really high. Pauses are required to reduce or prevent the metallic lithium formation. The metallic lithium formation can greatly interfere with the charging process according to Purushothaman et al. [7]. However, their studies only focus on the empirical calculation and simulation without any real experiment implementation. Finally, Ohmic Drop Compensation (ODC) method might also be used for fast-charging. As far as we know, this latter electrochemical method [10,11], has never been used for Li-ion battery fast-charging. Nonetheless, there are some studies that are based on this method for developing fast-charging chargers [12–16]. For instance, Saint-Pierre [14] conducted his studies, which focused on the charger's electronic circuitry rather than the impact of this method on the battery itself, which is the main purpose of this paper. His study shows that with this method, the charging time is reduced by more than 30 min. Lin et al. [12,13] also proposed a fast-charging charger with built-in resistance compensator (BRC) to achieve a fast and stable charging process on Li-ion battery packs. Huang et al. and Peng et al. also conducted their study on a similar area to improve their fast-charging charger [15,16]. Lin et al.'s system is able to charge the battery pack with adequate current and speed up the charging process time. They managed to shorten the charging time by using an ohmic-drop compensation method. This technique is applied to a battery pack and the compensated resistance consists of the external resistance of the battery pack as well as the connections. The compensation technique is performed for a very short delay. The results establish the improvement of the charging time by means of external resistance compensation technique of the battery pack

Unfortunately, the fast-charge method causes higher cell temperature increases that may induce fast ageing and even more battery thermal runway. Indeed, as the study made by Saito et al. [17] shows regarding the thermal behaviour of the Li-ion battery, the main factors of heat generation during both charge and discharge period were electrochemical polarization, electrical resistance and the battery electrochemical reaction. A thermal investigation of a cylindrical Li-ion battery ($LiFePO_4$/graphite) was also undertaken by Forgez et al. [18]. The outer surface and internal temperature of the battery were measured using a thermocouple, and subsequently the heat transfer coefficient and heat capacities were determined. They used the current-pulse method (2 Hz) of different current magnitudes for the charging and discharging processes of the battery. Their results show that the internal battery temperature rises to 55 °C for their charging/discharging conditions and there is about 10 °C maximum gap between the inner and outer surface temperatures. Similarly, Onda et al. [19] have also led their studies on thermal behaviour of the Li-ion battery during rapid charge and discharge. In their studies, they undertook charging and discharging processes ranging from 1C-rate to 3C-rate. Their results show that the battery temperature rises to 100 °C and 80 °C during discharge and charge respectively at a regime of 3C-rate. Conversely to the previous study [18], their results emphasize that there is no significant difference between the outer surface and the centre temperature of the battery (maximum difference observed is only about 1.9 °C at fast-charging process of 3C-rate).

Therefore, the aim of this study is to investigate the ohmic-drop compensation (ODC) method regarding the charging time, temperature increase and battery ageing. Experimental setups as well as the test bench are detailed in the second part of this paper. Next, the electrochemical and thermal behaviour of the battery during fast-charging method will be investigated and discussed. Lastly, the result of the life cycle impact of that method will be presented.

2. Experimental setup, materials and apparatus

2.1. Lithium iron phosphate battery, LFP

In this study, the Li-ion batteries used are C-LiFePO4 cylinder cells manufactured by PHET (model: IFR13N0-PE1150). This means that the 2 electrodes used in this battery are graphite for the negative electrode material and lithium iron phosphate for the positive electrode materials. The LFP battery was chosen because of its thermal stability, which allows it to undergo a fast charging process at high current. The nominal voltage for this battery is about 3.3 V at open-circuit. The usage range of temperature is different between charge and discharge; at 0 °C to 45 °C and −20 °C to 60 °C respectively which is really important information in this study case. The nominal capacity of these batteries is 1.1Ah. It must be pointed out that throughout this paper; C-rate values are referred to the nominal capacity.

2.2. Charging protocol with ohmic drop compensation

As in any electrochemical system, the cell voltage consists of the interfacial terms ($U_{interface}$) and volumic ones ($U_{volumic}$):

$$U = \sum U_{interface} + \sum U_{volumic} \quad (1)$$

$U_{interface}$ is the voltage between the both electrode/electrolyte interfaces at open circuit voltage (U_{OCV}) and both over-potentials and given by:

$$\sum U_{interface} = U_{OCV} + \eta_+ - \eta_- \quad (2)$$

$U_{volumic}$ is the ohmic drop induced by the charge transport in each volume of cell elements (current collectors, electrolyte, connections).

This ohmic drop is proportional to the current when considering the ohm's law:

$$\sum U_{volumic} \approx R_i I \quad (3)$$

where R_i is the internal resistance of the cell.

The main and side reactions are dominated only by interfacial terms. The upper-bound voltage limit U_f predetermined by the manufacturer to maintain cycling performances is an indication of maximum interfacial voltage ($U_{interface,max}$) to minimize side reactions.

Considering the current profile during the charging process, this maximum value of interfacial voltage is reached at the end of the CV stage:

$$\sum U_{interface,max} = U_f - R_i I_{cut-off} \quad (4)$$

When the cut-off current ($I_{cut-off}$) is achieved.