Journal of Energy Storage 4 (2015) 51–61

Contents lists available at ScienceDirect

Journal of Energy Storage

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

# Preisach modelling of lithium-iron-phosphate battery hysteresis

Federico Baronti [a], Nicola Femia [c], Roberto Saletti [a], Ciro Visone [b], Walter Zamboni [c,*]

[a] Dipartimento di Ingegneria dell'Informazione, Università di Pisa, Via Girolamo Caruso 16, I-56126 Pisa, Italy
[b] Dipartimento di Ingegneria, Università degli Studi del Sannio, Piazza Roma 21, I-82100 Benevento, Italy
[c] Dipartimento di Ingegneria dell'Informazione, Ingegneria Elettrica e Matematica Applicata (DIEM), Università degli Studi di Salerno, Via Giovanni Paolo II 132, I-84084 Fisciano, SA, Italy

ARTICLE INFO

*Article history:*
Received 14 December 2014
Received in revised form 10 September 2015
Accepted 10 September 2015
Available online 4 November 2015

*Keywords:*
Lithium-iron-phosphate ($LiFePO_4$) batteries
Hysteresis modelling
Classical Preisach model
Open circuit voltage
State-of-charge

ABSTRACT

The hysteresis of the open-circuit voltage as a function of the state-of-charge in a 20 Ah lithium-iron-phosphate battery is investigated starting from pulsed-current experiments at a fixed temperature and ageing state, in order to derive a model that may reproduce well the battery behaviour. The hysteretic behaviour is modelled with the classical Preisach model used in magnetic materials. The paper shows that the Preisach model can successfully be applied to the lithium-ion battery hysteresis. First, the model is discretised by using the Everett function and identified by means of experiments, in which first-order reversal branches are measured. Then, the model is simulated and compared to some experimental data collected with different current profiles and to a one-state variable model previously used in the literature. The results show that the hysteresis is well reproduced with rms errors around 2%. The advantages of the Preisach-based method, when compared to other models, are the formal and repeatable identification procedure and the limited computational resources needed for the model simulation that makes it appropriate for the online implementation on low-complexity hardware platforms.



## 1. Introduction

The effective storage of electric energy is becoming a challenge that may open the way to a sustainable use of the energy and to the reduction of the greenhouse gas emissions. The energy storage system is a fundamental block in many applications, from smart microgrids to electrified transportation systems, such as plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs). The battery technologies used in these applications are growing fast to increase power and energy densities, battery lifetime and reduce costs, also extending the driving range of EVs [1]. The battery is usually equipped with a Battery Management System (BMS) that performs many functions: protection, monitoring, thermal and electric management, online fuel gauging and so forth.

At present, the superior performance of the lithium-ion (Li-ion) technology makes it the most attractive among the batteries, even if some safety issues, such as the fire susceptibility, and management issues are of concern. A battery with lithium-iron-phosphate $LiFePO_4$ (briefly LFP) cathode [2] offers an excellent thermal stability, that means battery reliability and safety and a high number of cycles. It does not contain rare materials, with a positive impact on battery cost [3]. Although its power and energy density are not the best-achievable in the framework of Li-ion battery technology, its intrinsic safety, reliability and cost make LFP technology one of the most promising solutions for energy storage [4,5].

LFP batteries are characterised by an almost constant open-circuit voltage (OCV) when the stored charge is in the interval between 20% and 80% of its maximum value. In addition, the function mapping OCV as a function of the state-of-charge (SoC), *i.e.*, the ratio between the charge stored in the battery and its maximum value, is not single-valued, but exhibits a pronounced hysteresis [6]. This phenomenon has a strong impact in BMS online fuel gauging. Indeed, the battery voltage, being hysteretic, cannot be used easily for Coulomb counting compensation, as often done for other Li-ion chemistries.

This phenomenon needs an accurate and computationally effective model, particularly suitable for online estimation in a BMS, where the computational resources are often limited by cost. To this end, this paper proposes the use of the classical Preisach model of hysteresis, often used for magnetic hysteresis, with a discretisation based on the so-called Everett function [7]. The paper achieves two important goals. First, the numerical implementation of the model proposed is computationally affordable for online SoC estimation in BMS. Additionally, the paper introduces

* Corresponding author.
*E-mail address:* wzamboni@unisa.it (W. Zamboni).

http://dx.doi.org/10.1016/j.est.2015.09.004
2352-152X/

an easily executable experimental battery characterisation procedure that allows the identification of the model. The model is validated with experiments representing various SoC "histories" of a 20 Ah fresh LFP cell, tested with static and dynamic current profiles at a fixed temperature in one of our laboratories.

The paper is organised as follows. Section 2 introduces the nature of hysteresis in batteries and the related modelling attempts, motivating the particular Preisach approach proposed in this paper. Section 3 reports on experiments and test results, obtained in our laboratories, showing hysteresis in an LFP cell. Section 4 summarises the classical Preisach model, its application to batteries and its identification. Section 5 deals with the model validation, by comparing model simulations and experimental results. The limits of application of the model (ageing, temperature, current-rate and current dynamics) are discussed in Section 6 and, finally, some conclusions are drawn in Section 7.

## 2. Battery hysteresis: state-of-the-art and modelling

From a macroscopic point of view, OCV hysteresis in an LFP cell at given ageing state is characterised by the following properties. (i) It is a *static* phenomenon, as it remains after the battery current is switched off, even for a time exceeding the typical time constants of mass transport inside the electrodes. (ii) It is considered to be *rate-independent*, which means that it depends on the SoC history but not on the speed (battery current rate) with which SoC is changed. The rate-independence is matched with good approximation at least for low current rates, as shown in [8]. (iii) It exhibits sub-hysteresis loops included into a major one. Such properties match the ones exhibited by Nickel-Metal-Hydride (NiMH) batteries [8], deeply studied in the literature, where the open circuit potential of the nickel electrode shows a significant hysteresis [9–11].

An example of hysteretic behaviour experimentally measured on a 20 Ah LFP cell at 298 K is given in Fig. 1, where the full charge/discharge curves show a pronounced hysteresis (major loop).

Hysteresis in lithium-ion (Li-ion) batteries can be ascribed to thermodynamic entropic effects, mechanical stresses, and microscopic distortions within the active electrode materials during lithium insertion or extraction [12]. Evidence of hysteretic OCV behaviour has been reported for various anode and cathode materials. For instance, pronounced hysteresis effects have been observed in high temperature lithium insertion in hydrogen-containing carbons as a cathode material [13], as well as in innovative anode materials, such as NiO-graphene hybrid [14] and silicon oxycarbide (SiCO) [15]. The two-phase transition process

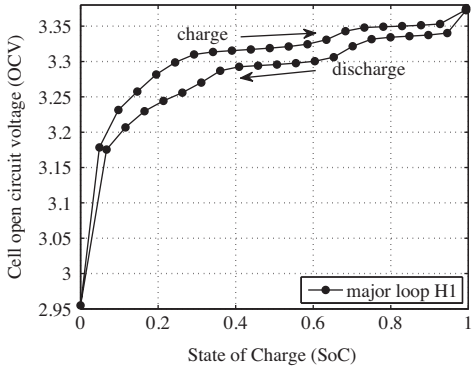


**Fig. 1.** Open-circuit voltage vs state-of-charge characteristic (hysteresis major loop) measured on a LFP 20 Ah cell at 298 K. The relaxation time for the OCV measurement is 1 h.

leading to macroscopic OCV hysteresis, and the OCV recovery effects lasting for several minutes/hours after a current load is interrupted, are described for LFP batteries in [12,16]. From a microscopic point of view, a thermodynamic consistent many-particle description of the electrode, based on the theory of many particle systems (ensembles of interconnected storage particles), is proposed in [17–19]. Such a model exhibits non-monotone behaviour leading to transitions between two coexisting phases and then to hysteresis.

Besides its physical origins, hysteresis is a phenomenon that must be considered in a large variety of battery applications, such as fast charging [20] and SoC estimation [21]. The availability of a reliable hysteresis model improves the accuracy of the algorithms for SoC estimation. The model should be simple for an easy implementation in embedded systems for advanced battery management. Therefore, large efforts have been directed to battery hysteresis modelling. As far as NiMH batteries are concerned, models based on first-principles equations [22], or the Nernst equation, including the entropy of reaction influence and an empirical expression to capture the salient features associated with voltage hysteresis [23,9] are adopted. A multilayer model for nickel active materials with significant deviations from Nernst model is proposed in [24], a circuit approach with an RC "hysteretic" branch, based on an improved Takacs model [25], is used in [26,27], where additional polynomial functions are employed to fit experimental data.

One of the models most used at the macroscopic/circuit level for Li-ion batteries is the one-state hysteresis (OSH) model [28], based on an approach adopted for magnetic materials [29]. The basic idea is that the major loop acts as a forcing term for a relaxation equation containing the signum operator. The model is simple and easy to apply. A circuit interpretation of this model is given in [30]. Similar signum-based models have been used in [31,32] for online lead-acid state estimation. A simpler approach is adopted in [33], where the LFP battery hysteresis is modelled including two SoC-dependent OCV sources, one for the charging and one for discharging current, selected through two ideal diodes. Some other models have been proposed in the literature. The model in [34] is aimed at improving transient response with a hysteretic exponential term. Dynamic models to represent OCV as an output of a state-space model are proposed in [35,36]. Finally, the Jiles–Atherton model, identified by a neural network, describes the battery hysteretic characteristic in [37].

Hysteresis is a phenomenon deeply studied in magnetics and the paradigm of magnetic hysteresis modelling is the Preisach model. It was originally proposed by Preisach [38] in 1935 and later formalised in a general way [39,7,40] to take into account the similarity of hysteretic behaviours in different fields. Therefore, the application of the classical Preisach model to describe LFP battery hysteresis appears quite natural. An example of the use of the Preisach model to NiMH battery is reported in [41], where OCV is chosen as independent variable. This choice is not appropriate for LFP batteries, as they show a very flat SoC–OCV characteristic. The not natural discretisation of the Preisach operator that leads to a cumbersome identification based on a long training is another drawback of [41]. A very preliminary attempt to model lithium-ion batteries hysteresis with the Preisach approach is reported in [42], where the density function of the Preisach operator is assumed to be an *a priori* known function. However, this assumption is not general, very restrictive, and is combined with a non-trivial neural network-based parameters identification procedure. Ref. [42] reports the application of the method only to the description of major loops and no validation is provided in the case of an arbitrary evolution of the battery SoC. Therefore, further work is necessary to obtain an effective and validated implementation of the Preisach model for hysteresis in LFP batteries. Our first attempt is described