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Synthetic methods for the evaluation of the State of Health (SOH) of nickel-metal hydride (NiMH) batteries

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ABSTRACT

The State of Health (SOH) of a battery is important to know the maximum energy that a battery can release while is operative and to plan the correct maintenance. In this work, we have implemented a diagnostic method to evaluate the SOH of single nickel metal hydride (NiMH) cells, that have an important role in power tools applications. Single NiMH cells of 1.2 V and 1.3 Ah have been characterized with Electrochemical Impedance Spectroscopy (EIS) technique to evaluate the SOH with synthetic methods. Through the study of an equivalent circuit model, we determine that three free parameters synthesize the information contained in an impedance spectrum. A new simplification allows us to construct a diagnostic diagram with only two degree of freedom. A mathematical approach based on the Dempster–Schafer Theory of Evidence has been implemented to interpret the diagnostic diagram. Combining the points obtained by the impedance spectra (IS) at different State of Charge (SOC) and SOH, the Theory of Evidence can improve the estimation of the SOH iteratively, a great advantage compared to the classic Theory of Probability.

1. Introduction

Batteries have become important in several applications, like hybrid stationary and energy production systems [1]. The hybrid stationary systems need the use of ESS for uninterruptible power supply (UPS) [2], load levelling, peak shaving services [3,4] and to predict the variable generation of renewable energy sources [5,6]. In automotive field, the integration of ESS is important to reduce pollutant emissions and to improve energy efficiency of plug-in hybrid electric vehicles (PHEV) [7]. Monitoring the state of the batteries is then important to know, possibly online, the SOC and the SOH, to avoid dangerous operating conditions for the accumulators and to minimize error valuations in the realization of control logics. While the SOC is a measure to indicate the charge that a battery can release in a cycle, the SOH indicates the available capacity of the battery relative to the first cycle of utilization. According to this, the SOH relative to a specific SOC gives information on the actual energy content of a battery. Although there are several techniques to evaluate SOC, with benefits and disadvantages [8], SOH is difficult to evaluate on-line in the field. Nevertheless the technology used, the batteries are subjected to physical and chemical degradation during its operations. The main factors of degradation are related to electrode corrosion and degradation of electrolyte. For example principal failure modes of a NiMH battery are the corrosion of negative electrode and the decrepitation of MH alloy particle [9], while the ageing mechanism of lithium-ion batteries is related principally to the processes that occur at the interface electrodes/electrolyte, that results in capacity fade and an increase in internal resistance due to the growth of a SEI (solid electrolyte interface) on anode side of the battery [10,11]. A lead-acid battery instead shows anode and cathode degradation principally due to sulfation of the electrodes, acid stratification and water loss in overcharge condition [12]. The easiest way to evaluate the SOH of batteries is a complete discharge test with the monitoring of the released capacity of the battery. This technique is however not recommended when the state of the battery must be evaluate on-line. For example, it isn't possible discharge completely a battery in EV [14] or renewable energy system [15], when the battery must be continuously operative. Complex techniques are therefore necessary.

Several methods are based on the evaluation and analysis of the internal resistance of the accumulator [16–18], with the only growth of the internal resistance as parameter for the evaluation of the SOH. However, in several technologies, the indication of the internal resistance is sensible to the SOC and to the connections

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between batteries and the elements of the system, that can induce errors in the evaluation of the SOH. Other methods study the voltage curve of the batteries versus charge releasing [19], but in applications where high load variations are observed, the discharge curves aren't an useful indication to determine the remaining useful life of the batteries. Some prognostic methods for the monitoring of the battery are reported in [20], while a review of adaptive techniques used in the SOH problem are discussed in [21]. The most used adaptive technique in the literature to determine the remaining capacity of the battery is the Kalman filter [22,23]. In the Kalman filter theory, the voltage of an operative battery is compared with the voltage of a model. The resulting error is used to improve the estimation of the internal state of the system. This technique needs however a battery model and a correct initialization of the model parameters, that must be chosen accurately to avoid errors in the estimation of the internal state. Kong et al. use an enhanced coulomb counting method to predict the SOH [24]. However, although coulomb counting is a good method to determine the SOC, in the evaluation of the SOH the battery must be completely discharged, so in several applications, like EV and PHEV, is not applicable.

In this paper EIS is used to evaluate the state of the battery [25]. Through a small signal excitation and observing the response of the system, EIS is an interesting and alternative technique for diagnosis and analysis of electrochemical systems in any working point.

EIS is an useful tool in the diagnostic problems, because more physical and chemical effects due to ageing can be studied through the IS. Some authors have characterized lead-acid batteries with EIS techniques to detect the SOH through an equivalent circuit model [26–28]. Other studies involve lithium-ion technology [29] to investigate aging effects. NiMH technologies were investigated to study variations of the model parameters with SOC [30], to reconstruct impedance spectra with a battery equivalent circuit [31] and to develop a fuzzy logic model to identify the SOC and the SOH [32]. Recently EIS was used to evaluate the impedance spectrum of lead acid batteries in stand-alone power plant, to evaluate the state of the accumulator on-line [33]. Most of these works study the parameters of an equivalent circuit model and their variations with ageing. Although these methods are good and can be used to determine the SOH with a limited error, it is necessary a non linear fitting procedure, performed on the obtained IS, that can produce errors if the initial parameters aren't chosen correctly or there are errors in the data acquisition.

In this work, 1.2 V and 1.3 Ah NiMH single cells have been tested to determine the SOH with synthetic methods. A protocol test has been adopted to investigate variations of the IS with available capacity of the battery and to study ageing mechanisms. In order to reduce the acquisition time of the IS, a special effort has been done to identify the relevant frequency points that characterize the IS itself. In order to make the information extracted by the EIS quickly accessible, two diagnostic diagrams have been built. The diagnostic diagrams, used to identify the SOH, are analysed through the formalism of the Theory of Evidence.

The Theory of Evidence is used for the first time in the evaluation of the SOH problem and it integrates well with the diagnostic diagrams. Indeed, compared to the probability theory, it is possible to improve the estimation of the SOH determining more diagnostic diagrams and combining the resulting information.

The final target of our work is the realization of a prototype battery management system (BMS) for the evaluation online of the state of the battery. The paper is organized as follows: the experimental setup is described in Section 2. The equivalent circuit model is discussed in Section 3. Analysis of the diagnostic diagrams is reported in Section 4. Numerical approach based on the Theory of Evidence is discussed in Section 5.

2. Experimental setup and test procedure

The experimental test requires the complete charge and discharge of the battery and the acquisition of the IS at different SOC and SOH. The tested batteries were Duracell NiMH 1.3 Ah, 1.2 V. The experimental setup was composed by a Keithley 2420 Source Meter for the discharging and charging processes of the batteries, a Gamry Instruments Series G 300 potentiostat to collect impedance data and an opto-isolated relay board (Devantech RLY816) to enable the connections between battery and Keithley for the discharge and charge processes of the cell and between battery and Gamry to acquire the IS. All the elements of the experimental setup are controlled through LabVIEW. The entire procedure for the acquisition of the experimental data is reported in the diagram flow chart in Fig. 1. The recharge of the battery is performed in constant current mode at 1C-rate (1.3 A). The program is able to sense the variation in slope of the voltage curve of the battery to declare completed the recharge process (typical of NiMH technology). The discharge is performed in constant current mode at 1C-rate until the voltage of the cell reaches a cut-off of 0.8 V. We utilize the discharge at the begin of the algorithm to determine the capacity of the battery. The acquisition of the IS occurs in galvanostatic mode, to better control the working point of the battery and to limit the errors during the acquisition of the data. The acquisition of the IS has been performed at 25 °C. The current signal amplitude has been set to 40 mA rms that corresponds to a variation on the output voltage of the cell of a value smaller than 10 mV (in this condition we can consider the system linear). The applied frequencies sweep from 5 kHz to 10 mHz. The IS are acquired at different SOC after a partial discharge of 360 s in

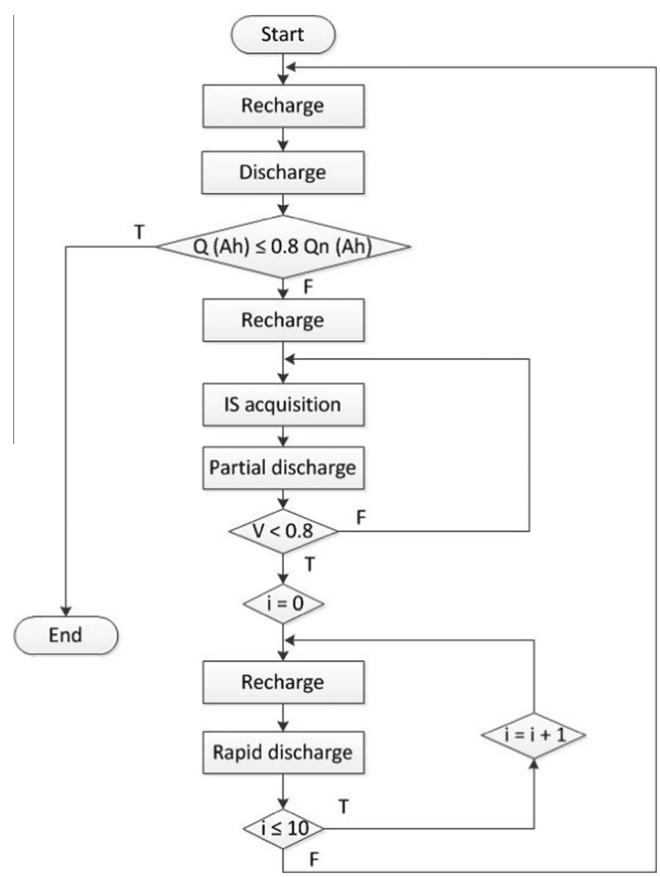

Fig. 1. Experimental procedure for the charging, discharging and acquisition of the IS of the battery.