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Development of a voltage-behavior model for NiMH batteries using an impedance-based modeling concept

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Abstract

To handle the complexity of modern automotive power nets, simulation-based design methods are important and suitable models of all system components including the battery as a main part are therefore mandatory. However, simulation models of energy storage devices are difficult to obtain. In particular, batteries are time-variant and strongly non-linear. An impedance-based modeling approach has been applied that copes with these characteristics and offers the development and parameterization of powerful models covering a wide dynamic range. As an example, this paper outlines the development of a NiMH battery model. Besides the impedance-based part of the model, the influences of the typical hysteresis effect of NiMH batteries is described in detail and an empirical modeling approach is introduced. The presented model is already successfully used by an automotive manufacturer which reflects the applicability of the modeling approach.

Keywords: NiMH battery; Hysteresis; Battery model; Simulation; Impedance spectroscopy

1. Introduction

As a successful example for impedance-based modeling and as an interesting application for hybrid electric vehicles, this paper introduces the development of a NiMH battery model. A non-linear impedance-based model core (see Section 2) is extended by a model part which considers the typical hysteresis phenomenon of NiMH batteries (Section 3). This part of the model is parameterized in the time domain and allows together with the impedance-based model core for a large validity range. The synergies when combining impedance-based modeling approaches and time-domain based model parts become observable.

The impedance-based modeling approach employs electrochemical impedance spectroscopy (EIS) [1]. The measurements were carried out with the EISmeter, an impedance spectroscope that operates in galvanostatic mode and has been developed especially for batteries and fuel cells at our institute [2]. Small-signal excitations (I_{ac}) and the evaluation of the system's response enable accurate investigations at nearly any working point (state of charge, temperature, dc-current). The models are built by joining universal electrical components such as inductors, capacitors and (non-linear) resistors. Physico-chemical processes can easily and effectively be modeled this way providing also a minimized computation effort. The method is applicable for all kinds of electrochemical energy storage devices [3] and [4].

A similar modeling approach is given in [5] for a NiMH battery, however, without considering non-linear resistances and without modeling the typical hysteresis phenomenon which significantly influences the NiMH equilibrium-potential. Unlike other battery technologies, the equilibrium potential of NiMH batteries is not unambiguously determined by the state of charge (SOC) due to this phenomenon [6] and [7]. Consequently, an empirical hysteresis model has been developed for the prediction of the equilibrium potential and is combined with the impedance-based model which determines the dynamic overvoltages during current flows.

The complete model implementation and a general overview on how to parameterize the models are given in this paper. The modeling approach is evaluated by comparing the measured and the simulated battery voltage corresponding to several current

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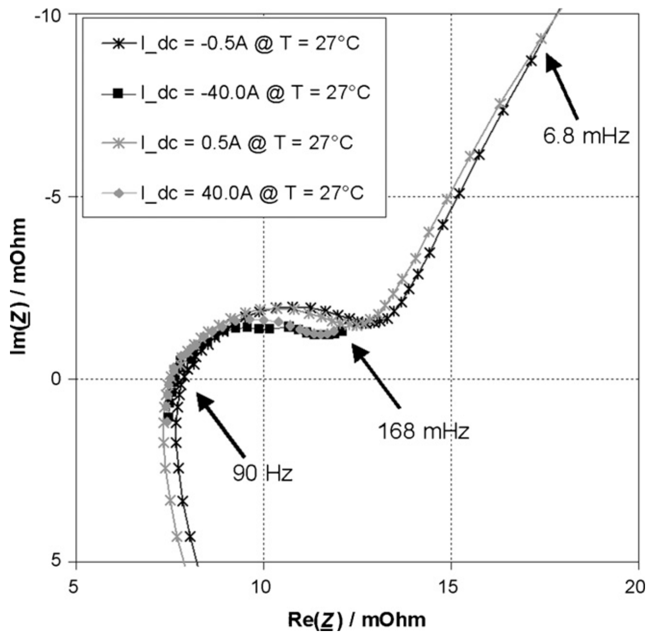

Fig. 1. Impedance spectra with different superimposed direct currents I_{dc} of a NiMH battery at 70% SOC and 27 °C (battery type: Sanyo Hr-DP, 6.5 Ah).

profiles with different dynamics and current rates. All investigations have been performed on cylindrical battery samples produced by Sanyo ("Hr-DP") and Panasonic ("HHR 650 D"), both rated with a nominal capacity C_N of 6.5 Ah.

2. The impedance-based core of the battery model

Impedance spectra (Fig. 1) were obtained by applying an ac signal (I_{ac}) with different defined frequencies and evaluating the system's responses. After the measurement of each frequency, the amplitude of the ac voltage signal was automatically evaluated during the measurement. For the next signal frequency to be investigated, the amplitude of the ac current signal was adapted to keep the voltage amplitude smaller than a definable value. Thus, the non-linearity of the battery is considered. Limited amplitudes of approximately 3 mV per cell are usable [1]. For accurate investigations at different working points, bias currents (I_{dc}) were applied and specific cell temperatures and SOCs were set for the measurement of each spectrum. The temperature and the SOC were kept fixed as accurately as possible during the measurement since the impedance is a function of both states. To assure comparable conditions at the beginning and at the end of the measurement of one impedance spectrum, the maximum change of the state of charge during this time was limited to $\Delta SOC < 5\%$.

The following characteristics can be identified by the evaluation of the NiMH impedance spectra (Fig. 1). The spectra show an inductive behavior (L) at high frequencies which is mainly caused by the metallic connectors of the battery. The pure ohmic resistance (R_i) can be detected by the minimum of the real part of the impedance spectra (at about 90 Hz). R_i reflects the limited conductance of the contacts, the active masses and the electrolyte. The semicircle is caused by charge-transfer processes

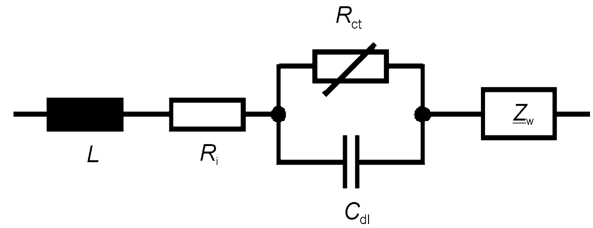

Fig. 2. Equivalent electrical circuit diagram of a NiMH battery representing the overpotential during charging and discharging without modeling of the equilibrium potential.

and charged double layers inside the battery. The changing diameter indicates the non-linearity of the charge-transfer processes. Different direct current rates I_{dc} have been superimposed to the small signal excitations I_{ac} to investigate this behavior. More detailed information on this measurement procedure can be found in Refs. [3] and [4].

The semicircle can be modeled by a parallel connection of a non-linear resistor R_{ct} and a capacitor C_{dl}. At lower measurement frequencies ($f < 168$ mHz), the diffusion behavior of the battery becomes apparent which is commonly modeled by a so-called Warburg impedance Z_w. Based on this data, an equivalent electrical circuit of a NiMH battery can be developed (Fig. 2) and, additionally, be parameterized.

Particular attention has to be paid to the non-linear behavior of the charge-transfer resistance R_{ct} of batteries. Generally, this behavior can be described by the so-called Butler–Volmer equation with I_0 as the exchange current, n as the number of transferred elementary charges, η as the overpotential, α as a symmetry coefficient, T as the absolute temperature and k as the Boltzmann constant ($8.617 \times 10E-5$ eV K^{-1}):

$$I = I_0 \left(\exp\left(\frac{n\alpha\eta}{kT}\right) - \exp\left(\frac{-n(1-\alpha)\eta}{kT}\right) \right) \quad (1)$$

A charge-transfer characteristic can also be observed for NiMH batteries. Fig. 3 exemplarily illustrates the current dependent values for R_{ct} (with $R_{ct} = (d\eta/dI)$) at 27 °C and 70% state of charge (SOC). Therefore, several impedance spectra (similar to

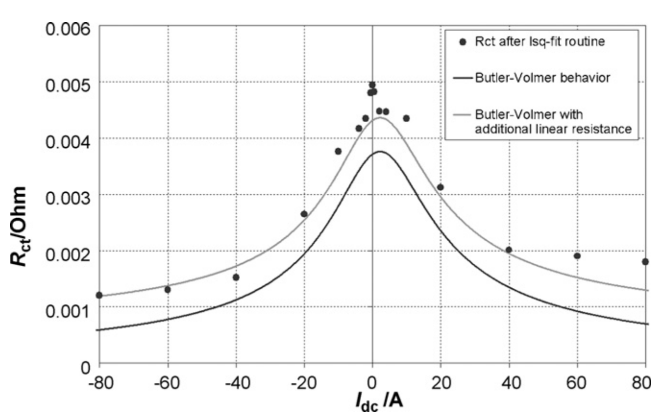

Fig. 3. Non-linear Butler–Volmer behavior (charge-transfer resistance) of a NiMH battery at 27 °C and 70% SOC (battery type: Sanyo Hr-DP, 6.5 Ah); black points: R_{ct} values determined by a least square fit routine, black curve: pure Butler–Volmer behavior ($n = 1$, $\alpha = 0.46$, $I_0 = 7$ A), grey curve: Butler–Volmer behavior with an additional linear resistance of 0.6 mΩ.