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Hybrid modeling of lead–acid batteries in frequency and time domain

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Abstract

This paper presents an improved impedance-based non-linear simulation model for lead–acid batteries. The parameterization of impedance-based models is difficult for operation profiles with high Ah throughput in short times. Such conditions result in non-steady-state conditions and do not allow precise measurements of impedance parameters. Therefore, the model has been extended by an electrolyte transport model which describes the generation and the transport of sulfuric acid inside the porous electrodes. This expands the model validity as higher Ah throughputs can be simulated now. A description of the Matlab/Simulink implementation and its parameterization in the time domain is given. Furthermore, the advantages and the limits of the improved model are discussed. The model allows for precise modeling of automotive batteries, both in conventional applications and in vehicles with electrically assisted propulsion. It is therefore an important tool for the design of automotive power nets.

Keywords: Impedance spectroscopy; Impedance spectra; EISmeter; Frequency domain; Time domain; Modeling; Simulation; Diffusion; Electrolyte transport; State-of-charge; Lead–acid; VRLA

1. Introduction

Dynamical simulation models for electrochemical power sources are an important prerequisite for the simulation of systems like cars with electrically assisted propulsion or conventional automotive electrical systems. Fast computing and small parameterization effort are favorable. However, batteries show several characteristics that make a simple modeling with high precision nearly impossible. Batteries are not stationary, they are highly non-linear, and their dynamical behavior depends on different parameters like temperature, state-of-charge (SOC) or short term history [6,8].

Electrochemical impedance spectroscopy (EIS) is an adequate tool for the development and the parameterization of battery simulation models considering these aspects. Small-signal excitations and the evaluation of the system's response enables accurate investigations at nearly any working point. Reasonably good simulation models can be achieved without having proper information about the chemical compound as well as the inner geometrical design of the device. The computing time for the simulation is very short compared with physically or chemically based models.

The purely impedance-based battery model for lead–acid batteries [2] consists of elements that are related to physico-chemical processes. These processes are modeled in terms of inductances, capacitors and resistors with linear or non-linear dependency on temperature, SOC and/or battery current. The elements have to be parameterized by a systematic evaluation of impedance spectra recorded at various operating conditions. This approach shows very good agreement in particular for highly dynamical operation of the battery. However, for longer discharge events the model output may deviate significantly from the measured battery voltage. This limitation is inherent to the impedance method, because the measurement frequencies during model parameterization must be chosen to high enough to assume a quasi-stationary state of the battery during each measurement [2]. Consequently, dynamic processes that govern long-term discharge behavior of the

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battery are not accessible for impedance methods. In particular, for lead–acid batteries acid concentration gradients as they develop during non-steady-state operation, are not covered by the purely impedance-based battery model.

This paper illustrates a hybrid modeling approach, which combines the impedance-based model and a basic electrolyte transport model. The former is developed and parameterized in the frequency domain, the latter in the time domain. The transport model describes the generation and the transport of sulfuric acid inside and between the porous electrodes. The hybrid model yields high precision in predicting the electrical battery performance even if strong variations of the acid concentration gradients occur. The parameterization and validation of the model has been carried out for a spiral-wound VRLA/AGM battery and typical operating conditions in a mild-hybrid vehicle. The same approach can be also employed for flooded lead–acid batteries.

2. The purely impedance-based simulation model

For a basic modeling approach, the Randles equivalent circuit can be employed ([8]; Fig. 1, left hand). The equivalent circuit is valid for both battery electrodes with differing parameters. It consists of an internal resistance R_i, an inductance L, a capacitance C and a non-linear resistance R. L is caused by the metallic connectors between the poles and the electrodes of the battery. The ohmic resistance R_i is due to the limited conductance of the contacts, the intercell connections, the grids, the active masses and the electrolyte. R_i depends on SOC, age and temperature of the battery. The parallel connection of the capacitance C and the non-linear resistance R represents the double layer capacity and the charge transfer resistance.

An equivalent circuit for a complete battery cell can be obtained by a series connection of two Randles circuits. A few modifications [2] have been carried out for the impedance-based lead–acid battery model, namely generalized capacitive elements (CPE: constant phase element [9]), a generalized dc-voltage source (considering the OCV potentials, $U_{0,\mathrm{cell}}$) and a parallel current path for gassing as the main side reaction.

For the parameter determination, several impedance spectra of the lead–acid battery have been measured at different working points considering not only the dependencies on the SOC and the battery temperature but also the current rate of the non-linear resistances. Therefore, different charge and discharge dc-currents have been superimposed during the impedance measurements. Fig. 2 shows several impedance spectra of a VRLA/AGM battery (measured at 70% SOC and room temperature) with varying bias dc-currents. The non-linearity of the battery, that is the non-linearity of the resistances R_1 and R_2 is obvious. More detailed information about the procedure of the impedance measurements, the evaluation of the impedance spectra and the modeling of the non-linearity can be found in [1,2].

For the model extension presented in this paper, the generalized dc-voltage source, which depends only on the SOC of the battery, has been replaced by a voltage source using the actual acid concentrations in both electrodes as the basis. The acid concentrations are calculated by means of an added electrolyte transport model.

3. Transport of sulfuric acid in VRLA batteries

An AGM/VRLA battery cell mainly consists of two porous electrodes with a highly porous separator in between. The electrolyte of the battery (sulfuric acid) is located inside the pores of these elements. The transport and the generation of the electrolyte can be characterized by means of the following differential equation [4]:

$$\varepsilon(t)\frac{\partial c(t)}{\partial t} = -c(t)\frac{\partial \varepsilon(t)}{\partial t} + \frac{\partial}{\partial x}\left(\varepsilon(t)^{\mathrm{ex}} D_{\mathrm{diff}}(c)\frac{\partial c(t)}{\partial x}\right) + G_{\mathrm{MR}} + G_{\mathrm{SR}} \tag{1}$$

where c corresponds to the acid concentration, ε to the porosity and D_{diff} is the diffusion coefficient of sulfuric acid [10]:

$$D_{\mathrm{diff}}(c)\,(\mathrm{cm}^2/\mathrm{s}) = (1.75 + 260c\,(\mathrm{mol/cm}^3)) \times 10^5 \times \exp\left(7.29 - \frac{2174\,\mathrm{K}}{T}\right) \tag{2}$$

G_{MR} and G_{SR} are sources of acid due to the main charge and discharge reaction and the side reaction (main reaction: “MR”, side reaction: “SR”). c, ε, D_{diff}, G_{MR} and G_{SR} are functions of the spatial dimension x. The differential equation can be separated into three terms which influence the local acid concentration $c(t)$:

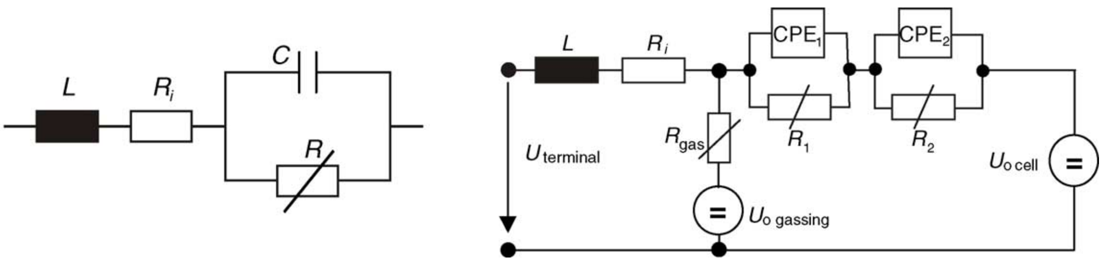

Fig. 1. Equivalent circuit of a battery half-cell (left hand); equivalent circuit for a complete lead–acid battery cell (right hand).