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Dynamics of current distribution within battery cells connected in parallel

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ABSTRACT

The current distribution of lithium-ion batteries connected in parallel is asymmetric. This influences the performance of battery modules and packs. The ratio of asymmetry depends on the differences between the battery cell parameters and the dynamics of the load profile. This detailed simulative study varies both of these factors and shows the influences on current and charge throughput. The cell parameters are based on real-world effects caused by production and operation. Differences in impedance generate higher current deltas and charge throughput differences compared to capacity differences due to manufacturing fluctuations.

The simulation model in this study uses mainly a linear open circuit voltage (OCV) so that the results are not influenced by nonlinearities. A subsequent analysis uses a defined nonlinearity in the OCV to show its impact on the current distribution. The results show that the temporary difference in current caused by the nonlinearity of the OCV exceeds the effect of the chosen parameter differences.

Finally, a comparison of the different cell dimensioning shows that high-energy (HE) cells display an inert behaviour with respect to current asymmetry. High-power (HP) cells are more dynamic. This means that impedance differences have a greater influence on HE and capacity differences on HP cells.

1. Introduction

Applications for battery cells and systems cover a wide field. Smartphones use only one battery cell. Power tools, mobile electronic systems and starter batteries have several cells in series and sometimes in parallel. Traction batteries for electric vehicles (EVs), as well as home or grid storage batteries, have an output voltage of several hundred volts, with series connections being needed to achieve these high voltages. The costs of semiconductors and the volume of electrical insolation limit the maximum voltage of these large battery systems. To increase the energy content, either the cells need to have a higher capacity or small cells must be connected in parallel.

Both approaches and hybrid forms can be found in commercial applications. The 2017 BMW i3 model uses no parallel connections at all. Its battery system consists of 96 cells connected in series, each with 96 Ah [1]. Nissan's Leaf features two parallel cells [2]. In the automotive field, Tesla uses the largest number of cells connected in parallel; its Model S uses up to 86 parallel cells. In the field of stationary storage, almost all manufacturers build systems with a large number of small cells connected in parallel.

Parallel connections are very flexible. Different requirements of different applications can be fulfilled with the same type of cell but a different number of parallel connections. However, as with cells connected on series, there are specific challenges in the operation of parallel cells. An asymmetric current distribution is a crucial phenomenon, though not much is known about this as yet. Current distribution depends on the individual performance of every cell and the characteristics of the electrical connections between these [3]. Uneven current loads result in diverging states of charge (SoC) during operation and inhomogeneous ageing. In this paper, we propose a state-space equivalent electric circuit model (EEC) that describes the current distribution in the parallel connection. It can scale the number of series and parallel cells as well as the number of resistor-capacitor (RC) circuits used to calculate the overvoltage. The model is validated by measurements with commercial 18650 cells.

The dynamic performance of a single cell is important to understand the behaviour of a parallel connection. In literature, the basic influences on the battery dynamics, listed from a low to high time constant, are ohmic resistances, skin effect, external inductance, solid electrolyte interface (SEI), electrical double layer capacitance (EDL), charge transfer (CT), mass transport, diffusion, open circuit voltage (OCV), self-discharge, and ageing of the battery cell, see Fig. 1 [4]. EEC models

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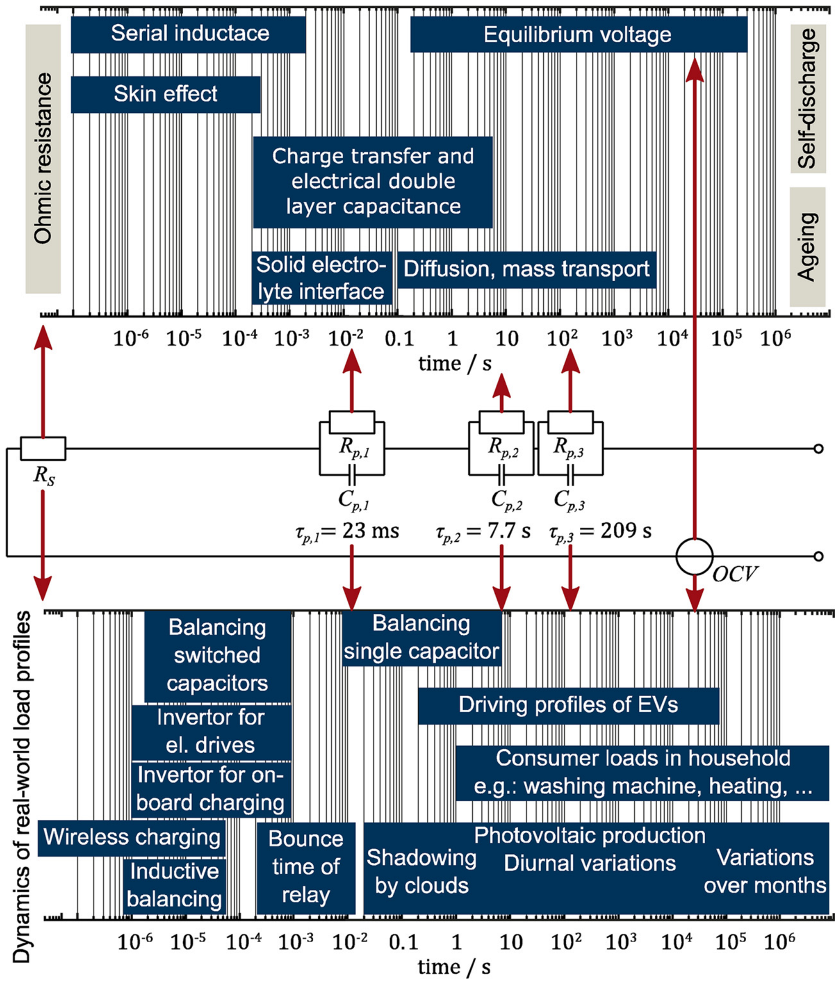

Fig. 1. Dynamic processes and time constants for a simulation model (according to Jossen [4]) and dynamics of real-world load profile [6–21].

are a simple method to simulate the effects of the battery cell voltage. Fig. 1 (middle) shows the EEC model which is used to validate the model in Chapter 2.2. The time constants $\tau_{p,k}$ are calculated from the resistance $R_{p,k}$ and the capacity $C_{p,k}$ as follows:

$$\tau_{p,k} = R_{p,k} \cdot C_{p,k} \tag{1}$$

Above the EEC, a timescale shows the physicochemical and electrical effects and their time constants. For example, the first RC circuit consisting of $R_{p,1}$ and $C_{p,1}$ has a time constant of $\tau_{p,1} = 23\,\text{ms}$. It represents the solid electrolyte interface, charge transfer and double layer capacitance described in [4] which all have time constants within this range. In the lower part of Fig. 1, the time constants of dynamic real-world load profiles are shown for comparison.

Voltage drops caused by the ohmic resistance occur immediately and are proportional to the current. They can be simulated with a resistor. Skin and inductive processes only have an influence in the first few micro- to milliseconds. They can be simulated with inductances and resistor–inductor circuits (RL). In many applications, these short-term effects are negligible. The same applies to long-term effects such as self-discharge and ageing. Often, an RC circuit or a ZARC element can be used to simulate the polarization voltage [4]. This works for SEI, EDL, CT, and mass transport effects [4,5].

Because of high dynamic effects with time constants $\tau < 10^{-4}\,\text{s}$ are not the focus of this paper, external inductances and the skin effect are ignored in this model. The variance of ohmic resistance leads to a high current asymmetry immediately after the begin of a load pulse [3]. With differences in the cell capacities, the current asymmetry at the beginning of the current pulse is small and increases over time [3]. In real-world applications, the dynamics of current variations are orders of magnitude apart, see Fig. 1. For example, the charge profile of a photovoltaic (PV) storage battery on a sunny day has time constants in the range of hours; shading of the PV panels by clouds leads to changes within seconds and switching a consumer load changes the load profile in milliseconds.

There has been extensive research into the effects of cell parameter variations on current distribution in connected cells. Table 1 summarises the substantiated papers on this topic. Numerous analyses of asymmetric current distribution have been performed [2,3,22–30]. Brand et al. showed that differences in the impedance of the cells lead to short-term effects and differences in cell capacity lead to long-term effects. The rule of thumb says that the current at the beginning of a current step can be calculated according to the current divider equation in an impedance difference scenario, whereas currents divide proportionate to the battery cell capacities (in a long-term behaviour) in a capacity difference scenario. [3]

Some studies have demonstrated the interaction of parameter changes through ageing and current distribution [22,23,25,26]. Osswald et al. performed electrochemical impedance spectroscopy (EIS) measurements [28] and analysed the inner cell current distribution. Only a few publications [3,23,25,26] focus on detailed analyses of the effects of 2p connections. Most studies use constant current (CC) to analyse the asymmetric current distribution. Only Bruen et al. use an EV load profile with a time step of $\Delta t = 1\,\text{s}$ [2,22]. To the knowledge of the authors, a methodical variation of cell parameters and the load profile dynamics has not been published yet.

No publication in Table 1 concentrates on the OCV. Yang et al.,