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Influence of circuit design on load distribution and performance of parallel-connected Lithium ion cells for photovoltaic home storage systems

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ABSTRACT

In parallel cell circuits within Lithium ion home storage systems, both the components as well as the topological structure of the circuit have an enormous influence on the current distribution among the individual cells and as consequence on the battery lifetime. For large battery assemblies welding techniques are often used for which a weldable current collector is needed. Due to the high specific resistance of the commonly used materials, this resistance measurably influences the current distribution.

In this paper the current distribution in battery modules with Li ion cells connected in parallel has been measured and modelled. The cell internal resistance, the current collector resistance and the topology of the circuitry have been varied in order to determine the influence of each of these parameters on the current distribution. Model calculations for the cycle lifetime of battery modules have been performed assuming realistic charge and discharge profiles matching the conditions to be found in commercially available home storage systems.

From the experimental data and the modeling results the most important parameters determining the homogeneity of the current distribution and the cycle lifetime of the battery modules have been extracted. Finally, design recommendations for Li ion batteries with cells connected in parallel are derived.

1. Introduction

Li ion battery systems are built according to a hierarchical design principle: the battery consists of one or more battery modules, which are in turn made up of a defined number >1 of individual cells. Battery modules composed of low-priced cylindrical cells with average capacities of 2–3 Ah (corresponding to 7–11 Wh) are very common in commercial home storage systems. Since this application requires total energy contents in the order of 1–10 kWh it is necessary to integrate ≈100–1000 cells in one or more battery modules. To fulfil safety requirements, it is very convenient to keep the battery voltage below 48 V, which makes it necessary to connect several cells in parallel, since the maximum voltage of a single Li ion cell is typically 3.6–4.2 V. In contrast to a series connection of cells where the current running through the cells is by design and inevitably exactly the same for each individual cell, in parallel circuits typically asymmetric current distributions occur. This is due to the fact, that parallel cells are exposed to exactly the same current only if the resistance in each branch of the parallel circuitry is exactly the same, which is never the case in realistic systems. As a consequence, the cells are subject to unequal charge throughputs and unequal temperature increases. This leads later on to different ageing levels of the cells and influence the performance and lifetime of the battery system. Kamalisiahrodui et al. [1] and Bruen and Marco [2] studied in general the current distribution in parallel-connected cells in configurations with 2 or 4 cells in parallel. Reasons for asymmetric current distributions in this case are e.g. sample variations of cell parameters like the electrical internal cell resistance R_{cell} and the

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nominal capacity C_n, which was already reported by Gogoana et al. [3]. They have shown that R_{cell} can spread up to 24.7% and C_n up to 3.6% within a batch of 72 cells. The influence of deviation in the initial cell parameters on the current distribution are for example presented in the work of M.J. Brand et al. [4]. Fleckstein et al. reported [5], that unequal temperatures within a battery module due to active cooling cause also an individual ageing behavior. Herein the unequal temperature influences for example R_{cell} of each cell, which leads to an asymmetric current distribution.

Asymmetric current distributions lead to unequal State of Charge (SOC) and also variations in the open circuit voltage U_{OCV} of the cells within the battery. In case of sudden current drop (e.g. by end of charging or discharging the battery), these U_{OCV} variations lead to exchange currents. These currents occur as long as the individual cell voltages cells are not perfectly balanced and strain the cells further. M. Dubarry et al. [6] analyzed in their work this cell balancing behavior in parallel Li ion cells and have experimentally shown for 2 connected cells an exchange current of corresponding approx. 1 C at a voltage difference of 0.5 V.

For the electrical integration of cells into a battery module, besides the Li ion cells a current collector is needed to which the individual cells are connected. Both the interconnects (weld, contact batches . . . etc) as well as the current collector represent electrical resistances affecting the current distribution within parallel-connected cells and as a consequence the ageing behavior of the system. Whereas the cells internal resistance and potentially also the interconnect resistance are subject to complex degradation mechanisms, the electrical resistance of the current collector can be assumed to be constant over time in a first-order approximation. However, its absolute value for each cell strongly depends on the circuit design and the collector material and geometry and can therefore be designed by the developer.

In this paper, we report about experimental and modeling results from an electrical-thermal model, showing how the uniformity of the current distribution among parallel-connected Li ion cells is determined by the circuit design itself. This study is based on materials and circuit designs, which can be found in commercial home storage systems. The impacts on ageing and performance during the operation with highly fluctuating renewable energy sources such as photovoltaic modules will be discussed.

2. Modeling

2.1. Battery cell model

For an accurate modeling of a Li ion battery system, it is mandatory to consider the electrical and thermal behavior of the cell and the system. Therefore we would like to present an equivalent circuit model (ECM) coupled to a thermal model.

2.1.1. Electrical sub model

Electrical battery models should be able to describe the electrical cell behavior and that of the battery system. In the specific case of parallel-connected cells additional interactions between cells resulting from different SOC due to non-uniform current distributions must be taken into account, which influence the cell characteristic like U_{OCV} and R_{cell}.

A summary of available ECM for single cell modeling is given by He et al. [7]. For our single cell model, we chose the Thevenin Model, including U_{OCV}, R_{cell} and one RC-circuit (with R_p and C_p), which represents over-voltages U_{RC} in form of diffusion, charge transfer and double layer effects (see Fig. 1 and Eq. (1)).

$$\dot{U}_{RC} = -\frac{1}{R_P(t)C_P(t)}U_{RC}(t) + \frac{I_{cell}(t)}{C_p(t)} \tag{1}$$

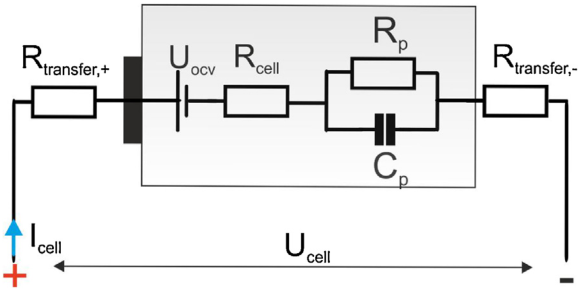

Fig. 1. Battery cell equivalent circuit model.

R_{cell} represents ohmic resistance effects caused by the electrodes, separator and the electrolyte. It depends on the cell chemistry, the SOC, the single cell temperature T_{cell} and also on the cell degradation caused by ageing. U_{OCV} depends in our model only on the cell chemistry and the SOC.

The relationship between SOC, U_{OCV} and the partial voltage dU_{OCV}/dQ has nonlinear characteristics, which can be implemented and simulated with a Look Up table (see also Fig. 2(a–b)). The resistance of the cell connection to the current collector $R_{transfer}$ is considered in the ECM as an ohmic resistance. $R_{transfer}$ for the positive and negative pole is measured with an HIOKI 3554 battery tester (1 kHz AC measurement current of 150 mA) and depends on the chosen connection technique as well as on the material of the cell body.

Among the many different cell chemistries to be found in commercially available cylindrical cells, two were chosen for this study, namely Lithium iron phosphate (LFP) and Lithium cobalt oxide (LCO). We chose those two cell chemistries basically because of their different U_{OCV} characteristics and their expected different influence on the current distribution. A very flat U_{OCV} curve over a large SOC area is typical for LFP whereas for LCO a more continuous slope of the U_{OCV} curve can be observed. The LFP cell has a name plate capacity of 3 Ah in a 26,650 case whereas the LCO cell Exhibits 2.45 Ah in an 18,650 case.

For these 2 cell chemistries R_{cell} and U_{OCV} were measured for 4 cells. R_{cell} was measured for several SOC by using a 0.5 C charge and discharge pulse for 20 s at temperatures of 25 °C and 40 °C (see Fig. 2).

R_p and C_p were determined by using the MATLAB© Optimization Toolbox as reported by Huria et al. [8]. Herein the nonlinear Levenberg-Marquardt algorithm is used, which fits the parameters R_P and C_P to minimize the least-squares error between the measured voltage $\hat{u}_{cell}$ and simulated voltage U_{cell} for each time step t during the 0.5 C charge and discharge pulses.

$$\underset{\theta}{\arg\min} \sum_{t=1}^{N} \left(U_{cell}(t,\theta) - \hat{U}_{cell}(t)\right)^2 \qquad \theta = [R_p, C_p] \tag{2}$$

$$U_{cell}(t) = U_{OCV}(t) - (R_{cell}(t) + R_{transfer,+} + R_{transfer,-})I_{cell}(t) - U_{RC}(t) \tag{3}$$

2.1.2. Thermal sub model

The current running through a cell produces heat, which depends on the current of the single cell I_{cell} and the ohmic resistances R_{cell} and $R_{transfer}$ given by the Joule heating law. The contact resistances $R_{transfer}$ must be taken into account, because in cylindrical cells the contact is thermally well coupled to the cell and therefore directly contributes to cell heating. In our first-order model we focus on the temperature development of a single cell subject to heat exchange (convection, radiation) with a homogenous environment. More precise higher-order models would have