Modeling Reversible Self-Discharge in Series-Connected Li-ion Battery Cells

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***Abstract*—Large battery systems like those in plug-in hybrid or pure electric vehicles contain strings of series-connected cells. Cell voltage imbalances within strings decrease useful string capacity and increase cell ageing. Balancing systems are often employed to alleviate imbalances but optimal design and sizing requires prediction of expected imbalance. This paper presents a methodology for simulating voltage imbalances caused by temperature-dependent reversible self-discharge processes in cells. Simulation results for a three-cell string with a 4°C operating cell temperature difference over 30 days show a maximum cell voltage divergence of less than 1mV. The same simulation with a malfunction-typical operating temperature difference of 20°C leads to a maximum voltage divergence of over 5mV. The results and underlying methodology are of value for battery pack manufacturers and designers of balancing systems.**

***Keywords*—Lithium-ion (Li-ion) Battery; Battery Management System (BMS); Cell Imbalance; Self-Discharge; Balancing Systems**

I. INTRODUCTION

Electric vehicle battery systems contain from several tens to thousands of lithium-ion battery (Li-ion) cells. While this chemistry offers a relatively high energy density, it is also highly sensitive to both overcharging and overdischarging. As a result, the cell voltages require continuous monitoring and the battery must be disconnected when boundaries of the safe operating region are exceeded. Individual Li-ion cells are chemically limited to output voltages of around 4V. To achieve the much higher voltage levels (300-400V) required to efficiently transmit the electricity to the electric motor, cells are connected in series to form cell strings. Since cells in each string share all charge and discharge currents, in an ideal situation where cells have the same initial state-of-charge (SOC), capacity and voltage-SOC characteristic, they inherently have the same output voltage at all times.

In practice, however, both manufacturing tolerances and operational factors such as temperature gradients lead to cell voltage variations within strings [1]. To keep this imbalance in series-connected cells from causing significant reductions in storage capacity and increased ageing, balancing systems are employed to draw energy from highly charged cells and/or supply energy to lower charged cells [2]. Knowledge of how rapidly cell voltages diverge is crucial for designing and sizing balancing systems appropriately.

To the best of our knowledge, this paper represents the first time that temperature-dependent self-discharge currents are taken into account on an individual cell basis for simulating series-connected strings of cells. We model a cell string as a low-frequency electric circuit model using MATLAB Simulink®.

II. THEORY AND METHODOLOGY

A. Battery Modeling and Self-Discharge

A standard way to model batteries is the Randles circuit. For low-frequency input, this consists of a resistor connected in series with a parallel RC circuit, which represent the polarization resistance and limits in the electrochemical transport, respectively. By adding in series a voltage source to represent the relationship of open-circuit voltage (OCV) and SOC, a single cell model is developed that can simulate both charge and discharge processes [3].

Cells have been shown to lose a certain amount of charge during storage through so-called leakage currents of two different kinds [4]. The first type of leakage current occurs due to reversible lithium-consuming reactions in the electrolyte, which reduces the stored charge but not the capacity of the cell. The second type of leakage current occurs due to irreversible lithium-consuming reactions in the electrodes, which reduces not only the stored charge but also the capacity of the cell. These two types of self-discharge will hereafter be referred to as reversible and irreversible self-discharge, or RSD and ISD, respectively. It should be noted that our model does not consider ISD. In most electric circuit equivalent based battery models, RSD is not considered. An exception to this is [5], where RSD is incorporated as a lump resistance in parallel to the capacitor representing the OCV.

B. Integrating Temperature Dependency

Our approach is to go a step further and represent RSD as a current source that is controlled as a function of the cell voltage and temperature. Very limited empirical data is available in literature regarding long-term self-discharge testing of Li-ion cells over a range of cell temperature and cell voltages or SOCs. Reference [4] provides data for two different temperatures (293.18K and 296.08K) at various cell voltages. Based on steady-state data at 4.1V for both temperatures and assuming $RSD=0$ for $T=0K$, we approximate self-discharge at 4.1V to grow exponentially with cell

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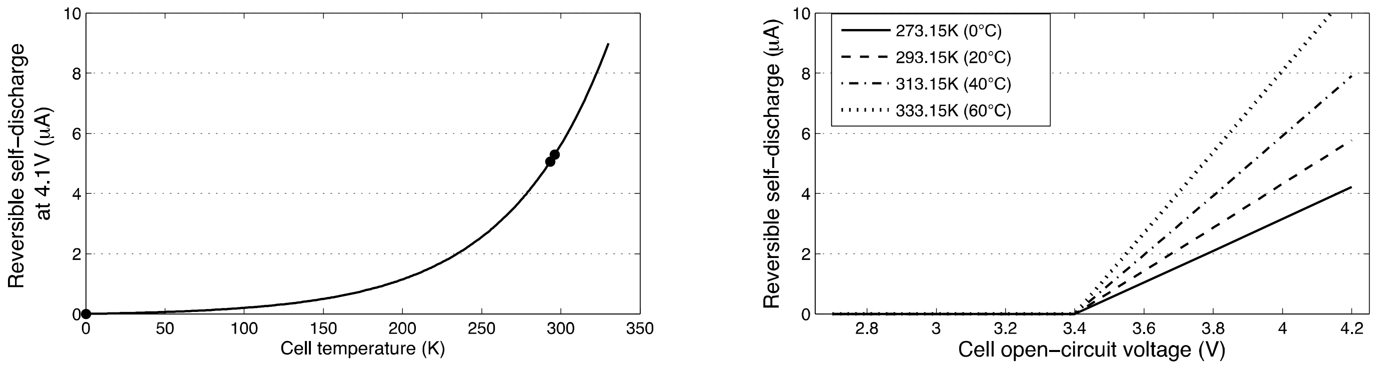

Fig. 1. Reversible self-discharge current rate based on data in [4]. Left: reversible self-discharge at 4.1V cell voltage as an exponential function of temperature. Right: reversible self-discharge as a piecewise linear function of cell voltage at various temperatures.

temperature. The voltage-dependency is then incorporated as a linear approximation of the steady-state data in [4] (see Fig. 1). This leads to our cell RSD function RSD_C in amperes:

$$RSD_C = max\left\{0,\ \left[(V_{OC} - 3.4V)\cdot 7.686 \cdot e^{0.01553\cdot T_C} - 5.38\right]\cdot 10^{-8}\right\} \quad (1)$$

where V_{OC} is the cell OCV and T_C is the cell temperature. We believe this to be the best possible assumption given the limited data available at present; with further data becoming available we will adjust and improve this model accordingly.

For our preliminary simulations presented here, we have assumed a very simple temperature profile:

$$T_C = \begin{cases} 293.15K, & if\, I < \frac{C}{10} \\ 303.15K + \Delta T_C & if\, I \geq \frac{C}{10} \end{cases} \quad (2)$$

where T_C is the cell temperature, I the absolute current through a three-cell string (i.e. both charging and discharging), and ΔT_C is the operating cell temperature offset for cell *c*. The operating cell temperature offset, which is the difference between the temperature of an individual cell and the average cell temperature during standard operation, represents our main simulation variable.

Our resulting Simulink® single cell model can be seen in Fig. 5. ISD has already been implemented in the model for future use, but for the simulation described here it has been configured to have negligible impact. Fig. 6 shows our system model, which includes the three series-connected cells as well as a current source to control charging and discharging.

C. Simulation Parameters

For each simulation a period of 30 days was chosen, as this represents a sufficiently long period over which voltage divergence can occur but a sufficiently short period so that ageing and ISD can reasonably be neglected. Throughout this timespan, the three-cell string undergoes one complete charge-discharge cycle per day, where discharging occurs at a rate of 1C and charging occurs at C/4. The charging and discharging processes both follow constant-current regimes, whereby the process is terminated when either an upper (4.2V) or lower (2.7V) boundary is crossed by the average cell voltage in the string. During times when the current is switched off, the control system reconnects the string once every two hours, only to disconnect after a timespan of 1s assuming the voltage boundary is crossed again. This control method was chosen to allow future implementation of varying charge and discharge currents, where reconnection occurs if the voltage drop over the polarization resistance drops sufficiently.

Cells were simulated to have capacities of 1.25Ah as information on temperature- and voltage-dependent self-discharge rates for this size was available, unlike for larger-capacity cells. The implemented SOC-OCV curve, which for Li-ion cells is typically capacity-independent, was gained from testing commercially available 0.9Ah cells using the pause estimation method suggested in [7] as shown in Fig. 2.

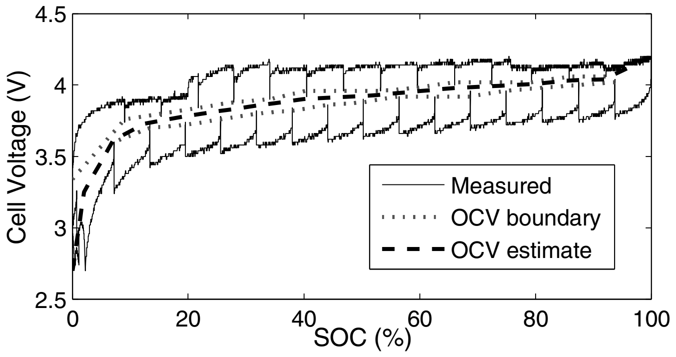

Fig. 2. Estimation of open-circuit voltage profile using 60s pause method

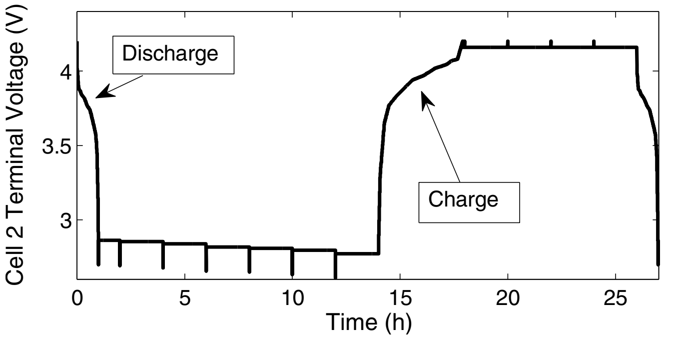

Fig. 3. Terminal voltage of cell 2 over initial 27h of simulation

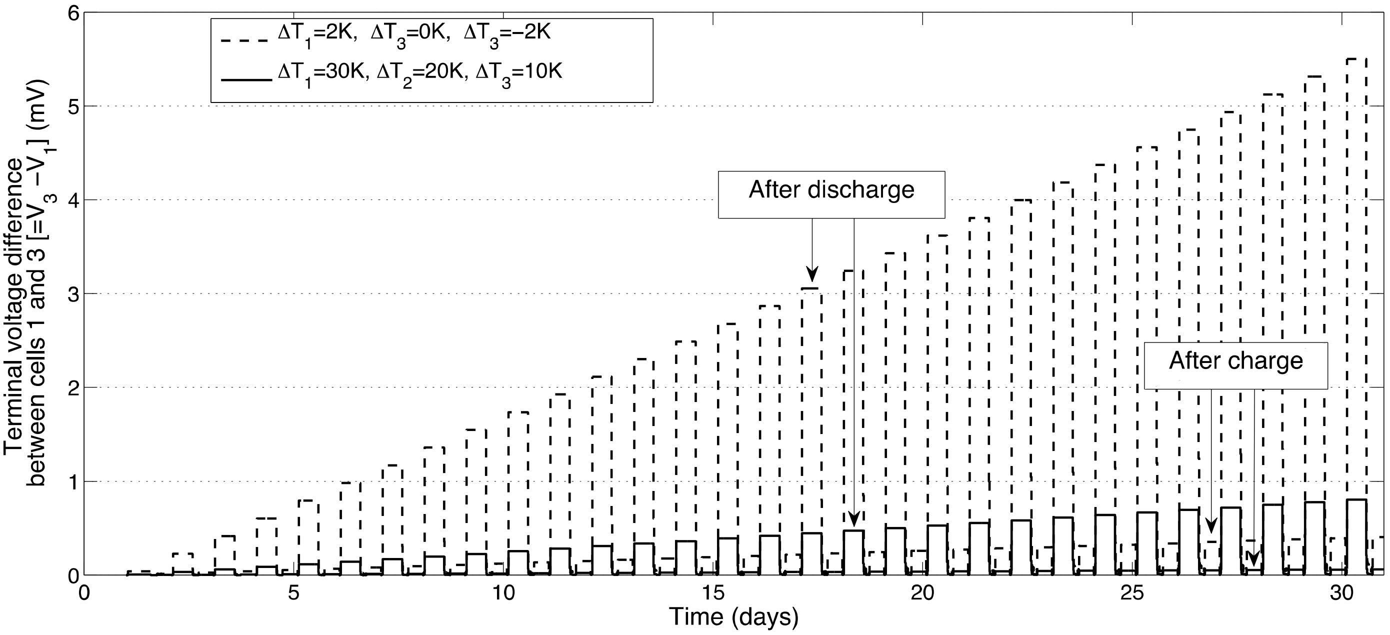

Fig. 4. Evolution of difference in terminal voltage between cells 1 (warmest) and 3 (coldest) for different operating temperature offsets

Using these general parameters, we then ran three simulations to illustrate the impact of different operating temperatures on cell imbalance. In the first simulation we set $\Delta T_1=2°C$, $\Delta T_2=0°C$ and $\Delta T_3=-2°C$. According to [6] this temperature gradient is a reasonable assumption for practical application where cells near the edges of the battery system have better cooling than cells inside. We also conducted a second simulation to evaluate the impact of more significant temperature gradients, which could be the result of either cooling system malfunction or inconsistent cell degradation leading to particularly high heat generation in some of the cells. For this simulation we set $\Delta T_1=30°C$, $\Delta T_2=20°C$, $\Delta T_3=10°C$.

III. SIMULATION RESULTS

Fig. 3 illustrates the voltage curve of cell 2 during standard operation for just over one day. Within the first hour, the battery discharges until the string reaches an average terminal voltage of 2.7V. At this point the discharging process terminates and the voltage rises notably due to the reduction in voltage drop across the polarization resistance. Around 12 hours after the beginning of the discharge process, the charge process starts and continues for approximately 4h until the maximum voltage boundary is reached. At times when the string is neither charging nor discharging, two-hourly temporary reconnections occur for reasons discussed previously.

The resulting terminal voltage divergence between the warmest cell (cell 1) and the coldest cell (cell 3) for the three simulations is shown in Fig. 4. After 30 days with a reasonably standard ±2°C temperature variation among cells during operation, and no variation during pauses, the coldest cell has a terminal voltage that is around 0.9mV higher than the warmest cell. The larger temperature gradient, as could be caused by various malfunctions, increases maximum final voltage differences to around 5.5mV. The underlying SOC differences between the warmest and coldest cells developed over the 30-day simulations are 0.003% and 0.020%, respectively. In all cases the voltage differences are much larger after discharging than charging. This is due to the OCV-SOC curve, which is steeper at very low SOC values than at very high SOC values. The higher the gradient, the more significant the difference in cell voltage caused by a given difference in SOC.

IV. DISCUSSION

To put these results into context, consider the effects of overdischarging described in [8]. 15 days storage at an OCV of 2.0V led to a 2% decrease in cell capacity and a 10% increase in cell thickness. Assuming a rated voltage of 2.7V, cell voltages of 2.0V can be reached with a voltage divergence of 1.4V if the discharging of a two-cell string is stopped when the average voltage crosses the minimum boundary.

Our simulation results suggest that steady-state RSD has a very low impact on cell imbalance. Under the condition of malfunction-typical temperature differences, a post-discharge voltage difference of 0.7V would be reached after approximately 10 years of operation. Given that the design life of battery systems of 8-10 years and the low likelihood of continuous malfunction-typical temperatures, these results suggest that temperature dependent RSD alone does not appear to warrant a need for balancing systems. However, in our preliminary simulations we have not yet taken into account a number of important factors, including:

- cell imbalances at the beginning of life, which can be of significant magnitude [1];
- reversible self-discharge rates during and after operation, which are higher than at steady-state [4]; and
- the impact of ageing and resulting capacity degradation on cell imbalance.

While these factors will need to be considered in future work to broaden the applicability of the model, our work has introduced a preliminary methodology for simulating the impact of temperature-dependent steady-state reversible self-discharge on cell imbalance.

V. CONCLUSIONS

Voltage imbalance in series-connected battery cells represents a significant problem for high-voltage battery systems such as those used in modern plug-in hybrid and pure electric vehicles. Temperature-dependent reversible self-discharge in individual cells is a major cause of cell imbalance. To the best of our knowledge, this paper presents the first attempt to simulate strings of individually modeled cells that take into account temperature-dependent reversible self-discharge. Successful simulation of three-cell strings with standard operating temperature differences of 4°C and malfunction-typical operating temperature differences of 10°C has been demonstrated. Future work will focus on improving the cell model and extending it to take into account further variations in both the cells and their operating environments. This model can then be implemented to compare and optimize balancing system designs and component sizes for given practical applications. There is also a significant need for accurate experimental testing in this field that supplies data to enable more advanced tuning and validation of models.

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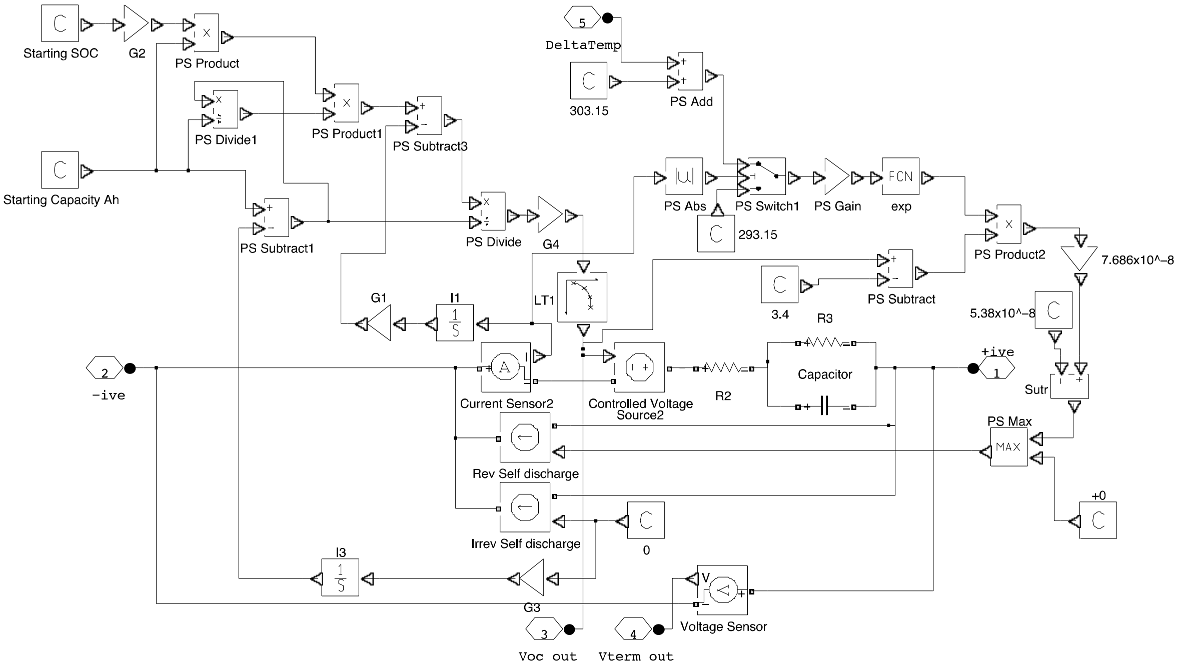

Fig. 5. Simulink® cell model containing voltage source, series resistor, RC block and both reversible and irreversible self-discharge sources

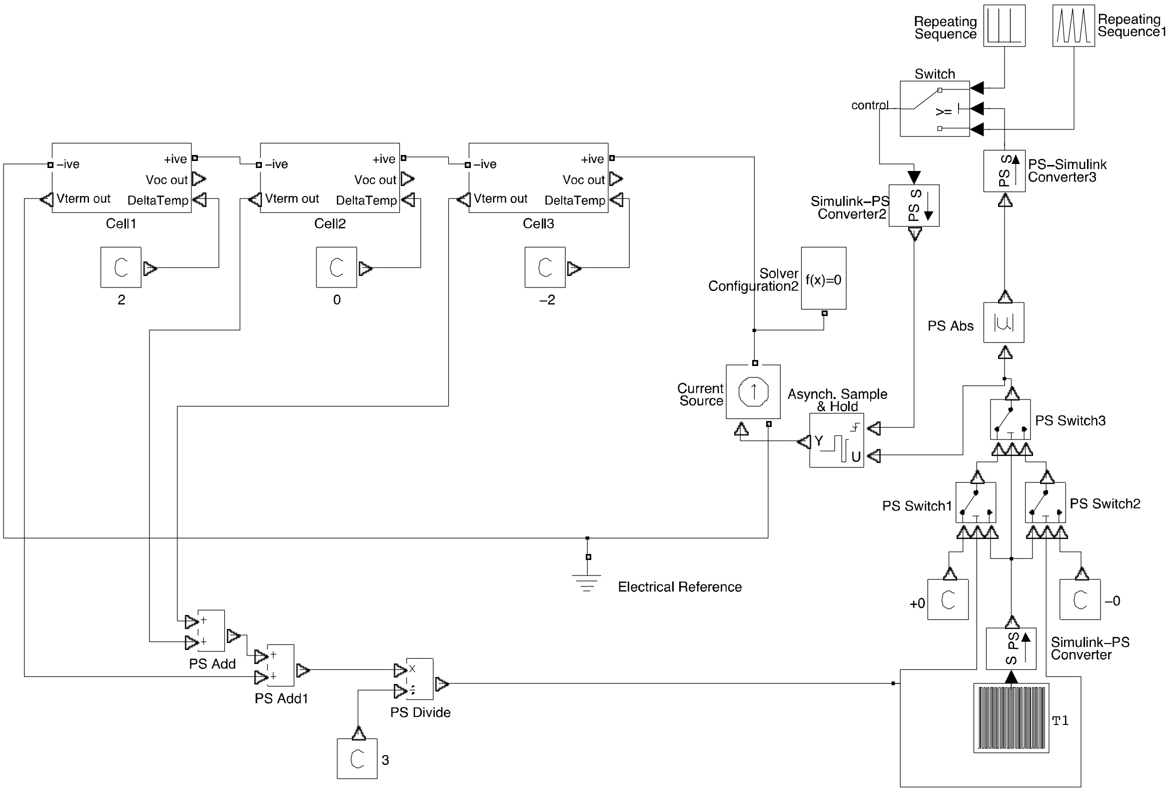

Fig. 6. Simulink® system model containing 3 cell models as well as a current source for charging and discharging