

Internal Cell Temperature Measurement and Thermal Modeling of Lithium Ion Cells for Automotive Applications by Means of Electrochemical Impedance Spectroscopy

Peter Haussmann and Joachim Melbert
 Ruhr-University Bochum

ABSTRACT

Battery safety is the most critical requirement for the energy storage systems in hybrid and electric vehicles. The allowable battery temperature is limited with respect to the battery chemistry in order to avoid the risk of thermal runaway. Battery temperature monitoring is already implemented in electric vehicles, however only cell surface temperature can be measured at reasonable cost using conventional sensors. The internal cell temperature may exceed the surface temperature significantly at high current due to the finite internal electrical and thermal cell resistance. In this work, a novel approach for internal cell temperature measurement is proposed applying on board impedance spectroscopy. The method considers the temperature coefficient of the complex internal cell impedance. It can be observed by current and voltage measurements as usually performed by standard battery management systems. The relevant frequency range considered for temperature measurements is chosen for high sensitivity and robust behavior and takes state of charge variations as well as aging effects into account. Transient temperature variations caused by various load profiles are analyzed in order to characterize the static and dynamic thermal properties of the cell. The resulting thermal equivalent model describes temperature changes inside the cell dependent on load current and ambient temperature. The temperature measurement approach and the thermal model are suitable for on board implementation in battery management systems. A dedicated battery excitation is not required, as signal components in the relevant frequency range are inherently present in typical driving current profiles. Thereby, significant improvements in terms of on-board diagnostics and battery safety can be achieved without any additional hardware effort.

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INTRODUCTION

Electrified automotive powertrains are the most promising approach to address the mid-term decrease in the availability of fossil fuels. In this context, the energy storage is of particular significance, as the characteristics of the battery determine the driving range. Lithium-Ion (Li-Ion) is currently the dominant battery technology for electric and hybrid vehicles. Ongoing research tries to increase the achievable energy density by improving the electrode material or by increasing the allowed open circuit voltage range. Both developments might lead to higher failure probability.

If an internal battery fault occurs, a significant risk of thermal runaway must be considered. Reported thermal runaways of the battery pack caused damage to the entire vehicle and posed a threat to the passenger's health. To ensure safe battery operation, reliable temperature monitoring is mandatory.

Battery surface temperature measurement is already available with reasonable implementation effort and cost. However, the internal cell temperature may exceed the surface temperature significantly,

depending on the load current. Incorporating temperature sensors into the cell itself, also the inner temperature can be monitored [1, 2]. However, implementing a temperature sensor into existing Li-Ion cell constructions is not feasible due to higher cost and safety aspects.

Electrochemical impedance spectroscopy (EIS) is a measurement technique to obtain the internal impedance of a Li-Ion cell, which strongly depends on the internal cell temperature. Internal cell temperature estimation methods by means of EIS are already published [3], typically depending on laboratory boundary conditions. As current and voltage are monitored by battery management systems (BMS) aboard electric vehicles, the on board implementation of EIS measurements is also possible [4].

The internal cell temperature can also be estimated by using thermal models of the cell [2, 3, 5]. As the thermal properties depend on the cell material composition and geometry, most models are only valid for a specific cell technology and geometry [3]. Thermal models for complete battery sets consisting of multi cell modules together with cooling assembly are based on complex finite element analysis [6].

In this paper, a novel EIS based approach to determine the internal temperature of lithium-ion cells is proposed. The method takes advantage of the significant temperature dependency of the internal cell impedance in a frequency range which is mostly unaffected by other parameters. Aging effects are considered to compensate measurement errors resulting from cells impedance variations versus life time.

A scalable thermal equivalent circuit model for Li-Ion cells is presented, which describes the dynamic thermal properties of a Li-Ion cell. Both self-heating due to the load current and ambient temperature variation are considered. The proposed EIS-based temperature measurement technique is used to obtain and verify the model parameters for an automotive Li-Ion cell applied in a plug-in hybrid (PHEV) vehicle.

Finally, the two different approaches to monitor the internal cell temperature in real automotive applications are discussed.

Measurements based on realistic automotive driving cycles are performed to demonstrate feasible implementation schemes for on board measurement and model based estimation of the internal cell temperature.

MEASUREMENT SYSTEM AND DEVICE UNDER TEST

In this work, specialized laboratory single cell test equipment developed by our research group is used [7, 8]. Equipped with a 600 A linear discharge current sink and a precision measurement and control unit, the tester can generate arbitrary load current profiles with 50 kHz bandwidth. The unit is supplemented by a switched power supply to provide charge currents up to 200 A. Simultaneous measurement of current, voltage and the external cell temperature is available at up to 20 kHz with an accuracy better than 0.1 %. The combination of high currents, wide bandwidth and high measurement resolution allows precise characterization measurements combined with realistic automotive heavy duty load cycling experiments.

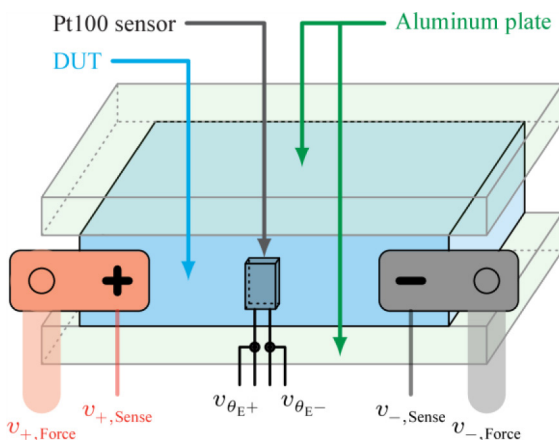


Figure 1. Assembly sketch of the DUT 4

The device under test (DUT) is an automotive Li-Ion cell for PHEV applications. It is located in a climate-chamber at a controlled ambient temperature. The cell is mounted between two 8 mm aluminum fixture plates, as depicted in Figure 1.

A Pt100 temperature sensor is pressed onto the DUT's surface between the power terminals to measure the surface cell temperature. A thermal insulation shields the sensor from ambient temperature effects. Kelvin 4-wire connections ensure accurate measurements of both the cell terminal voltage and the Pt100 signal.

INTERNAL CELL TEMPERATURE MEASUREMENT

Electrochemical Impedance Spectroscopy

EIS is an established in-situ measurement technique for the characterization of lithium ion cells. It grants insight into the electrochemical processes in the cell by analyzing the cell impedance

$\underline{Z}(f)$. Typical applications of EIS include the localization of aging effects in the cell during cycle life studies as well as the evaluation of the electrochemical properties of new material compounds.

Figure 2 shows a typical impedance spectrum of an automotive Li-Ion cell with 26 Ah capacity. The real and imaginary part of the impedance are depicted on the horizontal respectively vertical axis. The imaginary axis is usually inverted for a more convenient presentation of capacitive system behavior, which is dominant for Li-Ion cells [7].

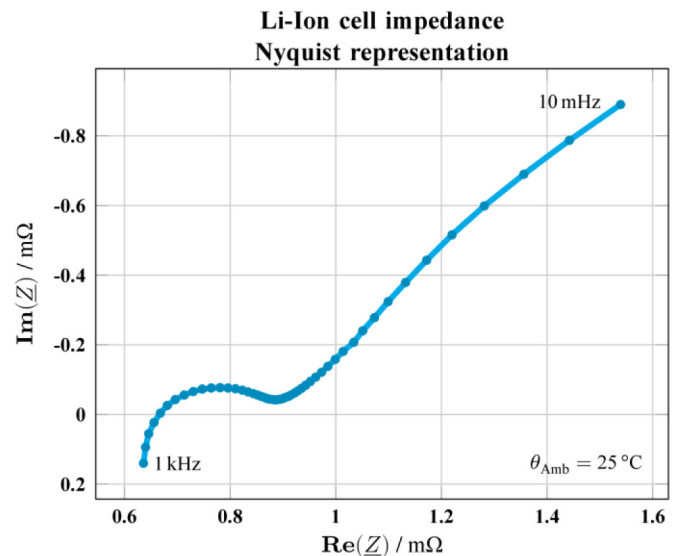


Figure 2. Nyquist representation of the impedance spectrum of a typical Li-Ion cell from 10 mHz to 1 kHz at 25°C

The impedance is calculated in the frequency domain according to Eq. (1).

$$\underline{Z}(f) = \frac{\underline{V}(f)}{\underline{I}(f)} \quad (1)$$

The cell voltage $\underline{V}(f)$ and current $\underline{I}(f)$ can be measured using suitable excitation signals, which must contain the frequency components of interest. Most laboratory equipment provides sinusoidal excitation signals, which subsequently stimulates the cell

at different frequencies. This procedure is widely known as stepped-sine EIS. Other laboratory excitation and evaluation concepts applicable to Li-Ion cells are discussed in [7, 9].

Our research group has developed a concept for the implementation of EIS measurements in automotive BMS systems. The method is based on real automotive driving data and does not require dedicated excitation signals. Figure 3 shows the impedance spectrum derived from realistic automotive driving data in comparison to a reference spectrum recorded using the laboratory stepped-sine EIS method [4].

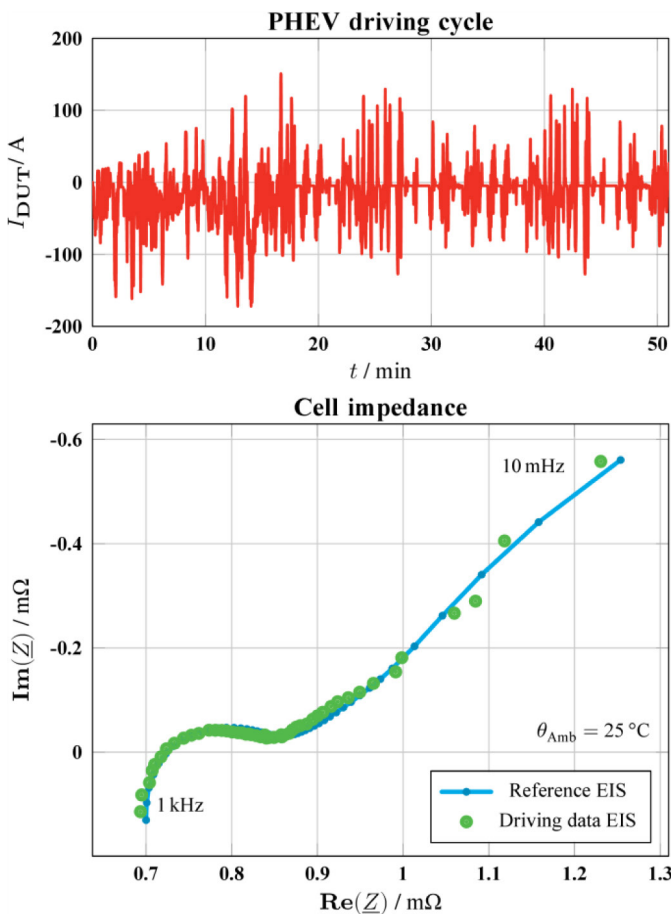


Figure 3. On-Board EIS implementation scheme based on real driving data vs. reference EIS

Assumptions for EIS based Measurements

Unlike solid metal conductors, the impedance of Li-Ion cells is not exclusively dependent on temperature.

The cell impedance is measured between the cell's power terminals and provides a cumulative information about the distributed current paths inside the cell. Consequently, the derived internal cell temperature is interpreted as the average temperature inside the cell.

To reduce the EIS measurement duration with respect to the intended application of EIS for real-time temperature measurements in vehicles, the SoC and temperature dependence of the impedance is

characterized at frequencies between 10 Hz and 1 kHz. Sinusoidal excitation is chosen for the laboratory analysis to achieve the best available signal-to-noise ratio [7].

Internal Impedance Influence Parameters

Depending on the specific material composition of the DUT, the internal cell impedance is influenced by various operation parameters, such as the internal cell temperature and the state of charge (SoC). Additionally, current load alters the state of entropy of the cell, which results in reversible temperature and impedance variation inside the cell [10, 11].

In this work, the influences of temperature and SoC are investigated in detail, as they are considered the most significant [3]. First, the qualitative impact of both parameters is investigated separately, followed by a quantitative comparison to define a suitable temperature measurement frequency f_m .

TEMPERATURE INFLUENCES

The cell material characteristics determine the temperature dependence of the internal cell impedance. Thus, the temperature impact on the impedance must be characterized for every cell technology individually.

In the following, the temperature dependence of the DUT's impedance is observed across a temperature range from 0 °C to 40 °C in steps of 5 °C at 20 discrete frequencies between 10 Hz and 1 kHz using stepped-sine EIS. Except for the negligible current load caused by the measurement procedure itself, the cell remains in an idle state at 50 % SoC during the entire experiment. A 5 h rest period follows each temperature step to ensure that the cell is in equilibrium.

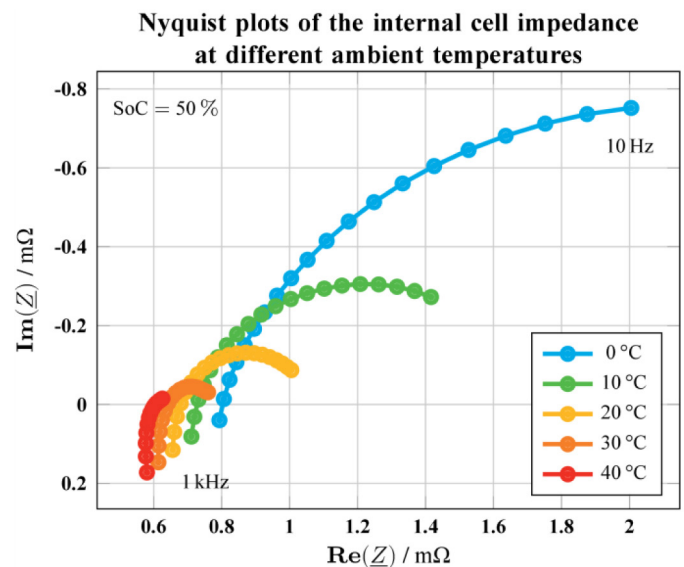


Figure 4. Nyquist plots of the internal cell impedance at different ambient temperatures