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Crosstalk Interferences on Impedance Measurements in Battery Packs ⋆

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Abstract:
In order to provide the required power and energy for e.g. automotive applications, a multitude of cells is assembled into a battery pack. For safety and control purposes it is of interest to equip every single cell with an Electrochemical Impedance Spectroscopy (EIS) measurement system. However, performing EIS measurements simultaneously on each cell in a battery pack introduces crosstalk interferences in surrounding cells. This causes EIS measurements in battery packs to be inaccurate. An experimental investigation on a battery pack showed that crosstalk is a linear phenomenon which is dependent on the measurement frequency, the relative position of the cells and the inter-cell spacing. Based on the experimental results and a proposed two-coil model with inductive coupling, a transfer-function description has been developed in order to simulate the crosstalk behavior. This model can be used as a supporting tool in the development of EIS-based measurement systems in battery packs.

Keywords: Crosstalk, Batteries, Electrochemical Impedance Spectroscopy, Electromagnetic interferences, Battery packs, Crosstalk modeling.

1. INTRODUCTION

Battery-powered applications such as (hybrid) electric vehicles are rapidly emerging in today's society. This causes an increased demand for large-capacity, small-sized, lightweight, safe and low-priced rechargeable batteries. Especially for Lithium-ion batteries, a Battery Management System (BMS) is needed to ensure safe use and to warrant a certain lifetime. Variables such as voltages, currents and temperatures must be monitored and managed within a specified range. Electrochemical Impedance Spectroscopy (EIS) is a non-destructive measurement technique which can assist in monitoring states (Howey et al., 2013) such as State-of-Charge (SoC) (Hung et al., 2014; Lee and Choi, 2011; Xu et al., 2013), State-of-Health (SoH) (Love et al., 2014; Zenati et al., 2010; Zhang and Lee, 2011) and temperature (Raijmakers et al., 2014; Beelen et al., 2015; Schmidt et al., 2013).

Most of the research on using EIS for SoC, SoH and temperature estimation is limited to demonstrating functionality on the single-cell level, often under laboratory conditions. In order to provide the required power and energy for automotive applications, single cells are connected in a series and/or parallel order to form a battery pack. To ensure safe usage of battery packs, the individual cells need to be monitored. It is therefore of interest to understand how EIS measurement systems can be used on individual cells in battery packs and how EIS measurements respond to large drive currents (high C-rates) and other interferences, as e.g. is shown in (Raijmakers et al., 2016).

This paper studies a phenomenon that is introduced when EIS is performed simultaneously on several cells in a battery pack. Namely, it is demonstrated that performing EIS on one cell causes interference with EIS measurements in surrounding cells. We will refer to this phenomenon as crosstalk between cells. When not properly dealt with, crosstalk yields inaccurate EIS measurements, which leads to inaccurate predictions of SoC, SoH and temperature. After the experimental demonstration of crosstalk between cells, a parameter variation study will be performed to determine the dominant parameters influencing crosstalk. For instance, the magnitude of the EIS current excitation, the location of the cells, and the distance between the cells will be varied. This parameter study allows to develop a model for EIS on complete battery packs in the form of a transfer-function matrix. This requires modeling the crosstalk itself. The model and measurements give in-depth insight into crosstalk interferences in battery packs, which can be used to prevent or compensate crosstalk to enable accurate EIS measurements in battery packs.

The remainder of this paper is organised as follows. In Section 2, it is experimentally demonstrated that simultaneous EIS measurements in a battery pack are interfered with crosstalk signals. Section 3 presents a systematic study of whether or not crosstalk depends on measurement current and whether or not it is a linear phenomenon, as

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well as the influence of cell position and inter-cell spacing on crosstalk interferences. This systematic study enables the development of a crosstalk impedance model in Section 4. Finally, we will indicate implications and draw conclusions in Section 5.

2. BACKGROUND OF CROSSTALK BEHAVIOR

In this section, the importance of analyzing crosstalk interferences in battery packs is discussed. For automotive applications, multiple cells are typically assembled into a battery pack in order to obtain the required voltages and currents to drive the vehicle. For analyzing crosstalk interferences in a battery pack, we consider an impedance transfer-function matrix $H(s)$, satisfying

$$\begin{bmatrix} V_1(s) \\ \vdots \\ V_n(s) \end{bmatrix} = \underbrace{\begin{bmatrix} H_{11}(s) & \dots & H_{1n}(s) \\ \vdots & & \vdots \\ H_{n1}(s) & \dots & H_{nn}(s) \end{bmatrix}}_{=H(s)} \begin{bmatrix} I_1(s) \\ \vdots \\ I_n(s) \end{bmatrix} \qquad (1)$$

where $V_i(s)$ and $I_i(s)$ are the output voltages and input currents, respectively, of cell i and H_{ij} are the transfer functions from cell j to cell i. Furthermore, the Laplace transform variable is given by $s = \sigma + j\omega$. For $\sigma = 0$ and excitation frequency $\omega = 2\pi f$, the impedances in $H(s)$ can be interpreted as frequency response functions from (sinusoidal) current input to (sinusoidal) voltage output, which can be experimentally obtained by performing EIS measurements (Orazem and Tribollet, 2008; Barsoukov and Macdonald, 2005). The diagonal terms in $H(s)$ represent the cell impedances and the off-diagonal terms the crosstalk impedances from cell to cell.

For a battery pack containing two adjacent cells, a block diagram with corresponding transfer-function matrix elements is shown in Fig. 1. To determine $H_{11}(s)$ and $H_{22}(s)$, a sinusoidal current is injected in $I_1(s)$ and $I_2(s)$, respectively, and sinusoidal voltages at $V_1(s)$ and $V_2(s)$ are measured. However, since $I_1(s)$ is coupled to $V_2(s)$ through $H_{21}(s)$ and $I_2(s)$ to $V_1(s)$ through $H_{12}(s)$, the measured voltages $V_1(s)$ and $V_2(s)$ are influenced as well. This leads to undesired crosstalk interferences and consequently incorrect EIS measurements.

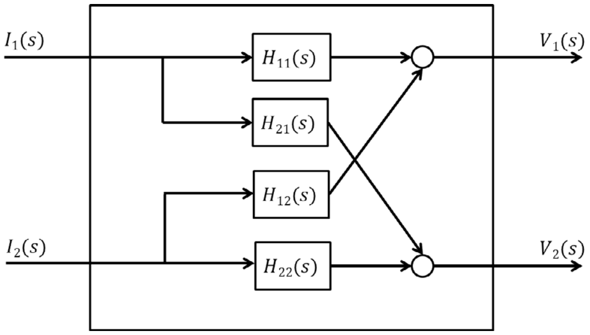

Fig. 1. Multiple-input multiple-output block diagram of a battery pack with 2 adjacent cells.

To experimentally demonstrate that the off-diagonal terms of $H(s)$ can be nonzero and that crosstalk can interfere with the measurements, a test setup has been assembled, which is shown in Fig. 2. It consists of two 25Ah rectangular prismatic Nickel-Manganese-Cobalt (NMC) Li-ion cells that have each been connected to a Single-Cell Supervisor (SCS) designed by NXP Semiconductors. These SCSs are capable of injecting a sinusoidal current with a specified frequency into the cell and subsequently measure the induced voltage, from which the impedance of the cell is obtained. This implies that the SCS of cell 1 will inject current $I_1(s)$ and measure the voltage $V_1(s)$, whereas the SCS of cell 2 will inject current $I_2(s)$ and measure the voltage $V_2(s)$.

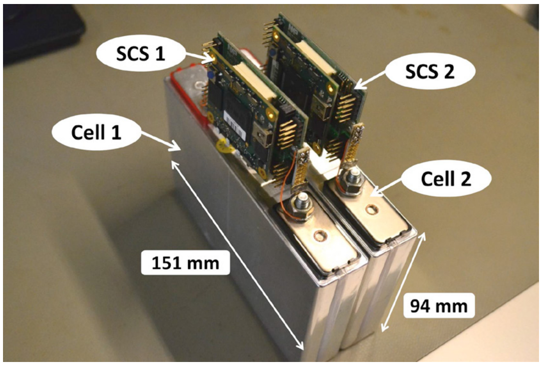

Fig. 2. Setup used for the impedance measurements.

The setup shows that when the two adjacent cells are injected with a current of the same frequency $f = \omega/(2\pi)$ simultaneously, there is indeed an offset in the impedance measured, when compared to the stand-alone impedance of each cell at the same frequency. This offset is caused by the fact that the 'perceived impedance' from $I_2(j\omega)$ to $V_2(j\omega)$, i.e., $V_2(j\omega) = H_{22}^\star(j\omega)I_2(j\omega)$, is given by

$$H_{22}^\star(j\omega) = H_{22}(j\omega) + H_{21}(j\omega)\frac{I_1(j\omega)}{I_2(j\omega)}, \qquad (2)$$

which is not equal to the actual impedance $H_{22}(j\omega)$ when $I_1(j\omega) \neq 0$. This effect is clearly visible in Fig. 3, where the cell impedance at a frequency of 2.84 kHz is shown without (blue circle) and with crosstalk (red cross) interference. Note that Fig. 3 was produced while the cells were not electrically connected to each oher, although the crosstalk would be the same if they were. To compensate for the offset induced in simultaneous EIS measurements at the same frequency in a battery pack, an in-depth experimental analysis and modeling approach is required, which are the topics of the next sections.

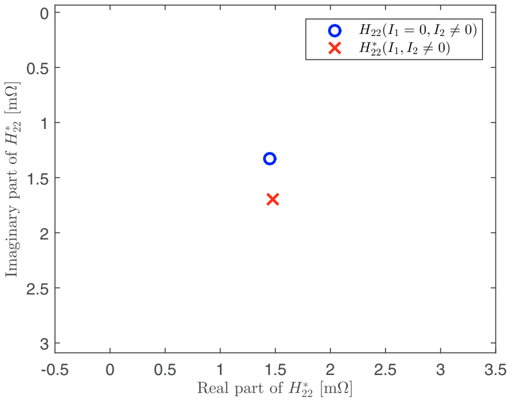

Fig. 3. Example of the offset in impedance induced by crosstalk interference at 2.84 kHz.