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Investigating and modeling the transmission channel of a prismatic lithium-ion cell and module for powerline communication

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ABSTRACT

Current lithium-ion battery management systems require a huge amount of connecting units for monitoring and controlling single cells. A sophisticated way of simplifying a complex wiring architecture is the use of a powerline communication system. By this approach the existing powerline is simultaneously used for data transmission. However, a thorough understanding of the channel characteristics in the high frequency range (1–110 MHz) is necessary to be able to design and implement such a system. This work deals with the characterization of the powerline channel of <10 Ah prismatic hard case Lithium-Ion cells and 10 cell modules with special respect to the interaction between single cells using impedance measurements. Based on the obtained knowledge, a circuit-based model of the transfer channel has been designed, allowing to estimate the behavior of larger battery systems. The model was also used to simulate different coupling methods to transmit and receive signals to the powerline.

1. Introduction

The most crucial component in current hybrid vehicles (HVs) and electric vehicles (EVs) is the traction battery system. It determines the lifetime, driving range and costs of the electrified vehicle. Lithium-ion cell technology needs further development steps as well as the battery management system (BMS). An optimized BMS increases the overall lifetime and performance and reduces weight because of a precise number of cells can be employed regarding the end-of-life criteria. The BMS needs to acquire exact parameters like voltage, current and temperature of each cell. Therefore each cell has to be physically connected. State of the art BMS for automotive applications use a modular architecture for monitoring single cells, where clustered monitoring units handle a certain number of battery cells and communicate the measured parameters to the higher central management unit [1]. Well-established communication networks in vehicles are the controller area network (CAN) and Flexray which use additional wires as the physical layer to transmit signals between the clients (e.g. sensors and onboard computers). Therefore, the high number of cells which are necessary for the high voltage supply (typically 400 V for EVs) require a huge wiring harness with the use of these communication networks.

A novel concept is the intelligent cell with its primary aim to create a distributed battery management system. Each cell has its own integrated BMS which monitors the current state and communicates the parameters [2]. This way the entire cells constitute a distributed BMS without the need for a higher central management system. The complex communication lines are generally reduced if the communication among each cell and also between a cell and the vehicle management system takes place over the powerline. However, the electromagnetic interference generated by the high frequency noise coming from the power train has to be considered in practical applications [3]. The already existing powerlines are simultaneously used for data transmission by adding a modulated carrier signal to the system. While powerline communication (PLC) is already established in fields of home network and power supply systems [4–6], this is not the case for battery management systems since high ASIL demands have to be fulfilled (up to ASIL D). The main difference between the power supply and the battery management systems is the integration of the clients. For power supply systems the clients (e.g. household modems) are in a parallel connection while for BMS the clients (single cells) are usually in a serial connection, which causes a higher attenuation of the communication signal (higher damping effects). To design a PLC for a distributed BMS, a battery

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model in the high frequency range is required due to the high required carrier frequency [7,8,3]. While a lot of battery models are developed for the low frequency range (<100 kHz) [9] battery cells are not sufficiently investigated in the high frequency range.

Doersam et al. investigate three different methods to measure the frequency dependent impedance of Lithium-Ion batteries up to 10 MHz and propose a method to calculate the impedance parameters of the battery [10]. They consider cylindrical cells which are placed in a battery housing as simple inductances in an equivalent circuit model. The main focus is rather on the investigation of the different measurement methods than on the modeling approach of the single cell or battery module. Jousse et al. deal with the implementation of a powerline communication in a battery energy storage system in a small-scale autonomous photovoltaic system [11]. The whole system is modeled up to 10 MHz using matrix formalism whereas the battery is considered as a low impedance. Additionally the application of a first prototype which uses a CAN protocol for PLC communication is designed and validated. However, the work focuses on the system level without investigating the battery in detail. Similar to the power supply systems the clients are connected in parallel. Hoene et al. derive battery cell models from the structure of a cylindrical battery cell regarding the battery as a solid conductor without considering single structural elements [12]. Additional impedance measurements on lithium-ion and nickel metal hydride (NiMH) batteries are performed in a frequency range between 100 Hz and 40 MHz. Less information is present about the utilized single cells as well as the approach to model batteries. Ouannes, Nickel and Dostert investigate a Lithium-Ion battery with focus on the powerline channel transfer characteristics between 1 kHz and 100 MHz [13]. They propose a circuit-based model of a single prismatic cell which enables the modeling of larger battery packs. The model parameters are fitted to measurement data which are carried out on the battery module. Furthermore, the channel characteristics are studied on the basis of the developed model. However, they do not investigate the single battery cell in detail to validate the complex model by theoretical calculations. Few information is provided about the utilized battery cell as well as the influence of the mechanical structure and the interaction of the single cells on the channel characteristics. The applied transmit and receive couple circuit on which the channel characteristics is studied are not discussed in detail.

This paper investigates the high frequency characteristics of a <10 Ah prismatic hard case Lithium-Ion cell and a module of ten cells with special respect to the interaction between single cells in a frequency range of 1–110 MHz. Based on the physical structure of the single cell a circuit-based model is proposed. Theoretical estimations determine the values of the model parameter and reduce the complexity of the model structure. The parameters are fitted to the data of the impedance measurements which are carried out on a single cell as well as on a battery module of ten cells to validate the estimations. The proposed model is used to design and investigate two different coupling networks for PLC. Furthermore, the channel characteristics with focus on the channel transfer function is investigated. This approach deals with the investigation and design of a transmission channel of a prismatic lithium-ion cell and module with a detailed look at the smallest unit of the battery system.

2. Impedance measurements of a single cell and a battery module

To design a PLC-system, a thorough understanding of the channel characteristics is necessary. In this section an impedance analysis is performed in order to characterize the behavior of a single cell, as well as of ten cells connected in series. A <10 Ah prismatic cell in a hardcase with carbon as the negative electrode and $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (NCM) as the positive electrode has been chosen since this type of cells can be usually found in automotive applications e.g. plug-in hybrid electric vehicle (PHEV). The capacitive interactions between the cells in the high frequency range and the influence of their position is investigated. Due to the high required carrier frequency for PLC the measurements focus on frequencies between 1 MHz and 110 MHz. The upper test frequency of 110 MHz is limited by the impedance analyzer (Agilent "4294A").

2.1. Test setup

Because of the charged state of the cells (3.6 V) they cannot be directly connected to the measurement instrument. A special test arrangement protects the impedance analyzer against high discharge current flow (see Fig. 1). Thereby, the capacitors C_1 and C_2 are calculated to block the DC current from flowing into the instrument, but also not to affect the test current. The measurement is performed by a four-terminal configuration. The terminals Hc and Lc are the current leads and the terminals Hp and Lp are the voltage sensing leads.

While the data sheet of the impedance analyzer defines the capacitance $C_2 = 1\ \mu F$ the capacitance C_1 depends on the minimum test frequency f_{min}:

$$C_1 \geq \frac{1}{10\pi f_{\min}} \tag{1}$$

The self-resonance frequencies of the capacitors should not be in range of the test frequency in order to avoid misinterpretations of the result.

2.2. Single cell

The high frequency characteristics of the battery depends significantly on the behavior of a single cell. A single cell consists of three externally measurable elements – the negative and the positive terminal and the battery housing (without terminals) which is 120 mm in length, 85 mm in width and 20 mm thick. The impedance measurements between the three elements show the characteristic behavior of the cell. Fig. 2(a) depicts the measurement points on the cell. One point is on each terminal (N and P), and two points are on the can (C1 and C2). The placement of C1 and C2 on the bottom of the can considers the maximum inductance and ohmic resistance of the can because the current flows through the largest distance. The comparison between the measured impedances with C1 and C2 shows the influence of the measurement point on the resonance frequency. Thus, it is not only possible to investigate the impedance between the two terminals, but also the interaction between a terminal and the can.

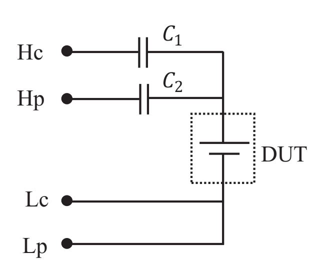

Fig. 1. Test setup for impedance measurement on a charged device under test (DUT). Capacitors C_1 and C_2 are used to block high discharge currents. Terminal Hc (high potential) and Lc (low potential) are used as current leads. Terminal Hp and Lp are used as voltage sensing leads.