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Impedance measurement for advanced battery management systems

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Abstract

We present a fast, low-cost approach to measure battery impedance 'on-line' in a vehicle across a range of frequencies (1-2000 Hz). Impedance measurement has promise for improving battery management since it is a very effective non-invasive method of diagnosing the internal state of an electrochemical cell. It is useful for estimating temperature, ageing, state of charge (SOC) and for fault detection. The aim of this paper is firstly to explore the usefulness of impedance for estimating SOC, focusing on lithium-ion iron phosphate (LFP) and nickel manganese cobalt oxide (NMC) cells, and secondly to demonstrate the performance of a low cost impedance measurement system that uses an existing motor drive similar to that of an electric vehicle to excite the battery current. We find that measurements made with this system are accurate to within a few per cent of results from an expensive, bulky commercial system. For SOC estimation in NMC cells, the charge transfer resistance and SEI layer resistance vary significantly with SOC. In LFP cells the parameter variation is much less obvious, although the double layer capacitance of the full pack may be a useful indicator of SOC.

Keywords: impedance, battery management system, electric vehicle, hybrid vehicle

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1 Introduction

Electric and hybrid vehicles employ a battery management system (BMS) to manage voltages, currents and temperatures for safety purposes, and to calculate state of charge (SOC), state of health (SOH) and other metrics. With respect to SOC, many systems measure only steady state values and use coulomb counting, with an empirical model and lookup table of previously measured parameters to account for changes in performance at different charge and discharge rates and with age [1]. More sophisticated systems use adaptive state estimation to fit dynamic model parameters on-line and deal with sensor noise and uncertainty, e.g. [2] who described a method based upon extended Kalman filtering to estimate SOC, power and capacity fade.

Electrochemical impedance spectroscopy (EIS) is a useful tool to investigate the reactions occurring in cells. This involves the application of a small AC variation in load impedance to a cell at different frequencies to measure the impedance (a complex number) as a function of frequency. With accurate calibration and in combination with other methods, EIS can be used to gain vital information about SOC and SOH of batteries [3]. Impedance measurement may also be used to analyze faults in battery packs [4] for example by comparing the impedances of multiple cells.

Although EIS is widely used in the laboratory, it is a specialized technique requiring costly, bulky equipment to achieve good results. Since batteries typically have very low impedances, accurate measurement is challenging due to the small voltage fluctuations for a given current fluctuation [5]. In this paper we explore a low cost measurement system for impedance that could be used online in a vehicle application, using as much of the existing vehicle electronics and BMS as possible. Our main initial goal is estimation of SOC from impedance, hence first in section 2 we examine the expected impedance variation with SOC for two specific chemistries, before showing some results from a low cost impedance measurement system in Section 3.

2 Impact of SOC on impedance

2.1 Lithium-ion nickel manganese cobalt oxide (NMC) cells

NMC cells exhibit a clear and well-behaved relationship between impedance and SOC. A preliminary investigation, Figure 1, shows the measured impedance variation from 0.1 Hz to 10 kHz for a single 4.8 Ah Kokam prismatic NMC cell (SLPB 11043140H) at various SOC and ambient temperature conditions with EIS measured around OCV in galvanostatic mode with a peak current magnitude of 250 mA using a Biologic VSP potentiostat/FRA system.

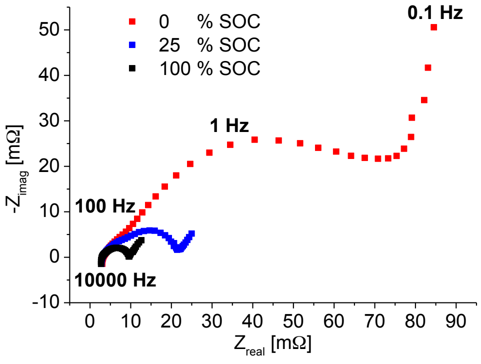


Figure 1: NMC cell impedance at various SOC

Using the equivalent circuit model (ECM) shown in Figure 2, model parameters were fitted to these data using the ZView fitting software, where L is the series inductance, R_s is the series resistance, R_{SEI} the solid-electrolyte interphase (SEI) resistance, CPE_{SEI} the constant phase element relating to the SEI, R_{CT} the charge transfer resistance, CPE_{DL} the constant phase element relating to the electrochemical double layer, and W a Warburg impedance modelling diffusion.

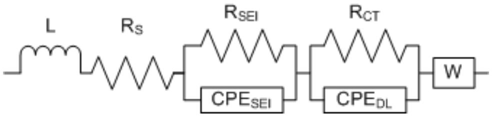


Figure 2: Equivalent circuit for fitting OCV EIS data

It was found that the parameters exhibiting the greatest variation with SOC for the NMC chemistry were the charge transfer resistance and SEI layer resistance as shown in Figure 3, both exhibiting a monotonic relationship with SOC. This relationship is also found to be consistent from one cell of this type to another, see [4]. The impact of temperature and SOH on these parameters must also be accounted for but this is not discussed here.

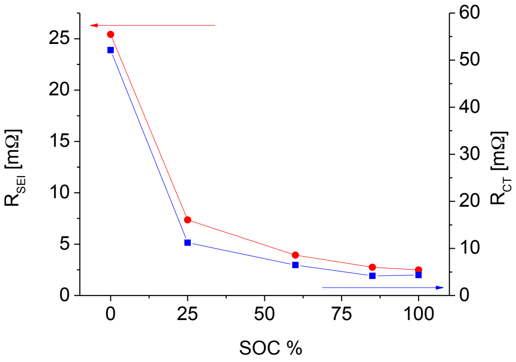


Figure 3: ECM parameters for NMC cell

2.2 Lithium-ion iron phosphate cells

Compared with NMC cells, lithium-ion iron phosphate (LFP) cells are more challenging to diagnose. We have previously reported [6] that SOC determination for LFP cells based on equivalent circuit fitting of *individual cells* may not be conclusive due to a significant spread of the values of the fitted parameters from cell to cell. However, individual cell fitted parameters could nonetheless be useful in estimation of cell health and for fault detection. It may be more plausible to track *overall pack* SOC with one or several fitted parameters pertaining to the EIS response measured across the entire pack.

In order to investigate this, a small battery pack consisting of four A123 Systems LFP cells (ANR26650M1A with nanostructured lithium iron phosphate cathode and graphite anode) in series was assembled. Nominal cell capacity and voltage were 2.3 Ah and 3.3 V respectively. EIS measurement was carried out with the same system as described previously, operating in stack mode, in other words simultaneously measuring the responses of the pack as well as every cell within it. Each EIS spectrum was recorded in galvanostatic mode (i.e. current control) at (i) open circuit voltage (OCV) with 250 mA AC current applied and (ii) under a DC bias with DC discharge current of 150 mA plus superimposed 130 mA AC current.

Figure 4 and Figure 5 show the measured EIS response of the full LFP pack around OCV and under DC bias respectively at various SOCs and at constant ambient temperature. It may be noticed that SOC has the most impact on the shape of the EIS curves at frequencies below 50 Hz and that there is very little variation with SOC compared to NMC cells. Under DC bias, cells behave non-linearly at very low frequencies (less than 1 Hz) and therefore these diffusion results have been removed in the DC biased data.

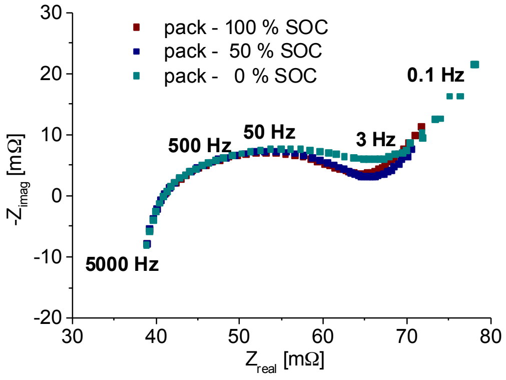


Figure 4: EIS response of 4-cell pack at OCV

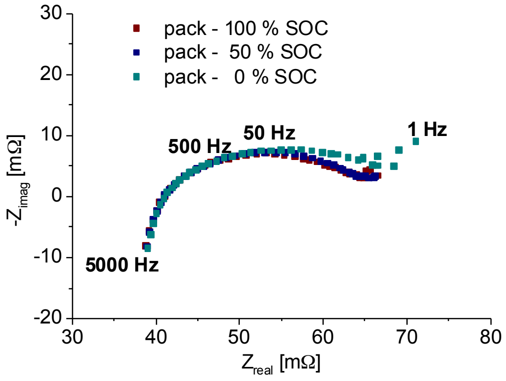


Figure 5: EIS response of 4-cell pack under DC bias

Equivalent circuit models (ECMs) were again used for fitting parameters, with the same model as before for the OCV case but this time fitting full pack data. For the DC bias case a modified model was used shown in Figure 6, where *W* the Warburg impedance is not included in the DC bias ECM for the reasons previously explained.

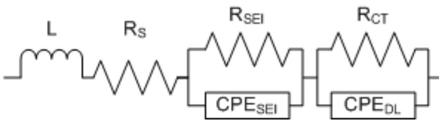


Figure 6: ECM for fitting of EIS data with DC bias

The parameters estimated are shown in Figure 7 and Figure 8 (values of R_s and L vary only a small amount with SOC and are therefore not shown).

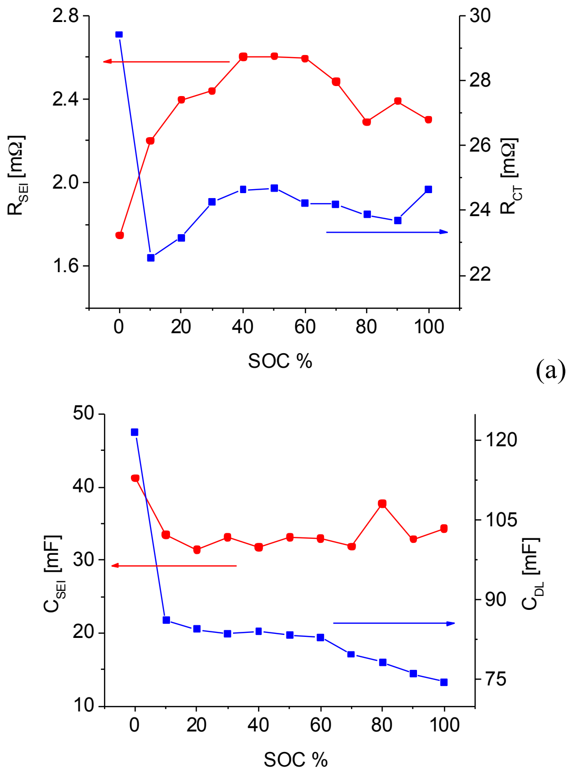
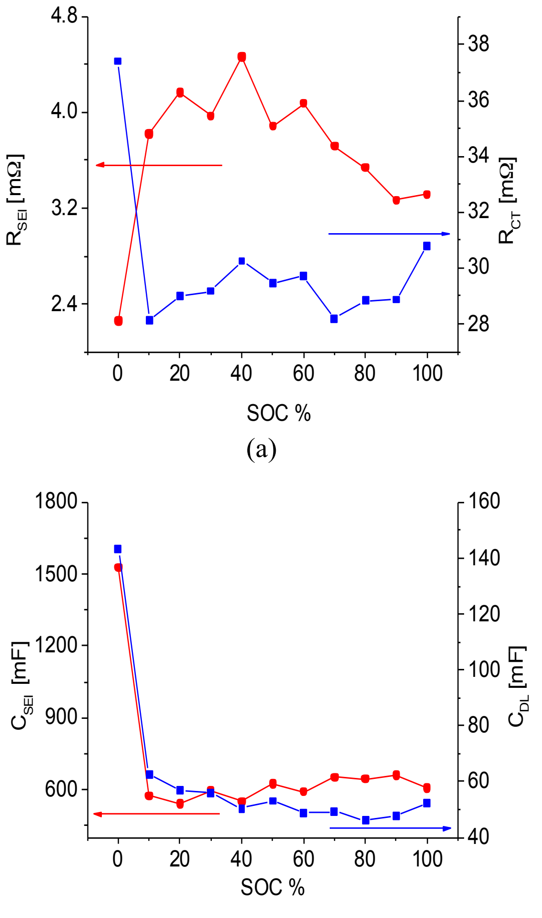


Figure 7: Fitted ECM parameters, full pack at OCV

As can be seen there is much less of a clear relationship with SOC compared to NMC cells. It may also be noticed that there are differences in values of the parameters under DC bias compared to OCV. Clearly the impact of DC bias must be accounted for if impedance is to be used reliably to estimate SOC under load [7]. For consistent results the EIS technique for SOC estimation might best applied only when the cells are at rest, around OCV, as for example a regular recalibration of other SOC methods such as coulomb counting.

The full pack double layer capacitance shows the variation with respect to SOC that is closest to monotonic and therefore may be a reliable single parameter to use for SOC estimation, although the temperature and SOH dependence of this parameter must also be accounted for and are not discussed here. Alternatively a combination of parameters could be used. The pack C_{DL} increases significantly below 10% SOC even under DC bias, which could be used as a rapid ‘empty’ detection system. More work is required, and is part of an ongoing research programme by the authors, to fully understand the impact of SOC and DC current on impedance, particularly for LFP cells, as well as the impact of temperature which has not been considered here and is significant [8].



(a)

(b)

Figure 8: Fitted ECM parameters, pack with DC bias

3 In-vehicle measurement of impedance

Having shown that impedance could usefully indicate SOC (particularly for NMC cells), in order for this to be realized in a battery management system, a simple and low cost hardware and software measurement system is required that is suitably accurate. Impedance measurement could be incorporated into a drivetrain with an integrated system such as that illustrated in Figure 9 in relation to an electric vehicle drive. The small signal current perturbation to excite the cells and pack to measure impedance comes either from variations in the main traction current due to passive noise on the DC bus from driver response or controller response, or from an optional additional excitation circuit, or from a combination of all of these approaches. The voltage and current in the cells and pack is measured, amplified and filtered then processed digitally using a statistical correlation technique to determine the cell’s impedance as a function of frequency. The SOC may be determined from the impedance frequency response of the pack assuming relationships such as those explored in the preceding section.

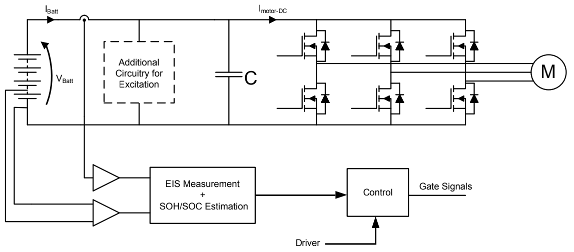


Figure 9: Battery impedance measurement in an electric vehicle drivetrain

In this work we focus on the use of a motor controller as the excitation source for the measurement of impedance.

A test rig shown in Figure 10 was constructed comprising a 30 W DC brushless servo motor with motor controller directly coupled to a second 30 W electrical machine to mimic the drivetrain of an electric vehicle and test the idea of using motor controller current excitation to measure battery impedance, as explained in our recent paper [9]. The approach of using an electrical machine as the excitation system represents a scaled-down prototype of a brushless DC drive system. This is relevant as a demonstrator because of the relationship in the scaling of the relevant parameters as the drive system is increased in power: in a full size electric vehicle, the battery packs will be larger, but so will the drive currents, and the perturbation current can be larger in absolute terms as the fraction of perturbation current to battery capacity can remain the same.

The rig was powered by four A123 Systems LFP cells of the type previously described, connected in series to form a 12-14 V DC supply. A flywheel was attached to the motors adding mechanical energy storage to smooth speed fluctuations. A National Instruments data acquisition system was used for analog and digital input and output, controlled by a computer. This produces the current excitation signal which is fed to the motor controller, and also measures the voltage across and current through the cells after amplification and filtering through a small separate circuit (not shown), which was calibrated as described in [9].

In order to process the current and voltage signals to extract the impedance from any arbitrary excitation signal, the cross spectral density of the current and voltage and power spectral density of the current were used in combination with the coherence spectrum as a means of removing poor quality data.

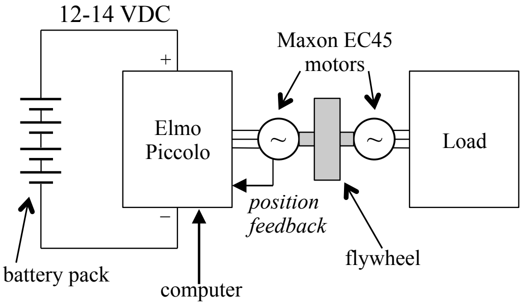


Figure 10: Motor controller battery test system

Using the test rig, both multi-sine and broadband noise current excitation spectra were tested. The results were compared to impedance measurements made with an electronic load and also to the Bio-Logic VSP system, using both multisine and broadband noise excitation signals, in order to demonstrate the accuracy of this low cost system and stability of using a motor controller as the perturbation source.

4 Results of low cost system

Figure 11 shows the measured impedance (bode plot) for a single A123 LFP cell comparing measurements made using multisine excitation and the commercial EIS system, a low cost electronic load, and the motor rig previously described. The comparison is good across the full range of frequencies investigated (1 Hz to 2 kHz) with RMS uncertainties around 5% in magnitude and 3° in phase. Using a broadband noise excitation signal (Figure 12) instead of a multisine signal achieves even better results, with RMS uncertainties around 2% in impedance magnitude and 3° in phase. This is because broadband noise is less prone to narrowband interference.

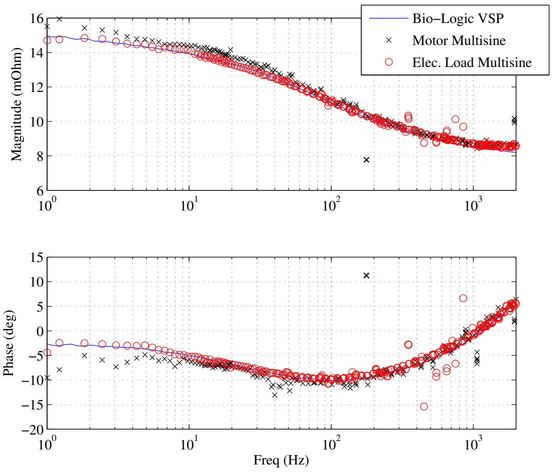


Figure 11: Comparison of results obtained using multisine perturbation

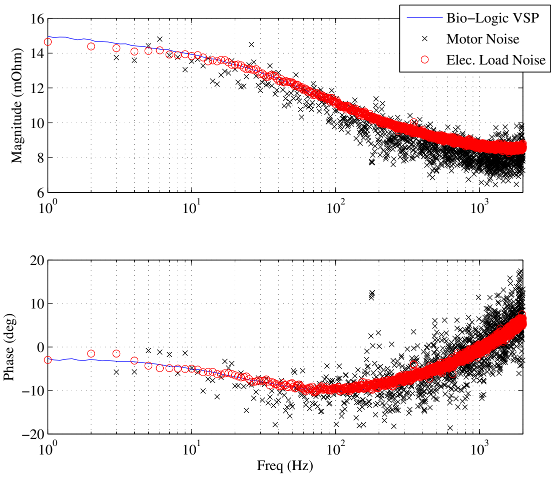


Figure 12: Comparison of results obtained using broadband noise perturbation

These encouraging results show that it is possible to obtain quite accurate impedance measurements on cells using a variety of excitation types and using a motor controller.

5 Conclusions

The usefulness of these impedance measurements for inferring indirect parameters of the cells or pack, such as SOC, depends on the exact relationships between the impedance spectra and the SOC as discussed in section 2 of this paper. For some cell chemistries, such as NMC, there is a clear relationship; but for others, particularly LFP the estimation could be much more challenging.

Although there is substantial work still to be done to demonstrate a complete working BMS that makes substantial use of impedance, this paper shows that two critical parts of such a system are plausible. These are first an accurate impedance measurement system that can be integrated into an existing powertrain in an electric vehicle, and second a clear relationship between impedance and a desirable parameter to estimate, such as SOC.

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