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Smart charging stations for accurate and reliable electric vehicle battery monitoring

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Dr Roberto Ferrero

Dept. of Electrical Engineering & Electronics

University of Liverpool

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Project team: Dr Roberto Ferrero (PI), Lecturer, University of Liverpool
Mr Arne Sandschulte, Research Assistant, University of Liverpool
Mr Chao Wu, Research Assistant, University of Liverpool

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List of Acronyms

ADC	Analog-to-Digital Converter
DfT	Department for Transport
BMS	Battery Management System
EIS	Electrochemical Impedance Spectroscopy
EV	Electric Vehicle
FPGA	Field Programmable Gate Array
PWM	Pulse Width Modulation

Executive Summary

Many Countries worldwide, including the UK, have set strict targets on the reduction of greenhouse gas emission, affecting in particular the transport sector. In the attempt to meet those targets, fully electric or hybrid vehicles, mostly powered by batteries, are gradually appearing on the market, with the aim to replace combustion engine vehicles. However, electric vehicles (EVs) have important limitations in terms of cost, mileage range and reliability, which are hindering the rapid take-up of this technology that would be required to meet the targets.

This project aims to address a critical and so far under-investigated aspect of the research in this field, namely the development of innovative measurement solutions to accurately and reliably monitor the state of health of EV batteries over time. This can be achieved at almost zero additional cost to the user, by designing smart charging stations that estimate the battery state (and potentially its residual life) every time the battery is recharged.

The methodology is based on the low-cost implementation of electrochemical impedance spectroscopy (a well-known and powerful diagnostic technique, commonly used in laboratory experiments) by using the power converters already available in the EV powertrain. The converter will be controlled in an innovative way to generate the required current perturbations to measure the impedance spectrum in the desired frequency range.

In this project, a simplified EV powertrain prototype has been successfully designed and assembled, composed of a 4.6 kWh LiFePO4 battery pack, a DC/DC power converter, a real-time converter controller and a signal conditioning, acquisition and processing system. An innovative control of the DC/DC converter has been tested, to inject AC perturbations into the DC current used to charge the battery. Such perturbations, together with appropriate signal conditioning and processing, are suitable to measure the battery electrochemical impedance, which in turn can provide a wealth of diagnostic information about the battery state of charge and state of health.

The project outcome confirms the feasibility of the proposed method, but highlights important challenges associated with the performance of the DC/DC converter, which is critical to guarantee a good quality of the battery voltage waveforms and thus also of the impedance measurements. The use of a commercial converter appears to be the best way to achieve the desired performance levels, but a collaboration with the converter manufacturer may be necessary to be able to control the converter with the flexibility required according to the proposed method.

1. Aims and objectives of the study

The Climate Change Act 2008 set the ambitious target of reducing greenhouse gas emissions by 80% by 2050, compared to 1990 levels, with an intermediate target of a 57% reduction by 2030, agreed in the Fifth Carbon Budget. However, the 2017 Progress Report to Parliament by the Committee on Climate Change stated that the progress is stalling, and emissions from transport have actually risen since 2012. It concluded that effective new strategies and policies are urgently needed to ensure emissions continue to fall in line with the commitments agreed by Parliament, and transport was identified as one of the priorities in the reduction of greenhouse gas emissions. In particular, a significant take-up of electric (or other ultra-low emission) vehicles beyond 2020 was recommended.

While some electric vehicles (EVs) for both private and public transport are already on the roads, their number is still far from the levels required to meet the emission targets, and a step-change in the uptake of this technology is urgently needed, as confirmed by the recent £246 million investment of the UK Government (the 'Faraday Challenge') on battery technology for automotive applications, as part of the Industrial Strategy Challenge Fund.

Cost, limited mileage and reliability are among the main factors that are hindering a full penetration of electric vehicles into the market. Battery manufacturing is pushing the boundaries of energy density, to decrease costs and increase the mileage, but innovation in manufacturing is not enough. Batteries are known to be much less reliable than internal combustion engines, essentially because they are much more complex devices. A regular monitoring of the battery state of health, much more accurate than what is presently available, is required to increase the efficiency and reliability of electric vehicles, but also to increase the user's confidence in them, which is equally important to guarantee the desired rapid take-up of this technology.

The vision behind this project is that such a regular and accurate monitoring of the battery state could be achieved by the charging infrastructure that is going to be developed in the next years. A smart charging station would be capable not only of recharging the batteries, but also of accurately and reliably assessing the state of health of the battery while being charged.

Achieving such an ambitious objective would have immediate benefits:

1) The user would become more confident to embark on long journeys and more willing to accept an electric vehicle as their only/main vehicle;
2) The risk of breakdown, with consequent recovery cost and impact on traffic, would be significantly decreased;
3) The data could be made available to the network provider and vehicle manufacturers for a collective monitoring of electric vehicles on the roads.

All this would contribute to decreasing the gas emissions, with important environmental benefits, and would align well with the DfT's priority to achieve a safe, secure and sustainable transport. In particular, the DfT's Single Departmental Plan includes the objective of promoting new technologies to reduce emissions, with the plan to end the sale of new conventional petrol and diesel cars and vans by 2040.

The objective of this project is to demonstrate the feasibility of the proposed approach, by implementing accurate battery monitoring techniques, based on the power electronics commonly used to charge battery packs, in a small-scale (a few kW) proof-of-concept prototype of a simplified EV powertrain (composed only of battery pack, power converter and battery management system), connected to an external charger and a data acquisition and processing unit.

2. Outline of the concept and methodology

Electrochemical Impedance Spectroscopy (EIS) is a well-established technique to monitor batteries as well as other electrochemical devices. The battery impedance spectrum is an unrivalled source of information about the internal condition of the battery. It allows distinguishing between the different internal processes, such as mass transport, charge transfer and Ohmic losses, because they affect the spectrum at different frequencies, from milli-Hertz to kilo-Hertz, as illustrated in Fig. 1. EIS is therefore a very useful technique to accurately estimate both the state of charge and state of health of a battery, as proved by a vast scientific literature on the subject [1-5].

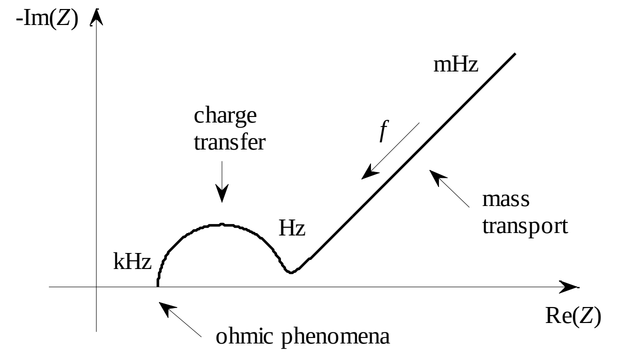

Fig. 1: Illustration of a typical battery impedance spectrum

EIS has been used in laboratory experiments for several years and has allowed significant progress in battery modelling, design and manufacturing. The standard implementation of EIS, however, is not suitable for condition monitoring in commercial applications, as it requires sophisticated and expensive instrumentation, such as frequency response analysers and electronic loads. As a result, only much simpler (and often less effective) monitoring techniques are presently implemented in most applications, including EVs. Typically, only DC currents and voltages (in addition to temperature) are measured for power management and diagnostic purposes, but they provide almost no information to identify the cause of any observed performance degradation and are therefore not much useful to predict future performance and residual life.

The innovative idea underlying this project is to overcome the limitation described above and perform low-cost EIS in EVs without any additional instrumentation installed on board, and therefore without any additional cost. This is made possible by the use of power converters (DC/DC and/or DC/AC), already included in the EV powertrain to connect the battery pack to the motor and to the external charging station. Switch-mode power converters are typically controlled to absorb/inject a DC current from/to the battery, but their control can be changed (with no or little hardware modifications) to add a small AC perturbation to the DC current, suitable to measure the impedance in the desired frequency range, as illustrated in Fig. 2.

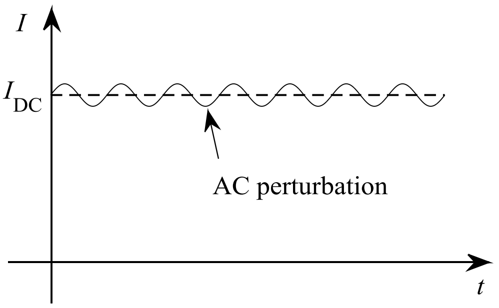

Fig. 2: Example of perturbed current used to measure the battery impedance while charging the battery

The novel aim of this project is to implement converter-based EIS during the battery charging process, i.e. when the EV is connected to a charging station. This solution presents several advantages compared to EIS measurement during the battery discharge (i.e., in normal EV operation):

1) No uncontrolled transients occur, as the only transient is the controlled and smooth battery charging, which is usually done at constant (DC) current for most of the transient;

2) The signal processing and data analysis, which require a relatively powerful processor, can be done by the smart charging station, with no need for such a processor to be on board of the EV;
3) The monitoring process has no impact on the EV performance during operation;
4) The hardware modifications required to the EV, if any, are minimum, which allow vehicle manufacturers to easily make their vehicles compatible with this technology;
5) The charging station could be easily connected to a data network to exchange data with a remote server.

This project aims at demonstrating the feasibility of the proposed method on a small-scale (a few kW) proof-of-concept prototype of a simplified EV powertrain (composed only of battery pack, power converter and battery management system), connected to an external charger and a data acquisition and processing unit. The adopted methodology to achieve this objective involves the following main tasks:

1) Design and assembly of a flexible power converter and battery management system (BMS) that allows implementing the necessary control functions (the embedded control of off-the-shelf BMSs does not usually allow that, even if the hardware has the capability to do so);
2) Implementation of suitable control functions in a real-time controller to create AC perturbations based on the power converter connected to the battery, while charging the battery at constant (DC) current;
3) Design and assembly of a suitable signal conditioning and acquisition system to acquire the battery voltage and current measurements, with the necessary accuracy and frequency bandwidth to allow performing EIS;
4) Implementation of signal processing algorithms to accurately calculate impedance values from the measured battery current and voltages, in non-stationary conditions (due to the charging transient);
5) Finally, exploration of the feasibility of achieving all the acquisition, processing and control functions above in a low-cost hardware platform, to keep the implementation cost for the proposed methodology as low as possible.

Apart from task no. 5 above, all measurements in the project are performed by using state-of-the-art sensors and signal acquisition devices to guarantee accurate results and reliable conclusions.

3. How the idea was generated

The idea of using power converters for low-cost EIS in commercial applications was proposed by the PI in 2014, firstly with application to fuel cells [6-7] and then to batteries [8]. These publications gained international recognition and led the PI to be awarded the 2016 Best Application Award by the IEEE Instrumentation and Measurement Society. Similar ideas have been recently proposed also by other independent researchers [9-14], but all the works published so far (to the best of the PI's knowledge) were applied only to small-scale batteries (or fuel cells), composed of one or few elementary cells, and were mainly focused on EIS measurement during the operation of the electrochemical device as power source (i.e. the discharge for a battery).

The application of this technology to EVs (or similar large-scale commercial applications) requires a significant amount of research in instrumentation and measurement to address the challenges that arise when monitoring tens or hundreds of cells, as in typical EV battery packs. This project aims to address some of those challenges, based on the experience gained by the PI in several years of research on condition monitoring of batteries and fuel cells, in particular related to conditioning, acquisition and processing of voltage and current signals.

The idea of measuring EIS during the battery charging, instead of battery operation, was generated to address one of the main challenges that appear when attempting to measure EIS during typical battery discharge cycles in EVs. The acquisition of a full impedance spectrum requires to cover a very wide frequency range, down to the milli-Hertz range or even below that; this means that the period of the current and voltage waveforms can be as long as several minutes. According to the definition of impedance, the battery is required to remain in steady-state conditions during the whole measurement time, but this is very unlikely to happen in the normal operation of EVs, characterised by continuous and unpredictable transients. On the contrary, during the charging process, the DC current is kept constant for most of the charging time, so the only transient that affects the battery voltage is the slow increase due to the charging itself. This can be more easily compensated by the signal processing and allows accurately measuring EIS down to much lower frequencies compared to EIS measured during battery discharge, in addition to all the other advantages listed in the previous section.

4. Assumptions made

The following assumptions have been made in the definition and development of this project:

1) The fact that EIS would be useful to estimate the state of charge and state of health of batteries is assumed to be true, regardless of the specific battery technology used in EVs, based on the vast scientific literature on the subject (see, e.g., [1-5]). This project focuses only on the technical challenges associated with the implementation of EIS in EVs based on power converters, not on the interpretation of the EIS results, which is partially already known and whose discussion is beyond the scope of the project.

2) Design details of power converters presently used in commercial EVs are not known by the PI because this information is not publicly available. However, based on the available knowledge, it is reasonable to assume that all EV powertrains include a DC/DC and/or DC/AC converter to control and convert the battery DC voltage and current during both the vehicle operation and the battery recharging; it is also reasonable to assume that such a converter operates in switch mode, because of the high power involved, although this is not strictly required for the proposed methodology to be valid, as long as the converter controller can control the battery voltage and current with a fast dynamics. It is worth noting that a faster or slower control dynamics would only imply a different limitation to the EIS frequency range that can be achieved, without hindering the validity of the whole method; moreover, if a faster dynamics is required this can be usually obtained with only minor (if any) hardware modifications.

3) The proposed method requires the voltages and currents of individual cells (or small groups of cells) to be measured; the necessary sensors and connections must therefore be available in the battery pack and BMS. This is assumed to be the case for all EVs (as well as most other applications), because voltages and currents are typically monitored by the BMS to achieve control and protection functions. The only issue might be in the frequency bandwidth of the instrumentation used to measure those signals (e.g., current transducer, amplifiers, filters, etc.), which may be slightly more limited than what is required to measure a full impedance spectrum; however, considerations similar to those made above for the control dynamics apply also in this case.

5. Technologies and equipment used

5.1 Battery pack

To test the proposed method, a LiFePO4 battery pack has been chosen, manufactured by K2 Energy and assembled by the project team at the University of Liverpool. LiFePO4 technology was chosen because it is among the most common solutions for EV battery packs, and because of its good safety characteristic, appropriate for the type of laboratory tests envisaged in this project.

The elementary cells used in the chosen battery pack are 26650 cylindrical cells, with 3.2 V nominal voltage and 3.2 Ah nominal capacity. These cells are assembled by the manufacturer in 1S28P modules, each of them composed of 28 cells in parallel, with an overall nominal capacity of 89.6 Ah. A battery pack was then assembled by the project team, composed of 16 of these modules connected in series, to reach a nominal voltage of 51.2 V and a nominal energy storage of approx. 4.6 kWh. The specifications of the cell, module and pack are summarised in Table 1, and photographs of them are shown in Fig. 3.

Table 1: Specifications of K2 Energy LiFePO4 batteries used in this project

	26650 cell (K226650E02)	1S28P module (K2B3V90E)	16S1P pack
Nominal capacity (@ C/5)	3.2 Ah	89.6 Ah	89.6 Ah
Average voltage	3.2 V	3.2 V	51.2 V
Nominal energy	10.24 Wh	286.7 Wh	4.588 kWh
Rec. discharge current (cont.)	≤ 3.2 A	≤ 90 A	≤ 90 A
Rec. charge current	≤ 1.6 A	≤ 18 A	≤ 18 A

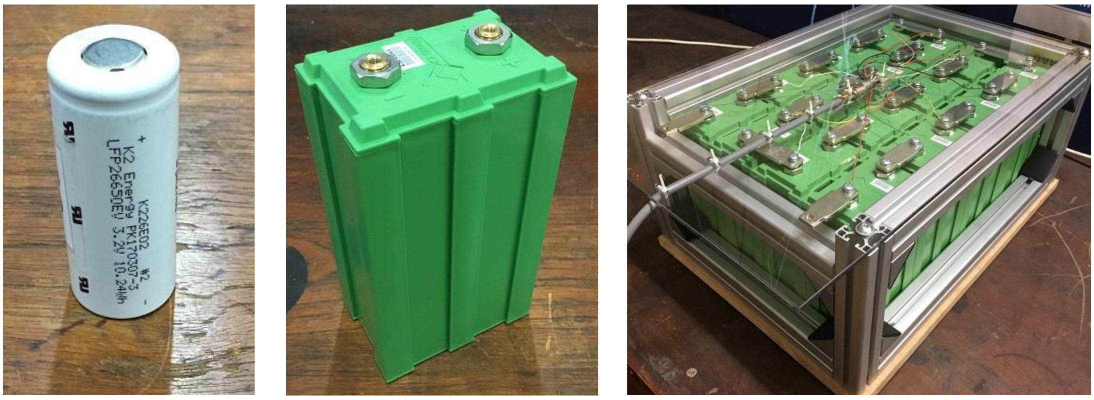

Fig. 3: Photographs of single cell (left), 1S28P module (centre) and 16S1P pack (right) used in the project

5.2 Power converter

To test the single cell, the module and the battery pack, a 1.5 kW, 80 V, 60 A adjustable power supply has been used, which meets the requirements to charge the pack up to the maximum recommended current. This power supply emulates the power source provided by the charging station and (in case of AC power) converted by the AC/DC stage of the EV on-board converter.

A switch-mode DC/DC buck converter was then designed and assembled to connect the power supply to the battery pack, in order to emulate the EV powertrain and to implement the proposed monitoring method, according to the aim of the project. The converter was designed to operate in PWM mode at 100 kHz switching frequency, and to output the DC current (up to 18 A) and voltage (up to 58 V) required to charge the battery pack, with a nominal input voltage of 65 V, provided by the power supply. The output LC filter was designed to practically remove the frequency components at (and above) the switching frequency from the output current and voltage, but to keep frequency components up to 1 kHz, in order to measure the battery impedance up to this frequency, if necessary.

A simplified equivalent circuit of the DC/DC converter is shown in Fig. 4, together with a photograph of the assembled prototype.

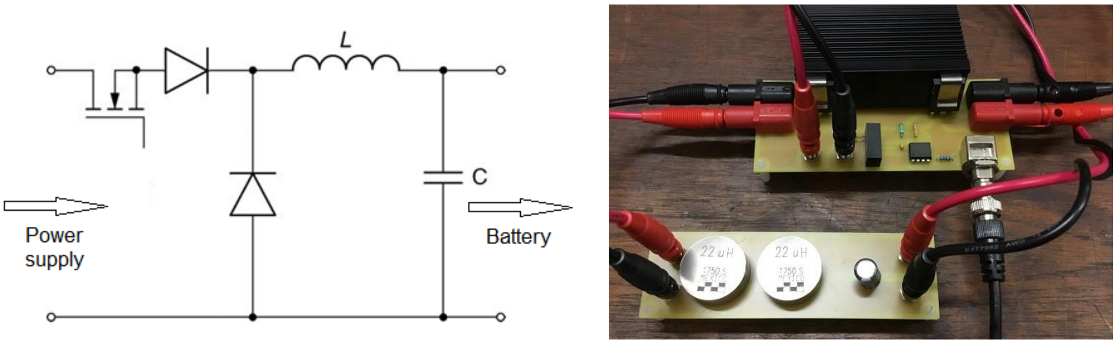

Fig. 4: Simplified equivalent circuit of the DC/DC buck converter (left) and photograph of the prototype used in the project (right)

5.3 Measurement and control

Two different hardware platforms have been considered in this project to acquire the current and voltage signals, process them and control the operation of the DC/DC converter. The main platform used is a National Instruments Compact-RIO (NI cRIO 9035), which is a state-of-the-art standalone system with embedded FPGA, real-time controller and a number of modules for analog and digital input/output. The FPGA and controller in the Compact-RIO have been programmed in LabVIEW to acquire the current flowing through the battery pack and the individual voltages of the 16 modules composing the pack, to process them in real-time and to generate the PWM signal for the DC/DC converter with a real-time control of the converter output current (i.e. the battery charging current). A photograph of the Compact-RIO, with the relevant acquisition and generation modules, is shown in Fig. 5.

Fig. 5: National Instruments Compact-RIO (main picture), used to implement the signal acquisition and control function, together with some of the isolation amplifiers (bottom-right corner) used to condition the battery module voltages before they are acquired

The battery current is measured by a Hall-effect closed-loop current transducer (LEM LA 25p), and acquired by a 16-bit 100-kSa/s ADC (module NI 9215). The voltages of the individual battery modules must be isolated and referred to a common ground before they can be acquired by the Compact-RIO; for this purpose, isolation amplifiers have been used (AD 204), which have a frequency bandwidth of 5 kHz, suitable for EIS measurements. The amplifiers are also used to remove a constant offset from the battery voltages, in order to increase the measurement resolution of the AC perturbation, by maximising the range of the ADC. A picture of the amplifiers is also shown in Fig. 5 (three channels only). The output range of the amplifiers is ±5 V, which matches the selected input range of a 16-bit 16-channel ADC (module NI 9205), used to acquire the 16 isolated battery voltages, with an aggregated sampling frequency of 250 kSa/s.

A PI controller has been implemented in the FPGA of the Compact-RIO to adjust the duty cycle of the PWM signal in real time in order to control the battery charging current according to a pre-defined reference (stored in the on-board memory); the PWM signal is generated by a fast digital output (module NI 9401). The reference current contains a DC component and a small (less than 5%) AC perturbation superimposed to it; the DC component is used to charge the battery, while the AC component is used to measure the battery impedance.

Temperature measurements are also available, as in most commercial battery packs, to monitor the temperature of the individual battery modules within the pack. An array of digital temperature sensors (DS18B20) is used for this purpose.

Finally, a low-cost hardware platform has also been considered in this project as a possible alternative to the National Instruments hardware for a low-cost implementation of the proposed monitoring method. The chosen platform is the BeagleBone Black board, shown in Fig. 6, which contains a Texas Instruments 1-GHz AM3358 ARM Cortex-A8 processor (supporting several open-source operating systems, such as Linux), as well as two separate 200-MHz programmable real-time units. The board features a number of digital input-output channels (including a fast PWM output) and an 8-channel, 12-bit, 200-kSa/s ADC, which is suitable to acquire the battery voltage and current signals with acceptable sampling frequency and resolution. The real-time units are used to acquire the input signals and control the PWM generation, whereas the main processor is used to process the voltage and current measurements, which does not have a strict real-time requirement.

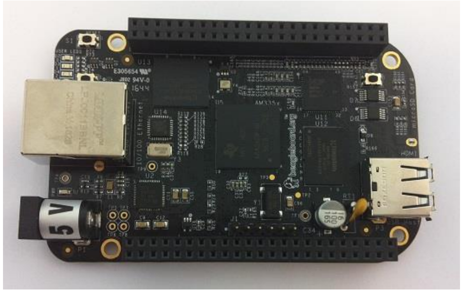

Fig. 6: BeagleBone Black board, used to explore a low-cost implementation of the proposed method

6. Outcome of the project

The main achievement of this project are discussed with reference to the list of tasks reported in Section 2:

1) The developed hardware, including both the power converter and the signal conditioning circuits, has been successfully tested. It meets the design specifications, although the performance of the power converter is not as good as that of commercial converters; this was expected and represents an important limitation in the whole prototype because it affects the quality of the current and voltage waveforms in higher-power tests, but does not jeopardise the validation of the proposed method.

2) The PI controller implemented in the Compact-RIO can accurately control the battery charging current and superimpose AC perturbations up to at least 100 Hz, which is enough to measure the part of the impedance spectrum of greatest interest. AC perturbations can either be sinusoidal or can contain several frequency components covering a wide frequency range, as illustrated in Fig. 7. The battery response to such a current perturbation is nonlinear (especially at low frequencies), but can be well approximated by a linear response (as required by the definition of impedance) because the perturbation is small, as confirmed by Fig. 7. An impedance value can therefore be calculated for each of the chosen frequencies, and monitored during the charging transient and over the battery life time.

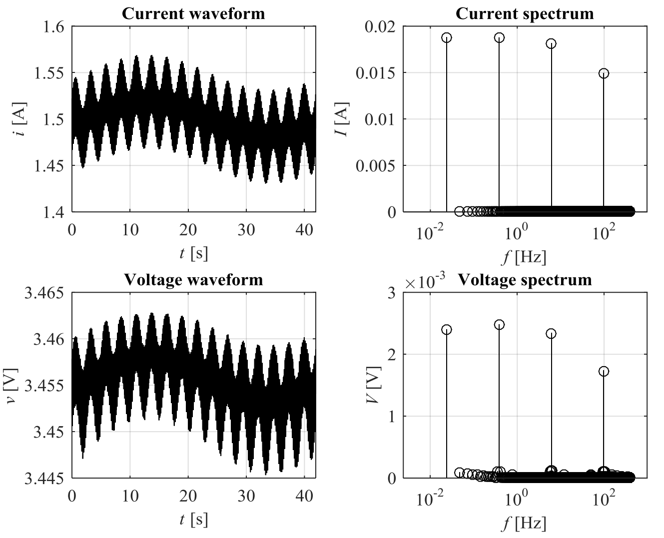

Fig. 7: Multi-sine current perturbation (top) containing frequency components from 20 mHz to 100 Hz, and battery voltage response to such perturbation (bottom)

3) Signal processing algorithms have been successfully implemented to accurately calculate the battery impedance from the measured voltage and current. The voltage is not a periodic signal because of the monotonic increase due to the battery charging; such a drift must be removed from the voltage waveform before the Fourier Transform is applied, to avoid errors in the impedance calculation. For most of the transient, the voltage increase can be well approximated by a linear drift and can therefore be removed with a relatively simple fitting algorithm that is suitable to be executed in real time. The algorithm has been tested and results are satisfactory.

4) Finally, preliminary but promising results have been obtained also with the BeagleBone Black board, to replace the Compact-RIO in lower-cost implementations of the proposed method. Successful tests have been completed with voltage and current acquisition from a single battery cell/module, with a sampling frequency of 16 kSa/s for each signal, and PWM generation at 100 kHz. The real-time control of the battery current and real-time impedance calculation have also been tested, with perturbation frequencies up to 100 Hz.

7. Limitations

At present, the main limitation of the whole prototype lies in the relatively poor performance of the power converter, compared to commercial standards. This affects the closed-loop current control system and, in turn, the quality of voltage (and to a lower extent, current) waveforms. Further improvements in the converter design may improve the performance, but the best way to overcome this limitation would be to use a commercial converter. This is the natural next step in the development of the project, but would greatly benefit from a collaboration with a converter manufacturer to be able to use the converter with all the flexibility required according to the aim of the project.

As a consequence of the above limitation, the impedance data acquired from the complete battery pack is limited in terms of both quantity and quality. Nevertheless, the proof of concept of the proposed monitoring method can be considered accomplished, because the developed system (hardware and software) can successfully inject the necessary AC perturbations into the battery charging current and measure the AC voltage response from the individual battery modules, which is what is required to measure the impedance. A better quality of the voltage waveforms, when achieved, will thus naturally lead to a better quality of the impedance measurement, with no modifications required to the system.

8. Practical applications to the UK transport system

The charging infrastructure for EVs will significantly expand in the next years, as the number of EVs on the roads increases. If a collaboration with a charging station manufacturer can be established for future developments of this project, the proposed technology could be eventually implemented in the design of a new generation of smart charging stations (compatible with a new generation of EVs) that can achieve an accurate monitoring of the state of health of the battery while recharging it.

This would help the take-up of EVs by increasing their reliability and the user's confidence in them, with the following potential benefits:

1) The user would become more confident to embark on long journeys and more willing to accept an electric vehicle as their only/main vehicle;
2) The risk of breakdown, with consequent recovery cost and impact on traffic, would be significantly decreased;
3) The data could be made available to the network provider and vehicle manufacturers for a collective monitoring of electric vehicles on the roads.

9. Next steps

The simplified EV powertrain prototype developed in this project is now fully operational, though with the limitations discussed above, and can therefore be used by the PI's research group to generate other useful data in the next months, with no need for additional financial resources, as a PhD student will be able to use the system as part of his PhD project. Part of the research activity in the next months will also aim at improving the performance limitations discussed above.

In parallel to this, engagement with all relevant stakeholders will continue, focusing in particular on establishing collaborations with industrial partners and strengthening the existing collaboration with the National Physical Laboratory to consider the measurement standards that may be needed to actually apply the proposed technology to the UK transport system.

Follow-on funding will be sought to carry out any additional research activity that may be necessary to increase the technological readiness level of the proposed solution.

10. Conclusions

A simplified EV powertrain prototype has been successfully designed and assembled, composed of a 4.6 kWh $LiFePO_4$ battery pack, a DC/DC power converter, a real-time converter controller and a signal conditioning, acquisition and processing system. An innovative control of the DC/DC converter has been tested, to inject AC perturbations into the DC current used to charge the battery. Such perturbations, together with appropriate signal conditioning and processing, are suitable to measure the battery electrochemical impedance, which in turn can provide a wealth of diagnostic information about the battery state of charge and state of health.

The project outcome confirms the feasibility of the proposed method, but highlights important challenges associated with the performance of the DC/DC converter, which is critical to guarantee a good quality of the battery voltage waveforms and thus also of the impedance measurements. The use of a commercial converter appears to be the best way to achieve the desired performance levels, but a collaboration with the converter manufacturer may be necessary to be able to control the converter with the flexibility required according to the proposed method.

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