A Flexible Real-Time Measurement and Control System for Enhanced In-Situ Battery Monitoring

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***Abstract*—As the applications of batteries in power systems are significantly growing in number and power ratings, the importance of an accurate battery monitoring has become even more critical. Most commercial applications use a Battery Management System (BMS) to monitor the state of the battery and ensure a safe, reliable and efficient operation. A BMS is typically designed to acquire DC (slowly changing) voltages and currents and to control the power transfer from the battery to the load, with a relatively slow dynamics. However, to enhance the state-of-health monitoring, recent works have proposed methods to achieve battery impedance measurements in commercial applications, at frequencies up to the kilohertz range, or higher. The typical BMS design would not be suitable to control the battery operation fast enough to create the required AC perturbations and to measure and process the battery AC voltage and current signals. In this paper, a low-cost architecture is presented, suitable to achieve the fast real-time acquisition and control but also a flexible signal processing and data analysis required to estimate the battery state, in addition to the normal functions of a BMS. The proposed solution is based on the BeagleBone Black board, which combines a general-purpose ARM processor with two real-time micro-controllers, analog-to-digital converters and digital inputs/outputs. The strategy to implement all the required functions is presented, and preliminary results are reported.**

***Index Terms*—Batteries, Battery management systems, Condition monitoring, Measurement, Control Systems, Real-time systems, Microcontrollers**

I. INTRODUCTION

The applications of batteries in power systems have been growing at a fast pace, driven by the development of renewable energy generation and the demand for decarbonization of transport. As batteries are increasingly employed in applications that must guarantee a high reliability, including (but not limited to) electric vehicles, an accurate monitoring of the battery state has become crucial.

All commercial applications of batteries require some sort of Battery Management System (BMS) to monitor the state of the battery while charging and discharging, as schematically illustrated in Fig. 1. The basic function of a BMS is the protection of the battery from under/over-voltage, over-current and over-heating, to avoid failure and ensure a safe operation. To achieve this aim, a BMS typically measures the battery (DC) voltage and current, as well as its temperature. If any of these quantities falls outside the specified safe range, the battery is disconnected from the load/charger, or at least the generated/absorbed power is limited. More advanced functions of a BMS may include cell balancing and other energy management strategies, to maximize the energy storage capacity, increase the efficiency and achieve a longer life time [1], [2].

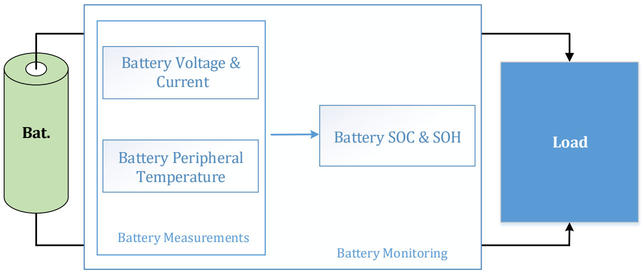

Fig. 1. Schematic illustration of typical BMS monitoring functions.

Signal processing and state estimation algorithms are often implemented in a BMS to estimate the State of Charge (SOC) and State of Health (SOH) of the battery. The algorithms can range from a simple numerical integration of the current to estimate the SOC variation, to much more sophisticated model-based data fitting and/or machine learning methods [2]. In most cases, however, the input quantities used for the estimation are only the battery voltage, current and temperature, measured during the operation. As these quantities normally change quite slowly, a BMS does not require a very high frequency bandwidth in the signal conditioning (filters, amplifiers, etc.) and acquisition (ADC) elements, which would be difficult to afford when a large number of cells have to be monitored in a battery pack. Therefore, most commercial BMS have a frequency bandwidth limited to approximately 1 kHz or less.

Even the most sophisticated SOH estimation methods have important limitations, mainly due to the limited information that can be extracted from the battery DC voltage and current, compared to the complexity of the electrochemical processes occurring within the battery. In the attempt to address this issue, recent works have proposed possible solutions to achieve Electrochemical Impedance Spectroscopy (EIS) [3], [4] in commercial applications, which would allow obtaining much more detailed and accurate diagnostic information about the

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battery state. The proposed methods are based on an innovative control of the power converters connected to the battery, in order to create the current (or voltage) AC perturbations that are required to measure the battery impedance [5]–[14].

Compared to the traditional BMS functions, the implementation of EIS measurements up to the kilohertz range requires a higher sampling frequency for voltage and current signals, a faster real-time control of the power converter connected to the battery, and the processing of a larger amount of data to calculate the impedance and estimate the battery state. Some works in the literature have simplified the controller implementation by using an open-loop control of the sinusoidal perturbation [7]–[9], while those using a closed-loop control have opted for a Digital Signal Processor (DSP) [6] or a Field Programmable Gate Array (FPGA) [10] to implement the real-time signal processing and control functions. In many cases, however, post-processing in external software, such as Matlab, was necessary to complete the data analysis and estimate the state of the battery [9], [10].

This paper proposes an alternative approach that combines a general-purpose ARM processor with real-time micro-controllers, to meet all the signal acquisition and control requirements while providing more flexibility in the signal processing and data analysis. The proposed architecture is based on the BeagleBone Black (BBB) board, which includes an ARM Cortex-A8 processor, two 32-bit micro-controllers, an 8-channel analog-to-digital converter (ADC) and digital input/output ports. Some basic measurement and real-time applications based on this board have recently appeared in the literature [15]–[18], and a preliminary investigation into its possible use for battery monitoring was presented by the Authors of this paper in [12], but with a limited dynamic performance. This paper presents a novel implementation strategy to achieve the fast dynamics required for high-frequency impedance measurements.

II. CONTROL AND MEASUREMENT SPECIFICATIONS

The battery dynamics is the result of the interplay of several electrochemical processes, occurring on very different time scales, from milliseconds to days. EIS is a very powerful diagnostic technique that allows distinguishing between the different processes, as each of them affects the impedance spectrum at different frequencies [3], [4]. A complete impedance spectrum should therefore cover a very wide frequency range, typically from millihertz to kilohertz.

Different batteries, in different conditions, have different impedance spectra, but a typical (simplified) spectrum is reported in Fig. 2 for illustration purposes, together with its interpretation in terms of equivalent electrical circuit. The millihertz range is dominated by the ion mass transport, the hertz range by the double layer charge transfer, and the kilohertz range by the ohmic phenomena. Monitoring the whole impedance spectrum is important because it allows estimating the SOC and SOH of the battery. In particular, the ohmic resistance, measured in the kilohertz range, can be conveniently used as a SOH indicator in lithium-ion batteries because it is not significantly affected by variations in the SOC, whereas it changes with the battery aging [3].

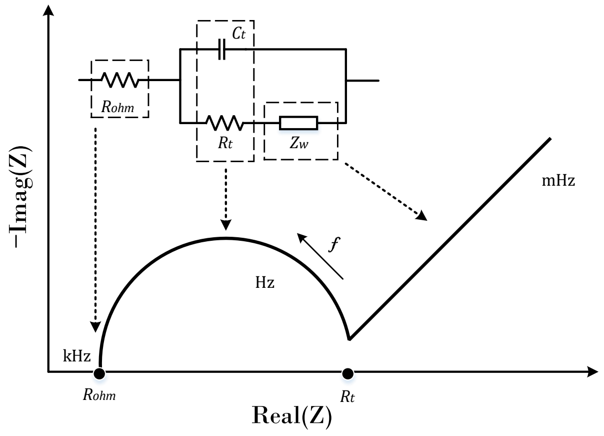

Fig. 2. Typical spectrum of a battery and corresponding equivalent circuit; Z_W is the Warburg impedance [3].

Measuring the battery impedance up to the kilohertz range requires a sampling frequency around 10 kHz or above to acquire the voltage and current waveforms. This is beyond the typical specifications of a BMS, which is designed to acquire only DC waveforms with relatively slow transients. Moreover, the AC perturbations in the battery current (or voltage) must be created in the first place, e.g. by controlling the DC-DC converter connected to the battery, and this requires a fast closed-loop real-time controller to guarantee a good waveform quality.

A simple example of a switch-mode DC-DC boost converter connected between the battery and the load is illustrated in Fig. 3. Assuming a pulse width modulation (PWM) control of the switch, and considering all elements in the converter ideal (i.e., with no losses), the relationship between the input and output voltages and currents is a function of the duty cycle d, i.e. the fraction of the switching period when the switch is closed:

$$V_o = \frac{V_i}{1-d} \quad , \qquad I_o = (1-d)\,I_i \tag{1}$$

where $V_{i,o}$ and $I_{i,o}$ are the average values of voltages and currents, either constant or slowly changing compared to the switching period. A fast control of the duty cycle can therefore create AC components in the battery current and voltage, suitable to measure the battery impedance at different frequencies. In order to create a good quality sinusoidal waveform, its frequency must be significantly lower than the converter switching frequency (PWM frequency). Nowadays, MOSFETs and IGBTs can easily reach switching frequencies up to 100 kHz and above (particularly in case of low-power MOSFET-based converters), so they are suitable to measure the impedance up to the kilohertz range, if a suitable control system can control the duty cycle on a timescale of a few microseconds, with a suitable resolution.

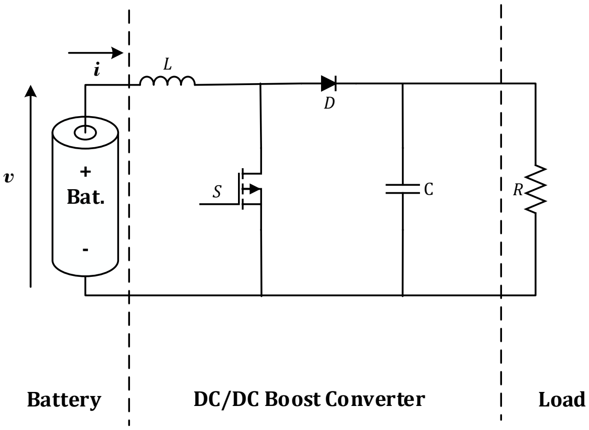

Fig. 3. Basic DC/DC boost converter connected between battery and load.

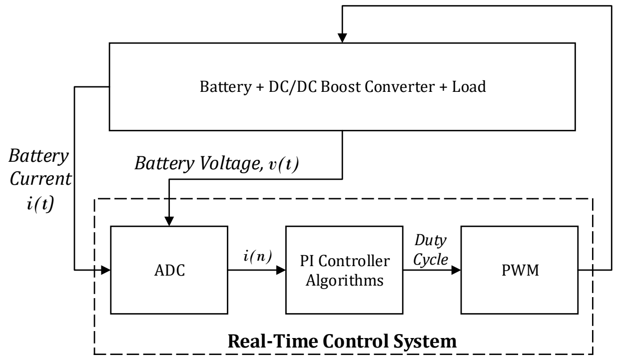

Fig. 4. Overall diagram of the proposed system architecture (acquisition and control).

Some works in the existing literature have proposed adding a sinusoidal modulation to the duty cycle to avoid the requirement of such a fast closed-loop control [7]–[9], but the relationship between the duty cycle and the battery current (or voltage) is generally nonlinear and it depends on the relationship between the output voltage and current (given by the load). Therefore this approach, though practically convenient, may lead to inaccurate results; moreover, the control of the perturbation amplitude is more difficult to achieve because it requires an accurate model of the whole circuit, as it is an open-loop control.

The objective of the work presented in this paper is the implementation of an affordable embedded control system that can enhance the functions of a standard BMS to:

1) acquire current and voltages of up to 7 cells connected in series, with a sampling frequency of at least 25 kHz for each signal;
2) use the current measurement as a feedback to control the duty cycle of the DC-DC converter in real-time, in order to create AC perturbations in the current with frequencies up to at least 1 kHz;
3) generate a PWM signal synchronized with the analog signal acquisition;
4) process the large number of samples acquired to calculate the battery impedance from the voltage and current measurements;
5) allow a flexible post-processing, data analysis and visualization to present the results to the user or to transfer them to a remote system.

A schematic illustration of the proposed system (acquisition and control part) is shown in Fig. 4.

It is worth noting that the operation of the proposed system is mostly independent of the power rating of the battery. The main limitation is the number of analog input channels (eight) available in the chosen hardware platform, which practically limits the number of cells that can be monitored simultaneously. While battery packs used in power system applications are usually composed of many tens or hundreds of cells, those cells are often grouped in modules, which can be regarded as equivalent larger cells for the purpose of the impedance monitoring (also because the individual cell terminals are often not accessible externally). If more analog channels are still necessary, external ADCs can be easily connected to the system through digital ports, thus increasing the number of cells or modules that can be monitored.

The power rating of the battery pack affects also the design of the DC-DC converter, and in particular it may limit the maximum achievable switching frequency. However, even in power system applications, most DC-DC converters nowadays can achieve switching frequencies higher than 10 kHz, which are adequate to measure the battery impedance up to 1 kHz.

III. IMPLEMENTATION STRATEGY

The BeagleBone Black board is a low-cost (approx. $50) Texas Instruments development platform with some unique features that make it a suitable choice for the design of the monitoring system described above. The main difference compared to DSP-based solutions described in the literature [6], [8] is that the BBB is based on a general-purpose 1-GHz ARM Cortex-A8 processor (AM3358). This makes it similar to a basic computer, supporting several operating systems such as Linux, and offers advantages in terms of flexibility, ease of programming and integration with commercial software. The ARM processor does not normally run in real-time, so it is not suitable for the real-time acquisition and control functions, but in the BBB it is combined with two 200-MHz programmable real-time units (PRUs) that share the same data bus with the ARM processor, thus allowing a fast and simple exchange of data. The real-time functions can therefore be implemented in those PRUs, while the ARM processor can process the signals to calculate the impedance, estimate the SOH from it and directly present the results to the user or transfer them to a remote system.

An important advantage of this solution, as opposed to standalone micro-controllers, is that the BBB's PRUs can be conveniently programmed through the main processor, within the PRU industrial communication subsystem (PRU-ICSS) architecture. This is allowed by dedicated libraries, some of which recently developed [19]. The real-time functions are threaded by the ARM processor, creating executive tasks to manipulate PRU's events under the PRU-ICSS mechanism. In a similar way, the host program acts as the communication bridge to transfer data between the PRU and the host (ARM) machine. The BBB includes a 512-MB RAM memory that can be used to store reference waveforms for the creation of the AC perturbations, as well as for transferring the measured signals from the PRU to the processor.

The BBB also includes an 8-channel, 12-bit, 200-kHz multiplexed ADC, suitable to acquire the battery voltage and current signals (properly conditioned), and a digital output suitable to create the PWM signal to control the DC-DC converter. Both the ADC and the PWM output can be controlled by the PRUs; this ensures real-time operation and a synchronization between the signal sampling and PWM generation. The solution presented in this paper is based on the acquisition of three analog input channels, two for the battery voltage and current and a third channel for temperature measurements (in case an analog sensor is used), as temperature is typically monitored by a BMS in addition to voltage and current. With those three analog inputs, the maximum sampling frequency that can be achieved is 66 kHz, which is enough for impedance measurements up to at least 10 kHz. The same frequency (66 kHz) is also a suitable choice for the PWM signal that controls the DC-DC converter. This is an optimal trade-off between high switching frequency and duty cycle resolution; as the PRU clock runs at 200 MHz, the PWM period contains approximately 3000 clock cycles, corresponding to a duty cycle resolution of 0.033%. If more than three analog input channels are used, the maximum achievable sampling frequency will decrease (down to 25 kHz for 8 channels), but it will still be enough to carry out EIS in an appropriate frequency range; on the other hand, the duty cycle resolution will improve as the switching frequency decreases.

The 15-μs (3000 clock cycles) PWM period is also enough to allow the PRU to execute all real-time functions, namely the acquisition of new samples from the ADC, the execution of the controller algorithm (e.g., a PI controller) and the calculation of the updated on-time and off-time for the PWM signal. This sequence of operations is illustrated in Fig. 5. In the operation of the boost converter, the duty cycle can ideally vary from 0 to 1, but an upper limit lower than 1 is recommended to prevent the battery from generating a too large current; this means that the off-time in the PWM signal will have a minimum duration, while the on-time can be as small as zero. All the real-time functions described above can therefore be implemented during the off-time, as long as their combined execution time is less than the minimum off-time, which is the case for the chosen design. This sequence of operations and the corresponding timing are illustrated in Fig. 6, in case of a 60% duty cycle, as an example. The total execution time for the ADC sampling and controller algorithm is less than 4 μs, which practically limits the maximum duty cycle to 74%.

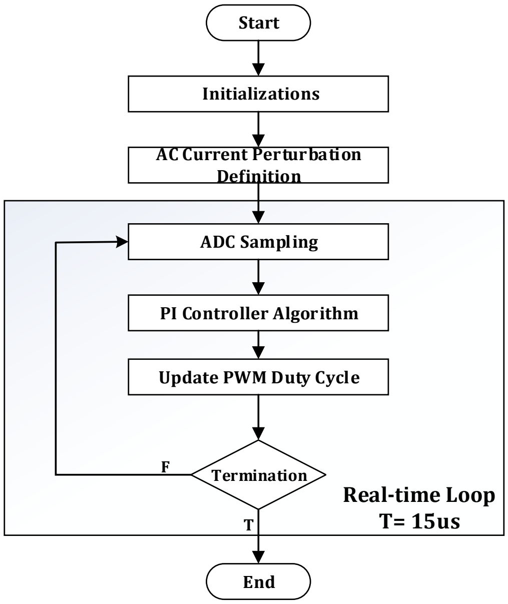

Fig. 5. Real-time functions implemented in the PRU.

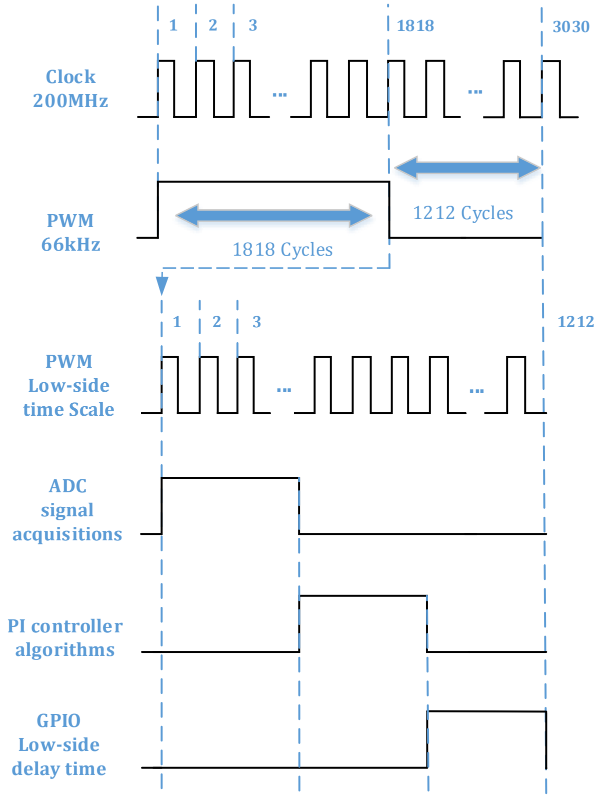

Fig. 6. Illustration of timing for the ADC sampling and PWM signal generation, in case of 60% duty cycle.

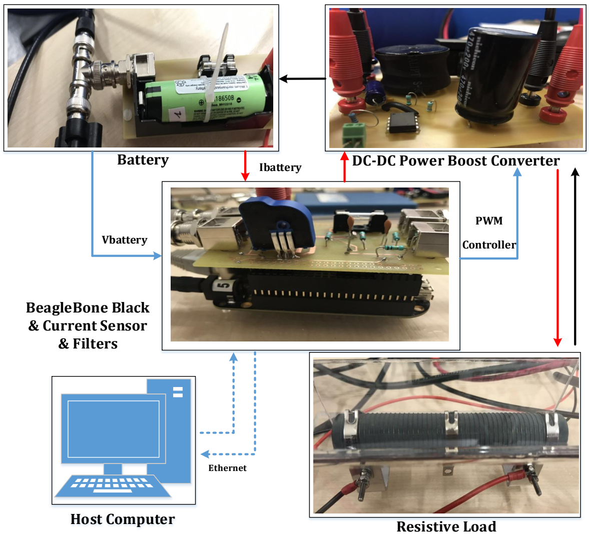

Fig. 7. Block diagram of the experimental setup.

IV. EXPERIMENTAL RESULTS

The proposed monitoring system has been tested on a Panasonic lithium-ion cell (NCR18650B), with 3350-mAh rated capacity and 3.6-V nominal voltage. A block diagram of the experimental setup is shown in Fig. 7. The cell is connected to a home-made DC-DC boost converter, with the same topology illustrated in Fig. 3, using a MOSFET as controlled switch and a 10-Ω resistor as load. The converter circuit has been designed to allow an AC ripple on the primary current at frequencies up to 1 kHz, according to the aim of the work; the input inductor has an inductance of 1 mH, whereas the output capacitor has a capacitance of 470 μF. The battery current is measured by a Hall-effect closed-loop current transducer (LEM LTS 6-NP), with an adjustable nominal current from 2 A to 6 A and a bandwidth up to 200 kHz. Both current and voltage signals are filtered by low-pass filters with a 2 kHz cut-off frequency, in order to decrease the amplitude of both noise and the switching frequency components in the signals; it is worth noting that the switching is synchronous with the sampling, so any residual signal components at the switching frequency (or its harmonics) would mainly affect the DC values and not the AC measurements, when sampled. The voltage signal needs also to be decreased in amplitude, by using a voltage divider, in order to match the ADC input range, which is limited to 1.8 V. In higher-voltage applications, or when several cells are monitored, an isolated voltage transducer may be used instead of the voltage divider, but this does not affect the operation of the proposed system.

The signal acquisition and control functions are implemented in the BBB according to the strategy described in Sec. III. In particular, a PI controller has been implemented in the PRU of the BBB to control the current waveform in real-time. The system has been tested in a wide range of frequencies up to 1 kHz, according to the aim of the work.

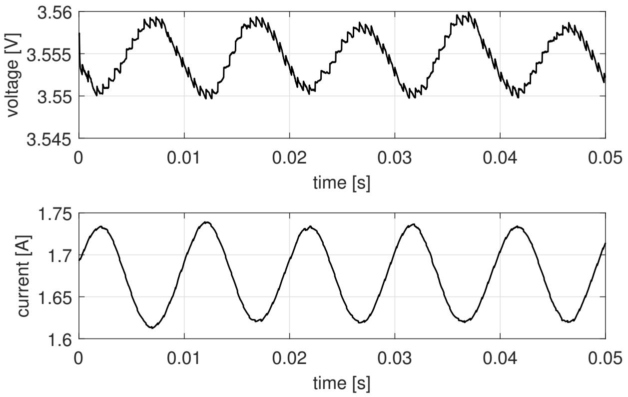

Fig. 8. Measured battery voltage and current waveforms, containing an AC perturbation at 100 Hz.

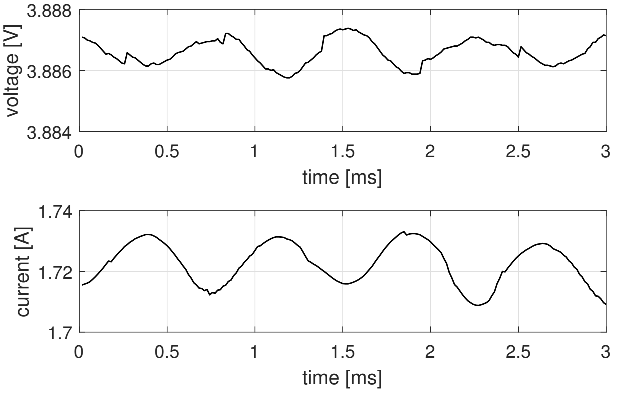

Fig. 9. Measured battery voltage and current waveforms, containing an AC perturbation at 1.3 kHz.

The controller can achieve high-quality waveforms at frequencies up to 100 Hz. This is illustrated in Fig. 8, which reports a sinusoidal current at 100 Hz, and the corresponding battery voltage response, measured with a separate data acquisition system, at the same sampling frequency used by the BBB, i.e. 66 kHz. The DC current value for the test has been set to 1.68 A, i.e. approximately 0.5C, and the peak-to-peak amplitude of the AC component is 0.1 A, i.e. approximately 6% of the DC value, which is a reasonable limit for practical applications.

Other experimental results are reported in Fig. 9, showing current and voltage waveforms at a frequency of 1.3 kHz, at the limit of the design specifications for the proposed system. In this case, the current peak-to-peak amplitude is smaller (approx. 0.02 A) than in the previous case, due to the challenges of achieving a high-amplitude perturbation at high-frequency with the present controller. The quality of the waveform is also slightly worse, but it can still allow impedance measurements with an acceptable accuracy.

The processing of the current and voltage waveforms to calculate the impedance, and the SOH estimation based on it, are however out of the scope of this paper and will be described in future works.

V. CONCLUSIONS

This paper presented an innovative solution for the design of an enhanced battery monitoring system, suitable to control a DC-DC power converter connected to the battery in order to create AC perturbations in the battery current, in a frequency range up to 1 kHz. This system has the potential to allow *in-situ* battery impedance measurements, to accurately monitor the state of the battery during its operation. Differently from other solutions recently published in the literature, based on micro-controllers, DSPs or FPGAs, the proposed system is based on a combination of a general-purpose ARM processor and real-time micro-controllers, conveniently embedded in a low-cost development board (Texas Instruments BeagleBone Black). This solution offers advantages in terms of flexibility, ease of programming, integration with commercial software (for data post-processing and visualization) and communication to remote systems. A strategy to implement real-time data acquisition and control functions in the BeagleBone Black board has been presented and tested on a prototype composed of a lithium-ion cell connected to a DC-DC boost converter. Experimental results confirm the ability of the system to create good-quality AC perturbations in the battery current, up to 1 kHz, thus meeting the design specifications. Although the proposed system has been tested only on a single battery cell, it can be applied to a larger number of cells or modules, with only minor adjustments, which have been briefly discussed in the paper.

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