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A Fast and Simple Broadband EIS Measurement System for Li-Ion Batteries

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***Abstract* – The application of a low-complexity current generator circuit and multisine signals for Electrochemical Impedance Spectroscopy (EIS) of Li-Ion batteries is presented. The proposed system is comprised of a Howland current pump driven by a general-purpose multifunction DAQ, which provides the excitation signal and acquires current and voltage waveforms from the battery under test. The presented results show that the proposed system can provide comparable results with respect to a reference instrument and potentially obtain a reduction in measurement time with respect to a single sine excitation method.**

I. INTRODUCTION

The measurement of battery impedance is crucial for online monitoring of State of Charge (SoC) and State of Health (SoH) [1]. Such monitoring is required in numerous applications, including electric vehicles, electronic systems, and stationary energy storage [2].

Typically, Electrochemical Impedance Spectroscopy (EIS) measurements are performed using a single sine excitation, which is repeated at several different frequencies [3]. However, broadband excitations, such as multisine, would require shorter measurement time and thus are better suited for online measurement and monitoring applications [4]. As an example, in [5] multisine signals are employed for EIS characterization of biological materials. Furthermore, in [6] multisine signals are used for detecting and modeling nonlinearities in EIS measurement systems for Li-Ion batteries. Other possible broadband excitations include binary and ternary sequences, which can be also applied to system identification [7][8].

In this paper, we present a low-complexity system for fast, broadband EIS on Li-Ion batteries. The system is based on a Howland current pump circuit for the excitation and a general-purpose data acquisition board (DAQ) providing the readout functionality. The basic version of the Howland current pump is used, even though several enhanced versions of the Howland current pump circuits are published in the literature [9]. Furthermore, a shunt resistor is employed for current readout, although several more refined readout methods are commonly applied, such as balancing AC bridge circuits. This is to keep the hardware complexity of the circuit to a minimum, since the proposed system measures both voltage and current, thus it can compensate for non-ideal behavior through signal processing. Also, the use of non-sinusoidal signals may result in additional constraints, more easily satisfied by simple electronic systems.

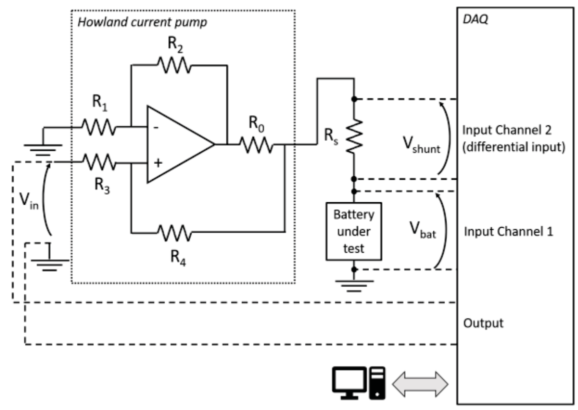

Fig. 1. Block diagram of the proposed system.

II. SYSTEM ARCHITECTURE

The architecture of the proposed system is shown in Fig. 1. The excitation signal V_{in} is generated by an output channel of the DAQ and fed to the Howland current pump circuit. This circuit, which acts as a transadmittance amplifier, converts the voltage excitation signal into a current signal, which is then fed to the battery under test [9]. Channel 1 of the ADC in the DAQ acquires the voltage signal across the battery, whereas the differential input at channel 2 acquires the signal across the shunt resistor R_s. This voltage signal is then transduced to current using the accurate estimate of the resistance R_s, which is measured in a preliminary phase by a DMM in 4-wire measurement mode.

In order to measure the battery voltage, the signal is DC-coupled to the DAQ channel 1. This is to avoid the usage of AC-coupling by means of a high-pass filter, which increases hardware complexity, requires calibration, and introduces uncertainty sources.

Once the acquired records of the voltage and current signals are available, they are processed numerically using frequency-domain techniques based on the discrete Fourier transform (DFT) to obtain estimates of the complex impedance.

III. EXCITATION SIGNAL DESIGN

The proposed system employs a random-phase multisine excitation signal, which is able to simultaneously excite multiple frequencies while avoiding crest factor increase [10]. This signal is comprised by the sum of multiple sinusoids at selected frequencies, each with an initial phase selected randomly in the $[0, 2\pi)$ interval. The excited frequencies are chosen such that they are logarithmically spaced, as in most EIS systems. This choice is motivated by the fact that battery impedance characterization requires analysis over a relatively wide range of frequencies, typically from tens of millihertz to several kilohertz [4].

Furthermore, the excited frequencies, the sampling frequency, and the number of acquired samples are chosen such that coherent sampling is ensured. This implies that the acquired record contains an integer number of periods of every frequency component of the multisine signal. This avoids spectral leakage in the DFT.

In order to correctly estimate the amplitude and phase, the DFT requires that at least one period of every sinusoidal component is included in the acquired record. This represents a lower bound on the duration of the observation window. Finally, to mitigate transient effect that occur at the beginning of the observation window, a portion of the acquired record should be discarded. As a consequence, at least two periods of the lowest excitation frequency should be acquired.

IV. EXPERIMENTAL RESULTS

The proposed system is implemented and tested experimentally using a 16-bit Keysight U2351A DAQ. The Howland current pump circuit depicted in Fig. 1 is implemented using a LF356 operational amplifier supplied at ±12 V. The following nominal resistor values are used: $R_s = 1\ \Omega$ $R_0 = 10\ \Omega$, $R_1 = R_3 = 10\ k\Omega$, $R_2 = R_4 = 1\ k\Omega$, resulting in a nominal gain of 1/100. The samples from channel 1 and 2 are acquired sequentially, and the delay between the channels is compensated in post-processing. The DFT of the acquired signals is computed and the impedance is estimated at the excited frequencies by dividing the complex voltage by the complex current.

Using such experimental setup, the operation of the proposed system is verified by comparison with a reference commercial impedance meter for battery EIS characterization, the Hioki IM3590. This instrument is configured with a frequency range consisting of 200 points from 0.05 Hz to 10 kHz, under fast setting operations. Using such configuration, the instrument needs 25 minutes to complete a full frequency analysis, averaging over 3 repeated measurement results for each frequency point, with a stated expanded uncertainty of 3% of the reading for the amplitude and 0.6 degrees for phase estimation.

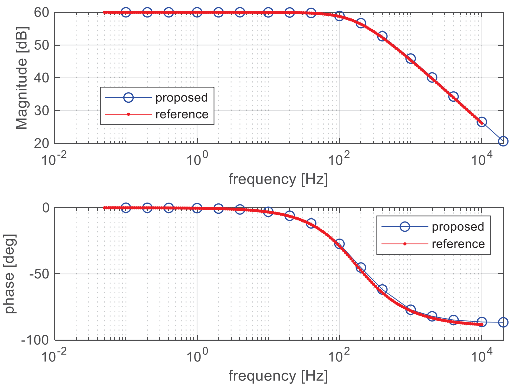

Fig. 2. Bode plot of experimental EIS results obtained on a RC parallel tank. Comparison between the proposed system with a multisine excitation and the reference instrument Hioki IM3590.

Initially, the correct functionality of the measurement system and the reproducibility of measurement results are proven by performing the impedance spectroscopy of a discrete RC circuit. This circuit is comprised by a 1-kΩ resistor connected in parallel with a 1-μF capacitor. For this test, the input excitation signal for the proposed system is a random-phase multisine, designed by taking into account the considerations and requirements described in Section III. In particular, it is comprised of sinusoids in the {0.1, 0.2, 0.4, 1, 2, 4, 10, 20, 40, 100, 200, 400, 1000, 2000, 4000, 10000, 20000} Hz set. The sampling frequency is set to 100 kSa/s and the number of samples to $2 \cdot 10^6$, resulting in an observation window of duration 20 s. The first half of the samples in the record are discarded to reduce initial transient effects, and the impedance is estimated on the resulting 1-million samples record.

The results in Figs. 2 and 3 show a good agreement between the impedance curves obtained by the proposed system and those obtained using the reference instrument. The measurement time of the proposed system is compared with that of the reference instrument. This comparison is performed by setting the Hioki IM3590 to perform the measurement at the same set of frequencies as the proposed system. Under such conditions, the measurement time required by the proposed system is 20 s, compared to 60 s required by the reference instrument.

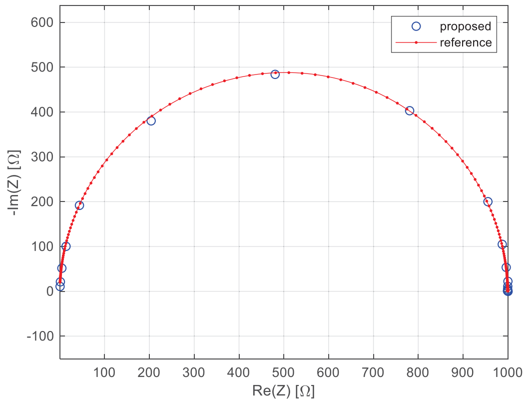

Fig. 3. Cole-Cole plot of experimental EIS results obtained on a RC parallel tank. Comparison between the proposed system with a multisine excitation and the reference instrument Hioki IM3590.

The proposed system is also compared with the reference instrument when applied for battery characterization. The battery under test is a LIR2032 Li-Ion coin cell, with a nominal voltage of 3.7 V. For this test, the designed random-phase multisine contains frequencies in the {0.05, 0.1, 0.2, 0.4, 1, 2, 4, 10, 20, 40, 100, 200, 400, 1000, 2000} Hz set. The sampling frequency is set to 10 kSa/s and the number of samples to $2.4 \cdot 10^6$, resulting in an observation window of duration 240 s. The root-mean-square value of the current signal generated by the Howland current pump is 2.6 mA and the crest factor is approximately 3.9.

The results are shown in Figs. 4 – 6, which are obtained for different values of the open-circuit voltage (V_{oc}) of the battery and by discarding the three lowest values in the frequency set. The measurement procedure is performed by starting from a fully charged battery, which is then discharged for 10 minutes, placed at rest at open circuit for 30 minutes before measuring V_{oc} and performing EIS measurement. This cycle is then repeated to achieve different lower values of V_{oc}.

The proposed system is calibrated by applying a frequency-dependent correction factor $H(f)$ to the raw impedance estimates. The complex correction vector $H(f)$ is computed as $H(f) = \frac{\tilde{Z}(f)}{Z_r(f)}$, where $\tilde{Z}(f)$ is the impedance measured by the proposed system and $Z_r(f)$ is the impedance measured by the reference instrument. Both $\tilde{Z}(f)$ and $Z_r(f)$ are measured at V_{oc} = 3.71 V.

Graphs in Figs. 4 – 6 show that the proposed system provides results that are reasonably close to those of the reference instrument. In particular, it can be noticed that the shape of the Cole-Cole plots is similar and shows the same tendency to become more elongated when V_{oc} decreases. Remaining differences between the two

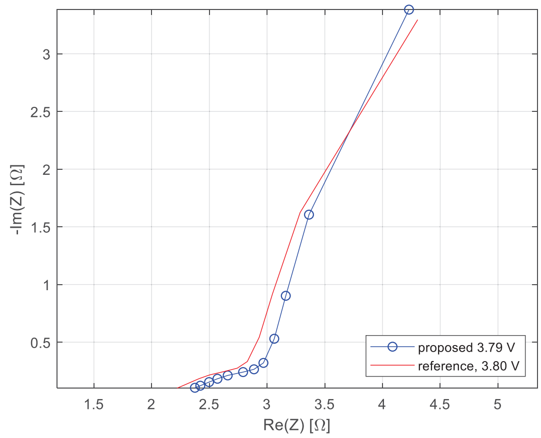

Fig. 4. Cole-Cole plot of experimental EIS results obtained on a Li-Ion battery at V_{oc} =3.79 V.

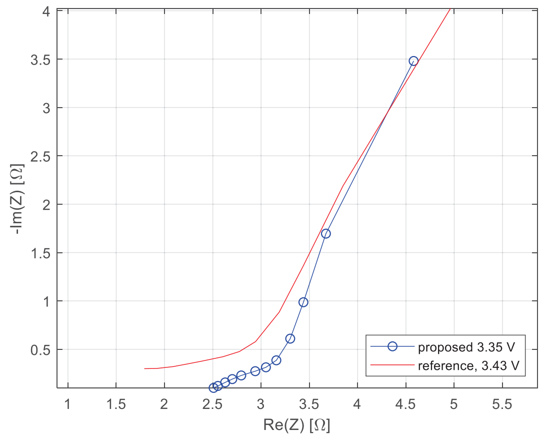

Fig. 5. Cole-Cole plot of experimental EIS results obtained on a Li-Ion battery at V_{oc} =3.35 V.

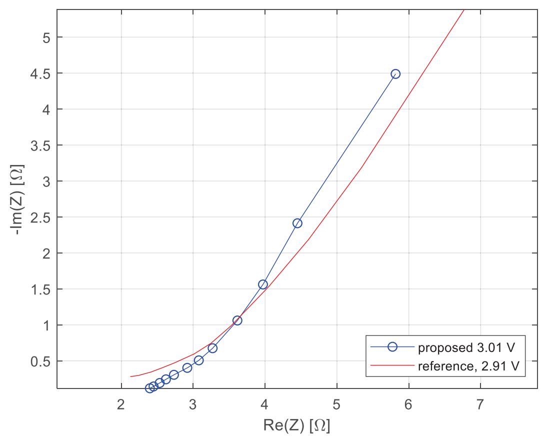

Fig. 6. Cole-Cole plot of experimental EIS results obtained on a Li-Ion battery at V_{oc} =2.91 V.

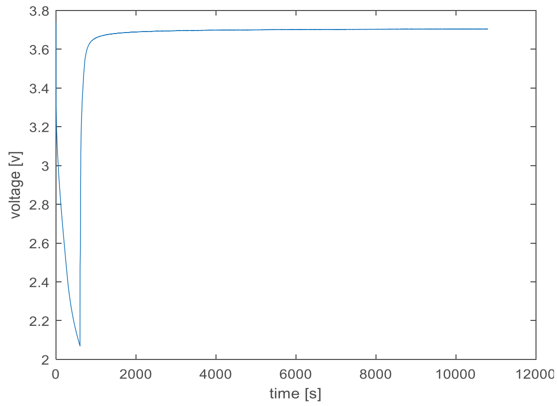

Fig. 7. Time evolution of the battery voltage for a constant-current discharge followed by rest.

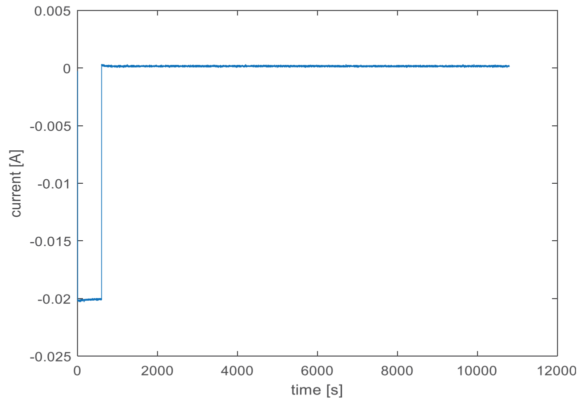

Fig. 8. Time evolution of the battery current for a constant-current discharge followed by rest.

datasets can also be attributed to the fact that data were collected in two laboratories located in different Universities and to the difficulty in reproducing the same starting battery electrical status, which from a general standpoint does not depend upon the instantaneous voltage value only, but also on the charge/discharge rates applied to achieve it.

Finally, as an example of the flexibility and reconfigurability of the proposed system architecture, Figs. 7 - 9 show the results of an additional test. In this test, the battery is discharged at constant current of 20 mA using the same Howland current pump circuit, without modifying the system architecture of Fig. 1, while simultaneously measuring the current and voltage with a sampling rate of 1 Hz. This additional operating mode could be used for defining and monitoring charging and discharging processes.

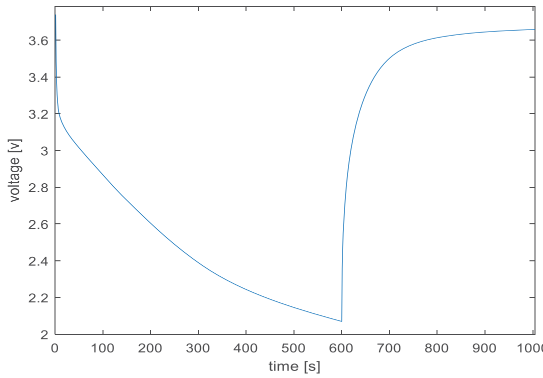

Fig. 9. Magnification of the first 1000 seconds of Fig. 7.

V. CONCLUSION

A low-complexity and flexible system for EIS on Li-Ion batteries was presented. The system is based on a Howland current pump circuit providing a multisine excitation current and a general-purpose 16-bit DAQ. The design of the excitation signal is discussed. The proposed system is validated by comparing its response to that of a reference commercial instrument on a RC circuit and a Li-Ion battery. It is shown that the proposed system can provide results comparable to those provided by the reference instrument, while potentially reducing measurement time and allowing for flexible monitoring of charging and discharging profiles.

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