xEVs 배터리의 그레이딩을 위한 광대역 다중 이진 신호 섭동을 이용하는 다채널 고속 임피던스 분광 시스템

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A Multichannel Fast EIS System Using Broadband Multi-Sine Binary Perturbation for the Grading of xEVs Batteries.

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ABSTRACT

Retired lithium-ion batteries are reused in second life energy storage applications. However, the overall performance of repurposed energy storage system (ESS) is limited by the unevenness of individual batteries use in it. Therefore, battery grading is required for optimal performance of ESS. Electrochemical impedance spectroscopy (EIS) based evaluation of battery aging is a promising way to grade lithium-ion batteries. However, it is not practical to measure impedance of mass retired batteries due to high complexity and slowness. In this paper, a broadband multi-sine binary signal (MSBS) perturbation integrated with multichannel EIS system is presented to measure impedance spectra for fast aging evaluation of lithium-ion batteries or modules. The measurement speed is 54-times higher than conventional EIS with single-channel configuration. The broadband MSBS is validated with reference sinusoidal sweep perturbation and corresponding root-mean-square error (RMSE) analysis is performed. Moreover, the accuracy of the presented multichannel EIS system is validated by impedance spectra measurement of Samsung INR18650-29E batteries and comparing it with those measured with commercial EIS instrument. A root-mean-square error (RMSE) under 0.512% is obtained for all 8-channels. Since the non-linearity of battery has significant impact on quality of impedance spectra. Therefore, Kronig-Kramer (KK) transform validation is also performed.

1. Introduction

Nowadays, lithium-ion batteries are widely used in various technologies easing our daily life. It is well known that high power and energy density, high charge-discharge efficiency and low cost of lithium-ion batteries have made them as a first-hand choice in electric mobility, portable electronics, and energy storage system (ESS) [1]. The capacity drops below 80% is considered end of life (EOL) for lithium-ion battery used in electric vehicles (EVs). However, they can store a significant amount of energy and can be used in repurposed second life application such as energy storage system (ESS). Since the optimal operation of repurposed system is highly depended on the similar characteristics of individual batteries. Therefore, battery aging is a crucial indicator in grading EVs batteries for repurposed applications.

Conventionally, modelling of microscopic phenomena such solid electrolyte interface (SEI), active material loss and lithium-ion plating are used to evaluate battery aging by estimating capacity loss, state of health (SOH) and remaining useful life (RUL). However, it is not scalable. Alternative way is aging evaluation based on AC impedance measurement of a battery. Electrochemical impedance spectroscopy (EIS) is a widely used tool for measuring AC impedance over a wide frequency range. The battery is perturbed through minuscule excitation signal and corresponding impedance is measured which gives insight of underneath electrochemical degradation processes. However, the conventional EIS uses sinusoidal sweep perturbation. Although it gives accurate measurement results but not applicable for mass batteries evaluation due to longer measurement time and complexity. Moreover, longer perturbation time is more prone to temporal changes in battery state during EIS measurement [1].

In this paper, a broadband multi-sine binary signal (MSBS) is applied to perturb the batteries simultaneously for the given frequency range and obtain impedance spectrum of lithium-ion batteries. MSBS inherent the advantages of both multi-sine and pseudorandom binary sequences (PRS). It means, measurement time is short compared to sinusoidal sweep excitation, the frequencies components are selectable and a simple two-level signal with good crest factor (CF=1.0). Moreover, an eight-channel EIS system is implemented on a 200 by 150mm PCB. A LabVIEW based graphical user interface (GUI) is developed to control the presented EIS system and display the impedance spectrum of eight-batteries simultaneously. The validation is carried out by measuring impedance spectra with presented setup and comparing with those of commercial EIS instrument. Accuracy and quality of measurements are verified through root-mean-square error (RMSE) analysis and linear Kronig-Kramer (KK) transform.

2. Multi-Sine Binary Signal (MSBS) Perturbation

MSBS is a two-level signal obtained through direct mapping of multi-sine to an equivalent binary signal. The multi-sine signal is clipped at average value, the amplitude instantaneous value greater than average is mapped to binary high (+1) and less than average is mapped to binary low (-1). The mapping of CMSS into MSBS is represented by (1). The obtained MSBS signal inherent both the advantages of PRS and multi-sine signals. Since it is a two-level signal, simple generation algorithms and hardware are required. The CF is equal to that of PRS (CF=1.0), and the frequencies of interest are selectable. Some additional harmonics appears along with frequencies of interest in the FFT of MSBS. However, the appeared harmonics have small amplitudes and 70 to 85 % of signal power can be concentrated on desired frequencies. The MSBS generation using (1) is represented by block diagram shown in Fig. 2. It is implemented in LabVIEW, the resulted MSBS signal is converted to look-up array for coding in DSP.

$$MSBS\ (n) = sign\left(\sum_{k=0}^{N} A_k.\sin\left(\frac{2\pi n}{N_k}\right)\right) \qquad (1)$$

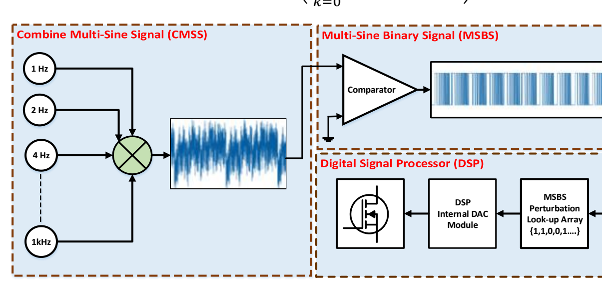

Fig. 1. Generation block diagram of MSBS

3. Presented Multichannel Fast EIS system

The block diagram of proposed high-speed multichannel EIS system is shown in Fig. 2. A low-cost MCU manufactured by STMicroelectronics having Arm cortex-M7 processor, two 12-bits built-in DACs, three 16-bit ADCs, dual mode quad SPI memory interface, 2 MBs programmable flash, communication peripherals and low power consumption is selected. To make the design compact and simple, the MSBS reference perturbation signal is generated using internal DAC. The reference perturbation signal is used to control the discharging of the battery through a high-precision current-sink based on voltage-controlled current source arrangement. The perturbation current magnitude through the MOFET is controlled through feedback from drain to gate. Since, there is 2 MB flash memory in the selected MCU. Therefore, the presented MSBS and DLIA reference are programmed as a look-up array in DSP and the internal DAC is used to produce the corresponding analogue perturbation reference signal represented by Eq. (2).

$$V(n)_{MSBS} = V_m . sign[\sum_{k=0}^{N} A_k . \sin(\frac{2\pi n}{N_k})] + \frac{V_m}{2} \quad (2)$$

Where V_m is the amplitude of perturbation reference signal and $V_m/2$ is the DC offset because the battery is only discharged during the perturbation.

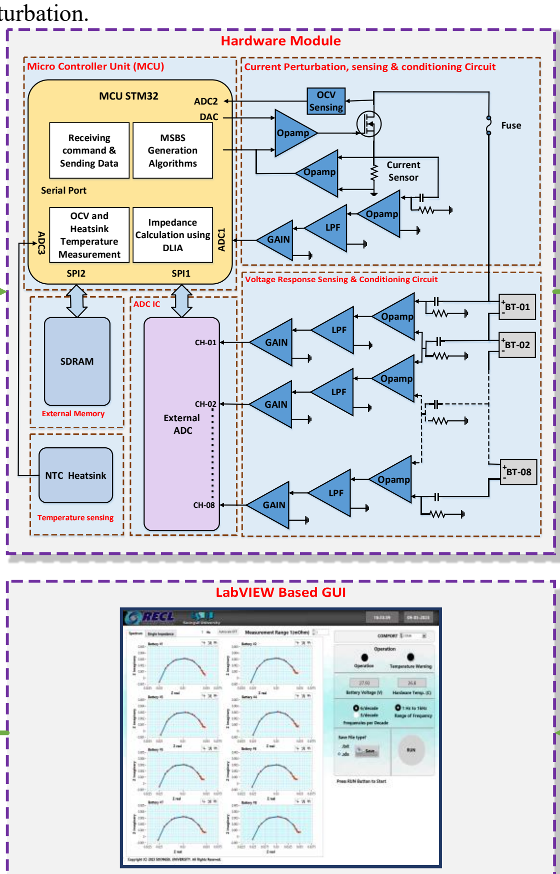

Fig. 2. Block diagram of presented multichannel fast EIS system.

The presented EIS system simultaneously perturbs eight battery cells or modules connected in series with combined voltage less than 100 V. A list of frequencies excited in MSBS are 1000, 500, 400, 250, 200, 100, 80, 50, 40, 20, 16, 10, 8, 5, 4, 2, 1 Hz. The batteries responses are measured through sensing and conditioning circuit which consists of high-pass filters, differential amplifiers, low-pass filters, and gain amplifiers. An external ADC IC (AD7606) is used to concurrently measure the batteries response passing through sensing and conditioning circuit. The recorded current and voltage responses of 8-channels are saved in external SDRAM. Since, the proposed EIS uses broadband MSBS perturbation with 8-channel configuration. Therefore, the measurement speed is multi-times faster than conventional EIS. The processing of saved current and voltage responses for all channels are carried out through DLIA algorithms implemented in DSP. Block diagram of DLIA is shown in Fig. 3. In first section, the current and voltage responses are demodulated by multiplying with respective references. The magnitudes and phases are obtained after passing through low-pass filter which are further used to determine the respective impedance spectrum of each channel respectively [2].

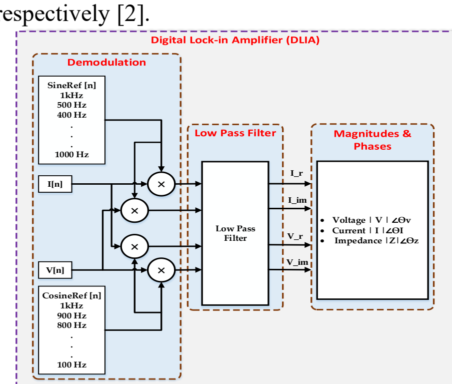

Fig. 3. Block diagram of digital lock-in amplifier (DLIA)

The LabVIEW based GUI shown in Fig. 2 performs three tasks. The generation of control commands through decoding user input, communication between PC and hardware module, and displaying the received impedance spectra.

5. Experimental Verification

The Experimental setup is shown in Fig.4 and the specifications of Samsung INR18650-29E batteries used in experiment are listed in Table 1. For validation, the impedance spectra of eight batteries connected in series are measured and compared with those of commercial EIS instrument named "BIM2" manufactured by BRS Messtechnik, Germany [3]. The Nyquist impedance plots obtained through presented multichannel fast EIS system and commercial EIS instrument are shown in Fig.5. To prove the accuracy of measurements, a RSME analysis is performed which shows under 0.512 % values.

Table 1. Specification of batteries used in experiment.

Battery Model	Nominal Voltage	OCV	Capacity
Samsung INR18650-29E	3.65 V	3.50 V	2.850 Ah

Table 2. Root-mean-sqaure error (RMSE %) compared to reference commercial EIS instrument

S. No	RMSE %	S. No	RMSE %
BT#01	0.432	BT#05	0.395
BT#02	0.476	BT#06	0.416
BT#03	0.512	BT#07	0.482
BT#04	0.456	BT#08	0.421

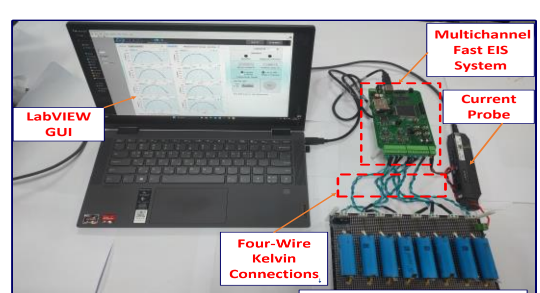

Fig. 4. Experimental setup

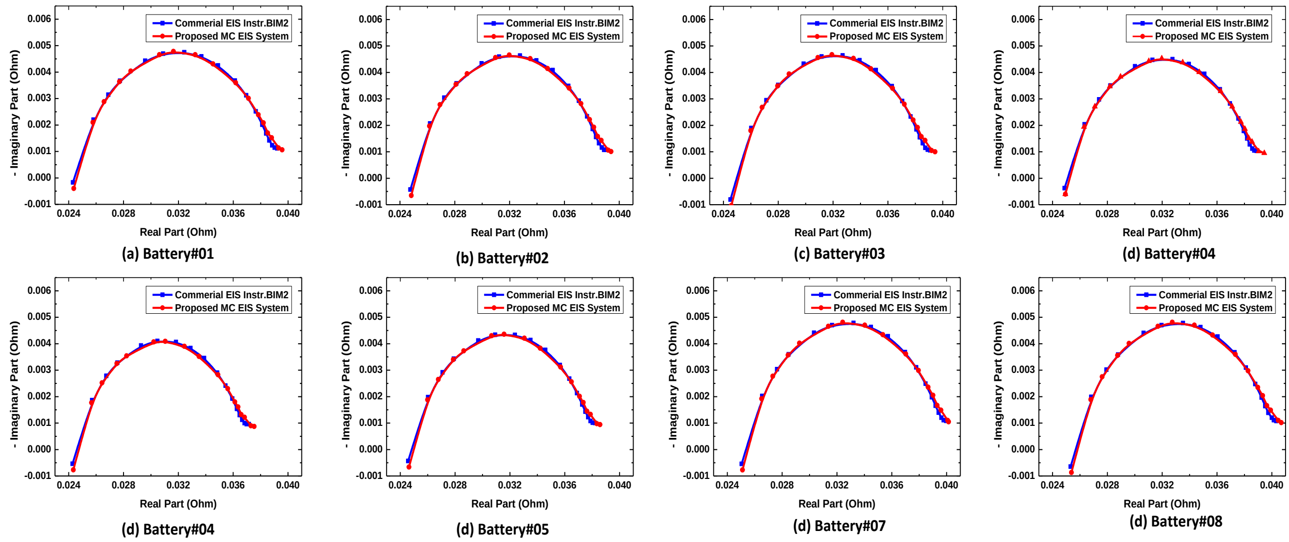

Fig. 5. Nyquist impedance plots comparison obtained with presented multichannel fast EIS system and commercial instrument "BIM2"

The EIS measurement should fulfil the criteria of a linear time-invariant (LTI) system such as linearity, causality, and stability. Therefore, the obtained impedance spectra are validated through KK transform. It describes the relation of real and imaginary component of impedance spectra obtain from a linear-time-invariant (LTI) system. The theoretical relation of real and imaginary component of impedance is given by Eq. (3) [4].

$$Z_{Re}(\omega) = \frac{2}{\pi}\int_0^{\infty}\frac{\omega'.Z_{Im}(\omega')}{\omega^2-\omega'^2}d\omega',\ Z_{Im}(\omega) = \frac{-2}{\pi}\int_0^{\infty}\frac{\omega.Z_{Im}(\omega')}{\omega^2-\omega'^2}d\omega' \quad (3)$$

Since, an EIS test is practically performed for limited frequency range. Therefore, Voigt circuit is used which consists of passive elements and the spectrum obtained from it will be KK compliance. The Lin-KK software developed by Karlsruhe Institute of Technology (KIT) is used for robust validation of KK-compliance test [5]. This tool is based on fitting the impedance spectra to a linearized Voigt circuit having multiple RC elements. Residuals of real and imaginary components are between measured and fitted data as represented by Eq. (5). The residual should be less than 0.5% for validity of measurement under the conditions of LTI system. An impedance spectrum data is valid if the residuals are random or white noise distribution.

$$\Delta_{Re}(\omega) = \frac{Z_{Re}(\omega) - \hat{Z}_{Re}(\omega)}{|Z(\omega)|}, \Delta_{Im}(\omega) = \frac{Z_{Im}(\omega) - \hat{Z}_{Im}(\omega)}{|Z(\omega)|} \quad (4)$$

The results of KK compliance for battery#01 is shown in Fig. 06. It can be seen that obtained impedance spectrum are best fitted to Voigt circuit. The residuals shown in Fig. 6b are unbiased (means no time variance), random and less than 0.5 % which prove the validity of presented MSBS perturbation and multichannel fast EIS system.

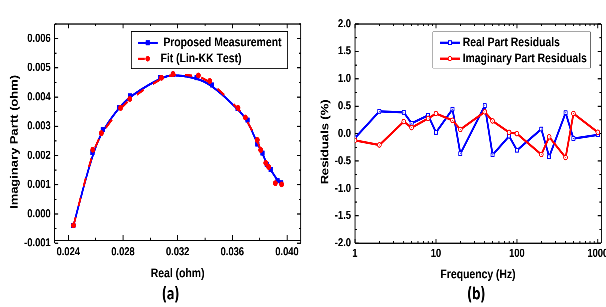

Fig. 6. (a) Voigt fitted EIS impedance spectrum to validate KK compliance (b) Real and imaginary

6. Conclusions

In this paper, a multichannel fast EIS system is presented using a broadband MSBS perturbation. It inherent the advantages of both multi-sine and PRS such as selectable frequencies, good crest factor CF=1.0, simple (two-level) and easy to generate using low-cost DSP. The validation is carried out by measuring impedance spectra with presented EIS system and comparing with those of commercial EIS instrument. A RMSE analysis and KK compliance verified the validity and accuracy. Since the presented EIS system possess two advantages over conventional EIS such as using broadband MSBS for perturbation and eight channels configuration. Therefore, its measurement speed is 54-times faster than single-channel conventional EIS instrument. In view of above analysis and validation, the presented EIS system is good solution for mass grading of lithium-ion xEVs batteries.

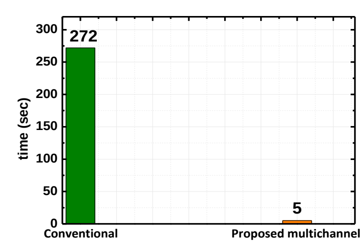

Fig. 7. Measurement time comparison of presented multichannel fast EIS system with conventional EIS.

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