A Fast Time Domain Measuring Technique of Electrochemical Impedance Spectroscopy Based on FFT

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Abstract—**Lithium-ion batteries have become critical components to industries as automotive, military, space, medical and consumer electronics. Electrochemical impedance spectroscopy (EIS) is a well-known technique employed on various electrochemical cells including lithium-ion cells, which is practical in estimating battery state of health, as ohmic resistance, formation of solid electrolyte interphase (SEI) film, activation on solid and liquid interface and diffusion process in the battery can be reflected in the Nyquist curve of EIS. However, the long acquisition time of standard EIS makes it unsuitable for rapid on-line impedance measurements. This paper presents a time domain measuring technique based on Fast Fourier Transformation (FFT). Time domain excitation, such as a multi-sine excitation, is applied to the measured system. The excitation and response of the system are acquired simultaneously. Through FFT, acquired signals are transformed from time domain to frequency domain, thus the impedance in frequency domain is calculated. The technique is verified on both lithium-ion battery equivalent circuit and real lithium-ion battery. The resulting impedance data show that proposed technique has good concordance with standard EIS and greatly reduceds the acquisition time compared with standard EIS.**

Keywords—Lithium-ion battery, State of health, EIS, Time domain, FFT

I. INTRODUCTION

Battery technologies, especially lithium-ion batteries, have become critical components to several industries including automotive, military, space, medical, electric utility and consumer electronics due to its advantages such as high output voltage, long cycle life, large energy density, no memory effect and so on. Battery systems can be very expensive and are usually important. Therefore，it is important that indicators such as SOH and RUL (Remaining Useful Life) be properly measured and analysed[1].

Studies have shown that Lithium-ion cells' state of health and performance is dependent on both the cell capacity as well as internal resistance[2, 3]. Various passive characteristic tests involving monitoring current and terminal voltages at different temperatures are only able to give valuable information on state of charge and capacity provided by the manufacturer[4].

The information from these tests are not sufficient to provide a full state of health assessment of the battery as various key information such as impedance rise and power fade is absent from these results. Resistance is typically determined using a volt/ohm meter at a specific measurement frequency with active pulse tests over an SOC range using a constant current signal and observing the voltage response[5]. But these approaches are not well suited for rapid battery diagnostics.

Electrochemical Impedance Spectroscopy(EIS), also known as AC impedance, has been proven to be a useful measurement of battery SOH. Data obtained from impedance measurements have been shown to correspond with resistance and power capacity simultaneously. EIS has been used to assess the performance of electrodes and batteries since its invention [6-8]. A typical EIS measurement is usually carried out by a Frequency Response Analyzer (FRA). The measured impedance of battery within a certain frequency range is manifested by Nyquist plots, from different frequency sections of which, we can observe reflections of ohmic resistance, formation of solid electrolyte interphase (SEI) film, activation on solid and liquid interface and diffusion process [9].

A full EIS, however, typically requires expensive and delicate equipment, operating in a laboratory environment. It also takes a long time, from 10 minutes to hours depending on the number of frequency points chosen and the lowest frequency selected. To reduce the time it takes to get a full EIS, this paper presents a time domain technique to measure EIS of a battery.

II. FUNDAMENTALS

The standard EIS procedure for electrochemical is by applying a sinusoidal voltage or current to the battery and recording its output response. The output response is usually a sinusoidal signal with a certain amplitude and phase shift. This procedure is usually repeated for a number of frequency points and thus the impedance spectrum of the battery is obtained in frequency domain[10, 11]. As the impedance is measured at a discrete number of frequencies one at a time, this procedure can be very time consuming. An alternative approach is based on time domain excitations, which greatly decreases the time it

takes to get EIS. Here excitation signals such as multisine signal or square wave signal are applied to measured system. Excitation signal as well as response signal is measured. These signals are transformed from time domain to frequency domain through mathematics transformations. Thus EIS of the measured system can be acquired. The result from the EIS measurements can be plotted in the Bode plane or Nyquist plane. For lithium-ion batteries, results are usually plotted in the Nyquist plane, where the inverse of the imaginary part of the impedance is plotted against the real part.

This paper presents a fast time domain measuring technique of electrochemical spectroscopy based on fast Fourier transformation(FFT). The schematic description of this technique is shown in Fig. 1. Suppose the sample frequency f_s, number of samples k, sampling time T, thus the min frequency of FFT satisfies:

$$f_{min} = \frac{f_s}{k} = \frac{1}{T} \qquad (1)$$

According to sampling theorem, the maxium frequency in the measurement satisfies:

$$f_{max} \leq \frac{f_s}{2} \qquad (2)$$

Thus the frequency range in the measurement satisfies:

$$f_{min} \geq \frac{1}{T}$$
$$f_{max} \leq \frac{f_s}{2} \qquad (3)$$

Through FFT, amplitude and phase angle of both excitation current and response voltage at different frequencies are acquired. Suppose f_n as the nth frequency measured, at this frequency, the amplitude and phase angle of current are I_n, θ_{n1}, while the amplitude and phase angle of the voltage are U_n, θ_{n2}, impedance of the system at frequency Z_n is:

$$Z_n = \frac{U_n \angle \theta_{n2}}{I_n \angle \theta_{n1}} = Z_n \angle \theta_{n2} - \theta_{n1} \qquad (4)$$

In this way, EIS of the measured system can be acquired. As signals of different frequencies are applied at the same time, impedance of the system at different frequencies are measured at the same time, the measuring time is greatly decreased while a certain error range can be ensured
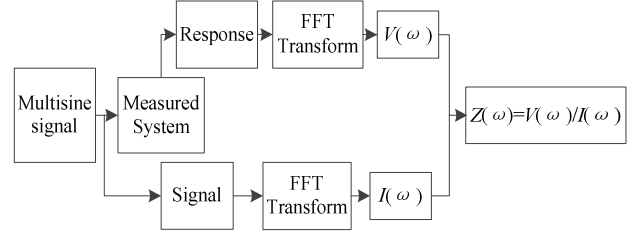

Fig. 1. The schematic description of the time domain measuring technique of electrochemical impedance spectroscopy based on FFT.

III. SIMULATION OF LITHIUM-ION BATTERY EQUIVALENT CIRCUIT EIS

The technique is first verified on lithium-ion equivalent circuit through simulation. A second-order lithium-ion battery equivalent circuit is shown in Fig. 2.
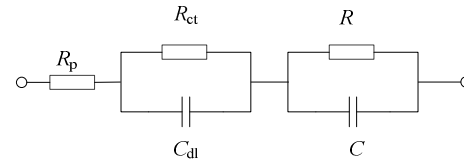

Fig. 2. A second-order lithium-ion battery equivalent circuit. R_p=7.4Ω, R_{ct}=7.9Ω, R=7.6Ω, C_{dl}=0.01F, C=0.001F .

A simulation model is built in MATLAB/Simulink shown in Fig. 3.
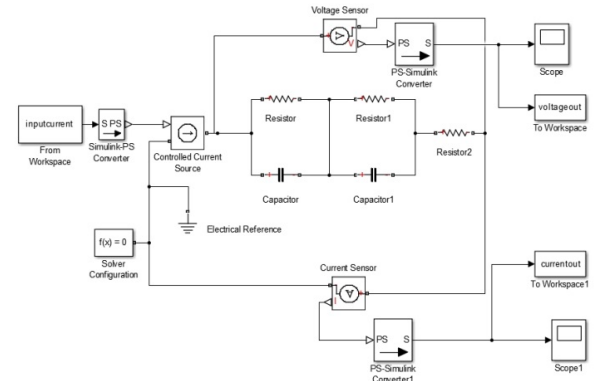
Fig. 3. Simulation model built in MATLAB/Simulink.

This Simulink model mainly includes controlled current source, equivalent circuit, current and voltage sensor and scope. First of all, data of multisine signal are generated in MATLAB. Then the data are transferred to the controlled current source to generate multisine current signal. The frequency range is 0.1Hz to 1kHz. The current signal is applied to equivalent circuit, and data of current and voltage are collected by current sensor and voltage sensor. The collected current and voltage signal are shown in Fig. 4.

Fig. 4. Current signal and voltage signal collected during simulation.

FFT is made to the current and voltage data collected in simulation procecure, and EIS of the equivalent circuit is obtained after data processing. Here the result is plotted in Bode plane, and is compared to theoretical result, as shown in Fig. 5. The simulation result is generally align with the theoretical result, which means the technique is theoretically applicable.

Fig. 5. Simulation EIS Bode curve of equivalent circuit compared to theoretical EIS Bode curve Measurement Of Lithium-Ion Battery Equivalent Circuit EIS.

IV. MEASUREMENT OF LITHIUM-ION BATTERY EIS

A. Experimental System

This measurement technique generates current excitation of certain frequencies and measures the voltage response(Galvanostatic Mode). The experimental system is shown in Fig. 6.

The system is composed of signal generator, V/I converter circuit, data acquisition and host PC. AFG3102 arbitrary signal generator produced by Tektronix is used as signal generator, which generates multisine signal. V/I converter converts voltage signal to current signal. As the signal generator generates voltage signal, V/I converter circuit is necessary. V/I converter circuit is shown in Fig. 7, which is based on constant current source circuit. In the circuit, operational amplifier A1 forms a inverting summing circuit, one input is the control voltage, the other is the output feedback of operational amplifier A3. The power amplification circuit is used to make up the insufficient output current of operational amplifier. Two Darlington tubes form a push-pull circuit to amplify output

current, while operational amplifier A2 forms a voltage following circuit with a high output impedance, with little shunt. Current flows through load R_L is determined by control voltage V_{in}, and will not change with the load.

NI myDAQ device by National Instruments is used as data acquisition device, and host computer with MATLAB software is used for generating data of mulisine signal and processing data.

Fig. 6. The experimental system for lithium-ion battery equivalent circuit.

Fig. 7. V/I converter circuit.

B. Experiment And Results

During the experiment, MATLAB software is first used to generate data of multisine signal and transfer the data to the signal generator. The signal generator then generates a multisine voltage signal. Through V/I converter circuit, the signal is converted to a current signal and applied to the equivalent circuit. The excitation current signal and response voltage signal are collected by data acquisition device and processed by host PC, and EIS of equivalent circuit is obtained.

CS impedance analyser is used to measure EIS of the equivalent circuit as well. The impedance analyser was produced by CorrTest company. It measures EIS through frequency sweep method, which is accurate but time-consuming. The frequency range measured is from 0.1Hz to 1kHz. The result of Bode curve and Nyquist curve are shown in Fig. 8 and Fig.9.

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It can be seen from Fig. 8 and Fig. 9 that this technique reflects trend of the curve and is quite accurate. As for the measuring time, it takes only 1 min to get EIS in 0.1Hz-1kHz, while the impedance analyser using frequency sweep method takes more than 5 mins.
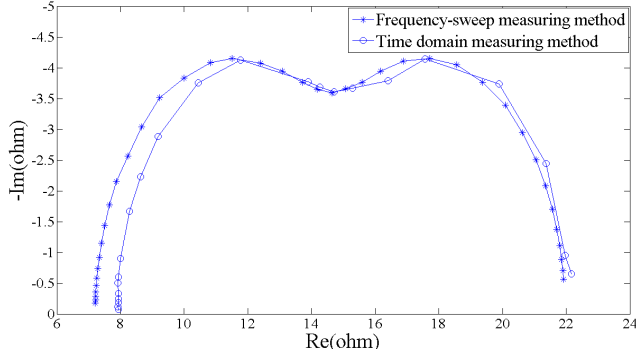

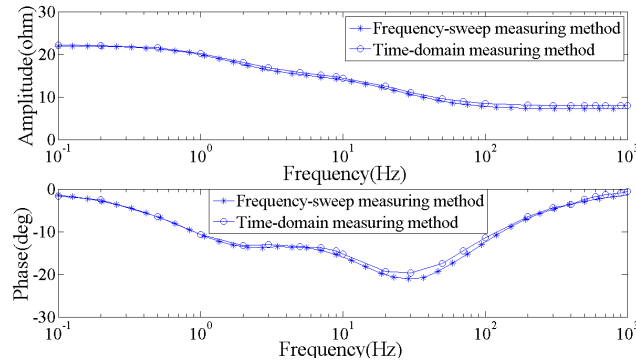Fig. 8.   Nyquist curve of lithium-ion battery equivalent circuit.

Fig. 9.   Bode curve of lithium-ion battery equivalent circuit.

V. MEASUREMENT OF LITHIUM-ION BATTERY EIS

A. Experimental System

Sanyo 14500P batteries made in Japan are used to verify the technique. The nominal capacity of the battery is 800mAh. As the impedance is small and the approximate linearity should be ensured, the amplitude of excitation current should also be small. Experiment system, similar to the system used in equivalent circuit measuring, is shown in Fig. 10.
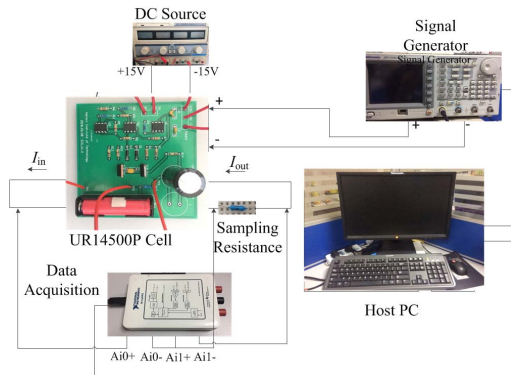
Fig. 10. The experiment system for lithium-ion battery 14500P.

B. Experiment And Results

Experiment for lithium-ion battery is similar to that for equivalent circuit. The frequency range measured is also from 0.1Hz to 1kHz. SOC of the battery is 50%. The result is also compared to that of CS impedance analyser in Nyquist curve and Bode curve, as shown in Fig. 11 and Fig. 12.

It can be seen from the Nyquist curve that the result is close to that of CS impedance analyser. Usually the EIS is plotted in Nyquist plane. In this technique, the amplitude and phase angle of impedance is obtained first, then the real part and imaginary part of the impedance are calculated. To analyze the error of this technique, Bode curve is used. In the Bode curve, it is clear that the phase angle is very close, while for the amplitude, the error in 0.1Hz-1Hz is more obvious. Similar conclusion can be drawn from Nyquist curve. In Nyquist curve, left side of the curve represents high frequency while right side represents low frequency. Here left part of the curve is closer to that of CS impedance analyser than the right part.
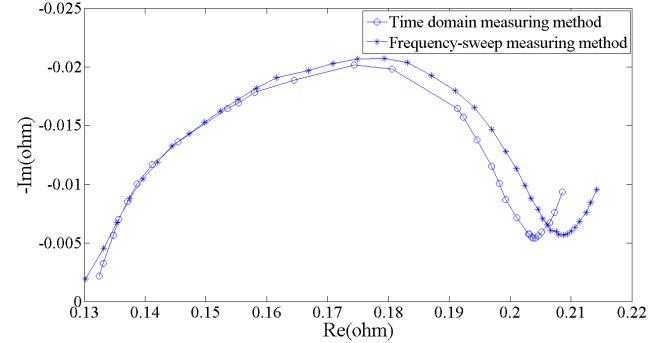

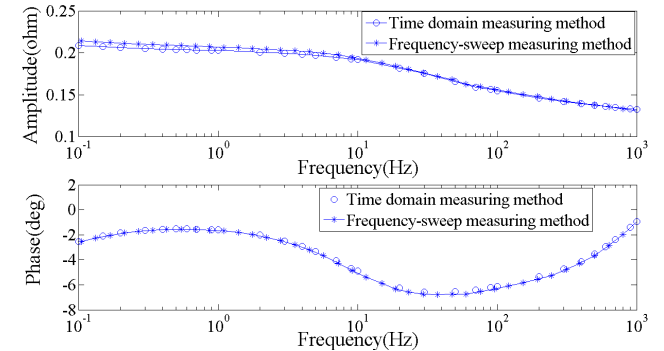Fig. 11. Nyquist curve of lithium-ion battery 14500P .

Fig. 12. Bode curve of lithium-ion battery 14500P.

The total average of amplitude relative error of this time domain technique is 1.24%, while for phase angle, the number is 2.73%. For different frequency, the relative error varies greatly. TABLE I. shows the relative error at different frequency range.

From the table, the average relative error for amplitude decreased with increasing frequency, while the average relative error for phase angle increases with increasing frequency.

TABLE I. AVERAGE RELATIVE ERROR AT DIFFERENT FREQUENCY RANGE

Frequency range(Hz)	Average relative error for amplitude(%)	Average relative error for phase angle(%)
0.1-1	2.37	2.23
1-10	1.58	2.64
10-100	0.70	2.80
100-1000	0.16	3.30

C. The Influence Of Battery SOC On The Measurement

Studies have shown that battery SOC (State Of Charge) has an influence on the measurement of EIS[12].To analyse the influence of battery SOC on the measurement, 14500P battery with 50% SOC is set as a standard, the same experiment is carried out on the same battery with high and lower SOC. The Nyquist curve are shown in Fig. 13 and Fig. 14, while TDMM represents time domain measuring method and FSMM represents frequency sweep measuring method.
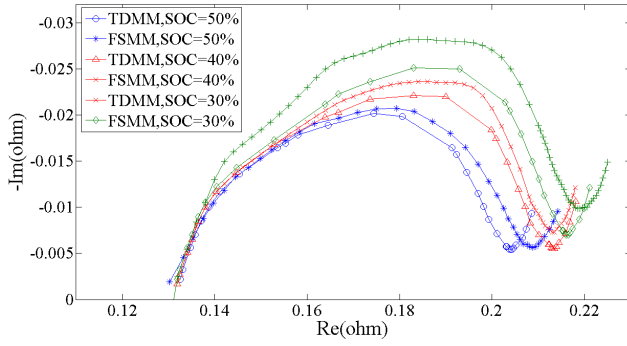
Fig. 13. Nyquist curve with lower SOC.
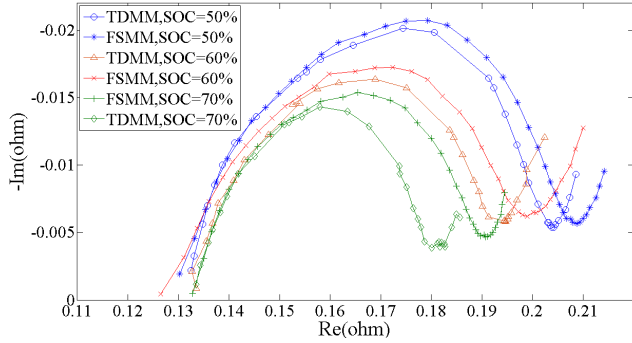
Fig. 14. Nyquist curve with higher SOC

It is clear that the radius of the semi-circle in the Nyquist curve increases as the SOC of the battery decreases. Also, to analyse the error, Bode curves at different battery SOC are plotted, as shown in Fig. 15 and Fig. 16. TABLE II. shows the relative error at different battery SOC.
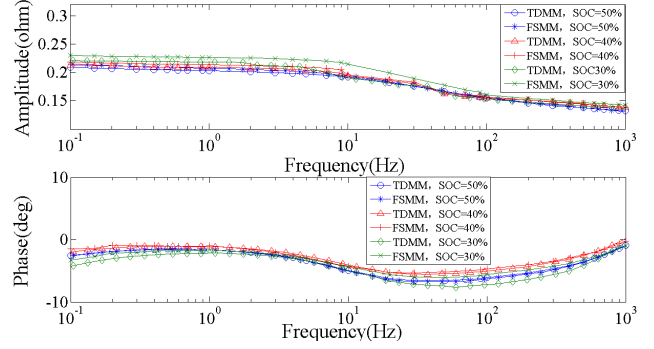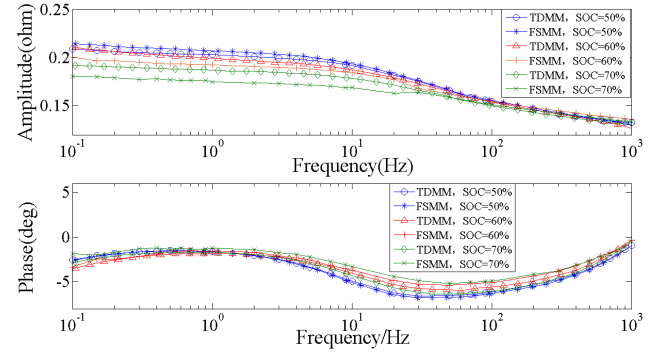

Fig. 15. Bode curve with lower SOC.

Fig. 16. Bode curve with higher SOC

TABLE II. AVERAGE RELATIVE ERROR AT DIFFERENT BATTERY SOC

SOC of Battery(%)	Average relative error for amplitude(%)	Average relative error for phase angle(%)
30	4.55	5.25
40	2.12	3.48
50	1.24	2.73
60	3.24	4.65
70	3.28	7.33

From Bode curves and the table, it can be seen that in the five different SOC state measured, the average relative error increases no matter SOC increases or decreases. The relative error is the smallest when SOC is at 50%. This agree with the conclusion that EIS measurement is not stable when SOC of battery is too high or too low. So this technique should be applied at 50% SOC.

VI. CONCLUSION

This paper researched a time domian measuring technique of EIS based on FFT. Compared with frequency sweep measuring method, this technique greatly reduces the measuring time while ensuring a relatively small error.

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