A successive approximation method to precisely measure leakage current of the rechargeable Lithium coin battery

X. Yue*, J. Kiely, S. Ghauri, M. Kauer, M. Bellanger and D. Gibson

X. Yue, J. Kiely and S. Ghauri (Department of Engineering, Design and Mathematics, University of the West of England, Bristol BS16 1QY, UK)

M. Kauer and M. Bellanger (Sharp Laboratories of Europe, Oxford, OX4 4GB, UK)

D. Gibson (Gas Sensing Solutions, Glasgow, G68 9HQ, UK and the University of the West of Scotland, Paisley PA1 2BE, Scotland, UK)

* Corresponding author, e-mail: alex.yue@uwe.ac.uk

This work was supported by Innovate UK (Contract No. 102156)

Highlights

- Acquiring leakage current of Li-coin battery in µAs without electrical battery model
- Observing the difference of applied current vs. leakage via a sign of voltage change
- Searching trickle charge state using successive approximation

Abstract

When the rechargeable Lithium coin battery is employed as the storage component for indoor energy harvesting, the leakage current of the battery cannot be ignored, especially in ultra-low-power applications. The leakage current of the Lithium coin battery is commonly believed in the low µA range. However the exact value is unknown. An experimental method to measure leakage current by applying a known charge current in µAs to a stabilized post-charge battery to observe the sign of the battery terminal voltage change is proposed. When the applied charge current is larger than the leakage current, a positive sign (terminal voltage increase) can be observed. Otherwise a negative sign appears. By gradually changing the charge current using the successive approximation search algorithm, the leakage current will finally converge to the applied charge current. The convergence happens after the sign changes in two successive search procedures, demonstrating that charge currents are approaching the leakage current from both directions. The accuracy of the approximation can be improved by adjusting the number of sign changes in the successive approximation search algorithm. The proposed method permits the full capacity of a rechargeable Lithium coin battery to be utilised in ultra-low-power applications.

Keywords: Leakage current, Lithium coin battery, trickle charge, successive approximation

I. Introduction

The Lithium coin battery is a competitive candidate for storing harvested energy for indoor energy harvesting powered autonomous wireless sensor node for the applications of internet of things (IoT) such as home healthcare and building automation due to its smaller size, higher energy density and higher peak pulse current than other energy storage components such as a supercapacitor.

Generally to say, the leakage current of the Lithium coin battery is low (<10 µA) so the leakage current has been ignored in conventional battery applications. However since the power density for indoor energy harvesting is limited, such as 10~20µW/cm^2 for photovoltaic (PV) energy harvesting, 0.1µW/cm^2 for GSM and 0.001µW/cm^2 for WiFi, the energy harvested through a reasonable dimension of the indoor energy harvester is limited. A µW level indoor energy harvester can only produce a µA level charge current to the Lithium coin battery. Therefore the leakage current of the Lithium coin battery should be acquired in µA level to precisely estimate the state of charge (SOC) of the battery for utmost using harvested energy in indoor applications.

The leakage current of a battery can be measured by the battery test equipment. However, existing battery simulators are not accurate for small capacity Lithium coin batteries (such as 10 µA measurement accuracy in the dynamic model battery simulator of Keithley 2281S). As the consequence, by now there is no leakage current data available for the Lithium coin battery.

The leakage current of a battery can be alternatively obtained via simulation of the electrical battery models. The challenge is that the battery is an electro-chemical component so its electrical model is non-linear and time-variable [1-3]. The reported accurate models can limit the maximum voltage error to 2% [4] or about 30 mV of terminal voltage [5, 6], which are good enough for high capacity battery applications where the charge/discharge current is at least hundreds mA, but not suitable for indoor energy harvesting powered IoT applications where charge and leakage currents are both in µAs.

This paper proposed a method to precisely measure the leakage current of the Lithium coin battery in µAs. It measures the leakage current by applying µA charge currents in a successive approximation way to a stabilized post-charge Lithium coin battery to observe the sign of the terminal voltage change for totally getting rid of the complicated calculation of the electrical battery model. The principles of the leakage current measurement and the successive approximation method are described in Section II. The measurement experiments for a Lithium coin battery's leakage current is reported in Section III to demonstrate that the proposed method works for the Lithium coin battery.

II. Leakage current and measurements

2.1 Leakage current of the battery

A battery is recommended to be charged in a constant current mode at the beginning to establish a pre-set voltage (V_1) and then transfers to the constant voltage charge mode to deeply charge the battery as shown in Fig.1. The initial charge current can be 1/2-C ~ 1-C where C represents the battery capacity in Ah. For example, the initial charge current of the 100 mAh Lithium coin battery can be set as high as 100 mA in the first hour. When the terminal voltage reaches the pre-set voltage V_1, the charge mode changes from constant current to constant voltage in which the charge current keeps decreasing with time. Usually, when charge current reduces to 3% of 1-C the charging process terminated, meaning that the battery is not charged to saturate condition so a post-charge diffusion process follows. The post-charge diffusion process makes the terminal voltage of the battery decrease exponentially from V_1 during the charge transfer/diffusion process and the terminal voltage will be finally stable at V_2 with a slightly decrease in linear due to the completion of the diffusion process. The internal current which causes the small linear terminal voltage drop after the completion of the post-charge diffusion is the leakage current of the battery. Leakage current is an important parameter for the evaluation of the SOC, but by now no measured figure of the leakage current for a Lithium coin battery has been reported.

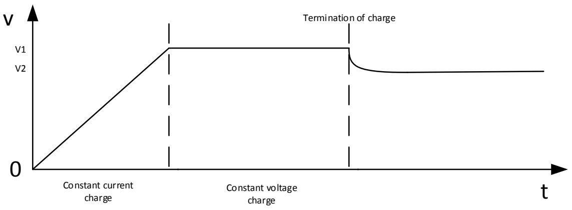


Fig. 1 *Lithium battery charge process. The leakage current causes a tiny voltage drop after the battery voltage is stabilized at V_2*

2.2 The proposed measurement method

The leakage current of the Lithium coin battery cannot be directly measured through terminal voltage since the terminal voltage data alone can hardly be interpreted as the leakage current when using an electrical battery model (due to the missing initial battery charge condition), but the leakage caused terminal voltage drop can be observed from a stabilized post-charge Lithium coin battery. Introducing an extra µA current source to the already stabilized post-charge Lithium coin battery may change the direction of the terminal voltage change, making the terminal voltage useful for leakage current measurement.

As shown in Fig.2, the Lithium coin battery model reported in [6] has been further simplified as an ideal battery (representing the already stabilized post-charge battery) with an equivalent series resistor (ESR) and a leakage path producing a leakage current of I_{leak}. When a µA level tiny charge current I_{charge} is applied to the battery, the sign of the terminal voltage change will be the same as that of the term (I_{charge} - I_{leak}) which is the effective charge current of the battery. When $I_{charge} - I_{leak} = 0$, the terminal voltage should not change, indicating a trickle charge state. Varying I_{charge} in two directions (increasing/decreasing) to search this trickle state, a sign swop point can be observed, indicating that the charge current is approaching the leakage current from both directions. By gradually reducing the charge current varying step, a precise leakage current measurement can be finally achieved.

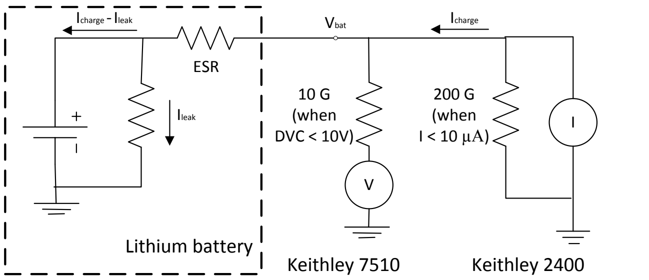


Fig.2 *Simplified Lithium battery model and experiment set-up. The sign of terminal voltage change has been linked to that of the term of (I_{charge}-I_{leak}), so I_{leak} can be experimentally determined by varying I_{charge} in both directions (increasing/decreasing) to search the sign swop point which indicates a passing through of the trickle charge state*

III. Measurement experiment

3.1 Experiment set-up

A leakage current measurement experiment has been set-up as shown in Fig.2. It employs a precise current source (Keithley 2400) which has an output impedance of 200GΩ when output current range is set to 10 µA, and a voltage recordable multi-meter (Keithley 7510) which has an input impedance of 10GΩ when DCV is set in the measurement range of 10.0V. Therefore the leakage current of the above test equipment is in fAs when working at an operating voltage of 4.0V, which is ignorable for µA leakage measurement. Parasitic capacitance effects of the test equipment can be reasonably ignored for this DC current and DC voltage measurement experiment when comparing to the equivalent capacitance of the Lithium coin battery. Two-wire measurement set-up rather than 4-wire one is employed since the wire resistance which produces an offset of the measured terminal voltage does not affect the sign of the terminal voltage change. The battery under test is the 50 mAh Lithium coin battery of CP 1254 from Varta Microbattery GmbH (Daimlerstraße 1, 73479 Ellwangen, Germany).

3.2 Battery preparation

CP 1254 has been charged by Keithley 2281S with a voltage limitation set to 4.0V and an initial charge current set as 40.0 mA. The charge current recorded by 2281S in the constant voltage charge mode is shown in Fig.3 (the blue curve), which shows an exponential charge current decrease with time. The curve terminated at about 1000 seconds in constant voltage charge mode when the 10 µA measurement limitation of the equipment is reached.

Using two exponential terms for curve fitting (similar to the two RC combination model reported in [7]),

$$I = a_1 \times \exp(-t/R_1C_1) + a_2 \times \exp(-t/R_2C_2) \qquad (1)$$

where $a_1 = 0.0245$, $R_1C_1 = 367.68$, $a_2 = 0.0137$ and $R_2C_2 = 26.50$, the fitted curve (red curve in Fig.3) shows a tendency of further decreasing of charge current, so the leakage current of the Lithium coin battery should not be larger than 10 µA.

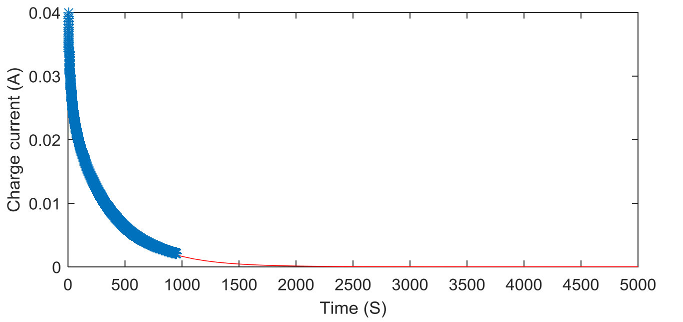


Fig.3. *Charge current recorded in the constant voltage charge mode. The blue curve is the measured charge current and the red curve is the fitted curve.*

The charged Lithium battery has been finally stabilized after the completion of the post-charge diffusion process. A linear terminal voltage drop of the stabilized post-charge Lithium battery has been recorded by the Keithley 7510 as shown in Fig.4. The recorded data shows a 0.75 mV voltage drop for 15 hours (50 µV voltage drop per hour), confirming that the Lithium coin battery is ready for precise leakage measurement. The measured results of 0.75 mV voltage drop for 15 hours also demonstrated that the electrical battery model-based method which has up to 30 mV terminal voltage error does not work for the case of calculating the leakage current of the Lithium coin battery in µAs.

Fig.4. *Measured liner terminal voltage drop with time demonstrated the Lithium battery has been stabilized after completion of the post-charge diffusion process*

3.3 Measurement results

The leakage current measurement experiment was carried out after the charged battery was stabilized. The recorded terminal voltage waveform is shown in Fig.5 where the charge current (I_{charge}) changes among three values of 0, 1.0 and 1.5 µA. At the beginning, when there is no charge current applied (I_{charge} = 0), a linear voltage drop caused by the leakage current can be observed. When a 1.5 µA charge current is applied, a voltage increase can be observed meaning that the leakage current is less than 1.5 µA. When stopping supplying the charge current, the presence of a voltage dropping curve (roughly being in parallel to the dropping curve at the beginning of measurement) verified that the applied charge current has no effect on the sign of the voltage change. A relatively flat voltage trace can be observed after 1.0 µA charge current is applied, meaning that the leakage current is almost the same as 1.0 µA. By repeatedly changing the charge current among 0, 1.0 and 1.5 µA, similar experiment results, shown in Fig.5, demonstrated that the measurement result is repeatable and reliable. It is worth noting that there is a voltage jump when charge current changes. This voltage jump is caused by the ESR of the battery, as shown in Fig.1. The amplitude of the voltage jump is ($I_{charge2} – I_{charge1}$) × ESR.

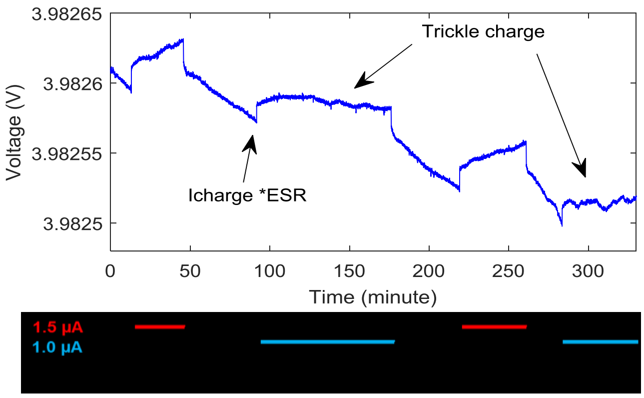
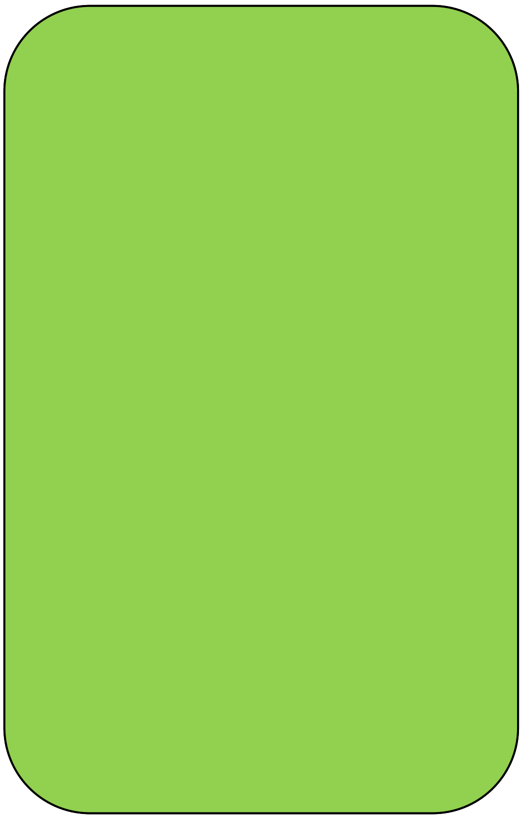


Fig.5. *Top: measured terminal voltage. When curve slope is positive, it holds I_{charge} > I_{leak}; when curve slope is negative, it holds I_{charge} < I_{leak}. Trickle change state (I_{charge} = I_{leak}) appears when the curve is flat. Bottom: applied charge current (I_{charge}) pattern. The trickle charge state happens in blue current pattern periods, so the battery leakage is 1.0 µA.*

A precise leakage current measurement procedure has been proposed as a successive approximation search algorithm [8], where the measurement period and the number of iteration are pre-determined constants. The charge current is adjusted [1 - sign × $(½)^n$] times for each search procedure. At the beginning of the search algorithm, the step of charge current change is larger for fast algorithm convergence. When the amplitude of charging current is approaching that of the leakage current, the steps of the charge current amplitude change is getting smaller, resulting in a relatively accurate leakage current measurement. The search algorithm can terminate for the first time when a sign change occurred indicating a passing through of the battery trickle charge state, but for a better measurement accuracy, more iteration can be involved. The iteration number, which is counted when signs swop in two successive search procedures (the sign change event is detected by using the criteria of (previous_sign × sign < 0)), makes the step of charge current amplitude change reducing related to the term of $(1/2)^n$ when n increases (n denoting the n^{th} iteration).

A full successive approximation search algorithm is described as below.



3.4 Discussion

Simply modelling the battery as in Fig.2 will be easily challenged, since the terminal voltage of the battery is affected by the charge transfer process and the mass transfer process/diffusion of ions inside the Lithium battery. These charge redistribution process mainly happens after a relatively high current (at least mAs) charge/discharge, while the method proposed here is implemented to the already stabilized post-charge battery, so the non-linear effects of the mass/charge transfer caused by the battery charge activities from the extra charge current in µA can be ignored.

The leakage path shown in Fig.2 implies that the leakage current should be tested under the highest voltage of the battery. However the constant voltage charge mode should be adopted at the highest battery voltage, in which a gradually reduced charge current is produced. Comparing to the up to 50 mA initial charge current specified for CP1254, the up to 10 μA charge current employed in this method can be considered as almost no charge at all. So this constant current charge experiment at high battery voltage does not challenge the ‘common sense principle’ that trickle charge state appears in the constant voltage charge mode. In fact, as we can see from Fig.5, the terminal voltage change is in μV for the applied μA charge current, so it is safe to use μA level constant current charge mode for leakage current measurement.

As shown in Fig.5, when voltage slopes ($\Delta V/\Delta T$) of 4 no-charge periods are compared, a slight slope change can be observed meaning that the terminal voltage data is not reliable for precise leakage current calculation when using an electrical battery model. By introducing a tiny extra charge current, the leakage current is experimentally measured by observing the sign of the terminal voltage change, which is more noise tolerant than measuring the absolute voltage value.

One of the potential application is to integrate this method to battery test equipment (referring to the leakage current test system configuration shown in Fig.2). However, the post-charge stabilization time of a battery depends on a set of parameters such as battery capacity and the charge history and therefore further research work is required for this application.

IV. Conclusion

The μAs leakage current of the Lithium coin battery has been precisely measured by a novel successive approximation leakage current measurement method which employs the sign of terminal voltage change of the already stabilized post-charge Lithium coin battery as a sign of the term of ($I_{charge} - I_{leak}$) when a known μA charge current I_{charge} from an extra current source is applied. Experiments demonstrated that the proposed method is reliable and measurement results are repeatable. The measured 1.0 μA leakage current of Lithium coin battery (CP1254) enables the use of the full capacity of the Lithium coin battery in ultra-low-power applications where current is most likely to be budgeted in μA. The proposed method is straightforward and it is generic enough for leakage measurements of other batteries without considering the electrical battery model parameters.

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