A Battery Management System Adapted for an Energy Harvester with a Low-Power State of Charge Monitoring Method and a 24 Microwatt Intermittently Enabled Coulomb Counter

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***Abstract*— This paper presents a battery management system with methods for monitoring both the battery state of charge (SOC) and the discharge amount consumed by a wireless sensor device. The proposed SOC estimation method achieves a low-power operation by using a pulse-shaped input current to obtain the frequency-dependent internal impedance of a battery, and by eliminating the AC-source and sample-hold circuits which are conventionally required. The discharge amount from the battery is monitored with a proposed discharge-estimation algorithm that enables an intermittently enabled Coulomb counter (CC), which leads to low-power operation, keeping the error as low as 2.5 percent — the same result from an always-on CC. Measured power consumption has shown a reduction from 340 microwatt with a conventional always-on CC to 24 micro watts using the proposed method. These two techniques enable the power management system to achieve sub-milliwatt operation.**

Keywords—battery state of charge, Coulomb counter, internal impedance, low-power consumption

I. INTRODUCTION

With the growth of the Internet of things (IoT) in recent years, it is estimated that 50 billion devices will be connected to the network in 2020 [1]. When constructing an IoT system or a service using data obtained from many devices, problems arise such as radio wave interference, network blocking and device management. In device management, battery management is especially important; unexpected device shut down leads to disconnection, data loss and eventually network system or service shut down. For example, in a data server monitoring service at a data center; utilizing the temperature sensor data to control the air conditioner, if the data loss occurs due to the battery of a wireless sensor device being depleted, it leads to a loss in the reliability of service. As the number of devices increases, the importance of battery management further increases.

Coulomb counting is a well-known method for battery remnant charge measurement. It accurately counts the integral value of the output charge from the battery. When the Coulomb counter(CC) was used in the device with large steady-state current consumption like a note PC or a smart phone, the power consumption of the CC was relatively small with respect to that of the device. However, for a low-power device such as a wireless sensor device used in recently developed IoT systems, the power consumption of the CC becomes relatively large, therefore, it is difficult to add on the battery remnant charge measurement components (TABLE I). For example, a device steady-state current consumption of a smart phone calculated from the battery capacity and available time with standby mode awaiting a 3G network is 4 mA. While the CC consumes 100μA, accounting for only 2.5% of them. On the other hand, the current consumption of a wireless sensor device's steady-state current is 160μA or 50μA. The addition of the CC causes an increase of 62% or 150% of them. It does not seem efficient that the battery remnant charge measurement requires two to three times the battery amount. The large current consumption of the CC originates from the mechanism of the CC that continuously operates an analog amplifier as an integrator.

While the CC measures the charge extracted to the outside of the battery, a method for measuring the battery internal state including state of charge (SOC) is known in the field of battery material development. Conventional SOC estimation methods obtain accurate results by measuring the battery's internal impedance along with the output voltage and estimating the

TABLE I. STEADY-STATE CURRENT CONSUMPTIONS FOR VARIOUS IOT DEVICES AND COULOMB COUNTER.

Devices	Consumption
Note PC [2]	486mA
Smart Phone [3]	4 mA
Wireless Sensor Device 1 [4]	160μA
Wireless Sensor Device 2 [5]	50μA
Coulomb Counter[6]	100μA

open circuit voltage (OCV) [7]-[9]; however, they require a frequency-variable AC current source and sample-hold circuits as shown in Fig. 1. Synchronous measurement of voltage and current for multiple frequencies is also necessary, therefore resulting in a large circuit area, increased measurement times and high power consumption.

In this paper, we propose two approaches for the battery remnant charge measurement with low power consumption. The first is direct SOC calculation, simplifying the method in the field of battery material development. And the second is intermittent CC, eliminating continued CC operation.

II. PROPOSED STATE OF CHARGE ESTIMATION

We propose an SOC estimation circuit using a microcomputer in the wireless sensor device as a substitute for the AC current source (Fig. 2). The microcomputer runs the measurement program with precise timings and a known rectangular current. It automatically synchronizes voltage measurement and current control, so synchronous measurement of the current itself can be omitted. Additionally, because the rectangular current includes harmonic frequencies as an odd multiple of repetition frequency, multiple impedances are simultaneously extracted by fast Fourier transform (FFT). Fitting the measured internal impedance of various frequencies to the battery equivalent circuit as shown in Fig. 3, the DC component of impedance R_{DC} can be extracted without the need for the multiple measurement of various frequencies or a long measurement period; it then leads to OCV calculation, eliminating conventional measurement circuits as shown in Fig. 1. As stated above, the proposed method can improve both power and circuit-area overheads. Measured data using the proposed method of SOC estimation is shown in Fig. 4. A pulse-shaped input current of 10–30 mA with a 6.25 Hz repetition frequency is input to a 110-mAh lithium-polymer battery. The scatter graph shows the internal impedance for multiple frequencies on the complex plane calculated with a one-time measurement data (Fig. 4). The internal impedance extraction method firstly involves the voltage spectrum being calculated by FFT of the voltage wave. Secondly, the voltage spectrum is divided by the previously calculated current spectrum, resulting in internal impedance. As an intersection of the dotted half circle and real axis, the 0-Hz component of internal impedance R_{DC} can be obtained at about 1.25 Ω.

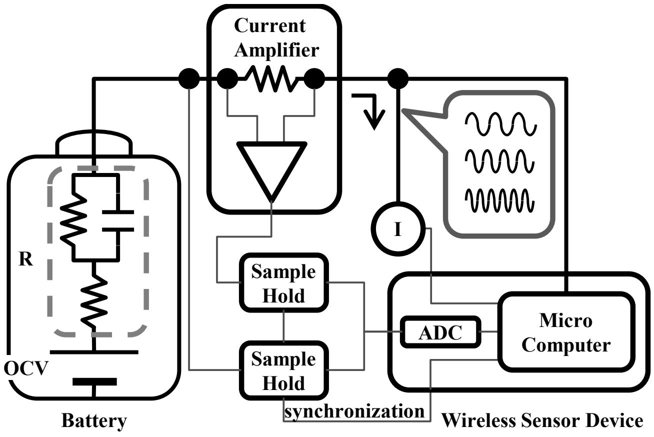

Fig. 1. Conventional circuit for SOC estimation [7].

Fig. 5 ,Fig. 6 and Fig. 7 show measured battery output voltage ,calculated internal impedance and estimated open circuit voltage with various temperatures for a 110-mAh lithium-polymer battery, respectively. Because internal impedance was influenced by temperature(Fig. 6), it causes a difference in the output voltage despite the fact that the charge remained the same (Fig. 5).

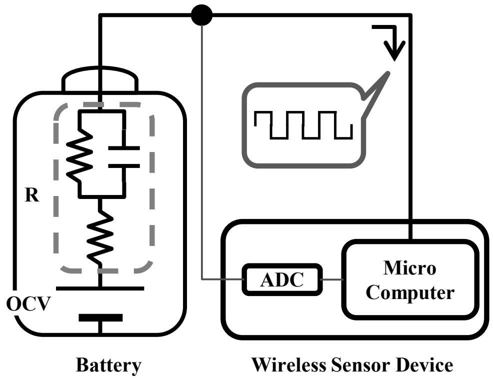

Fig. 2. Proposed circuit for SOC estimation.

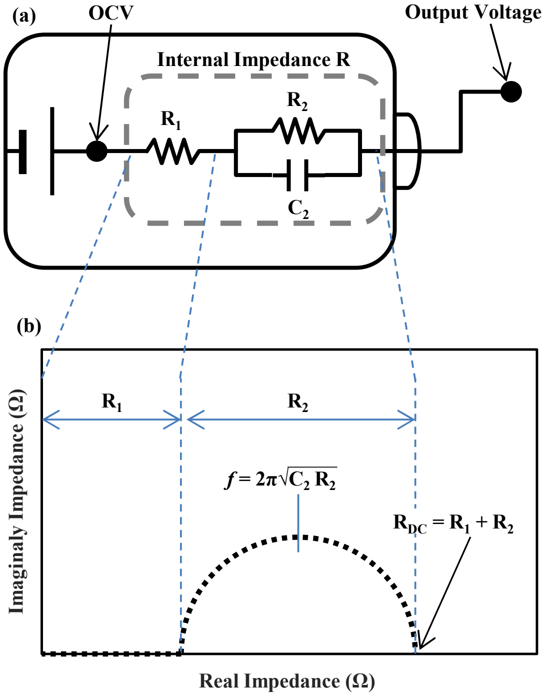

Fig. 3. (a)Battery Equivalent Circuit and
(b)Appearance of Internal Impedance in Complex Plane.

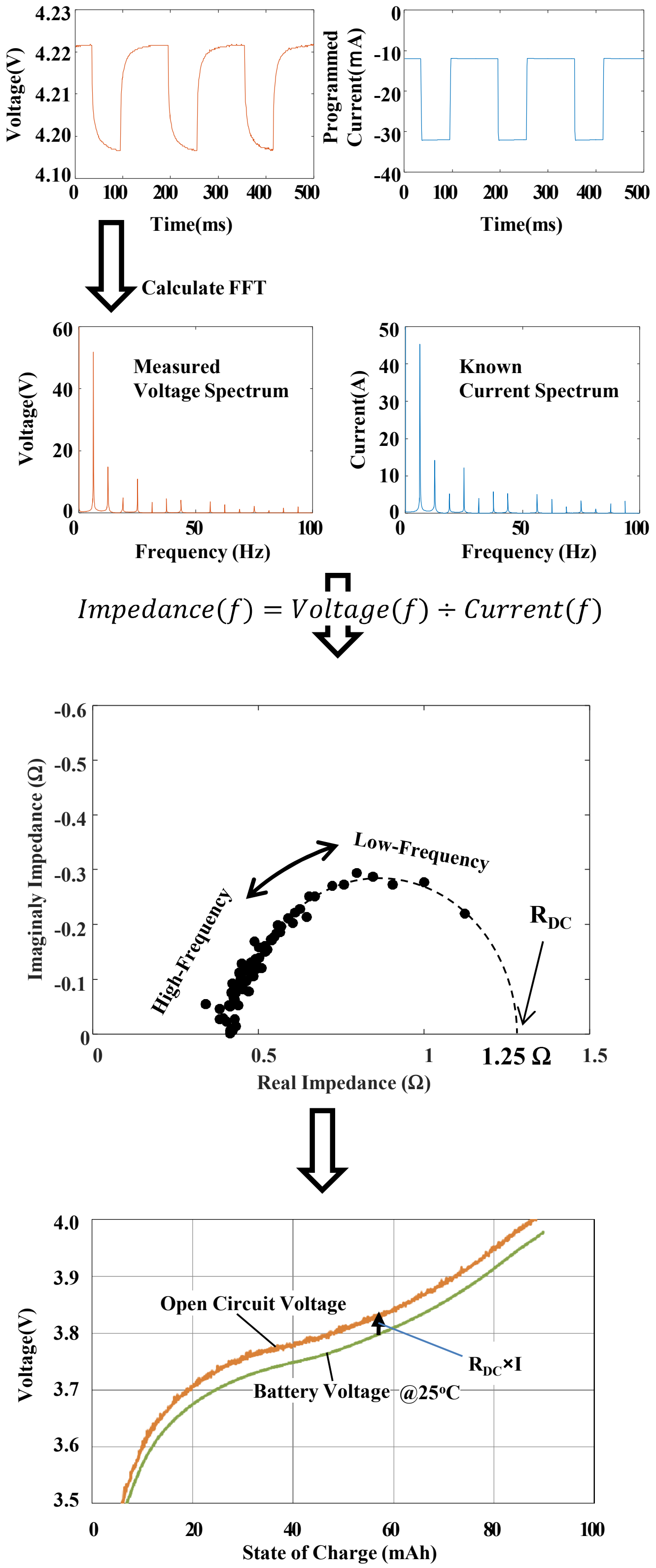

Fig. 4. Measured data using the proposed method of SOC estimation

The proposed method removes the influence of internal impedance resulting in same open circuit voltage (Fig. 7). Therefore, only one reference graph, such as OCV line in bottom of Fig. 4, is enough to estimate the SOC by picking up the intersection of it, even the output voltage varies under various conditions such as current and temperature. The estimation error was defined as the difference from the remaining charge obtained by CC to the estimated SOC. Using the relation between OCV and the remaining charge at 25°C as the reference, the SOC estimation error at 0°C is 53% for measured output voltage without internal impedance correction as shown in Fig. 8 (0°C is the blue line). However, the proposed OCV method with internal impedance measurement reduces the error to 16% (Fig. 9). TABLE II is a summary of estimation error at other temperatures.

In this way, the method can extract multiple points of impedance and estimate the low-frequency point from a one-time measurement to calculate OCV without a frequency-variable AC current source, a current amplifier and sample-hold circuits which were conventionally required. TABLE III shows the comparison summary of the method. The proposed method achieves low-power operation in proportion to reduced measurement time.

In contrast, the Coulomb counter needs continuous measurement to know the battery remaining charge. It is possible to reduce the average current consumption by operating only when the battery remaining charge is required, and by putting it in sleep when not needed. For example, when the measurement cycle is 5 minutes, a conventional circuit (Fig. 1) consumes 2400 μW (preliminary calculation) and the proposed circuit (Fig. 2) consumption achieves only 28μW by reducing the circuit size and measurement time.

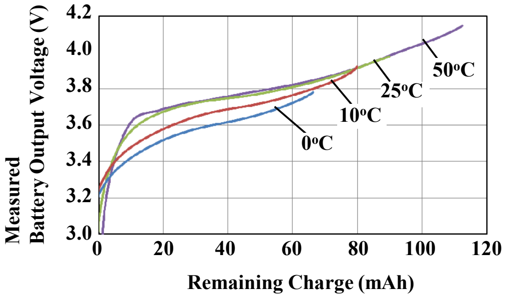

Fig. 5. Measured battery output voltage.

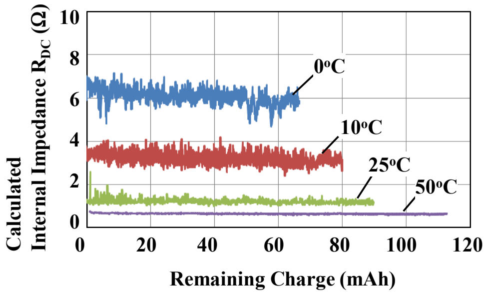

Fig. 6. Internal impedance R_{DC} calculated with measured data.

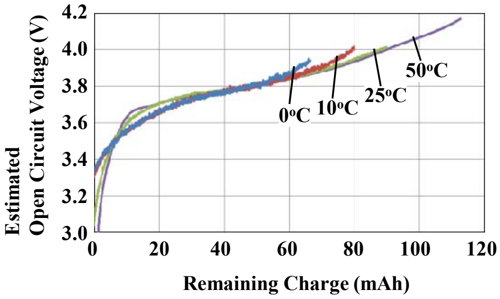

Fig. 7. Estimated Open circuit voltage.

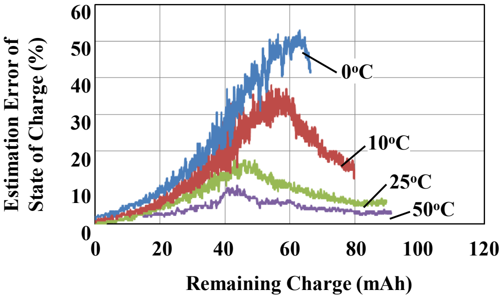

Fig. 8. Estimation error of SOC calculated from output voltage shown in Fig. 5.

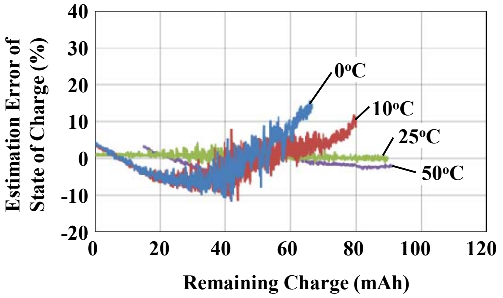

Fig. 9. Estimation error of SOC calculated from OCV shown in Fig. 7.

TABLE II. SOC ESTIMATION ERROR FOR VARIOUS TEMPERATURES.

Battery temperature	Estimation error of battery remaining charge	
	Output voltage measurement	This work
0°C	53.0%	15.8%
10°C	38.0%	11.7%
25°C	18.0%	4.4%
50°C	10.5%	4.5%

TABLE III. COMPARISON SUMMARY OF SOC ESTIMATION WITH INTERNAL IMPEDANCE.

	Conventional	This Work
Circuit components	ADC, frequency-variable AC current source, sample hold for synchronous measurement	ADC
Measurement subject	Voltage & current synchronously	Voltage
Input waveform	Many sine waves for each measurement frequencies	One rectangular current
Measurement times	Number of internal impedance data points of each frequency	Once
Current consumption (simulation)	2400µW	28µW

III. PROPOSED DISCHARGE-ESTIMATION ALGORITHM

Counting charges into and out of the battery using a Coulomb counter (CC) gives the most accurate result; however the CC needs to operate continuously. A commercial product [6] consumes 340 µW at a 4-V power supply as shown in Fig. 10, which is an unacceptably large amount of power for sub-mW sensor devices [10]-[12]. To reduce the power consumption of the CC, we propose a discharge amount estimation algorithm with a low-power detection circuit, focusing on intermittent operation of the wireless sensor device. The wireless sensor device has two types of state. The first is the function state measured with sensors and sending data to the gate way. The function state consumes the same amount of charges at each function time. And the second is the sleep state to reduce current consumption. The sleep state consumes sleep current constantly. To detect the state, a current change edge detection circuit (CCED) is composed of a band pass filter and a quantizer, detecting the change edge of the device's operating current (Fig. 11). Firstly, the CCED counts the numbers of the current change edge N_0 and the CC accumulates the total discharge amount of C_0 within the period T_0. In a separated time period of T_1, the circuit also counts N_1 and C_1 respectively as shown in Fig. 12. Here Q_A and I_B are defined as the discharge amount of the device's single function and the standby current respectively. This results in the following equation:

$$I_B \times T_0 + Q_A \times N_0 = C_0 \qquad (1)$$

$$I_B \times T_1 + Q_A \times N_1 = C_1 \qquad (2)$$

$$C_X = I_B \times T_X + Q_A \times N_X \qquad (3)$$

By solving simultaneous equations (1) and (2), the unknown parameters Q_A and I_B are obtained. Q_A and I_B renewal can be performed when the battery output voltage or the environment, such as temperature, around the wireless sensor device have changed. The time period between renewals of Q_A and I_B is defined as T_X, and the numbers of the current change edge during the period is represented as N_X. Then, even if the CC is powered down while maintaining CCED operation, the discharge amount C_X can be calculated from (3) only with N_X and T_X by using the known parameters Q_A and I_B.

Both N_X and T_X are obtained from low power components, CCED and timer, in the microcomputer. This intermittent CC operation leads to low power consumption. Fig. 13 shows a photograph of the proposed evaluation board and Fig. 14 shows the measured SOC for a lithium 1200-mAh battery that is calculated by subtracting the sum of C_X from the battery capacity. The true line shows the measured value of CC that was inserted in series to the proposed circuit and operated constantly. The proposed method requires only 5 times and a total of 2.3 hours measurement with the CC to restore Q_A and I_B. Although the CC only operates 1.9 % of the total battery operating time of 120 hours, an estimation error can be suppressed to 2.5 %. As shown in Fig. 15, due to intermittent CC operation, the proposed CC with CCED consumes 24 µW (@ 4V), while the conventional always-on CC consumes 340 µW (@ 4V). This means a reduction in power consumption of 93 %. TABLE IV is a comparison summary of the conventional and proposed discharge estimations. The proposed method enables low-power operation with an error of 2.5 %, which is the same as the conventional method.

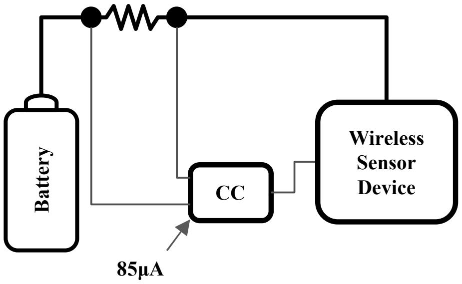

Fig. 10. Conventional block diagram with CC.

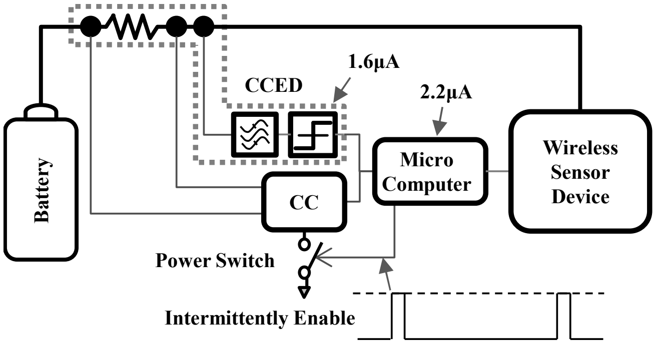

Fig. 11. Proposed block diagram with CC.

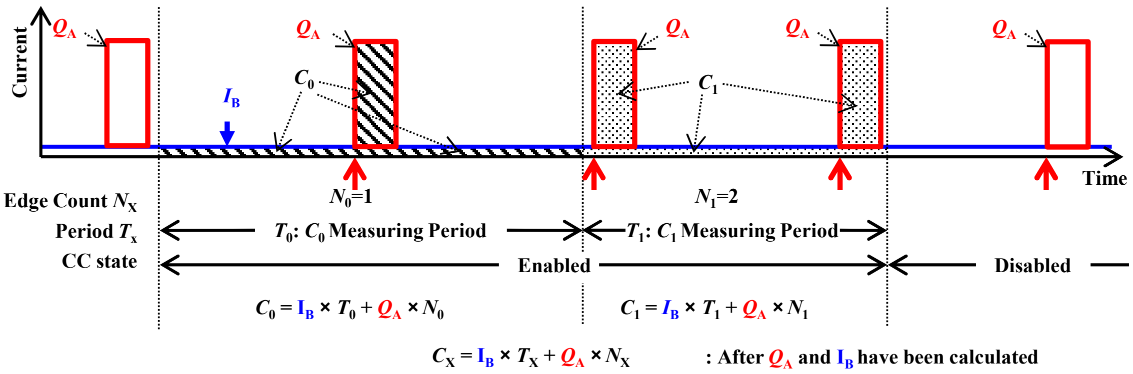

Fig. 12. Timing chart of the proposed calculation method.

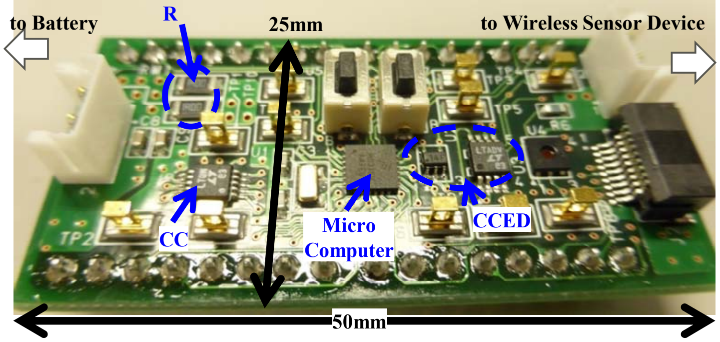

Fig. 13. Photograph of evaluation board with intermittent CC.

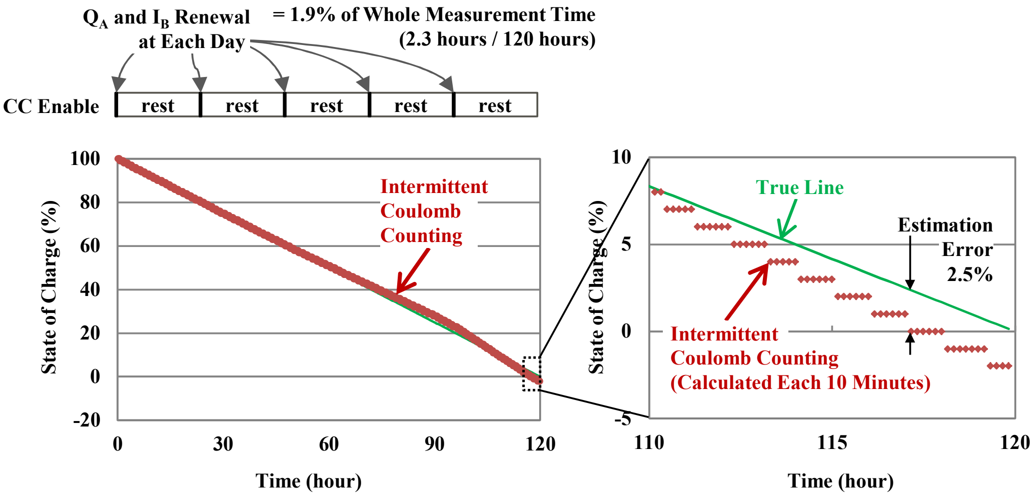

Fig. 14. Measured state of charge.

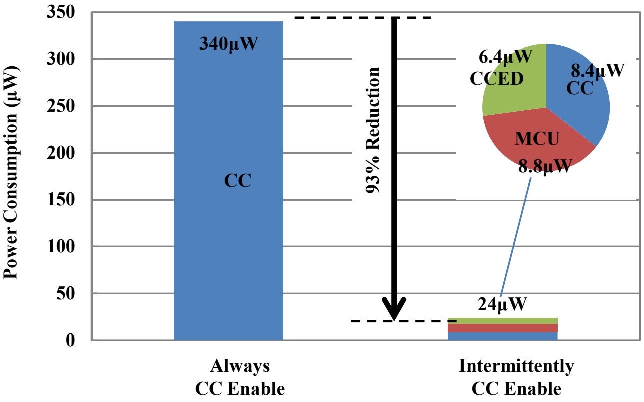

Fig. 15. Measured power consumption.

TABLE IV. COMPARISON SUMMARY OF DISCHARGE AMOUNT ESTIMATION.

	Conventional Method[6]	Proposed Method
Error	2.5%	2.5%
Consumption	340μW	24μW

IV. CONCLUSIONS

We proposed a low-power battery monitoring method for estimating SOC and the discharge amount in a battery management system. The SOC estimation can be improved by accurately calculating OCV using the proposed internal-impedance extraction from the battery. The proposed method also leads to low-power operation with compact measurement components to eliminate AC current source and sample-hold circuits, and with fast internal impedance extraction by rectangular current including multiple frequencies at a single measurement. SOC estimation can be achieved by removing the influence of temperature, and the estimation error was reduced from 53% to 16% at 0ºC. The power consumption with the proposed method is reduced from 2400μW to 28μW with each 5-minute measurement. Due to intermittently enabled CC operation, the power consumption of the discharge amount estimation can be improved to 24 μW from 340 μW as with the always-on CC method, while maintaining a measurement error at 2.5% — the same as with the conventional method. A combination of the proposed methods can be applicable to low-power wireless sensor devices with sub-mW energy harvesters. Since the harvester continuously generates electric power, it is difficult to manage the battery by CC or SOC estimation separately, however by combining them, complete management including the amount of generated power can be performed. Our proposed methods made it possible to predict and control a battery exhaustion period in some low-power devices by precisely managing battery levels.

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