DESIGN AND ANALYSIS OF LI-ION BATTERY FUEL GAUGE ALGORITHM FOR MOBILE SYSTEMS

By

WONG TECK SING

A Dissertation submitted for partial fulfilment of the requirement for the degree of Master of Science (Electronic Systems Design Engineering)

August 2016

ACKNOWLEDGEMENT

Firstly, I would like to thank my supervisor, Dr. Nur Syazreen Ahmad for mentoring me, providing guidance, suggestions, and supporting my work throughout my study as a postgraduate student in Universiti Sains Malaysia (USM). I learned a lot from Dr. Nur Syazreen Ahmad, truly grateful to have this opportunity to work with her and to complete the thesis under her supervision. Her comments and advice have been invaluable. Thanks for the supports by USM Engineering Faculty on the sharing talks and writing workshops to help on improving our thesis writing skills. In addition, special thanks to Usains Holdings Sdn. Bhd. who partnered with USM in hosting this master program. Thank you for the logistics planning and curriculum arrangements.

I would like to thank my family and friends who supported me through this master program, showing patience, providing guidance and experience sharing from seniors of this master program.

TABLE OF CONTENTS

ABSTRAK

Peralatan eletronik dengan bateri seperti telefon bimbit, “smart watch” dan “smart glasses” telah menjadi sebahagian daripada keperluan dalam kehidupan harian. Selain daripada kecanggihannya, jangka hayat bateri juga merupakan salah satu daya tarikan kepada pengguna. Kebanyakan peralatan elektronik mudah alih menggunakan Lithium-Ion (Li-Ion) bateri kerana ketumpatan tenaga yang baik, keupayaan boleh dicas semula, dan yang paling penting keringanannya. Ramai pengguna kecenderungan untuk membeli peralatan elektronik yang mempuyai bateri yang tahan lama supaya tidak perlu mengecas semula peralatan itu seringkali atau membawa bekalan kuasa semasa di luar. Walau bagaimanapun, kebanyakan penunjuk bateri system tidak dapat menunjukkan baki bateri yang tinggal dengan tepat. Ini telah meninggalkan tanggapan negatif kepada pengguna atau pembeli, dan juga memberi kesan negatif kepada jualan produk itu. Oleh itu, penganggaran tahap bateri dengan tepat untuk aktiviti dan pengoptimum penggunaan bateri adalah penting untuk memberikan pengguna pengalaman yang berkualiti.

Untuk tesis ini, reka bentuk algoritma penganggaran tahap bateri akan direka untuk meningkatkan kejituan penganggran tahap bateri Li-ion. Reka bentuk ini adalah berdasarkan itegrasi kaedah pengiraan coulomb dan voltan litar terbuka bateri. Reka bentuk ini telah ditunjukkan bahawa boleh mengurangkan ralat penganggaran kepada ±3% dan memenuhi spesifikasi industri.

ABSTRACT

Personal battery-powered devices like mobile phones, smart watches and smart glasses have become part of necessity in our daily life. Apart from sophisticated features, the battery lifetime or standby time is also one of the attractiveness of the devices. Most of these mobile or wearable devices use Lithium-Ion(Li-Ion)-type batteries as they offer a variety of advantages such as the capability of holding the charge longer, the ability to be recharged numerous times, and most importantly, being lightweight. Many people tend to purchase those with longer battery standby time so that they do not have to recharge the devices very often or carry a backup power supply when they are on a travel. However, in many cases, the battery indicators of the devices do not exactly represent the remaining charge of the battery. This does not only lead to inaccurate description of the devices, but also leaves negative impressions to the users or buyers, which consequently affects the sales of the products. Hence a solution to accurately estimate available battery charge for remaining activities and optimization of battery usage based on device activities is important to give users a high quality user experience.

In this thesis, a fuel gauge algorithm design is proposed to increase estimation accuracy of the state of charge (SOC) of the Li-ion battery. The design is based on the integration of coulomb counting and open-circuit-voltage methods. It is shown in this work that this technique is able to reduce the error to ±3%, which is a standard industry specification requirement.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

ADC	Analog to digital convertor
C_{Th}	Thevenin capacitor of battery
CC	Coulomb counter / Coulomb counting
FCC	Full charge capacity
FG	Fuel gauge
I	Current
I_{Th}	Thevenin current flowing through thevenin resistance of battery
I2C	Inter-Integrated Circuit Communication Bus
IC	Integrated Circuit
IR	Voltage from multiplication between current and resistance
Li-ion	Lithium ion
mAh	mili-Ampere/hour
MaxCap	Maximum capacity available in battery, in mAh
MCU	Microcontroller unit
OCV	Open-circuit voltage
OS	Operating System
PC	Personal Computer
R	Resistance
RDC	DC Resistance, resistance measured under direct current
Rint	Internal Resistance of battery
R_{Th}	Thevenin resistance of battery
SOC	state-of-charge, percentage of charge remaining in a battery
SW	Software

USB	Universal Serial Bus
V	Voltage
V_{OC}	Open-circuit Voltage, same as OCV
V_{Th}	Thevenin voltage drop across thevenin resistance of battery

CHAPTER 1

INTRODUCTION

1.0 Chapter Overview

This introductory chapter consists of six sections. Section 1.1 provides the background of the study and explains concepts of battery fuel gauge in mobile system. Section 1.2 explains the challenges in capacity estimation of Li-ion battery and the importance of the study to mobile system battery life. Problem statements and research objectives are presented in Section 1.3 and Section 1.4 respectively. Section 1.5 provides the research limitation and Section 1.6 provides thesis outline.

1.1 Background

The fuel gauge (FG) in mobile electronics is usually used to measure the state-of-charge (SOC) of Li-ion battery. Li-ion battery is a popular power source and has been broadly used in many mobile systems includes tablets, mobile phones and smart wearable devices. However unlike a real fuel liquid tank which occupied a physical dimension and has actual volume that can be measured, the actual energy stored in Li-ion battery has no actual physical form to be measured. Hence SOC is defined as the parameter to measure the energy available in Li-ion battery. The SOC is defined as equation (1.1) [1], where this ratio of current capacity value Q(t) to maximum capacity rating (Q_n) of battery is usually expressed in unit of percentage, %.

$$SOC(t) = \frac{Q(t)}{Q_n} \tag{1.1}$$

Where

SOC(t) = State-of-charge of Li-ion battery

Q(t) = Current capacity of the battery, in mAh

Q_n = Maximum capacity rating of the battery, in mAh

FG algorithm is developed in chip and system software (SW) to record and keep track of the charge/discharge activities of Li-ion battery in mobile system. Battery SOC shown to user is calculated by complex FG algorithm calculation based on battery current flow, open circuit voltage (OCV) and maximum battery capacity value.

Figure 1.1 shows the typical FG system in current mobile system design. A sense resistor, R_s is connected between battery and load. Both discharge and charge current value is sampled by FG IC in ms (millisecond) interval, and at the same time, voltage of the battery is measured. Then the voltage and current information of the battery is further processed by FG algorithm in the software to calculate a battery SOC number in percentage (%) to show in user interface. In most of FG IC, coulomb counter is integrated in the design to keep track of the charge number charged in and discharged out of battery and keep in IC as a number to be use by FG SW to convert into appropriate capacity number in mAh.

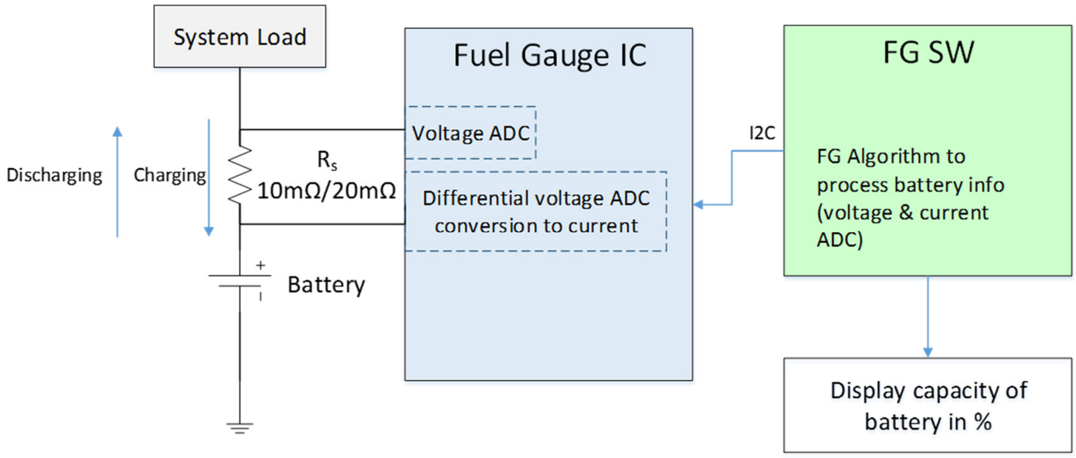

Figure 1.1: FG System block diagram

1.2 Importance and Challenges of Battery Fuel Gauging

The main design challenges for mobile and wearable devices are power consumption and battery pack size limitation. Li-ion battery usually occupied the biggest area space in mobile devices design that the pack size of the battery actually dominates the size of the end product. Smaller pack size leads to smaller capacity of power and vice versa. The common capacity of battery used for wearable devices are below 1000mAh range [2][3] since weight and size of battery is significant to ensure comfort of users. Hence FG algorithm design of mobile devices is important to optimize the battery pack size vs power consumption of the system.

As the mobile system design now tend to have requirement of higher performance and offer varieties of features, the energy available in battery become an important criteria for software to decide whether the system can enter turbo mode or need to force the system to go into power-saving mode with limited application access (for example high power consumption applications like camera feature force disabled) based on the remaining capacity. The error in SOC estimation may lead to bad user experience. If the SOC estimated is higher than actual SOC, insufficient battery SOC before any warning appeared might cause the user to face unexpected situations such as sudden power off, sudden dropped phone call or lost of document due to dead battery. If the SOC estimated is lower than the actual SOC, this will cause bad user experience of short battery life impression with the device.

1.2.1 Importance of Battery Fuel Gauge Design Accuracy

A FG accuracy is measured by the error between estimated SOC and actual SOC of the battery as shown in equation (1.2) [4] where lower SOC_{error} value indicates better accuracy level. FG accuracy is equal to SOC error.

$$SOC_{error} = |SOC_{actual} \quad SOC_{estimated}| \tag{1.2}$$

If for instance a battery FG accuracy is ±7%, battery level shows 10% will have actual leftover 3% of SOC in battery if the error is -7%. If the system is designed to start turning off non-critical functions for power saving purpose at 10% SOC, and begin to warn user on risk of force turn off device at 3% of SOC, to avoid bad experience of unwarned force turn off when battery 0% low voltage limit triggered, software would need to be design to accommodate for the FG design accuracy worst case.

For example of power saving mode entry at 10% SOC, to accommodate for the worst case error of -7%, the system need to start turning off non-critical applications and alert user on low power when FG reported 17% SOC but at the same time the battery might be having real SOC of +7% which is 24%. The possible situations are summarized in Table 1.1.

Table 1.1: Possible situations when system entered power saving at 17% SOC

SOC	SOC_{error}	SOC_{actual}	Result
17%	-7%	10%	Worst case of accuracy is well handled since system supposed to enter power saving mode at 10% of actual SOC.
17%	+7%	24%	Wasted 14% SOC of battery life that can be used for running heavy applications due to early power saving mode entry.

While for example of system force turn off warning at 3% SOC, To accommodate for worst case of -7% accuracy, the system will need to begin force turn off warning at 10% estimated SOC where actual might be only 3% leftover SOC. The possible situations are summarized in Table 1.2.

Table 1.2: Possible situations when system warn user for force turn off at 10% SOC

SOC	SOC_{error}	SOC_{actual}	Result
10%	-7%	3%	Worst case of accuracy is well handled since system supposed to turn off at 3% of actual SOC.
10%	+7%	17%	14% SOC of battery life wasted due to underestimation of SOC.

To illustrate the impact of the waste of 14% SOC battery life described in Table 1.1 and Table 1.2 due to ±7% accuracy to the actual device, let's take SAMSUNG NEXUS S with 1500mAh battery as an example. Assume the Li-ion battery has an average voltage of 3.8V, this system will be able to support 5700mW loading for 1 hour. Wasted 14% SOC battery life of this system indicate a waste of 798mWhr (14%

* 5700mWhr) power for actual user use case, in case of MP3 audio playback with SAMSUNG NEXUS S which consume 165mW of power [5], 798mWhr power actually indicate 4.8 hour of MP3 audio playback. Hence better accuracy of battery FG design lead to longer usage time of the mobile device and better battery life experience.

1.2.2 Challenges of Battery Fuel Gauge Design

Figure 1.2 shows an example of battery voltage vs charge/discharge time. The flat voltage level in Figure 1.2 is the nominal voltage called MPV (mid-point voltage) [6], which is the point where the change in battery voltage is minimal for a long period of time. The EODV (end of discharge voltage) [6] in Figure 1.2 is the stage where the battery voltage drops significantly with bigger slope rate compared with MPV stage. At this stage, the energy contained in the battery is almost drained, continuous discharge will lead to dead battery without any voltage output. Non-linearity of battery voltage in the flat battery voltage MPV stage vs actual SOC of the battery lead to the biggest design challenge of battery FG algorithm. Most of the time the battery voltage is in an almost constant voltage level with low voltage change rate where the actual SOC left in battery would be hard to estimate.

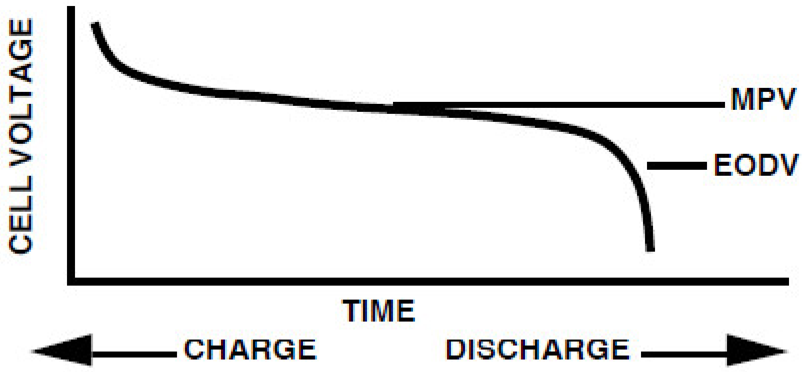

Figure 1.2: Battery charge / discharge curve [6]

Besides the non-linearity behavior of the battery voltage, the varying battery internal impedance also adds to the difficulty in the battery SOC estimation. Figure 1.3 shows a schematic diagram of a simple battery model with an internal resistance R_{int} which is due to battery pack internal circuitry path resistance and contact resistance. Theoretically, the battery open circuit voltage (OCV) can be calculated as in equation (1.3) where V represents the measured battery voltage and I represents the charge/discharge current:

$$V_{OC} = V + IR_{int} \tag{1.3}$$

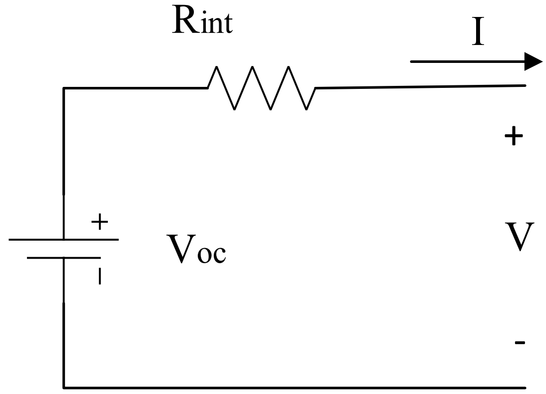

Figure 1.3: Schematic diagram of simple battery model

Thevenin model with a parallel RC network as shown in Figure 1.4 is introduced [7] to represent the actual dynamic internal resistance characteristic of the battery to model the complex internal battery electrochemistry. The capacitor C_{Th} affects the transient response characteristic of the battery voltage that changes during charging and discharging current flow. By including this dynamic characteristic of battery, the battery OCV can be derived in Thevenin model as below equation (1.4):

$$V_{Th}(t+1) = \frac{V_{Th}(t)}{R_{Th}C_{Th}} + \frac{I(t)}{C_{Th}}$$
$$V_{OC} = V + V_{Th} + IR_{int} \tag{1.4}$$

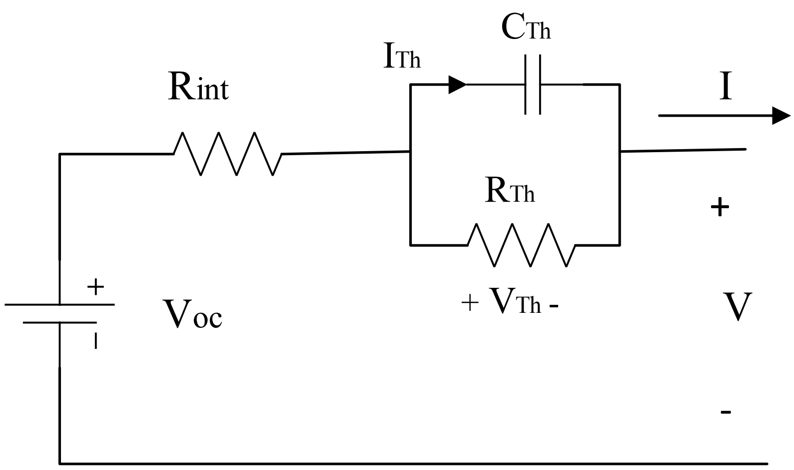

Figure 1.4: Thevenin model of battery [7]

1.3 Problem Statement

Coulomb counting method has been introduced as one of the SOC estimation technique into battery FG algorithm to estimate the battery energy remained at the long MPV stage in battery voltage. Coulomb counter assume that every charge current go into battery will be discharge out as energy to be use by system. A full coulomb counter calibration would require a full charge of battery to maximum voltage of the battery (typically 4.2V or 4.35V for a Li-ion battery) and a full discharge to the system shut down voltage (most system will define in range of 3.3V to 3.5V of battery open circuit voltage level) to get an accurate estimation of total charge contained in a battery. However, in real life cases, users usually do not always charge and discharge battery to 100% and 0%. Moreover, there are a lot more factors that impact the accuracy of coulomb counting method, for example temperature, battery cycle life, discharge current and battery self-discharge effect. Hence error often exists in SOC estimation of battery and error gets accumulated over time.

1.4 Research Objective

To optimize the power available in the 800mAh Li-ion battery, FG algorithm of this work needs to be designed with low computing power while maintaining a desirable high accuracy value. The objectives of this thesis are as follows:

- To design a suitable FG algorithm such that the SOC estimation error is reduced to achieve high industry standard accuracy of ±3%
- To analyze the performance of the FG algorithm and to compare the result with commercial part in market

1.5 Research Scopes and Limitations

There are limitations in this study due to time and budget constraints, these are the limitations of the research:

- This study will focus on one specified model of 800mAh Li-ion battery only
- FG algorithm accuracy study will be focused on discharge process of battery only (no charger power source condition)
- The current load of the battery will be focused on 0.1C, 0.25C, 0.5C and 0.75C (within 1C rate)
- The temperature will be limited to environment room temperature of 25degree Celsius in lab

1.6 Thesis Outline

Chapter 1 introduces the background of Li-ion battery FG study in the very beginning. Then, it highlights the problems in estimation of SOC of Li-ion battery and also importance of high accuracy battery SOC estimation in mobile products. Lastly, problem statement and research objective of this study is outlined. Chapter 2 provides the literature review. Chapter 3 presents the methodology to design. Chapter 4 presents the results outlined in the methodology presented in Chapter 3. Chapter 5 draws the conclusion of this study and presents the future works that can be extended to further improve the scope and depth of this study.

CHAPTER 2

LITERATURE REVIEW

2.0 Chapter Overview

This chapter reviews the existing FG algorithm designs for Li-ion battery. Section 2.1 explains on the common parameters definitions in FG. Section 2.2 explains on the Li-ion battery characteristics based on the open circuit voltage (OCV) non-linearity behavior, environment effect, usage model, storage length effect and also the aging effect, the impacts to the battery capacity which lead to the challenges in FG algorithm design in SOC estimation. Section 2.3 introduces the basic hardware requirements for FG to enable the capability to obtain battery's parameters for state-of-charge (SOC) estimation. Section 2.4 reviews various algorithm methods for SOC estimation and FG solutions available in the market.

2.1 Parameters Definitions in Fuel Gauge

2.1.1 State-Of-Charge (SOC)

SOC is the parameter to measure the energy available in Li-ion battery. The SOC is defined as equation (1.1) in Section 1.1, which is the ratio of current capacity value to maximum capacity rating of battery. Usually SOC in FG algorithm is measured in percentage.

2.1.2 C-Rate of Charge / Discharge

Charging / discharging rate is usually normalized with the battery capacity which expressed in C. For example a battery of capacity rating 800mAh will be fully discharged in 1 hour with 800mA of current load, is discharging with 800mA current load, the discharge rate can be expressed as 1C. Similar with charging, if an empty battery with capacity of 800mAh is been charge with 400mA constant current which is the half of the capacity rating, the charging rate can be rated as 0.5C, and the empty battery is expected to be fully charged after 2hours. The C-rate represented actual current flow value with different battery capacity. Table 2.1 summarized the C-rate conversion of an 800mAh battery.

Table 2.1: C-rate conversion table for 800mAh battery

C-rate	Actual charge/discharge current
0.125C	100 mA
0.25C	200 mA
0.5C	400 mA
0.75C	600 mA
1C	800 mA

2.1.3 Cycle Count

Cycle count of a battery measures the aging rate of battery. Usually cycle count is accumulated as 1 cycle count when the discharged capacity is equal to the battery capacity rating. For example if an 800mAh battery has been discharge for total discharge power of 1600mAh, the accumulated cycle count will be 2.

2.1.4 Maximum Charging Voltage

The maximum charging voltage is the maximum voltage level that the battery can be charged to. The maximum voltage level of Li-ion battery is usually limited by the chemistry and material design of the battery. The common maximum charging voltages for Li-ion battery are 4.2V and 4.35V. In FG algorithm design, 100% of SOC usually refer to the state where the measured battery voltage is almost at the maximum charging voltage.

2.1.5 Minimum Discharging Voltage

Minimum discharging voltage is the voltage level defined as 0% SOC in FG algorithm design. Minimum discharging voltage is usually decided based on system loading, temperature or system design requirements like the minimum operating voltage of the components on system. Minimum discharging voltage should be set higher than battery specification specified minimum voltage to avoid battery under voltage stressing.

2.2 Li-ion battery Characteristic

The challenges of Li-ion battery are non-linearity of battery parameters like open circuit voltage, dynamic change of battery capacity due to temperature change, reduction of total capacity due to aging effect and battery self-discharge effect. FG algorithm is created based on assessment of these non-linearity characteristics and environment dependencies parameters that impact the battery capacity, to provide a better battery's SOC estimation.

2.2.1 Temperature Effect

Temperature effect on Li-ion battery has been actively discussed in a lot of previous works [8][9][10][11] due the significant changes to battery capacity and internal impedance that greatly impact battery performance. Generally, Li-ion battery does not work well at low temperature and performs better at higher temperature. However, Li-ion battery internal chemical reaction become active [12] at high temperature, further results in reduction in life cycle of the battery[13]. Further increase of temperature will causes potential thermal runaway that may lead to battery explode. Generally battery is safe to operate at temperature range of -20°C to 60 °C [12][14]. Figure 2.1 shows the impact of the temperature to battery discharge capacity for a Sanyo 570mAh rating Li-ion battery. [15]

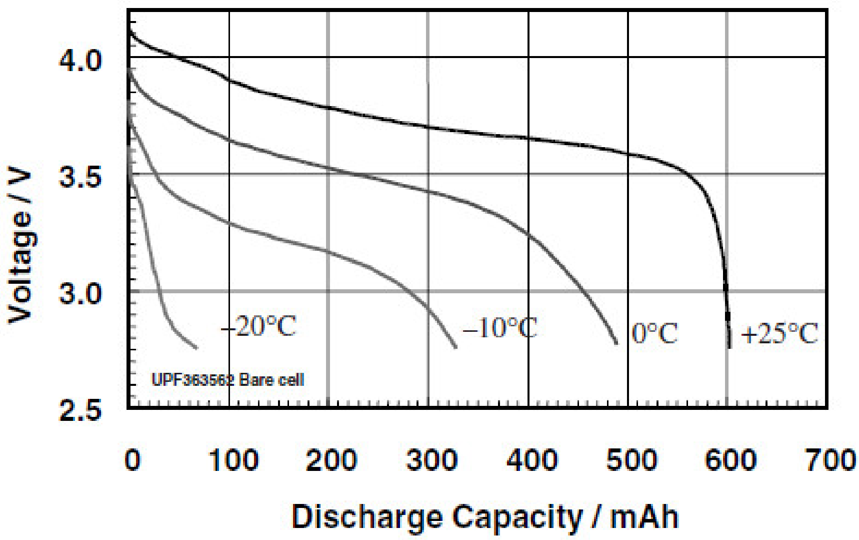

Figure 2.1: Battery voltage vs discharge capacity at temperature -20°C, -10°C, 0°C and 25°C at 1C discharge rate [15]

As shown in Figure 2.1, at temperature change of 25°C to 0°C, the capacity dropped more than 20% which is from ~600mAh to ~480mAh. At below 0°C, the battery capacity drop at much higher rate with temperature drop. For temperature above 25°C, the battery capacity will increase with a relatively much slower rate than the low temperature (below 0°C) [10].

Temperature has significant effect on Li-ion battery where lower temperature reduces the capacity of the battery, low temperature range (below 0°C) increases the rate of capacity reduction.

2.2.2 Discharge Rate Effect

The discharge rate effect to battery capacity has been discussed in literature and book [8] [15] where higher discharge rate results in lower capacity utilization as shown in Figure 2.2.

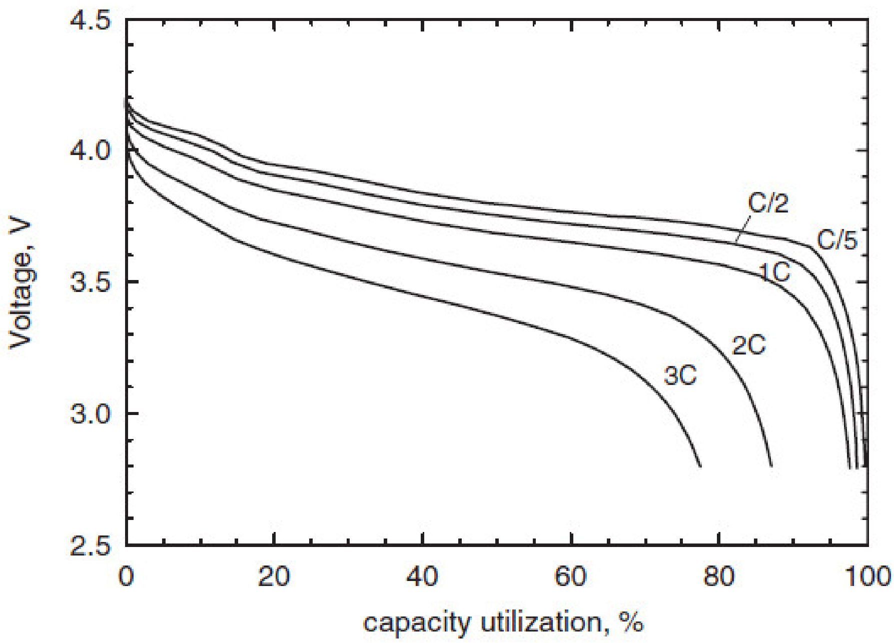

Figure 2.2: Capacity utilization % of polymer Li-ion battery at different rate [15]

In Figure 2.2, C/5 is lowest discharge rate and 3C is the highest discharge rate. With higher discharge rate, the capacity utilization decreases indicates that the capacity available to be discharge from battery is also lesser. The capacity utilization percentage is high for discharge range below 1C discharge rate indicates that charge into the battery will be almost equal to the charge out of battery.

2.2.3 Battery Aging Effect

Batter aging is one of the main problem of Li-ion battery usage where the performance of the battery will decrease over long period of time. When the power available is limited, accuracy of the FG becomes significantly important so that the battery life can be maximize.

Figure 2.3 shows charge/discharge cycle characteristics of Li-ion battery collected from 20 batteries, done by NTT Docomo. From the data collection, most of the battery capacity gradually dropped to 80% after ~600cycles of charge/discharge and degradation rate accelerates after the ~600cycles where the most of the batteries' capacity reduced to below half after 800cycles of charge/discharge.

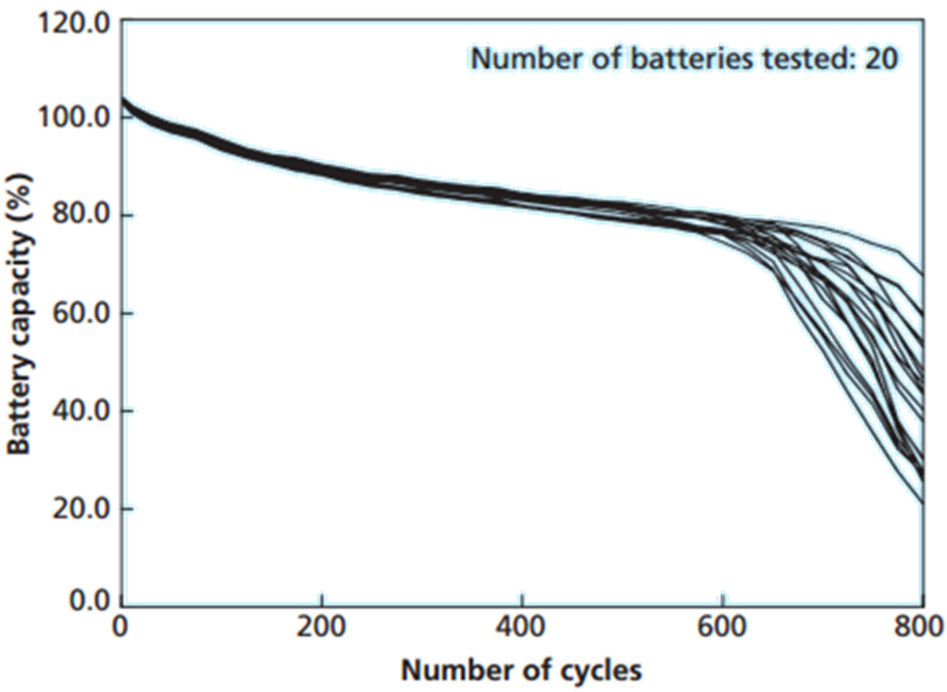

Figure 2.3: Charge-discharge cycle characteristics of batteries[16]

Below are some of the factors that can decrease the cycle life and accelerate the degradation aging rate of Li-ion battery:

- Environment conditions: high temperature[13], high charge / discharge rate [17] or higher SOC levels [18]
- Aging due to period of storage [16]
- Aging due to higher full charge cut off voltage [17]

2.2.4 Battery Self-Discharge

Self-discharge happens in battery due to the chemical internal reaction of the battery [19] where energy stored internal of battery reduces over time. Li-ion battery has an advantage of low energy loss with lower self-discharge rate compared to other batteries with different chemistry as shown in Table 2.2. Self-discharge rate of battery increases with rise of temperature [19].

Table 2.2: Rates of self-discharge for three different chemistry battery [6]

CELL TYPE	NI-MH	NI-CD	LI-ION
Self-discharge rate at 20°C (%/month)	20-30	15-20	5-10

For FG with coulomb counting SOC estimation, self-discharge effect will not be included into coulomb counting since the loss of charge from self-discharge is not able to be tracked from external current sense resistor [20]. However as shown in Table 2.2, self-discharge rate of Li-ion battery is not significant to normal user device daily usage since the loss is only 5-10% per month. The self-discharge effect will only be visible over long period of storage.

2.2.5 Battery Open-Circuit Voltage (OCV) Characteristic

Since there is no method to measure level of chemistry charges internal of Li-ion battery [1], battery voltage is the most common direct parameter that can be measured to estimate the battery SOC [1]. Figure 2.44 shows load discharge curve for a sample of Li-ion battery where lower voltage indicate lower in capacity. However the battery voltage vs capacity lines are non-linear where the battery voltage change is small most of the time with high change rate when the capacity is low.

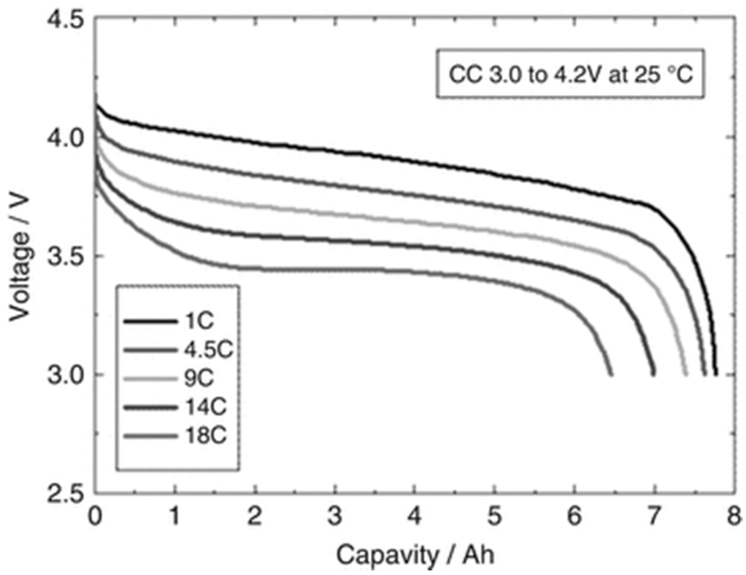

Figure 2.4: Load discharge curves for Li-Ion battery type [21]

Figure 2.5 shows open circuit voltage (OCV) vs state of charge (SOC) curves under temperatures 62.5°C, 27°C and 3°C of a Li-ion battery. The different between OCV change of Li-ion battery at normal temperature vs higher temperature is very small [10][22]. The open circuit voltage has visible voltage drop at low temperature. For low SOC (0% - 10% from Figure 2.5), the open circuit voltage ramp down rate is high. This higher skew rate at low SOC range actually helps to reduce the estimation error for SOC estimation with OCV level.

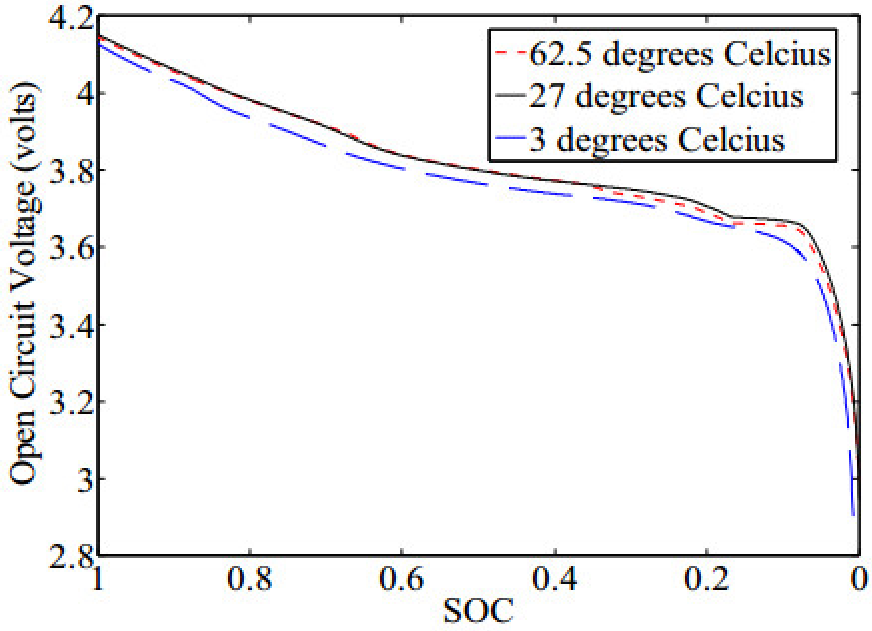

Figure 2.5: OCV vs SOC under different temperatures [22]

2.3 Battery Fuel Gauge Hardware Requirement

This section will discuss about typical hardware requirement for battery FG design.

2.3.1 Battery Voltage ADC

Battery voltage ADC is a basic and fundamental hardware for FG design for SOC estimation. The hardware capability to measure battery voltage accurately is important in FG. Taking the OCV curve measured from a 800mAh Li-ion battery as example which shown in Figure 2.6, with either FG ICs like On Semiconductor's LC709203F [23] or Richtek RT9428 [24] with ±7.5mV voltage measurement accuracy, the error of estimating the SOC at OCV of 3815mV will be ±2%. Hence the accuracy of voltage ADC is important to keep the SOC estimation in high accuracy which meets industry specification of ±3% [23] [24] [25] [26].

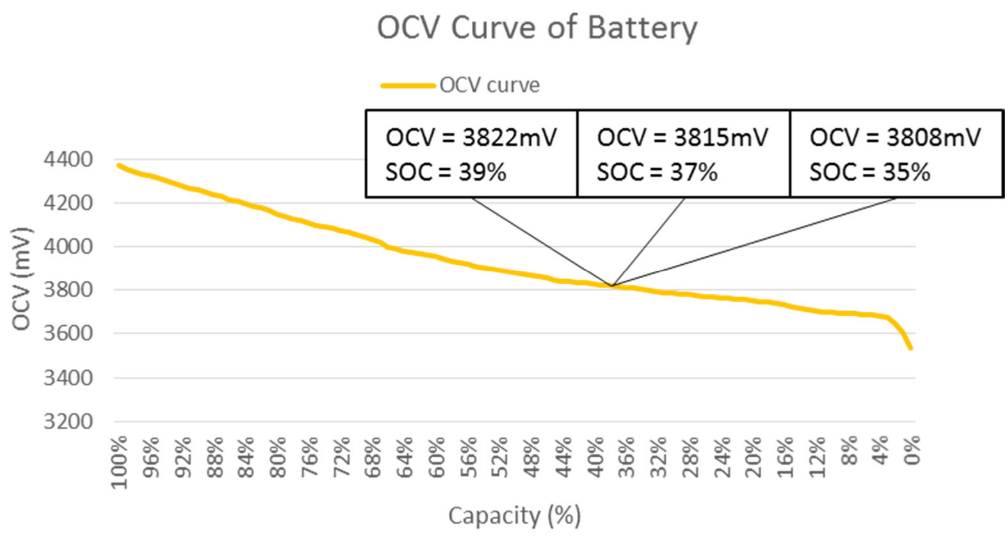

Figure 2.6: OCV vs SOC of an 800mAh Battery

2.3.2 Battery Current ADC

Most battery FG designs implements coulomb counting method with high precision small resistance resistor (typical values are 10mΩ/20mΩ [27] [28] [29] with 1% precision). 100mA of current flowing through 10mΩ resistor will have only 1mV of voltage drop across the resistor. Typical FG IC monitors the voltage drop across the current sense resistor, converts the voltage drop to coulomb number and continuously accumulates the number in coulomb meter. Hence high accuracy battery current ADC is very important in FG design to ensure error accumulated in coulomb meter is sufficiently low.

2.4 Battery Fuel Gauge Algorithm

There are various algorithm methods to estimate SOC of battery. Some literatures classified SOC estimation method into four categories [1][30]:

- Direct Measurement: Methods to estimate SOC by referring to the direct measurements of physical battery variables, like battery voltage and battery impedance.
- Booking-keeping estimation: Methods to estimate SOC by charge/discharge current measurement and integration of current over time to keep track of the SOC.
- Adaptive systems: Methods with either machine learning or adaptive techniques to do automatic SOC adjustment based on different conditions.
- Hybrid methods: Methods that combine two or more SOC estimation methods to optimize SOC estimation performance with advantages from different methods

Table 2.3 summarized example of algorithm methods for the four categories of SOC estimation. Direct measurement methods and book-keeping estimations methods are common in FG algorithm design of commercial parts for mobile devices. Details of these two methods will be further elaborate with example in next sections. The adaptive systems and hybrid methods algorithm described in Table 2.3 are usually implemented in electric and hybrid vehicles with Li-ion battery and not common in mobile devices due to higher computing power required for calculations with complex matrix operations [31], hence they will not be covered in detail.

Table 2.3: SOC estimation algorithm classification [1]

Categories	Algorithm methods
Direct measurement	i. OCV method ii. Impedance method iii. Terminal voltage method iv. Impedance spectroscopy method
Book-keeping estimation	i. Coulomb counting method ii. Enhanced coulomb counting method
Adaptive Systems	i. Kalman filter ii. Back propagation (BP) neural network iii. Fuzzy neural network iv. Radial basis function (RBF) neural network v. Support vector machine (SVM)
Hybrid Methods	i. Coulomb counting and Kalman filter combination ii. Coulomb counting and electromotive force (EMF) combination iii. Per-unit system and extended Kalman filter (EKF) combination

2.4.1 Coulomb Counter SOC Estimation Method

Coulomb counting is an example of book-keeping estimation. It is the most common and also basic method to estimate battery SOC [32][33]. This method is implemented by assuming total charge into battery is the total charge available to be discharge from the battery.

Coulomb counting method is very straight forward where the formula is as in equation (2.1):

$$SOC = SOC_0 + \frac{1}{MaxCap}\int_{t_0}^{t} I_{batt}\, dt \tag{2.1}$$

where

SOC = State-of-charge of battery, in %

SOC_0 = Starting point of the coulomb meter, in %

MaxCap = Maximum capacity in battery, in mAh

I_{batt} = Battery charge/discharge current, in mA

SOC_0 is the starting point percentage where the value is usually estimated based on voltage level of the battery vs the pre-calibrated battery OCV table in software, MaxCap is the maximum capacity number obtained from actual 0% to 100% of charge cycle which usually a value that close to the capacity rating of the battery, and I_{batt} is the battery current flow in/out of the Li-ion battery where this value could be either positive or negative based on the voltage drop across sense resistor (usually in very precise small resistance value of 10mΩ/20mΩ) measured from the FG chip ADC pins.

Coulomb counting hardware implementation in FG IC is usually designed as a counter to increment/decrement of charge. The counter accumulates coulomb number based on the current flow measured from the sense resistor. Coulomb counter can be expressed as equation (2.3), to replace the complicated integration calculation formula shown in equation (2.1) which is not preferable in low cost microcontroller's design. Formula to calculate SOC with coulomb counter can be express as equations (2.2), (2.3) and (2.4) below:

$$SOC = \frac{CC_0 + CC}{MaxCap} \tag{2.2}$$

$$CC = \sum_{0}^{t} I_{batt} \tag{2.3}$$

$$CC_0 = OCV\% \times MaxCap \tag{2.4}$$

where

SOC = State-of-charge of battery, in %

CC_0 = Starting point in the coulomb counter, in mAh

CC = Coulomb meter number, in mAh

MaxCap = Maximum capacity in battery, in mAh

I_{batt} = Battery charge/discharge current, in mA

OCV% = Estimated SOC based on battery OCV, in %

CC_0 is the starting point in the coulomb counter where it is usually initialized by multiplying OCV% obtained from OCV-based SOC estimation with the maximum capacity (MaxCap) in FG initialization data, CC is the coulomb counter which increment/decrement to track charge flow of battery.

Coulomb counter is a straight-forward method to estimate SOC. However coulomb counter SOC estimation has several challenges as follows:

- Capacity is not constant and it changes with temperature and discharge rate. Lower temperature and higher discharge rate will result in reduced capacity. [25]
- After long period and multiple cycles of charge/discharge, coulomb counting and measurement errors will be accumulated and might cause significant inaccuracy in SOC estimation. Battery has to be fully charged from very low SOC to 100% (maximum fully charged battery voltage) to recalibrate for high accuracy of maximum capacity coulomb number. [31]