An improved Coulumb Counting method for SOC estimation of Li-ion with initial SOC determination and temperature drift compensation.

Your Name
ID: Your ID

September 2021

"No two things have been combined better than knowledge and patience"

Prophet Muhammad SAW

Abstract

This paper proposes an improved Coulumb Counting (CC) method for the SOC estimation of Lithium-ion battery. The conventional CC method suffers from few drawbacks in which it strongly depends on the precision of current sensors, initial value of SOC and the nominal capacity of the battery. A lot of research has been conducted to explore the possibility of improving the CC method. However, the research that has been performed only cover one or two limitations at a time. Therefore, this research is conducted to study an improved CC method with the focus on determining the correct value of initial SOC, eliminating the temperature drift of the current sensor, as well as calibrating the nominal capacity of the battery cell. An Adaptive System method is used to determine the initial value of SOC, while temperature compensation circuit is introduced to eliminate the temperature drift of current sensor. A calibration of the battery cell at full state and empty state is also performed to ensure the nominal capacity value is correct after each cycle of charge and discharge operation. The effectiveness of this improved CC method will be simulated using Matlab under different charging and discharging profile of battery cell with a wide range operating temperature. It is expected that this improved CC method will provide a high accuracy of SOC estimation with almost negligible deviation from its actual SOC value.

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Chapter 1

Introduction

1.1 Background

Over the past few decades, battery technology is greatly expanding due to its high efficiency and low pollution [2]. It has been employed mostly in industrial application, electric vehicles and smart grid application. Lithium-Ion (Li-ion) is one of the batteries that is widely available in the market with a high demand from consumers due to its low self-discharge rate and high energy density. Despite of those advantages, this Li-ion battery requires a protection circuit to maintain the voltage and current within its safe operating area which usually incorporated by Battery Management System (BMS). The BMS is also responsible to estimate the internal variables of battery to give a thorough understanding of its SOC and State of Health (SOH). In general, SOC is a metric that quantifies the amount of energy left within a battery cell in compared to the energy it had when it was full [7]. By having a precise SOC estimation, it can provide information to the user of how much longer the battery can be used before it needs another cycle of charging [7]. Figure 1.1 shows the block diagram of correlation between BMS and SOC [1].

Acquiring an accurate SOC estimation is a crucial process because it will provide an insight regarding the battery performance for a period of time and therefore avoid any unpredictable system interruption. Moreover, the precise SOC estimation can prevent the battery from being over charged and over discharged which may lead to a permanent damage to the battery. However, estimating an accurate value of SOC has becomes a challenge due to the non-linear behaviour of the battery cell [2][1]. Moreover, it constantly operates outside the equilibrium state during cycling [1]. In every cycle of charging and discharging, the battery will experience degradation which highly depends on the temperature and its operating profile. This degradation also contributes to the complexity in determining the SOC level of the battery.

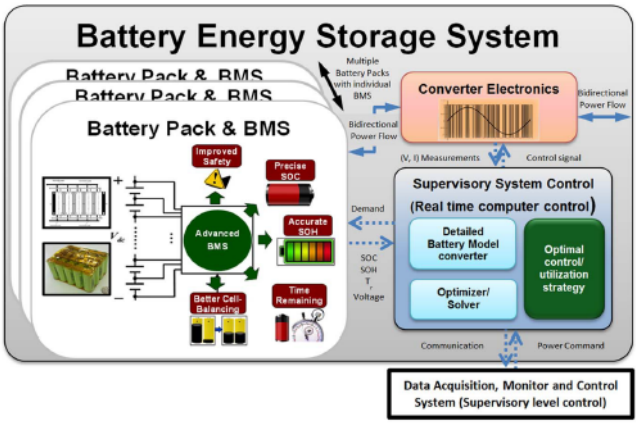


FIGURE 1.1: Correlation between BMS and SOC as depicted in [1]

As a matter of fact, SOC cannot be measured directly from the cell, therefore, an estimation method is developed to predict the SOC level of cell [3][8]. Conventionally, the SOC estimation is performed by measuring the parameter of coulumb and current flowing in and out of the cell [9]. This data is then combined with the historical data from previous cell's operation to develop the precise value of SOC. Aside from that, there are few other parameters that need to be considered in order to determine the SOC. Few of the parameters include cell temperature, operation of the cell when the measurements are being taken, the cell age and few other relevant data from cell manufacturer. Usually, the parameters that need to be considered mainly depends on the method that is being employed in determining the SOC. In this research paper, the main method to be used is CC method. Therefore, the parameters that need to be considered in estimating SOC will mainly based on CC method. The accuracy of this CC method can be diverted by not knowing the precise value of initial SOC and other parameters such as self-discharge rate and leakage effects [4]. On top of that, aging is an important parameter for the application of this method because CC method does not have the capability to follow the changes of deteriorated battery condition. Therefore, in order to determine an accurate value of SOC, it is necessary to update the reference capacity of battery cell which experiences changes due to the aging condition [4][10]. The estimation of SOC at varying ambient temperature should also be considered to simulate the dynamic behaviour of battery that changes accordingly with different operating condition [4].

1.2 Problem statement

Coulumb Counting (CC) method is a widely used method to determine the SOC of Li-ion battery cell due to its simplicity and good accuracy estimation. However, this method strongly depends on the precision of current sensors, initial value of SOC and the nominal capacity of the battery, which then serves as the drawbacks of the method. Many research

has been conducted to investigate the method on how to improve the CC method. However, the research that has been done only cover one or two limitations at a time. Therefore, this research is conducted to study an improved CC method with the focus on determining the correct value of initial SOC, eliminating the temperature drift of the current sensor, as well as calibrating the nominal capacity of the battery cell.

1.3 Hypothesis

There are several hypotheses for the research including:

(i) The hybrid method proposed, as a whole, will be able to improve the accuracy estimation of SOC.

(ii) The Adaptive System method will be able to give a robust value of initial SOC under different operation profile of battery cell.

(iii) The temperature compensation circuit will be able to eliminate the temperature drift of the sensor which then improve the precision of SOC estimation.

(iv) The calibration of the battery cell at full state and empty state will be able to provide the accurate value of nominal capacity after each cycle of charging and discharging.

1.4 Research objectives

The objectives of the research are:

(i) To improve the overall accuracy of SOC estimation of Li-ion battery by eliminating the main drawbacks of conventional CC method.

(ii) To reliably determine the initial value of SOC by using an Adaptive System method.

(iii) To eliminate the effect of temperature drift of current sensor by introducing temperature compensation circuit.

(iv) To reduce the nominal capacity error after each cycle of charging and discharging by performing calibration at the empty state and full state of the battery cell.

1.5 Scope of research

This research involves a comprehensive study on the method of estimating the SOC of battery cell by adopting an improved Coulumb Counting method. This study will be performing on the stack level of battery cell with an assumption that the battery pack is to be used in power electronics industry. Simulation using Matlab will be performed under different charging and discharging profile, at extreme cases of operating temperature.

1.6 Research expected contribution

(i) The overall accuracy of SOC estimation is expected to be improved by eliminating the main drawbacks of conventional CC method.

(ii) The Adaptive System method is expected to be able to determine the correct value of initial SOC.

(iii) The effect of temperature drift of current sensor is expected to be eliminated by using temperature compensation circuit.

(iv) The calibration of the battery cell at full state and empty state is expected to be able to provide the accurate value of nominal capacity after each cycle of charging and discharging.

1.7 Outline of the Research Proposal

This research proposal is structured and arranged as follows:

Chapter 1 provides a general discussion of the SOC concept of Li-ion cell. Also, this chapter includes key background that is focused on in this project. The main objectives of this study and its hypotheses are described comprehensively.

Chapter 2 details a thorough literature review about the methods available in estimating SOC. This chapter focuses on conventional CC method and the improved CC method that has been implemented by other researchers. The research gap is established in this chapter which will become the future work of this paper.

Chapter 3 describes the methodology used in achieving the main objectives of the thesis. Mathematical formulation analysis and flowchart algorithm for improved CC method is described in this chapter.

Chapter 4 presents the expected results based on the implementation of proposed improved CC method. Few cases of implementation is proposed to analyze the capability of proposed method in fulfilling the research objectives.

Chapter 5 presents the overall conclusion of this research proposal

Chapter 2

Literature Review

2.1 Introduction

Figure 2.1 shows the track of method in estimating the SOC of Li-ion battery.

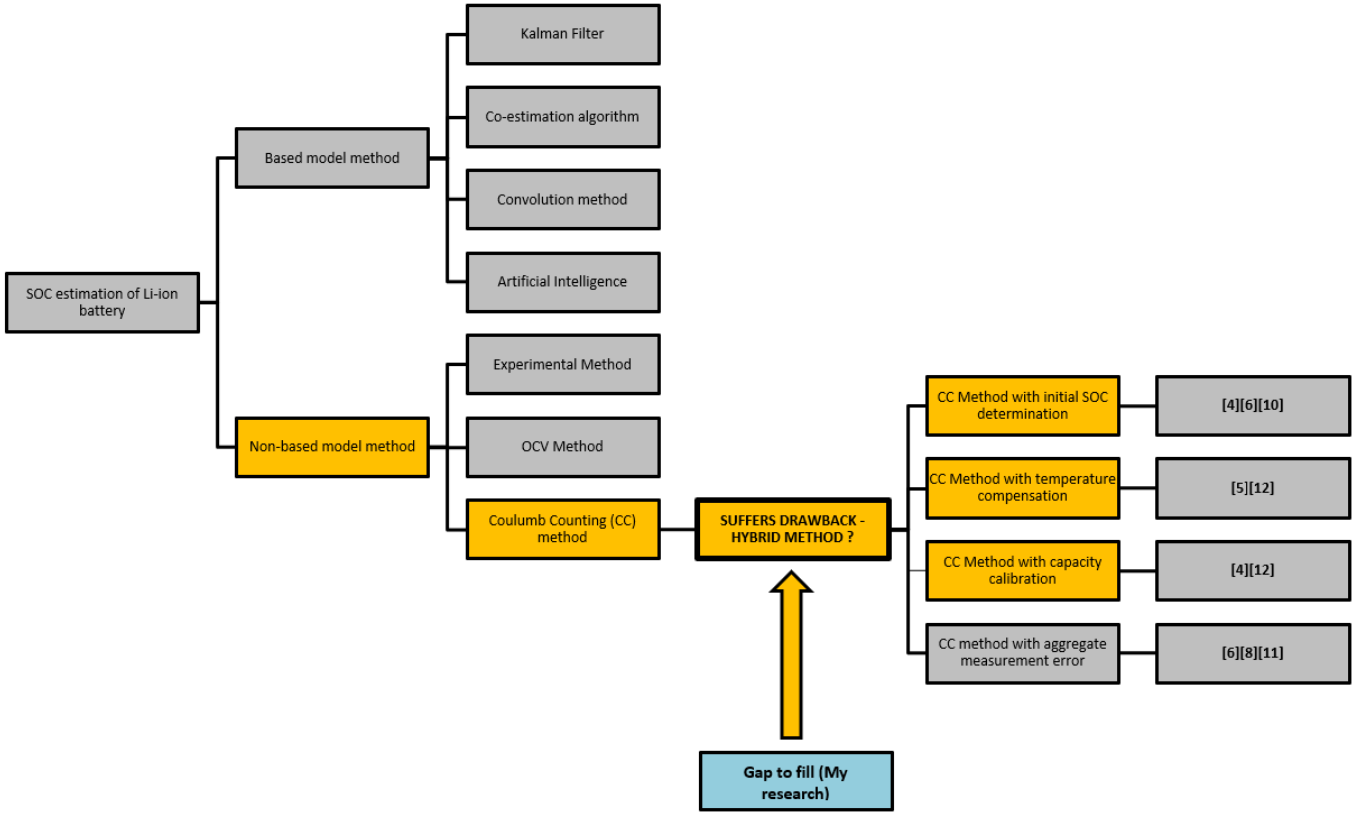


FIGURE 2.1: Tree diagram of SOC estimation method of Li-ion battery

2.1.1 Recent research on the method in estimating the SOC of Li-ion

Figure 2.2 summarizes the method that has been developed by many researchers to estimate SOC of battery cell. In this subsection, a thorough literature review on the method of SOC estimation will be explained which will be focusing on the hybrid method associated with CC method. Based on [2][3][4], conventionally, the method of estimating SOC can be classified into two categories which are model based method and non-model based method.

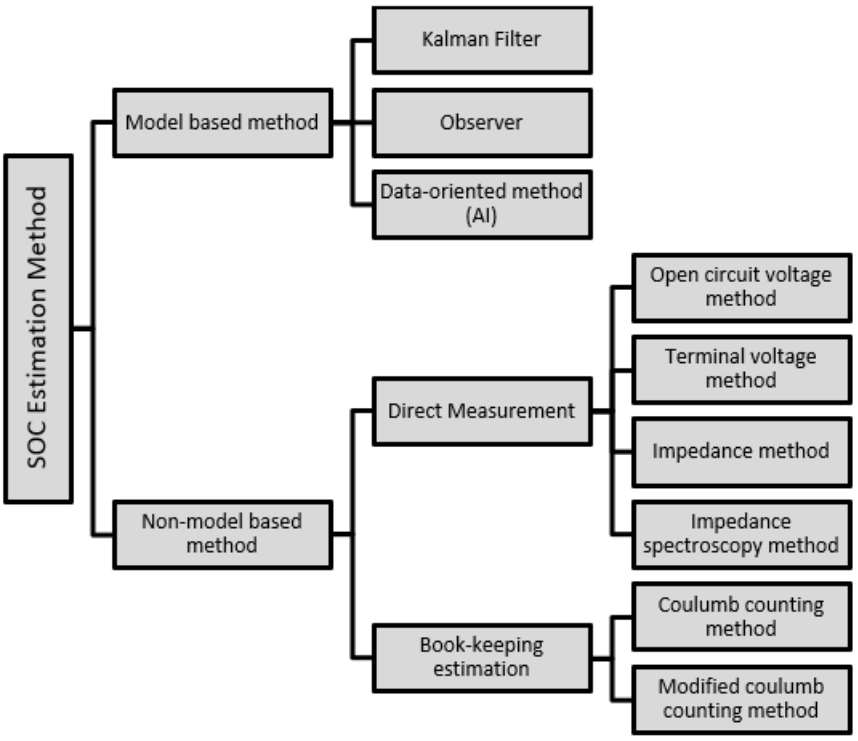


FIGURE 2.2: Method of SOC estimation as described in [2][3][4]

Model based method is a method that used various models and algorithms to estimate the SOC in which it requires an equivalent model to simulate the battery behaviour [4][6]. Accordingly, the accuracy of this method mainly depends on the efficiency of the battery model and the precision of its characterized parameters [4][6]. For example, Kalman Filter series algorithm uses the battery load voltage as its observation parameter which makes it even more complex because many factors need to be considered in the system state space equation [6][5]. As a result of this complexity, the algorithm has been simplified by ignoring few crucial parameters such as non-linear equilibrium potential, rate-dependent capacity and temperature effect [6]. Meanwhile, as for data-oriented method, it is usually operates based on a large number of system parameters thus a large computing capacity is needed. Moreover, its accuracy depends on the quantity and quality of training data which then makes it unsuitable for the real time application [6][5]. Therefore, considering that this model based method is restrictive in terms of hardware implementation, non-model based

method has been explored in this research paper in order to estimate the SOC of battery cell.

Non-model based method on the other hand is a simple method with lesser complexity which makes it more practical to be implemented. This method does not require intensive models or additional signals to estimate an accurate value of SOC. Among all of the non-model based methods, CC method is the most prevalent method that is used to estimate the SOC of battery cell in which it involves a temporal integrating of battery current during charging and discharging operation [4]. This method is favourable to be implemented because of its simplicity, asides from giving a good average precision of SOC estimation. Nevertheless, this method introduces some drawbacks as described below [5]:

(i) Precision depending on the initial value of SOC. Particularly, the initial value of SOC is unknown in the first working cycle and therefore it is usually is taken as zero. The only time that the initial SOC is considered known is when it is fully charged (100% SOC level) and fully discharged (0% SOC level). This initial value of SOC can be calibrated in the subsequent working cycle based on the record of a complete charge and discharge cycle.

(ii) Precision depending on the nominal capacity value. Nominal capacity varies with external environment and the number of cycles that the battery is charged and discharged. In general, nominal capacity is referring to the capacity of the battery at room temperature in the first working cycle and it is usually calibrated by real capacity in the subsequent working cycle.

(iii) Precision depending on the current sensor. The deviation in real-time current mainly contributed by the sensor sensitivity error and measurement error. A high-precision hall current sensor is often used to measure the current. It has advantages of good linearity, wide measurement frequency bandwidth, and excellent dynamic performance and so on. However, hall current sensor is vulnerable to the ambient temperature resulting in serious temperature drift, which is not easy to eliminate by calibration in real-time system.

In [8], the authors have introduced a combined method between CC method and fuzzy logic method to improve the accuracy of SOC estimation. The fuzzy logic method has the ability to reduce the non linearity behaviour of battery cell with a given proper database. However this method requires a large memory space. Therefore, a combination method of these two can greatly overcome the drawbacks of both method. This paper focuses on eliminating the aggregate error introduced by initial SOC by implementing the fuzzy logic method. Through these combined method, firstly, the actual SOC of the battery is measured by a battery

measurement unit. Concurrently, the SOC is estimated by CC method. The value of actual SOC and estimated SOC are fed to the input of fuzzy controller, and the error is compensated to obtain a new value of SOC. The new value of SOC is the improved value of SOC after eliminating the accumulated error due to the initial value of SOC.A simulation under different operation of battery cell with a wide range of operating temperature is performed to study the effectiveness of the combined method. The SOC estimation using the combined method gives an error range of 1.5% to 3% in compared to the actual SOC value. This paper however does not take an interest in knowing the accurate value initial SOC, rather, it takes an approach of compensating the error being introduced.

In [4], an enhanced CC algorithm is introduced to estimate the SOC in multimedia applications which integrates the piecewise SOC-OCV relationship to determine the initial value of SOC. On top of that, a periodic calibration at empty and full state of battery is implemented to overcome the cumulative error of the measurement. Based on [4], the initial SOC is determined by measuring the initial Open Circuit Voltage (OCV) which is approximated by piecewise linear curve. This curve is then divided into eight segment and each segment can be expressed as a linear relation. For each segment, a relevant coefficient is varied according to the OCV intervals. The relevant coefficient with its voltage range is provided in order to determine the value of initial SOC. The method proposed has been simulated using Matlab and further implemented on the hardware platform. The results between simulation and hardware implementation shows a discrepancy of 2% which indicates that this method is reliable in estimating an accurate value of SOC. This paper however, does not consider the temperature drift effect on the current sensor.

In paper [10], a hyrid method combining CC method and adaptive system method has been implemented to estimate the SOC of Li-ion battery. The adaptive system method has the ability to adjust with the changes in the system which makes it suitable to overcome the drawback introduced by CC method. This adaptive system method will be used to determine the initial value of SOC through the VOC-SOC lookup table. In order to determine the value of VOC, firstly, the terminal voltage is measured and corrected by the temperature condition. The terminal voltage is then further corrected by drop voltage from the current and impedance. This corrected VOC value is then converted to VOC-SOC lookup table to determine the initial value of SOC.This initial value is then fed into CC method to estimate the overall SOC of the Li-ion battery.The simulation and experiment set up are performed on 100Ah Li-ion battery under constant current and variable current simulation. Based on the results obtained, the proposed SOC estimation method is able to predict SOC closely and it can represent the dynamic behaviour of the battery cell. This paper however does not take into account the effect of aggregate errors introduced by CC method.

The authors in [6] constructed an enhanced CC method for SOC estimation by expanding the Peukert equation for discharging process and Coulumbic efficiency for the charging process. Since the Peukert equation and Coulumbic efficiency is unsuitable for dynamic load and varying temperature, an effective current factoring based on current rate and temperature is developed to overcome this. Furthermore, an SOC mapping approach is introduced to determine the initial SOC, as well as to eliminate the accumulated measurement errors. The SOC estimation using the method proposed has been conducted under varying temperature condition. Under varying temperature, the maximum error remains lesser than 2.69% due to the initial error in some of the discharge cases. In spite of that, the results shown that the SOC being estimated able to follow the reference SOC. Despite of this, this paper does not consider the effect of temperature drift from thermistor.

The paper in [5] has proposed a closed loop temperature compensation circuit to remove the effect of the temperature drift of thermistor. Generally, the temperature compensation method can be divided into two main categories which are hardware compensation method and software compensation method. The authors in [5] has chosen hardware compensation method because software compensation method is unsuitable for real time system with large data volume. The hardware compensation method can further be classified into open loop compensation and closed loop compensation. The open loop estimation requires high power stability and ignoring the effect of square term of temperature change, therefore, closed loop compensation method is employed in [5]. This proposed method has been simulated using Multisim software and futher proved by conducting an experiment on a Li-ion battery with nominal voltage of 3.2V and nominal capacity of 10Ah. The simulation and experiment has been performed under various temperature range. From the simulation and experiment, the SOC estimation without the embedded temperature compensation circuit gives an error as high as 45.68% whereas the SOC estimation with the embedded temperature compensation circuit gives an error of only -1.54%. The result has proved that the temperature compensation circuit is able to contribute to a more accurate SOC estimation. However this paper did not take into account the error introduced by initial value of SOC, as well as aggregate error from measurement and noise.

The authors in [11] have suggested a combined method comprising of CC method and Adaptive Kalman Filter (AKF) method. The AKF method has the advantages of estimating a precise value of SOC even with large initial SOC error and high current sensor error. This AKF method however requires a large computational resources. A random value of initial SOC and current measurement are fed into the simulation and the results show that this combined method able to follow closely the actual value of initial SOC. By using only CC method, the estimation error reached to a value of 3.6% whereas, by using AEKF, the estimation error introduced is 3.3%. The estimation error is reduced to a maximum value of 1.8% by using the hybrid which then proved that this method is reliable in determining the

SOC value of the battery cell. However, this AKF method might introduce an abusive usage to the battery when it estimates the incorrect value of initial SOC, which then will considerably reduce the state of health of the battery. Moreover, this paper does not consider a wide range operating temperature of the battery cell which might give a significant amount of effect to the SOC estimation of battery cell. On top of that, the elimination of temperature drift of current sensor is also not taken into account.

2.2 Summary of research on the method of improving the accuracy of SOC estimation

CC Method with initial SOC determination			
Reference	**Research Contribution**	**Method**	**Research Gap**
[4]	Proposed methods of determining the correct value of initial SOC	Piecewise OCV-SOC relationship	Does not consider the effect of sensor error
[6]		SOC mapping approach	Does not consider the effect of sensor error and nominal capacity error
[10]		Adaptive System method	Does not consider the effect of sensor error and nominal capacity error

CC Method with temperature compensation			
Reference	**Research Contribution**	**Method**	**Research Gap**
[5]	Proposed methods of compensating temperature drift of current sensors	Temperature coefficient introduced	Does not consider the effect of initial SOC errors and nominal capacity error
[12]		Temperature compensation circuit	Does not consider the effect of initial SOC error

CC Method with capacity calibration			
Reference	**Research Contribution**	**Method**	**Research Gap**
[4]	Proposed methods of capacity calibration after each cyle of charging and discharging	Calibration at empty and full state of battery cell	Does not consider the effect of sensor error
[12]			Does not consider the effect of initial SOC error

FIGURE 2.3: Summary of research on the method of improving the accuracy of SOC estimation

Based on the literature review that has been completed, in order to improve the accuracy of SOC estimation, papers [8][5][11] have covered one drawback from CC method whereas papers [4][10][6] have covered two drawbacks from the CC method. In [8][11], these papers have mitigated the first drawback of CC method which is the error being introduced to the system due to incorrect value of initial SOC. Meanwhile, paper [5] focuses on compensating the third drawback which is the temperature drift of current sensor. The authors in [4][6] has focused on the first and second drawbacks which are to determine the initial value of SOC and perform periodic calibration. Meanwhile, paper [10] has highlighted the first and third drawbacks of CC method - initial SOC determination and temperature drift compensation. From this literature review, it can be concluded that most of the research papers only cover one or two drawbacks at a time in order to improve the accuracy of SOC estimation of CC method. Therefore, this research proposal has suggested few combined methods to improve the accuracy of CC method by compensating its three main drawbacks altogether.

Chapter 3

Research Methodology

3.1 Research design and procedure

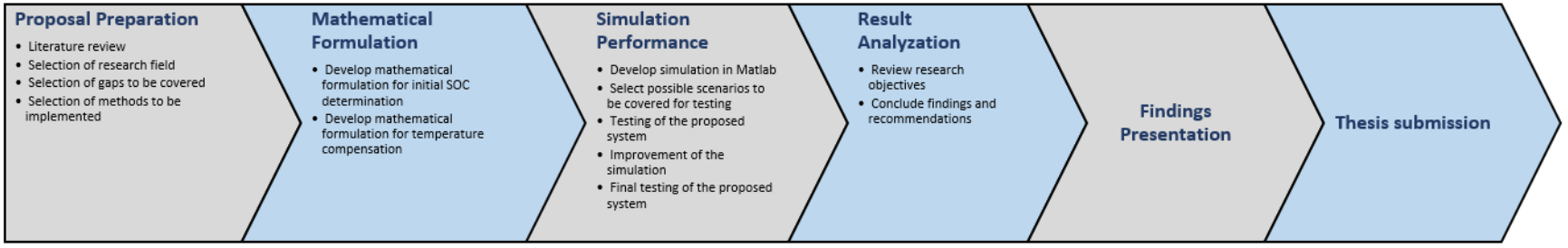


FIGURE 3.1: Flowchart of the research design and procedure

Figure 3.1 shows the flow chart of research design and procedure for this project. It starts off with proposal preparation which includes literature review process, selection of research field, selection of gaps to be covered and selection of methods to be implemented. Based on these selections, the mathematical formulation will then be developed and adopted in the simulation stage. As for this project, there are two mathematical analysis needed which are used for initial SOC determination and temperature drift compensation. Next, simulation using Matlab will be performed to test the proposed methods. Before running the simulation, selection of possible scenarios will be considered so that the overall result represents the actual dynamic behaviour of battery cell and its application in real life. The results obtained will then be analyzed and its findings will be concluded. Lastly, the findings will be presented and the thesis will be submitted.

3.2 Mathematical formulation analysis

3.2.1 Mathematical formulation analysis of SOC in CC Method

In general, SOC is defined as the ratio of its current capacity $Q(t)$ to its nominal capacity Qn as shown below [2]:

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

However, the formulation of SOC is respectively different based on the method being used to estimate the SOC. In CC method, the SOC is estimated by using the discharging current of a battery and integrating it over time. The following formula is used to estimate the SOC of battery cell using CC method [2][9][4][6][5]:

$$SOC(t) = SOC(t-1) + \eta \int_{t_0}^{t_0+\tau} \frac{I_b}{Q_n} dt$$

Where $SOC(t-1)$ is initial SOC, η is the Coulumbic efficiency and I_b is the discharging current of the battery cell. The CC method estimates the SOC by accumulating the charge transferred in and out of battery cell over time along with the additional term of initial SOC [9]. In real situation, the releasable charge is always lesser than the stored charge during the operation cycle [9][6]. Therefore, the η value which represents the Coulumbic efficiency is multiplied to the integration term as a correction factor.

For the improved CC method, the formula analysis of SOC will be categorized based on their operation modes. There are three operation modes which are charge mode, discharge mode

and self-discharge mode. During the operation of charging, the coulumb counter will be characterized by Q_{gained} which represents the quantity of charges accumulated during τ [4]. This Q_{gained} can be expressed as shown below. The change in SOC at the same operating period is also established by the following next equation.

$$Q_{gained}(t+\tau) = Q_{gained}(t) + \Delta Q;$$

$$\Delta SOC(t+\tau) = \frac{Q_{gained}(t+\tau)}{Q_{rated}} \times 100\%$$

The instantaneous value of SOC can be obtained by accumulating the previous SOC value and the instantaneous SOC value. The following expression shows the SOC estimation during charging operation:

$$SOC(t+\tau) = SOC(t) + \Delta SOC(t+\tau)$$

Meanwhile, during the operation of discharging, the coulumb counter will be characterized by Q_{lost} which represents the quantity of charges lost during τ [4]. This Q_{lost} can be expressed as shown below. The change in DOD at the same operating period is also established by the following next equation.

$$Q_{lost}(t+\tau) = Q_{lost}(t) + \Delta Q$$

$$\Delta DOD(t+\tau) = \frac{Q_{lost}(t+\tau)}{Q_{rated}} \times 100\%$$

$$DOD(t+\tau) = DOD(t) + \Delta DOD(t+\tau)$$

The instantaneous value of SOC for discharge operation can be obtained by the following expression:

$$SOC(t+\tau) = 1 - DOD(t+\tau)$$

Whereas for self-discharge operation mode, an assumption of Li-ion cell reaches 5% rate of self-discharge per month is made with the condition it has been stored at an adequate period [4][12]. The quantity of charge dissipated in this mode can be quantified by the expression below:

$$Q_{OC}(h+1) = Q_{OC}(h) - q_{per/hour}$$

Where $q_{per/hour}$ is the amount of charge losses per hour and h is the hour of storage.

The value will then be added to the amount of charge lost during discharge and substracted from the amound of charge gained during charge as expressed in the equation below [4][12].

$$\begin{cases} Q_{lost(OC)} = Q_{lost} + Q_{OC} \\ Q_{gained(OC)} = Q_{gained} + Q_{OC} \end{cases}$$

This loss compensation is made at each open circuit period and before switching to different operation mode of battery cell [4][12].

3.2.2 Mathematical formulation analysis of temperature drift compensation

There are two methods that can be considered for the implementation of temperature compensation which are open loop temperature compensation and closed loop temperature compensation. Since open loop compensation method required high power stability besides ignoring the square term of temperature change (ΔT^2), therefore, closed loop compensation method is considered in this project.

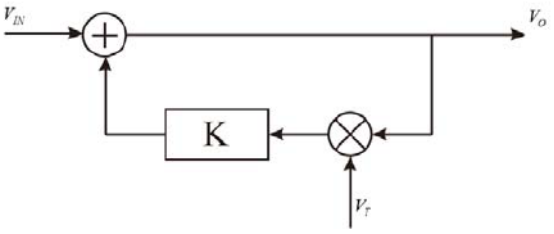


FIGURE 3.2: Sample: Block diagram of temperature drift compensation circuit [5]

Based on [5], the system transfer function for the closed loop temperature drift compensation circuit in Figure 3.2 is defined as below:

$$\frac{V_o}{V_{in}} = \frac{1}{1 - KV_T};$$

$$V_{in} = [1 + \alpha(T - T_0)]\, V_{IN(0)};$$

$$V_T = \beta(T - T_0)$$

Where K is the amplification factor of proportional element, V_o is the output voltage of current sensor with temperature compensation, V_{in} is the Laplace transformation of the current sensor output at T degC, $V_{IN(0)}$ is the current sensor output at T_0 degC, α is the temperature coefficient of hall current sensor, V_T is the output voltage of temperature compensation circuit and β is the corresponding sensitivity. By having the formula of V_{in} and V_T substituted to the transfer function, we will get the following transfer function below:

When $\alpha = -K\beta$, the ratio of V_o/V_{in} is constant thus the sensor output is no longer correlated to the ambient temperature which emphasizes that the temperature drift of hall current

$$\frac{V_o}{V_{IN(0)}} = \frac{1 + \alpha(T - T_0)}{1 - Kb(T - T_0)}$$

sensor is eliminated [5]. This closed loop temperature compensation circuit will be embedded in the BMS circuit and the output will be fed into the algorithm of CC method. Example of the realization of this closed loop circuit has been illustrated in [5] as shown in 3.3.

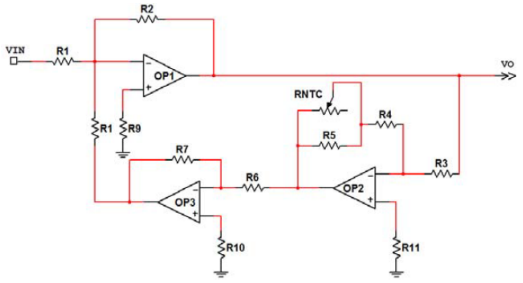


FIGURE 3.3: Sample: Realization of closed loop temperature compensation circuit [5]

3.3 Simulation analysis

For this project, the simulation of the proposed flow algorithm will be performed using Matlab. The proposed flow algorithm of CC improved method is shown in the next subsection which comprises the initial SOC determination, battery calibration at full state and empty state and temperature monitoring after the temperature drift of current sensor being compensated.

3.3.1 Flow algorithm of improved CC Method with compensation of three major drawbacks

Figure 3.4 shows the proposed flowchart of improved CC method with the compensation of three major drawbacks. Generally, the conventional algorithm of CC method does not have the highlighted item 1 and 2 as shown in the Figure 3.4. Besides, the input of the highlighted item 3 does not consider the effect of temperature drift to the SOC estimation. Therefore these three items highlighted in the flowchart will be the main contribution of this project.

The flowchart depicts the management of battery monitoring by switching from a battery operating mode to another in accordance with the transition conditions [4][12]. There are three operation modes of battery cell which are charging, discharging and self-discharging. These operation modes are recognizable by determining the direction of the current flowing through the battery system [4]. Positive value of current flowing in represents charging operation whereas negative value of current represents discharging operation. The estimation

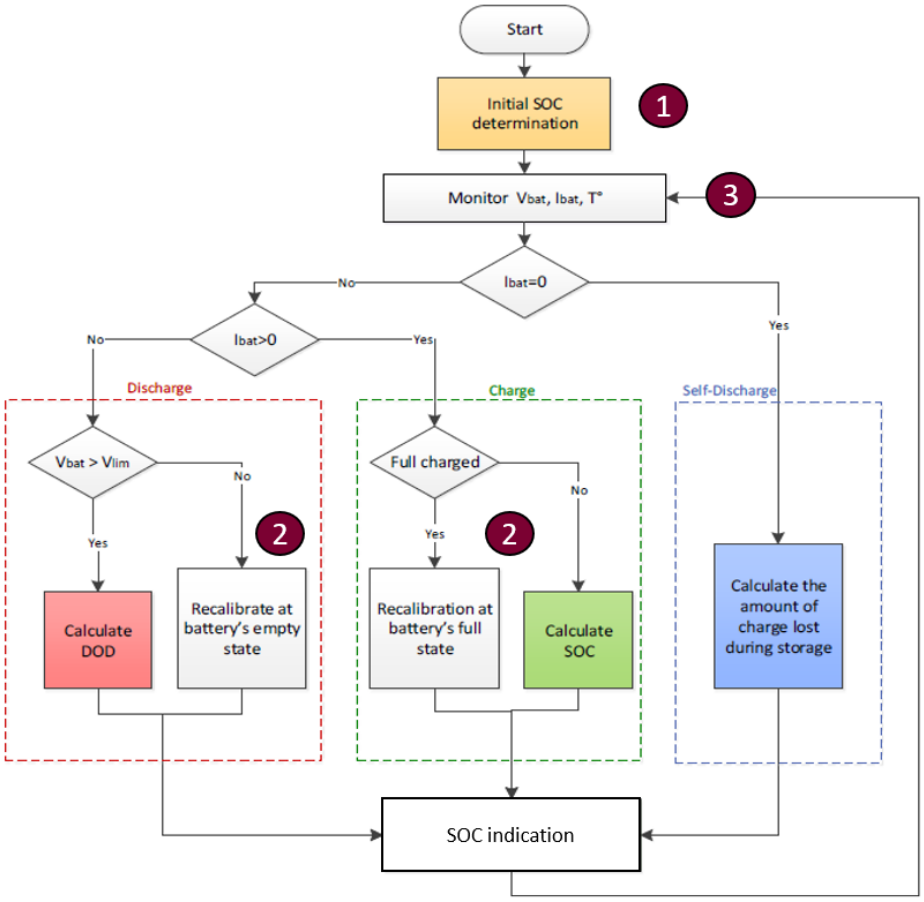


FIGURE 3.4: Sample: Flowchart of improved CC method with the compensation of three major drawbacks [4]

of SOC using CC method is based on the monitoring of V_{bat}, I_{bat} and T^2. Coulumb counter is used to track the SOC during all operation modes of battery cell. The mathematical formulation to be used in this algorithm can be referred in Section 3.2.1

3.3.2 Flow algorithm of initial SOC determination

Adaptive system method will be used to determine the initial value of SOC through the OCV-SOC lookup table. In order to determine the value of OCV, firstly, the terminal voltage is measured and corrected by the temperature condition. The terminal voltage is then further corrected by drop voltage from the current and impedance. This corrected OCV value is then converted to OCV-SOC lookup table to determine the initial value of SOC.This initial value is then fed into improved CC method to estimate the overall SOC of Li-ion battery cell. Figure 3.5 shows the flowchart of adaptive system method that is used to determine the value of initial SOC.

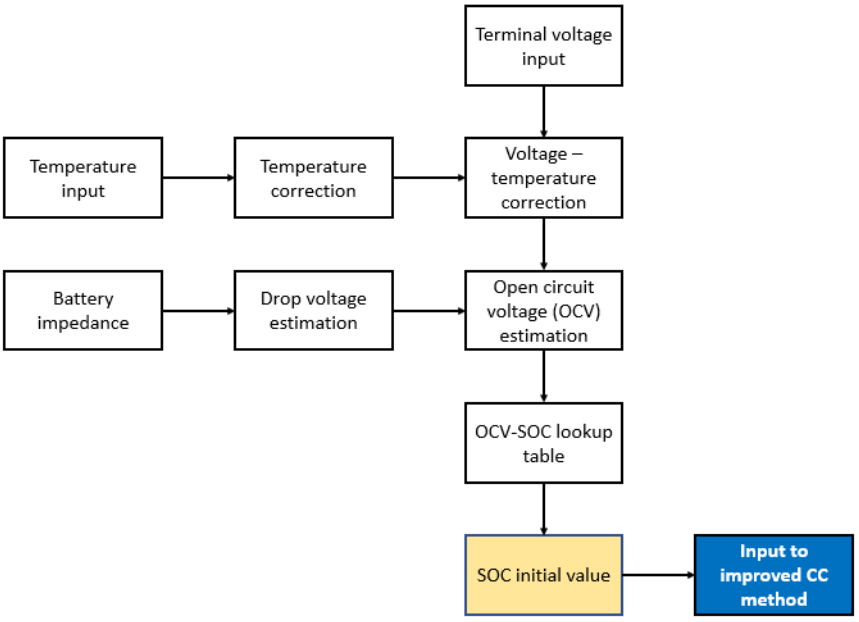


FIGURE 3.5: Sample: Flowchart of adaptive system method to determine the initial SOC

3.3.3 Calibration of nominal capacity

Based on [12], the battery cell is considered fully discharged when the cell voltage drops below than 3V. When it is fully discharged, the battery can no longer be used and needs to be recharged. After each cycle of charging and discharging, the Q_{max} of battery cell needs to be calibrated which represents the maximum capacity that can be released by the battery. As the battery ages, the maximum capacity that can be released will no longer be the same as the fresh battery, therefore, the calibration of nominal capacity will be performed to ensure the correct value of SOC can be estimated.

3.4 Gantt Chart

Tasks	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Proposal Preparation												
Literature Review												
Selection of research field												
Selection of gaps to be covered												
Selection of methods to be implemented												
Mathematical Analysis & Simulation Performance												
Develop mathematical formulation - initial SOC determination												
Develop mathematical formulation - temperature compensation												
Develop simulation in Matlab - improved CC method												
Select possible scenarios to be covered for testing												
Testing of the proposed system												
Improvement of the simulation												
Final testing of the proposed system												
Result Analyzation												
Review research objective												
Conclude findings and recommendations												
Findings presentation												
Thesis submission												

FIGURE 3.6: Gantt chart for the research proposal

Chapter 4

Expected Results

4.1 Expected results of overall SOC estimation

Figure 4.1 shows the sample of expected results from [6] which compares the estimation value of SOC using conventional CC method and enhanced CC method with regards to its reference value of SOC. Figure 4.1 also compares the absolute error gained using conventional and enhanced CC method to estimate SOC.

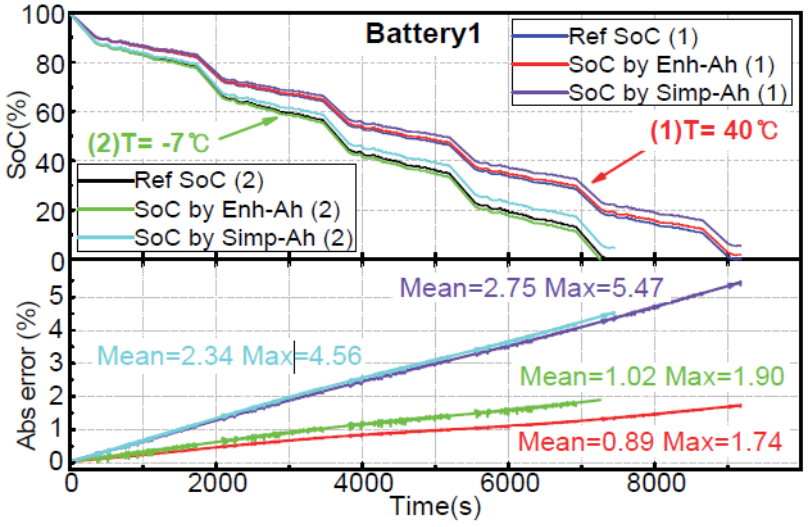


FIGURE 4.1: Sample: Expected results for the SOC estimation by implementing conventional CC method and enhanced CC method [6]

For this project, the simulation will be performed and the results of SOC estimation and error deviation with regards to the implementation of every single technique will be analyzed. The improvement in accuracy of SOC estimation will be analyzed based on the following implementation:

(i) SOC estimation and error deviation by considering single drawback only

(ii) SOC estimation and error deviation by considering two drawbacks

(iii) SOC estimation and error deviation by considering all three main drawbacks

The results from above implementation will be compared to its reference SOC value, aside from comparing it with the results of SOC estimation using conventional CC method. Aside from that, Figure 4.2 also shows sample of expected results for SOC estimation with the implementation of closed loop temperature compensation circuit.

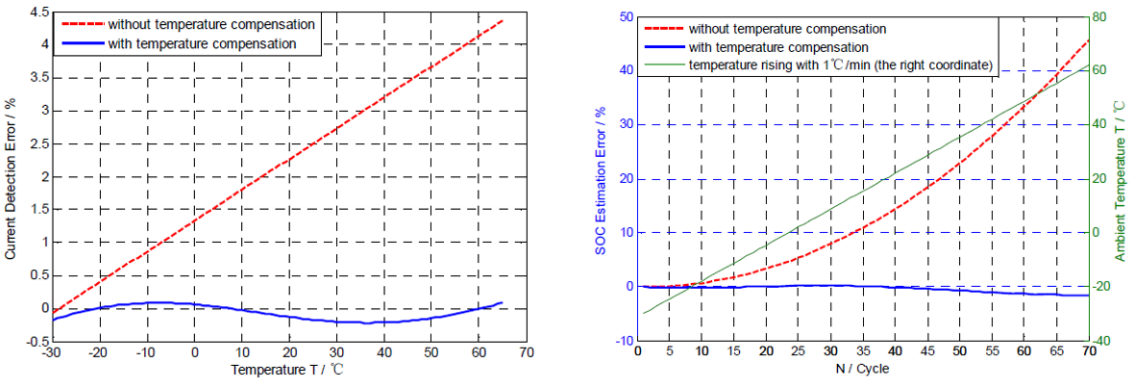


FIGURE 4.2: Sample: Expected results for the SOC estimation by implementing the technique of closed loop temperature compensation [5]

Chapter 5

Conclusions

This paper emphasizes the importance of SOC estimation for battery cell and the methods to estimate SOC. Acquiring an accurate SOC estimation is a crucial process because it will provide an insight regarding the battery performance and therefore avoid any unpredictable system interruption. CC method is a widely used method to determine the SOC of Li-ion battery cell due to its simplicity and good accuracy estimation. However, this method strongly depends on the precision of current sensors, initial value of SOC and the nominal capacity of the battery, which serves as the drawbacks of the method. Many research has been conducted to investigate the method on how to improve the CC method. However, the research that has been done only cover one or two limitations at a time. This paper proposes an improved CC method to estimate the SOC of battery cell by compensating three major drawbacks of conventional CC method. In order to determine the initial value of SOC, adaptive system method will be implemented to the system. Meanwhile, as for the compensation of temperature drift by current sensor, a closed loop temperature compensation circuit is introduced. Whereas for nominal capacity correction, a periodic calibration will be performed at empty state and full state of battery cell. The mathematical formulation for CC method at each operation mode of battery cell is analysed. Aside from that, the mathematical formulation for temperature compensation circuit has also been detailed in this paper. On top of that, the flow algorithm of the improved CC method with the additional process of initial SOC determination, temperature drift compensation and nominal capacity calibration is illustrated. The simulation of the proposed method is performed using Matlab. It is expected that the combination of this method will be able to provide high accuracy of SOC estimation compared to the conventional CC method.

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