# SOC ESTIMATION FOR BATTERY MANAGEMENT SYSTEM

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**Master Thesis**

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# ABSTRACT

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Batteries are often used as the primary energy storage element of rechargeable electrical systems. Today, as battery-powered devices increase and develop, the efficient use and duration of use of the battery has become critical.

In this context, knowing the state of charge (SOC) value of the battery is an important parameter that contributes to the efficient use of the battery and to prolonging the life of the battery by preventing overcharge-discharge. Therefore, it has become very important to calculate the SOC value in batteries with high precision.

In this thesis, in order to calculate the SOC value of the battery accurately and with high precision, modified Kalman Filter method using dynamic circuit model, Voltage-based method using battery terminal voltage with Rint circuit model, and Coulomb counting method are presented. These methods are also validated by simulation studies. In addition, the advantages and disadvantages of these methods and their comparision are explained.



**Keywords:** State of Charge, Circuit Model, Kalman Filter, Voltage based method, Coulomb Counting.

**ÖZET**

PIL YÖNETIM SISTEMI IÇIN SOC TAHMINI

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Aküler, şarj edilebilir elektrik sistemlerinin genellikle birincil enerji depolama öğesi olarak kullanılmaktadır. Günümüzde akü ile çalışan cihazlar arttıkça ve geliştikçe akünün verimli kullanımı ve kullanım süresi kritik bir hale gelmiştir.

Bu kapsamda, akünün *şarj durumu* (SOC) değerinin bilinmesi, akünün verimli kullanılmasına, aşırı şarj–deşarjı önleyerek pilin ömrünün uzatılmasında katkı sağlayan önemli bir parametredir. Dolayısıyla akülerde SOC değerinin yüksek hassasiyetle hesaplanması oldukça önem kazanmıştır.

Bu tezde, Akü SOC değerinin doğru ve yüksek hassasiyetle hesaplanması için, dinamik devre modeli kullanan Kalman filtresi, Rint devre modeli ile akü terminal voltajını kullanan Voltaj tabanlı yöntem ve Coulomb sayimi olmak üzere 3 temel metod modifiye edilerek sunularak yöntemlerin başarısı yapılan simulasyonlar ile desteklenmiştir. Ayrıca bu metodların birbirine göre avantajları ve dezavantajları incelenerek sunulmuştur.

**Anahtar Sözcükler:** Şarj Durumu, Devre Modeli, Kalman Filtresi, Voltaj tabanli yöntem, Coulomb sayimi.

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Mustafa Fahmi Ahmed AHMED

01/05/2022

## STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Eskisehir Technical University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

Mustafa Fahmi Ahmed AHMED

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| SOC | State of Charge |
| SOH | State of Health |
| SOE | Safe Operating Envelope |
| BMS | Battery Management System |
| KF | Kalman Filter |
| CC | Coulomb Counting |
| OCV | Open Circuit Voltage |
| t | Time |
| V | Volt |
| A | Amper |
| AH | Amper Hour |
| EMF | Electromotive Force |

# 1. INTRODUCTION

Batteries are electrochemical devices that may be charged to store energy and discharged to release that energy when it is required. Because of its reusability, batteries are utilized as the primary energy source in most electronic gadgets and instruments that we use in our daily lives, such as portable computers and cell phones. Batteries are also employed as a backup energy source in vehicles, aircraft, and public buildings.

Certain types of batteries, such as lithium-ion, lithium-polymer, and lead-acid batteries are available on the worldwide scene due to the wide range of applications for batteries [1].

Therefore, to get the most out of the battery, a Battery Management System (BMS) is founded to identify an essential parameter of the battery that called the battery State of Charge (SOC), which indicates how much usable energy is left in the battery at any time in addition to other parameters. Hence, according to BMS fundamentals, the battery must be reliable, capable of delivering the necessary power and energy based on demand, safe to operate, and efficiently used, to ensure that, continuous monitoring of its metrics such as SOC is required, because it does not only show the battery's remaining capacity but also its performance, it's vital to estimate the SOC correctly. If the SOC is incorrectly estimated, the battery management system's operation and management will suffer.

Unfortunately, direct measurements of SOC are not practicable due to a variety of challenges [2], including:

- Because battery pack contains hundreds of cells connected in series, each cell's accumulated potential is unique, making it difficult to develop unified compensation or elimination methods.
- Precision is required for voltage measurement because other parameters are estimated using the voltage measurement to achieve low carried percent errors, therefore a voltage precision of around 1 mV is required [3].
- Additionally, the components used to construct some batteries like the Lithium-Ion battery significantly reduce the battery's safe operating area including current, temperature, and voltage [3].

There are several ways/methods for estimating the SOC; three of these methods are considered in this thesis, including the Coulomb Counting Method, Voltage-Based Method, and Kalman Filter Method. To apply those methods MATLAB software is used in this thesis to obtain a precise SOC.

### 1.1. Literature Survey

A variety of SOC estimation techniques are studied and developed because the use of batteries is becoming more and more diverse and also the accurate information about SOC is crucial. Because batteries are increasingly employed in such an outsized amount of applications. However, for higher efficiency and longer life, special considerations must incline to their operating conditions for preventing physical damage. Therefore, there's a vital and fundamental need for BMS. These have to be able to accurately assess, estimate and control the battery's SOC, State of Health (SOH), and Safe Operating Envelope (SOE). These three parameters allow the BMS to determine the usability of the battery and extension of its lifetime.

The most purpose of this thesis is to elucidate three methods that assist the users of batteries to grasp SOC under assorted circumstances in a very time-efficient and robust manner. The effect of aging and so the qualities that indicate the SOH is additionally added within the longer term research. Among the nice degree of research literature that has been created, some techniques are selected for review during this chapter of the thesis because these techniques are popularly cited by authors and become the favorable foundations of the numerous other advanced approaches to SOC estimation. The articles that are chosen for literature review are: Battery Modelling additionally to Kalman Filter, and Voltage based method.

Regarding Battery Modelling, some research [4] has been conducted to analyze the battery electric circuit for presenting the circuit as a mathematical model that can describe the behavior of the battery in order to determine the SOC. The most favorable model is the state space representation of the battery circuit, which ranges from first to multi order, depending on the required accuracy for determining the SOC. The results of those investigations are claiming that the second order state space representation for a battery modeling is the most favorable model for estimating the battery's SOC regardless the number of the state variables that can be used within Kalman Filter to describe the battery cahrging and discharging behavior and thus to estimate the battery cell voltage (terminal voltage) .

Furthermore, other researchers [5] have used Thevenin model (PNGV battery model) to form a state space equations to be used within Kalman Filter as well, to determine the battery SOC by determining the battery open circuit voltage (OCV) by MATLAB Simulink software application.

For the Voltage Based method , which is taken into the account as one the best methods to estimate the SOC because it does not require a costly hardware and is straightforward to present the battery circuit in a mathematical way, the appliance of this method required pre-data collected as an experiment on a particular style of battery , and researchers used MATLAB Simulink to estimate the battery terminal voltage supported these data [6].

In addition, [7] describes the battery's simulation during charging or discharging by using MATLAB / Simulink using battery model to understand the mathematical relationship between battery input and output parameters in order to measure the battery OCV with respect to the battery's SOC.

### 1.2. Research Objective and Contribution

The objective of this research is to help with battery SOC estimation because accurate and reliable monitoring of important battery states like its SOC is the cornerstone for a battery management system, and it is therefore critical for batteries to operate safely and effectively. Despite the fact that the topic has been extensively researched, there are still significant research gaps.

The important obejectives and contributions of this work in this regard are summarized as follows:

- Revise mathematical models found in the literature when used to estimate state of charge and modify them to be applied in MATLAB for the purpose of SOC estimation by producing the state space representation for the battery's electric circuit (as in Kalman Filter method in this thesis).
- Modify available estimation techniques to mathematically represent the battery model to estimate the SOC (as in Voltage-based method in this thesis).

- Develop MATLAB software algorithm to estimate the battery SOC (as in Coulomb Counting method in this thesis).
- This work will contribute to the literatures as a source to improve SOC estimation methodologies to be implemented later on the BMS.

## 2. BATTERY MANAGEMENT SYSTEM

A BMS is an electronic system that controls the operation of a chargeable battery (cell or battery pack) by preventing it from operating outside of its safe operating area, monitoring its state, calculating secondary data, reporting it, controlling its environment, authenticating it, and/or balancing it, additionally to assuring its reliability and continuing operation. it's vital to keep up stability throughout the pack because cells collaborate to produce energy to the load [1].

The BMS monitors and regulates a battery pack to prevent damage, advance the battery's life, and ensure that it functions safely. The system's efficiency, dependability, and safety are all dependent on these functions.

Current, voltage, and temperature are just a few of the metrics that BMS can monitor and identify the battery's status based on these data and undertake any necessary reset procedures to safeguard the package.

The BMS is critical not only for indicating the battery's health, but also for protecting the battery during operation. Each battery cell and chemistry have a safe operating voltage, temperature, and current range. BMS can detect and control cells that fall within or exceed these ranges. Cell balancing is another critical safety feature of BMS. One cell within the pack may be weaker or stronger than the others, charging or discharging at a faster rate. Without adequate compensation, this can have a detrimental effect on the overall health of the pack. When a single circuit shorts or fails, it can have a detrimental effect on the stability of the entire pack. Cell balancing balances the charge between individual cells according to their capacity. The BMS assists in monitoring and controlling the amount of charge required from each cell in the pack, ensuring that the SOC is distributed evenly [8,9].

### 2.1. Battery Management System's indicators

The SOC and state of health (SOH) of the battery are critical indicators for determining its usability and capabilities. together the SOC and SOH provide an overview of the batteries' functionality, charging status is probably the simplest and most common procedure that a person will encounter. Charge states are indicated by battery percentages on phones, laptops, and even electric cars. The SOC is used in electric vehicle batteries to determine the vehicle's remaining range before it needs to be recharged, however, this does not indicate the battery's overall health. While the SOC can indicate a battery's short-term capacity by indicating how much power is remaining, it cannot indicate a battery's true capacity.

Because cell capacitance decreases with age, the SOC may read 100%, but the true capacitance will likely be less than that after a while [2].

However, the SOC remains a critical component of BMS, for instance, the SOC of each cell in a battery pack must be known in order to distribute the load evenly across the cells in the package.

Like SOC, SOH indicates a battery pack's long-term capability. The SOH is a calculation that considers charge acceptance, internal resistance, voltage, and self-discharge to determine how the battery can operate most efficiently. It is typically compared to a new battery cell to determine the cell's position over the course of its life. Because SOH is typically measured against a new cell, BMS must maintain a record of the battery's initial conditions and a log of measurements over the battery's life to provide a more accurate indication of battery health [3].

### 2.2. Battery Management System's Procedure

The BMS is used in battery pack testing to keep track of the state of each cell and how it interacts with the rest of the pack. It can aid in the detection of defects and flaws in a cell within a pack, as well as a better understanding of how current, voltage, temperature, and other factors fluctuate throughout the testing process. In testing to see how the battery performs during charge/discharge cycles, SOC and SOH are two essential metrics. Good battery testing software will be able to send these figures to external interfaces, allowing researchers to gain a better grasp of how battery packs behave.

Basically, BMS is a system takes some inputs such as

- Every cell Voltage and pack voltage.
- Temperature from sensors which typically sprinkled throughout the pack to get the sense of temperature distribution of the cells.
- And also takes as an input the current flows into or out of the pack during charging and discharging [10].

The BMS runs some algorithms to generate an accurate estimation of outputs, one of the primary outputs is the SOC, it also generates a SOH, in addition to Safe Operating Envelope (SOE) which allows the user to know how much current which we can either charge or discharge the battery at any given time, and finally the BMS also outputting faults or status signals that the application controller needs to be aware of, Figure 2.1 shows the BMS procedure.

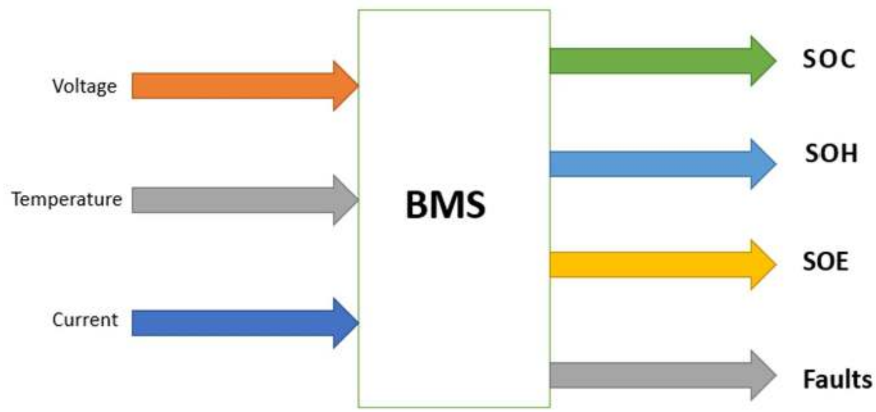



**Figure 2.1.** *Battery Management system procedure*

### 2.3. Battery Management System's Performance

The BMS has three major functions:

1- It protects the battery pack from overcharging (excessively high cell voltages) and over discharging (excessively low cell voltages) and extending the battery pack's life. This is accomplished by continuously monitoring each cell in the battery pack and determining the exact amount of current that can enter (source, charge) and exit (load, discharge) the battery pack without causing damage.
2- It estimates the State of Charge by monitoring cell voltages and recording how much energy travels in and out of the battery pack. This figure serves as a fuel gauge, displaying how much power remains in the pack.
3- It regularly checks for shorts, loose connections, wire insulation breakdowns, and weak or damaged battery cells that need to be replaced to ensure the battery pack's health and safety.

In addition to secondary functions that the BMS performs such as:

1- Intelligently leeches excess energy from cells that have been charged more than others in order to balance the battery pack's cells. Because the battery pack is only as powerful as its weakest cell, this gives the battery pack the maximum usable energy (capacity).

2- Controls the temperature of the battery pack by monitoring its temperature. It also continuously monitors the fan's output to ensure that it is operating properly.

3- Provides real-time information and values to other devices such as motor controllers, chargers, displays, and data loggers through a number of techniques (CANBUS, analog outputs, and digital outputs).

4- Stores error codes and comprehensive diagnostic data to aid in the diagnosis of battery pack issues [11].

# 3. BATTERY MODELING

SOC estimation may well be a critical parameter within the battery management system; it's one of the key technologies especially when utilized in electric vehicles, and its accuracy directly affects the vehicle's energy control strategy and performance [12]. However, thanks to the battery's complex electrochemical properties, it exhibits a high degree of nonlinearity during operation which makes the SOC cannot be determined directly, but it's only possible to estimate it by  using externally measurable parameters such as battery terminal voltage, charge and discharge current, and on forth. Additionally, the accuracy of SOC estimation process is well influenced by variables like temperature, cycle time, discharge rate, voltage, and noise [13]. As a result, it is necessary to develop an appropriate battery model to estimate the SOC of the battery. a certain and appropriate battery model can accurately reflect the connection between the battery's external parameters and internal state, furthermore as simplify and specify the SOC estimation problem. The complexity of the model and also the processor's computational cost also affect the BMS system's decision-making and control [14]. As could also be seen, developing an accurate and straightforward battery model and accurately estimating battery state of charge encompasses a right away effect on the energy control strategy and performance. The battery model that possesses to be established is per the battery's external characteristics because the battery's internal chemical action is also a posh non-linear process, as an example, when the charging and discharging currents changes, the battery is polarized, which means that the battery terminal voltage doesn't reveal a pure resistance characteristics but continuously changes in an exceedingly nonlinear manner. Polarization of the battery lands up during a rise within the resistance of the charging and discharging current flowing through it [15]. After extended use, the battery will still experience aging problems, like capacity degradation and internal resistance increase, causing the battery's state of charge to deviate significantly from its true state [16]. Individual batteries fabricated from different monomers perform differently; from the battery monomer to the battery module to the battery pack, the power performance is significantly reduced. These factors complicate the task of developing an accurate battery model capable of accurately describing all battery performance. Individuals can only use a selection of methods to simulate the battery's characteristics from various angles. At the moment, battery models that are frequently used include electrochemical mechanism models, equivalent circuit models, and data-driven models.

### 3.1. Equivalent Circuit Model

The equivalent circuit model replicate the dynamic characteristics of the battery by using circuit components like voltage sources (constant), resistors, and capacitors, to make a circuit model to accurately estimate the battery's SOC, the model must better reflect the battery's static and dynamic characteristics. However, the order of the model mustn't be too high, as this reduces processor calculations and makes engineering easier to conduct [17].

There are two forms of equivalent circuit models: integer-order models and fractional-order models. Figure 3.1 [18] discribes the most common used models in purpose of SOC estimation which includes

- The Rint model [19] describes the dynamic characteristics of an influence battery by serially connecting a perfect voltage source $U_{oc}$ and therefore the battery's DC internal resistance $Ro$. $Ro$ and $U_{oc}$ are proportional to SOC and temperature, respectively. This model contains a simple structure and is simple to implement, but it's imprecise and fails to account for the polarization phenomenon occurring inside the ability battery. this is often a perfect situation, but it's unsuitable to be used in electric vehicles.

- Thevenin's model [20] is premised on the Rint model, but includes a parallel RC network to simulate the battery's polarization effect. This model incorporates a straightforward structure and a high level of simulation accuracy. Additionally, it can discuss with the polarization effect occurring within an influence battery, when A battery is charged or discharged, the voltage at both ends changes abruptly and gradually. $Ro$ is employed to simulate abrupt resistance characteristics, while $R_p$ and $C_p$ are accustomed simulate the capacitance characteristics of gradual voltage changes within the Thevenin model.

- A PNGV model created by connecting a capacitor $C_b$ nonparallel with the Thevenin model [21]. The change within the battery's circuit voltage induced by current integration throughout the course of the battery's long-term charging and discharging operation is described by this capacitor. The PNGV model could be a nonlinear equivalent model which will handle high currents, step-type charging, and more complicated charging and discharging scenarios. Reference [22] suggested a PNGV battery model with variable parameters, specifying $Ro$, $R_p$, and $C_p$ as variable parameters that change looking on the battery SOC, lowering the model's complexity and calculation time. The accuracy of the model is improved by the flexibility to simulate the battery's dynamic working characteristics in real time [23]. A second-order RC equivalent model are often formed by adding an RC network to the equivalent circuit, which improves the equivalent circuit's ability to simulate the dynamic properties of the battery and hence improves the battery's state of charge estimate accuracy [24,25]. to elucidate the dynamic and static properties of the battery, the multi-level RC equivalent circuit model normally comprises quite two sets of RC polarization parameters. The more RC components used, the more precise the estimation of the battery's state of charge becomes; nevertheless, as state dimensions grow larger, parameter identification becomes tougher, calculations become more complex, and over-fitting issues become more common. The battery model must meet the necessities for accurately portraying the battery's dynamic attributes while also responding to the system's real-time performance in terms of complexity. When accuracy and system reliability are considered concurrently, it's preferable to use the Thevenin model and therefore the second-order RC circuit model [26]. At the instant, an outsized number of battery modeling studies have demonstrated that in practical applications, only models of under third order are required to fulfill accuracy requirements, and most recent studies use second-order RC models to develop SOC estimators [27].

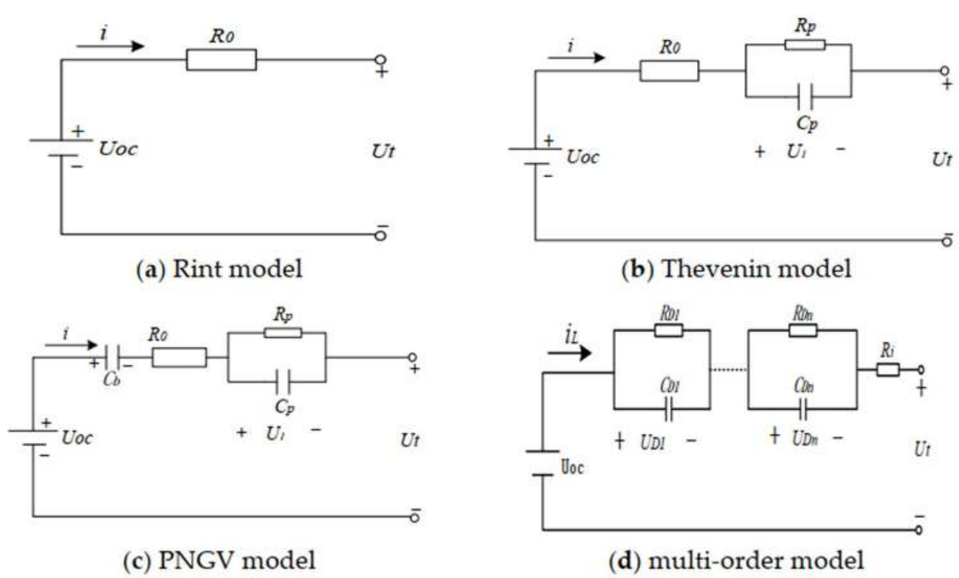



**Figure 3.1.** *Electric Circuits for Battery Model [28]*

Furtherore, a battery's mathematical modeling is critical for the following reasons:

(i) Developing efficient battery management system.

(ii) Contributes significantly to the advancement of charging/discharging techniques and the expansion of battery capacity.

(iii) To protect batteries from serious damage caused by overcharging or overdischarging.

(iv) A more efficient and safe method of examining battery behavior under a variety of operating conditions.

(v) Determining the operating limits that maximize the lifetime of a system for a particular application**.**

### 3.2. Mathmetical Derivations of Battery Modelling (State Space Modelling)

Due to their simplicity, this part focuses on the development of mathematical equations for the most frequent battery equivalent circuits, as shown in Figure 3.2, in addition to state space representations of these circuits.

#### 3.2.1. Dynamic Battery Model

A dynamical battery model [28], also referred as a second order model, is another type for battery modeling. This model is created from state variable equations, as illustrated in Figure 3.2. There is a bulk capacitor $C_{bk}$ that stores energy in the shape of charge, a capacitor that simulates the surface capacitance $C_{surface}$ and diffusion effects within the cell, a terminal resistance $R_t$, a surface resistance $Rs$, and an end resistance $Re$ in this model. $V_{Cb}$ , and $V_{Cs}$ are the voltages across both capacitors, respectively [29,30].

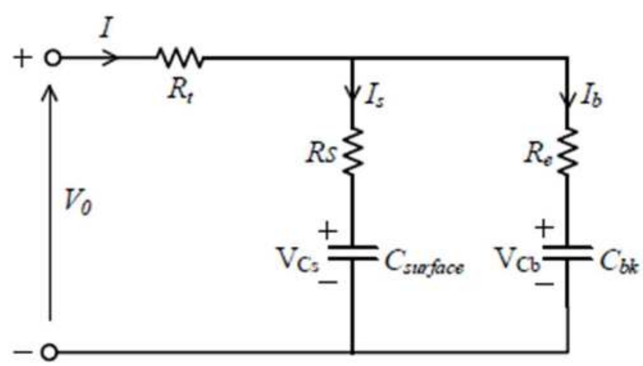



**Figure 3.2.** *Battery Model (Dynamic Model)*

The state variables $V_{Cb}$, $V_{Cs}$ and $V_O$ conjure a state space model as they're the mathematical description of a dynamic system 'state'. In practice, a system current state is employed to predict its future behaviour. State space models are made from paired first-order differential equations are in state-variable form.,the terminal voltage $V_0$ is calculated using the voltages and the current shown in Figure 3.2 as:

$$V_0 = I\ R_t + I_b R_e + V_{Cb} \tag{3.10}$$

or

$$V_0 = I\ R_t + I_b R_s + V_{Cs} \tag{3.11}$$

By equating the (3.10) and (3.11), and after simple algebraic manipulation, which results in

$$I_b R_e = I_s\ R_s + V_{Cs} - V_{Cb} \tag{3.12}$$

From KCL, ,

$$I = \ I_s + I_b$$

$$I_S = I\ - I_b \tag{3.13}$$

substituting (3.13) into (3.12) yields to

$$I_b(R_e + R_s) = I\ R_s + V_{Cs} + V_{Cb} \tag{3.14}$$

The current through the capacitor $C_{bk}$, is $I_b = C_{bk}\dot{V_{Cb}}$, and substituting into (3.12), the following equation is obtained after rearrangement

$$\dot{V}_{Cb} = \frac{I\ R_s}{C_{bk}\ (R_e+R_s)} + \frac{V_{Cs}}{C_{bk}(R_e+R_s)} - \frac{V_{Cs}}{C_{bk}(R_e+R_s)} \tag{3.15}$$

By applying a similar derivation on the surface capacitor voltage

$$\dot{V}_{Cs} = \frac{I\ R_e}{C_{surface}\ (R_e+R_s)} + \frac{V_{Cs}}{C_{surface}(R_e+R_s)} - \frac{V_{Cb}}{C_{surface}(R_e+R_s)} \tag{3.16}$$

assuming $K = \frac{1}{C_{bk}(R_e+R_s)}$ and $L = \frac{1}{C_{surface}(R_e+R_s)}$

(3.15) and (3.16) can be written as

$$\dot{V_{Cb}} = K.IR_s + K.V_{Cs} - K.V_{Cb} \tag{3.17}$$

$$\dot{V_{Cs}} = L.IR_e - L.V_{Cs} - L.V_{Cb} \tag{3.18}$$

Further, (3.17) and (3.17) can be combined to form a state variable relating voltages $V_{cs}$, $V_{cb}$and current flow I, which is

$$\begin{bmatrix} \dot{V_{Cb}} \\ \dot{V_{Cs}} \end{bmatrix} = \begin{bmatrix} -K & K \\ L & -L \end{bmatrix} \begin{bmatrix} V_{Cb} \\ V_{Cs} \end{bmatrix} + \begin{bmatrix} K.R_s \\ L.R_e \end{bmatrix} I \tag{3.19}$$

The output voltage is derived from (3.10) and (3.11). by adding both equations, the following is obtained

$$2V_0 = 2IR_t + I_bR_e + I_sR_s + V_{Cb} + V_{Cs} \tag{3.20}$$

by subtituting $I_b = \frac{R_s}{R_s+R_e}$ , and $I_s = \frac{R_e}{R_s+R_e}$ into (3.20) , it is simplified as

$$V_o = \frac{V_{Cb}+V_{Cs}}{2} + \left(R_t + \frac{R_eR_s}{R_e+R_s}\right) I \tag{3.21}$$

by computing the time derivative of the output voltage and assuming $\frac{dI}{dt} \approx 0$ , the result becomes

$$\dot{V}_0 = \frac{\dot{V}_{Cb}+\dot{V}_{Cs}}{2} \tag{3.22}$$

then by substituting the values obtained earlier from (3.17) and (3.18) into (3.22), the result become

$$2\dot{V}_0 = (-K + L)V_{Cb} + (K - L)V_{Cs} + (KR_s + LR_e)I \tag{3.23}$$

from (3.21) the voltage across $V_{cs}$ is

$$V_{Cs} = 2V_0 - 2\left(R_t + \frac{R_eR_s}{R_e+R_s}\right) I - V_{Cb} \tag{3.24}$$

then after subtituting into (3.23) the following is obtained

$$\dot{V}_0 = (-K + L)V_{Cb} + (K - L)V_0 + [K(0.5R_s + R_t + N) + L(0.5R_e - R_t - N)]I \tag{3.25}$$

Thus the final state space description of the system is

$$\begin{bmatrix} \dot{V}_{Cb} \\ \dot{V}_{Cs} \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} -K & K & 0 \\ L & -L & 0 \\ -K + L & 0 & K - L \end{bmatrix} \begin{bmatrix} V_{Cb} \\ V_{Cs} \\ V_0 \end{bmatrix} + \begin{bmatrix} K.R_s \\ L.R_e \\ L(0.5R_s - R_t - N) + L(0.5R_e + R_t + N) \end{bmatrix} I \tag{3.26}$$

where $K = \frac{1}{C_{bk}(R_e+R_s)}$ , $L = \frac{1}{C_{surface}(R_e+R_s)}$, and $N = \frac{R_eR_s}{R_e+R_s}$

# 4. STATE OF CHARGE (SOC) PRINCIPLES AND ESTIMATION METHODS

The state of charge of any battery refers to its amount of charge in regard to its capacity which mostly expressed in percentage points (0 percent = empty, 100% = full), it's commonly accustomed describe this state of electric battery in use. The precise measurement of SOC will provide optimal battery performance, an extended lifetime, and therefore the prevention of irreversible physical damage to the battery.

Because determining a battery SOC may be a difficult task that varies due to the battery type and application, much development and research has been tried in recent years to reinforce SOC estimation accuracy. one in all the key objectives of battery management system is accurate SOC estimation, which can help increase system performance and dependability while also extending the battery's lifetime. In reality, accurate battery SOC estimation helps prevent unplanned system outages and stop batteries from being overcharged or drained, which might cause lasting harm to the interior structure of the battery. However, because battery discharge and charge involve complicated chemical and physical processes, properly estimating the SOC under various operating conditions is difficult.

## 4.1. Battery SOC estimation methods

SOC cannot be measured directly in most cases, but it can be calculated in two ways offline and online. As a result, a number of approaches for assessing the level of charge of a battery in real time have been presented, in gneral there are four classifications for SOC estimation [10], as indicated in Table 1.

| Classification | Method |
|---|---|
| Direct measurement | Open circuit voltage method<br>*Terminal voltage method*<br>Impedance method Impedance spectroscopy method |
| Book-keeping estimation | *Coulomb counting method*<br>Modified Coulomb counting method<br>Those two methods deal with Short Circuit Current (SCC) |
| Adaptive systems | Neural network<br>Support vector machine<br>Fuzzy neural network<br>*Kalman Filter* |
| Hybrid methods | Coulomb counting and EMF combination<br>Coulomb counting and Kalman Filter combination<br>Per-unit system and EKF combination |

***Table 1.*** *State of Charge estimation methods*

Below is a brief description of the methods that used in this thesis.

#### 4.1.1. Direct measurement methods

Direct measurement is an off-line technique that makes use of the physical properties of the battery, such as impedance or terminal voltage. The most common methods are open circuit voltage measurement, terminal voltage measurement, impedance measurement, and impedance spectroscopy.

##### *4.1.1.1. Open circuit voltage method*

The term "OCV" refers to the battery's open circuit voltage (discharged battery). It is the most straightforward method for estimating SOC. The OCV is a linear function of SOC in some battery chemistries. Thus, by determining the OCV, we can easily predict the battery's state of charge. Whereas with other Li-ion chemistries, the OCV vs SOC curve is flat, therefore the correlation between the OCV and SOC cannot be exactly the same for all batteries, Under such circumstances, this method's use is restricted. With additional limitations associated with this method this is a non-interactive method, For an accurate measurement of the OCV, the battery should be disconnected from any load for at least two hours[12]. Additionally, OCV varies not only with SOC, but also with a cell's internal resistance., the SOC range of 20% to 80% OCV does not vary significantly,This complicates SOC estimation in this region. Thus, to summarize, it is a laboratory technique that should only be used at extremes (When battery is nearly full or empty). Additionally, it is an excellent method for estimating the initial SOC [13].

#### *4.1.1.2. Terminal voltage method*

The terminal voltage method is predicated on the voltage drops at the terminal caused by internal impedance during discharge, and thus the voltage (EMF) of the battery is proportional to the terminal voltage. Thanks to the actual fact that a battery's EMF is approximately linearly proportional to its state of charge, and therefore the battery's terminal voltage is additionally approximately linearly proportional to its state of charge. The terminal voltage method has been used at various discharge currents and temperatures [31]. However, at the top of battery discharge, the terminal voltage method's estimated error is large, because the battery's terminal voltage drops abruptly [12].

### 4.1.2. Book-Keeping methods

The book-keeping estimation methods is based on data on battery charging and discharging current, this method enables the inclusion of certain internal battery characteristics such as self-discharge, capacity loss, and discharging efficiency. Two types of estimation methods for book-keeping have been used: the Coulomb counting method and the modified Coulomb counting method [12]. Which they both considered as on-line and off-line techniques.

#### *4.1.2.1. Coulomb counting method*

The Coulomb counting method [32] estimates the SOC by measuring the battery's in and out current and integrating it over time. The SOC is calculated using the Coulomb counting method, which is based on the charging/discharging current, and previously calculated or assumed SOC values.

Equation (3.1) is used to compute the final SOC

$$SOC_t = SOC_{initial} \pm \frac{1}{C} \int I(t)dt \tag{4.10}$$

where $SOC_t$ is the final SOC (estimated), $SOC_{initial}$ is the initial SOC ,$C$ is the battery's capacity, $I(t)$ is charging/discharging current , and $t$ is the time

Temperature, battery history, discharge current, and cycle life are all factors that affect the accuracy of the Coulomb counting approach.

#### 4.1.3. Adaptive Systems method

Adaptive systems are self-designing systems that may adapt automatically to changing environments. thanks to the actual fact that batteries are littered with a range of chemical factors and have a nonlinear state of charge, adaptive systems provide a viable solution for estimating state of charge [12]. Recent advancements in AI have resulted within the development of diverse new adaptive systems for SOC estimation such as: Back propagation (BP) neural networks, radial basis function (RBF) neural networks, formal logic methods, support vector machines, fuzzy neural networks, and Kalman Filters are among the newly developed methods.

##### *4.1.3.1. Kalman Filter*

In 1960, Kalman Filters (KF) were presented as a recursive solution to optimum linear Filtering for both state observation and prediction problems [33]. It is an optimal estimator that infers parameters of interest from indirect, incorrect, and uncertain observations. It keeps track of the system's estimated state as well as the estimate's variance or uncertainty. It's also known as linear quadratic estimation, and it's an algorithm that uses a series of measurements taken over time, all of which contain noise and other inaccuracies to produce estimates of unknown variables that are more precise than a single time measurement, while also minimizing the mean square error of estimated parameters. It is based on linear dynamic systems discretized in time domain, in which the current state is calculated using the estimated state from the previous time step and current measurement. Figure 4.1 depicts the Kalman Filter utilized in the proposed system with inputs and outputs.

Herewith. The Kalman Filter, unlike other estimating algorithms, automatically provides dynamic error limits on its own state estimates. By modeling the battery system to include them in its state description, the Kalman Filter guesses the values of the desired unknown quantities (such as SOC) and offers error bounds on the estimations. It then changes into a model-based state estimation technique with an error correction mechanism that can anticipate SOC in real time.

Kalman filtering requires a battery model and a comprehensive understanding of its features. It also demands a significant amount of computational power and proper startup.

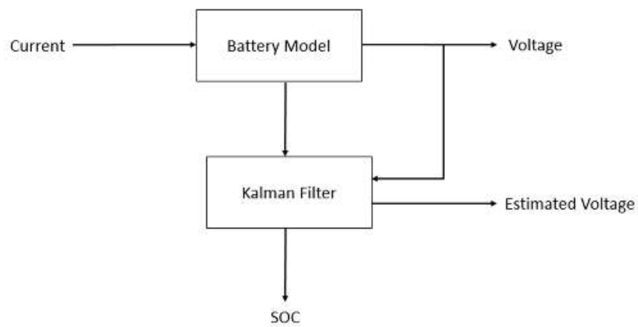



**Figure 4.1.** *Kalman Filter for SOC estimation*

## 4.2. Kalman Filter for SOC Estimation

### 4.2.1. Methodology

Figure 3.2 shows the dynamic model of a battery that can be used for any type of batteries in order to study the dynamic behavior of the battery for charging and discharging process which used within the Kalman Filter method in purpose of estimating the battery state of charge based on the terminal voltage, thus as mentioned in section (3.1.3.1) a state space representation is produced to be used in this method, Kalman Filter is a linear Filter that deals with discrete linear systems for estimating the output of the system which is represented by the terminal voltage $V_o$ in this case.

Hence, a battery dynamic model can be written in the form of

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{4.2.1}$$

where

$$\dot{x}(t) = \begin{bmatrix} \dot{V}_{Cb} \\ \dot{V}_{Cs} \\ \dot{V}_o \end{bmatrix}, \quad x(t) = \begin{bmatrix} V_{Cb} \\ V_{Cs} \\ V_o \end{bmatrix} \tag{4.2.2}$$

$$u(t) = I, \quad y(t) = V_o$$

By reshaping the previous calculations, the final state space representation of the system can be form like

$$\begin{bmatrix}\dot{V}_{Cb}\\ \dot{V}_{Cs}\\ \dot{V}_{o}\end{bmatrix} = \begin{bmatrix}-K & K & 0\\ L & -L & 0\\ -K+L & 0 & K-L\end{bmatrix}\begin{bmatrix}V_{Cb}\\ V_{Cs}\\ V_{0}\end{bmatrix} + \begin{bmatrix}K.R_s\\ L.R_e\\ K(0.5R_s - R_t - N) + L(0.5R_e + R_t + N)\end{bmatrix} I \qquad (4.2.3)$$

where $K = \frac{1}{C_{bk}(R_e+R_s)}$ , $L = \frac{1}{C_{surface}(R_e+R_s)}$, and $N = \frac{R_e R_s}{R_e+R_s}$

If the applied input $u$ (which is the current (I)) assumed to be a constant a discrete-time equivalent model of the system will be:

$$x(n+1) = A_d x(n) + B_d u(n) \qquad (4.2.4)$$

$$y(n+1) = C_D x(n+1) \qquad (4.2.5)$$

$$\text{where } A_d \approx I + A.T_c, \quad B_d = B.T_c, \quad C_d = C \qquad (4.2.6)$$

$I$ is the identity matrix and Tc is the sampling period. İn addition to two additive gaussion noises. $w$ represents system disturbances, and $v$ represents the measurement noise.

$$x(n+1) = A_d x(n) + B_d u(n) + w \qquad (4.2.7)$$

$$y(n+1) = C_d x(n+1) + v \qquad (4.2.8)$$

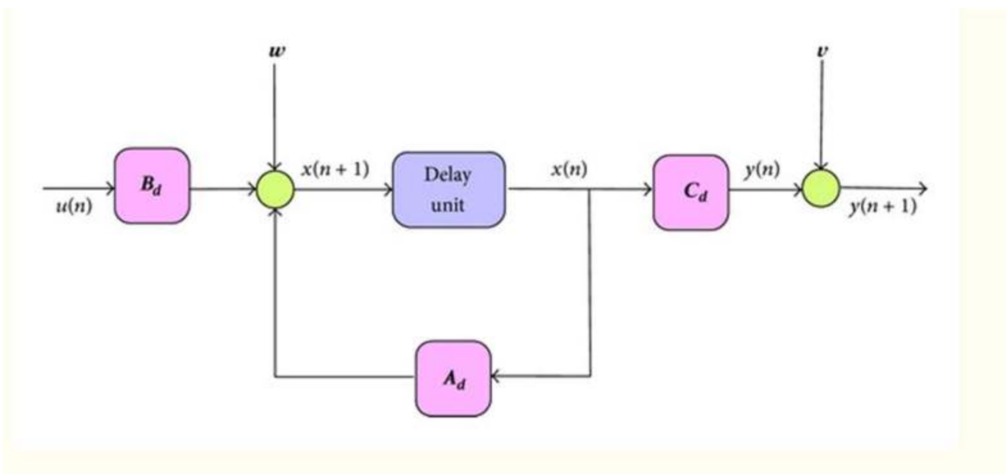



**Figure 4.2.** *Model (Discrete) with Noises w & v*

Consequently, Figure 4.2 parallelly connected to Kalman filter as denoted in Figure 4.3 below.

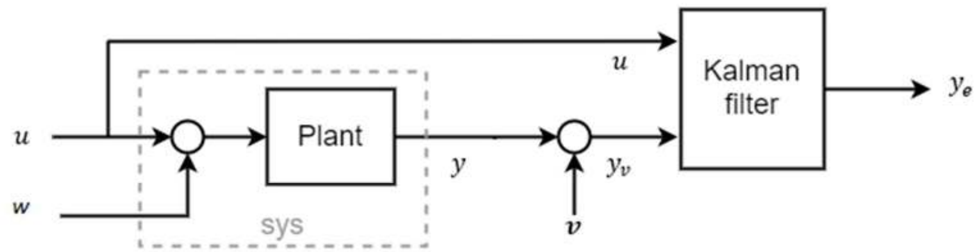



**Figure 4.3.** *Kalman Filter connected with a system*

According to Figure 4.3 the system's input is the current, which assumed to be constant, and the system's output is the terminal voltage ($y$), but due to the two noises of the system the output will be ($y_v$) a noisy terminal voltage, after connecting the Kalman Filter to the system, Kalman Filter now has two inputs which they are the constant current ($I$) and ( $y_v$), thus the output will be the fillteredterminal votlage ($y_e$).

Hence, according to the linearity of KF, open circuit voltage is calcualted according to eqaution (4.2.9), then based on linear formula of SOC-OCV the final state of charge is estimated according to equation (4.2.10)

$$OCV = V_T(y_e) + I.R_{drop} \tag{4.2.9}$$

$R_{drop}$ is the $Rt$ as shown in Figure 3.2, furthermore the final SOC is calculated according to equation below.

$$SOC = \frac{1}{a_1}(OCV - a_{0)} \tag{4.2.10}$$

$a_1$ is the terminal voltage ($y_e$) when the SOC is equal to 100 %

$a_0$ is the terminal voltage ($y_e$) when the SOC is equal to 0%

By using MATLAB software [34], and by submitting the numerical values of the circuit parameters listed in Table 2. [4,35], the state space matrices are obtained.

| $C_{bk}$ | $C_{surface}$ | $R_e$ | $R_S$ | $R_t$ |
|---|---|---|---|---|
| 88372.83 F | 82.11 F | 0.00375 Ω | 0.00375 Ω | 0.002745 Ω |

***Table 2.*** *Circuit model parameters*

The results after applying equation (4.2.3) are:

$$A = \begin{bmatrix} -1.51x10^{-3} & 1.51x10^{-3} & 0 \\ 1.6238 & -1.6238 & 0 \\ 1.6223 & 0 & -1.6223 \end{bmatrix}$$

$$B = \begin{bmatrix} 5.66x10^{-6} \\ 6.08x10^{-3} \\ 1.05x10^{-2} \end{bmatrix}$$

$$C = [0 \quad 0 \quad 1]$$

$$D = [0]$$

Assuming that battery parameters are time-invariant quantities, the KF algorithm is applied. Hence, the following updated matrices are obtained after applying equation (4.2.6), when Tc = 1:

$$A_d = \begin{bmatrix} 0.9984 & 1.51x10^{-3} & 0 \\ 1.6238 & 0.6238 & 0 \\ 1.6223 & 0 & 0.6223 \end{bmatrix}$$

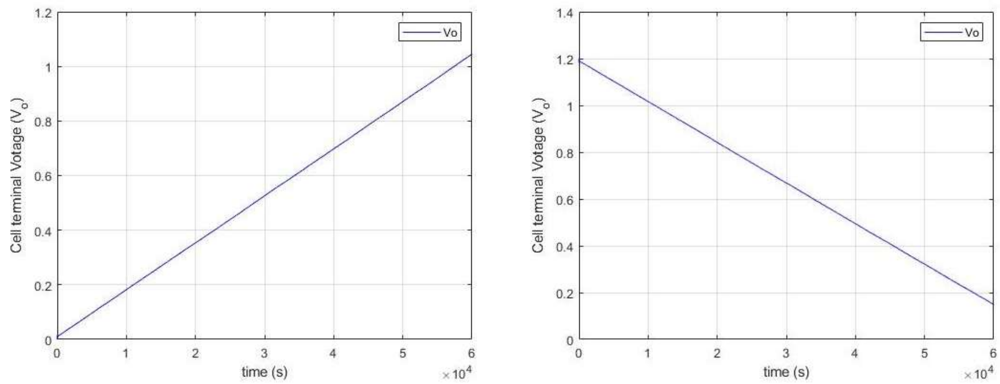
$$B_d = \begin{bmatrix} 5.66x10^{-6} \\ 6.08x10^{-3} \\ 1.05x10^{-2} \end{bmatrix} \qquad C_d = [0 \quad 0 \quad 1]$$

**4.2.2. Results**

As shown in Appendix A which is the Matlab script file created for this thesis, the system output represented by the terminal voltage ($ye$) is estitmated when the input ($u$) is assumed to be constant (I=1.53 A) and the battery is fully discharge, in other hand the SOC=0

The charging characteristic is illustrated in Figure 4.4. a, whereby the initial terminal voltage $Vo$ starts from 0 V up to approximately 1 V (1.05 V to be exact) within 60000sec. (Which is 100 minutes).

For discharging process, the initial value of terminal voltage, $y_0 = V_O$ is set to 1.2 V, the dynamic behaviour showing the discharge characteristic is shown in Figure 4.4.b. From this figure, it is observed that the discharge process is similar to charging; but now with linearly decreasing $V_0$ slope. The $V_0$ drops from 1.2V to 0.15 V in 60000 seconds (100 minutes); this is similar to the charging process as it literally takes 100 minutes to reach $Vo$ = 1 V from zero potential.




a-Dynamic Behavior of KF estimator with charge constant current of 1.53 A

b-Dynamic Behavior of KF estimator with charge constant current of 1.53 A

**Figure 4.4.** *Dynamic Behavior of KF with constant current =1.53 A*

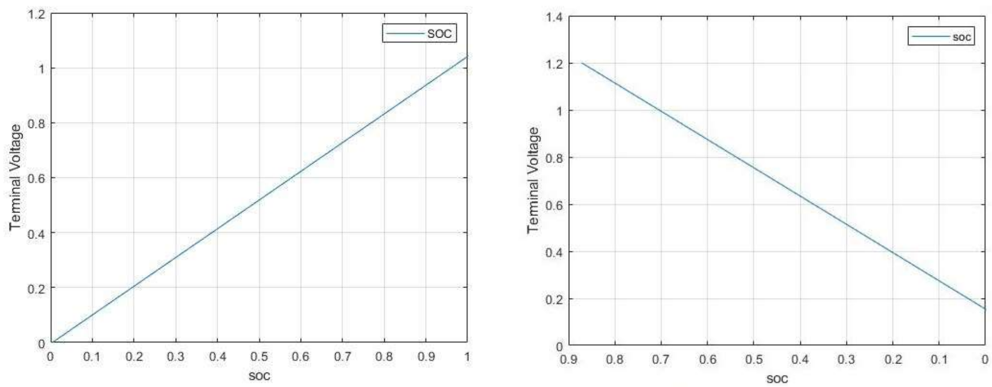
Root-Mean Squared (RMS) of the estimated error is calculated as well, as shown in Table 3., which is the error from Kalman Filter, the results shows that the KF error is far smaller compared to the measured error, with values of 1.0014 for meausrement error and 1.9186×10−4 for estimation error during charging and discharging processes.

| RMS error | Charging Process | Discharging Process |
|---|---|---|
| Measurement, $y - y_v$<br>$y$ is the terminal voltage of the system<br>$y_v$ is the noisy terminal voltage of the system | 1.0014 | 1.0014 |
| Estimated (KF), $y - y_e$<br>$y$ is the terminal voltage of the system<br>$y_e$ is the filtered terminal voltage | $1.9186x10^{-4}$ | $1.9186x10^{-4}$ |

***Table 3.*** *Recorded RMS Error when input current =1.53 A*

Furthermore, the OCV is calculated based on estimated terminal voltage $y_e$ for the purpose of estimating the SOC.

Figure 4.5. a show the estimated SOC during charging process and figure 4.5. b shows the estimate SOC during discharging process with reference to filter terminal voltage.



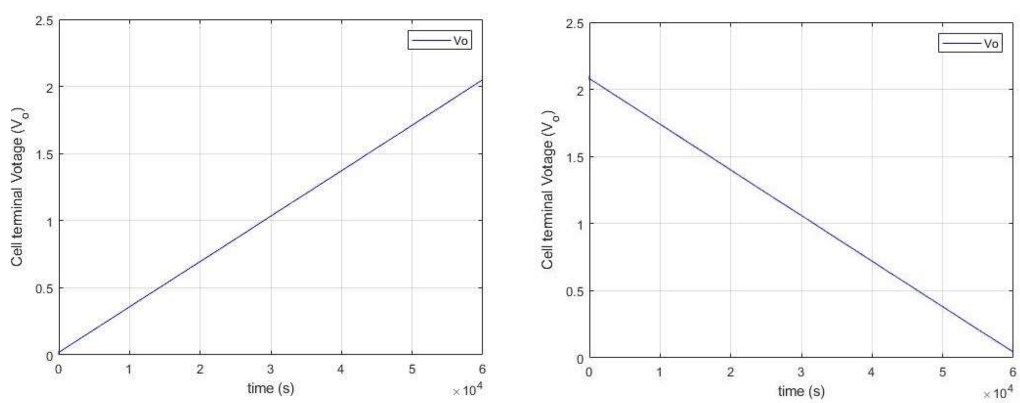

a- SOC during charging process

b-SOC during discharging process

**Figure 4.5.** *SOC vs Estimated Terminal Voltage*

By repeating the above procedure and changing the input current to (I=3 A), The charging characteristic is illustrated in Figure 4.6. a whereby the initial terminal voltage $Vo$ starts from 0 V up to approximately 2.2 V (2.15 V to be exact) within 60000sec. (Which is 100 minutes).

For discharging process, the initial value of terminal voltage, $y_o = Vo$ is set to 2.2 V, the dynamic behaviour showing the discharge characteristic is shown in Figure 4.6. b From this figure, it is observed that the discharge process is similar to charging; but now with linearly decreasing $V0$ slope. The terminal voltage $Vo$ drops from 2.2V to 0.14 V in 60000 seconds (100 minutes); this is similar to the charging process as it literally takes 100 minutes to reach $Vo$ = 2.2 V from zero potential.




a-Dynamic Behavior of KF filter with charge constant current of 3

b -Dynamic Behavior of KF filter with discharge constant current of 3

**Figure 4.6.** *Dynamic Behavior of KF with constant current =3 A*

Regarding the Root-Mean Squared (RMS) of the estimated error which is calculated as well, as shown in Table 4., the results shows that the KF error is far smaller compared to the measured error, with values of 1.0014 for meausrement error and 1.9186×10−4 for estimation error during charging and discharging processes.

| RMS error | Charging Process | Discharging Process |
|---|---|---|
| Measurement, $y - y_v$<br>$y$ is the terminal voltage of the system<br>$y_v$ is the noisy terminal voltage of the system | 1.0014 | 1.0014 |
| Estimated (KF), $y - y_e$<br>$y$ is the terminal voltage of the system<br>$y_e$ is the filtered terminal voltage | $1.9186x10^{-4}$ | $1.9186x10^{-4}$ |

***Table 4.*** *Recorded RMS Error when input current =3 A*

The open circuit voltage is calculated based on estimated terminal voltage $y_e$ for the purpose of estimating the SOC.

Figure 4.7.a shows the estimated SOC during charging process and Figure 4.7.b shows the estimate SOC during discharging process with reference to filter terminal voltage.

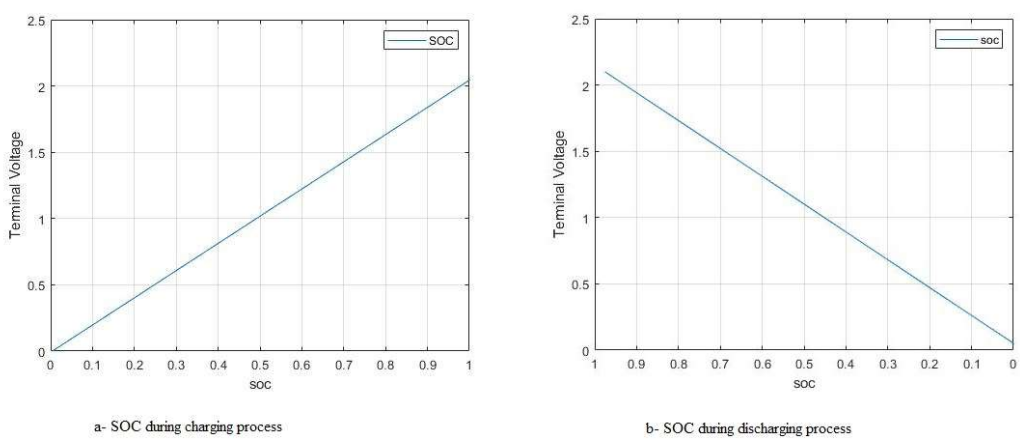
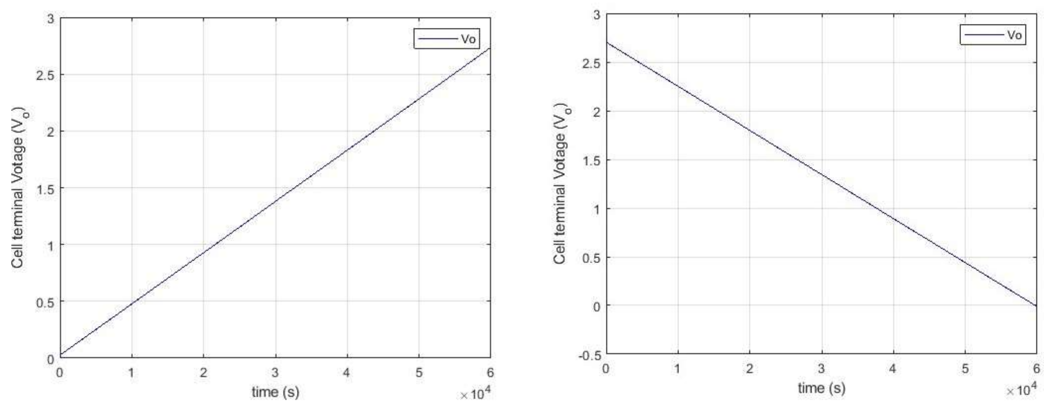



**Figure 4.7.** *SOC vs Estimated Terminal Voltage*

Changing the input current to (I= 4 A), The charging characteristic is illustrated in Figure 4.8. a, whereby the initial terminal voltage $Vo$ starts from 0 V up to approximately 2.7 V (2.73 V to be exact) within 60000sec. (Which is 100 minutes).

For discharging process, the initial value of terminal voltage, $y_o = Vo$ is set to 2.7 V, the dynamic behaviour showing the discharge characteristic is shown in Figure 4.8. b. From this figure, it is observed that the discharge process is similar to charging; but now with linearly decreasing $V0$ slope. The terminal voltage $Vo$ drops from 2.7V to 0.01 V in 60000 seconds (100 minutes); this is similar to the charging process as it literally takes 100 minutes to reach $Vo$ = 2.7 V from zero potential.




a- Dynamic Behavior of KF with charging constant current =4 b- Dynamic Behavior of KF with discharging constant current =4

**Figure 4.8.** *Dynamic Behavior of KF with constant current =4 A*

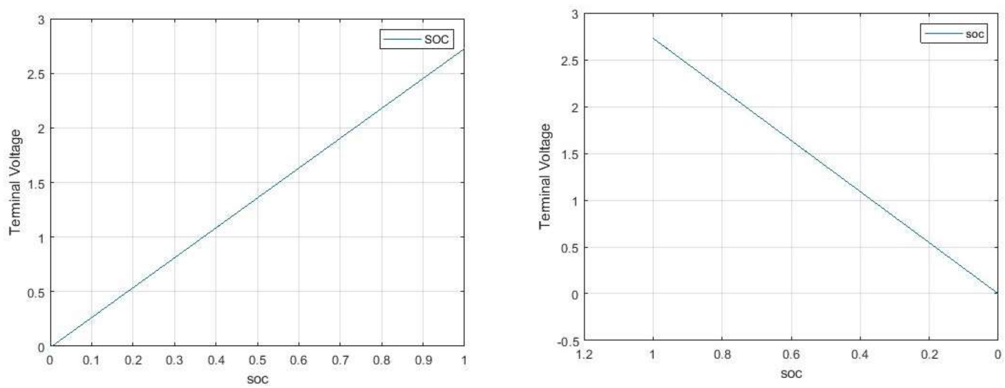
For the Root-Mean Squared (RMS) of the estimated error which is calculated as well, as shown in Table 5., the results shows that the KF error is far smaller compared to the measured error, with values of 1.0014 for meausrement error and 1.9186×10−4 for estimation error during charging and discharging processes.

| RMS error | Charging Process | Discharging Process |
|---|---|---|
| Measurement, $y - y_v$<br>$y$ is the terminal voltage of the system<br>$y_v$ is the noisy terminal voltage of the system | 1.0014 | 1.0014 |
| Estimated (KF), $y - y_e$<br>$y$ is the terminal voltage of the system<br>$y_e$ is the filtered terminal voltage | $1.9186x10^{-4}$ | $1.9186x10^{-4}$ |

***Table 5.*** *Recorded RMS Error when input current =4 A*

The open circuit voltage is calculated based on estimated terminal voltage $y_e$ for the purpose of estimating the SOC.

Figure 4.9.a shows the estimated SOC during charging process and figure 4.9.b shows the estimate SOC during discharging process with reference to filter terminal voltage.




a - SOC vs Terminal Voltage during charging process

b- SOC vs Terminal Voltage during discharging process

**Figure 4.9.** *SOC vs Estimated Terminal Voltage*

As a result, changing the current magnitude (increasing the input value), an increment is terminal voltage is noted, thus a proportionally relationship with respect to the terminal voltage and the input current is noted as well.

In addition, according to tables (3,4,5) the measurement error and the estimation error are the same regardless the input current value, which means this method has small error and thus it is accurate.

### 4.3. Voltage-Based SOC Estimation method

The first step in developing a high-fidelity battery model for a battery management system is to create one. To enable a BMS to estimate battery critical parameters such as SOC the BMS must incorporate an accurate battery model and a robust estimation strategy. Thus, a battery model is a collection of mathematical equations describing what occurs physically inside the battery in terms of layman (simple language that anyone can understand) as illustrated in the Figure 4.10, by applying the same current profile to the battery and the battery model, both should generate the same voltage profile, with an error near zero between the two signals. The model can predict the battery's behavior in such a way that, when an estimator is used, critical parameters such as the battery's SOC can be predicted.

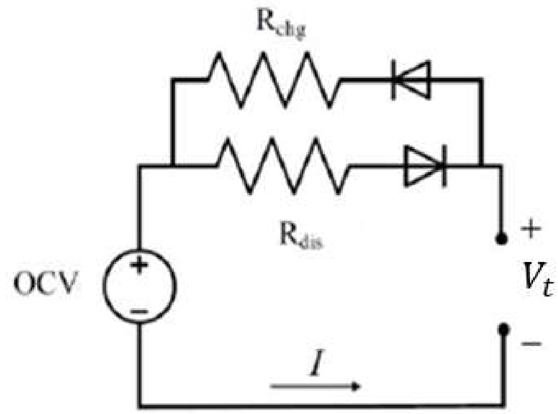



**Figure 4.10.** *Equivalent Circuit Model*

### 4.3.1. Methodology

Using the implementation of characteristics controlling equations and lookup tables to estimate the SOC of a battery, based on experimental data [36] saved in an excel sheet (Appendix B), look up tables including those data such as charging resistance, discharging resistance, and battery voltage are used in MATLAB Simulink and mscript, a 4V battery was charged and discharged at different current value (1.53 A, 3 A, and 4 A). The terminal voltage is determined by using a MATLAB Simulink model and mscipt (Appendix C part 1,2) to determine the state of charge. Figure 4.10 is a battery model that consist of open circuit voltage source, internal resistance (R-charge & R-discharge) and terminal voltage, in order to estimate the battery state of charge a voltage-based method is applied to measure the battery's terminal voltage, futhermore the battery's SOC deduced through the relationship between SOC and the terminal voltage [37].

The relationship between state of charge and terminal voltage can be described as below

$$V_t = OCV(SOC) - I.R_{dis} \qquad (4.3.1)$$

for discharging cycle , and

$$V_t = OCV(SOC) + I.R_{dis} \qquad (4.3.2)$$

for charging cycle

Where $V_t$ is actual terminal voltage

The change in SOC can be calculated by determining how much current is flowing into or out of the battery, mathematically we can describe the battery state of charge as an equation like:

$$SOC = SOC_0 \pm \frac{1}{C}\int_0^t I(t)dt \qquad (4.3.3)$$

Where $SOC_0$ is the initial state of charge, $C$ is the battery capacity in Amper hours and $I$ is charging/discharging current
Applying MATLAB Simulink software, 1-Dimentional lookup tables are used to obtain the terminal voltage as shown in Figure 4.11.

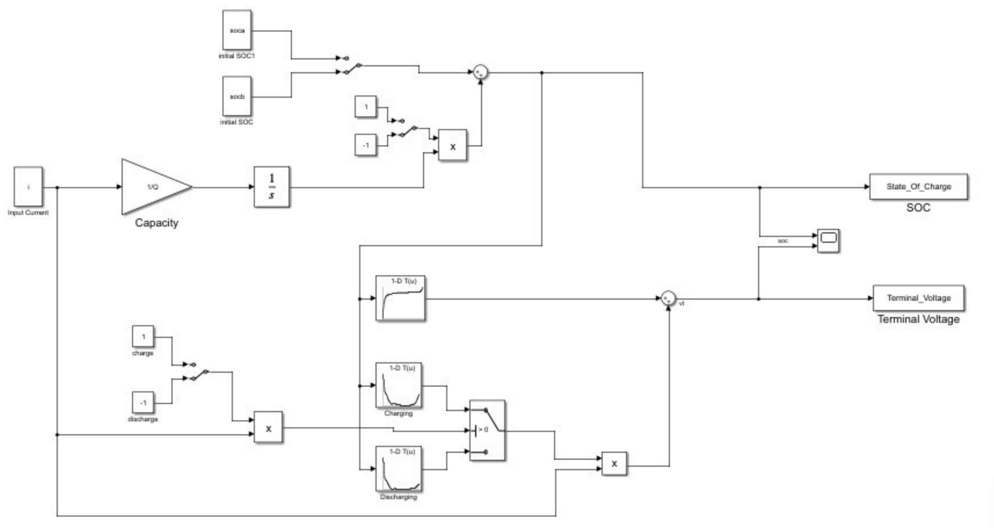



**Figure 4.11.** *Simulink Model of Voltage-Based Method*

In this model lookup tables are used to represent equations (4.3.1, 4.3.2, 4.3.3) and those tables are

- Open circuit voltage according to SOC.
- Charging resistance according to SOC.
- Discharging resistance according to SOC.

### 4.3.2. Results

After simulating the battery model via MATLAB Simulink (Figure 4.11) and MATLAB Script, The input current assumed to be constant (1.53A), and the initial state of charge assumed to be zero, hence running the Simulink model the result in figure (4.12) shows an increasing in the terminal voltage while there is increment in the state of charge during charging cycle and oppositely during discharging cycle.

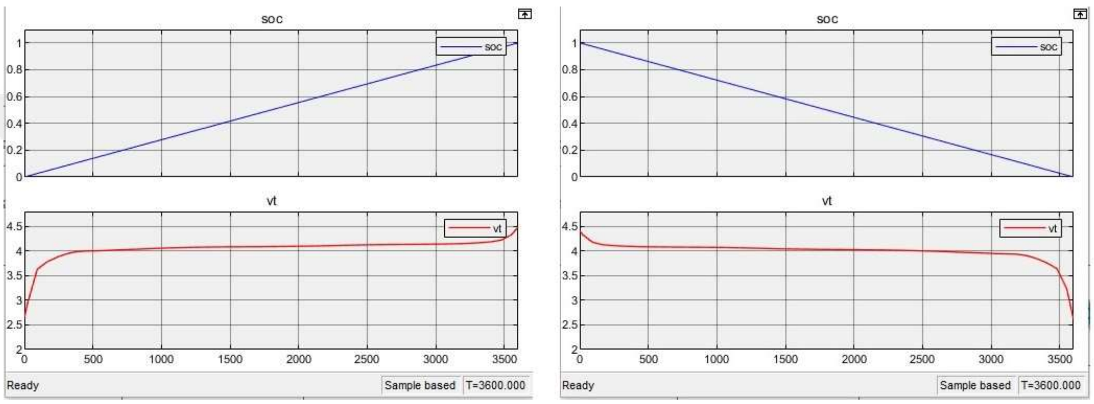



**Figure 4.12.** *Simulink scope results for SOC & Vt (left charging cycle, right discharging cycle) I=1.53 A*

From the results obtained from the scope block in the Simulink model an excel file is obtained in order to draw a relationship between the battery state of charge and its terminal voltage, because the experimental data [36] assumed that the battery parameters is a function of state of charge, hence, a MATLAB script created to draw the relationship between the state of charge (SOC) and the terminal voltage (VT) as shown in Figure 4.13 for charging and discharging cycles,

The battery start charging from zero to 100% state of charge, or in other hand the terminal voltage starts from 2.6 V and reached 4.48 V within time of one hour,

Then started fully charged or 100% state of charge as shown in figure 4 (right) for discharge cycle the terminal voltage start form 4.4 V and falling down until it reached 2.6 V as zero state of charge for a time of one hour as well.

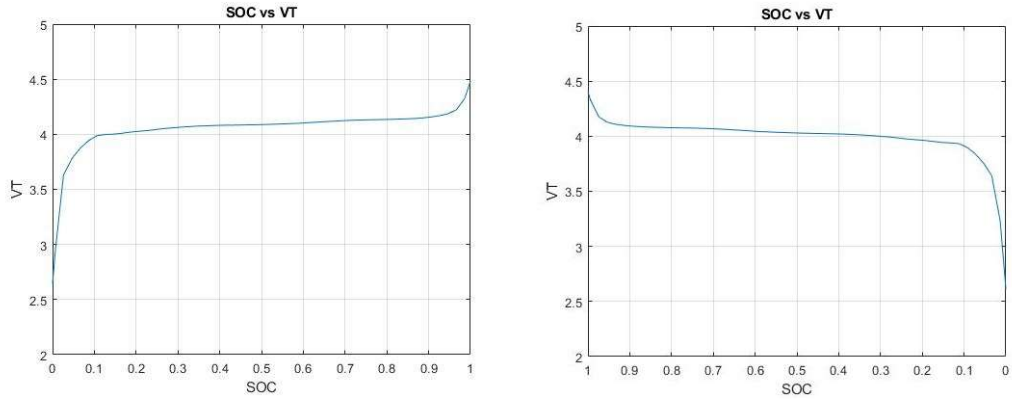



**Figure 4.13.** *SOC vs VT (left during charging cycle, right during discharging cycle) I =1.53 A*

Changing the input value (I=3 A), the Simulink result represented in Figure 4.14 for charging and discharging cycles, the terminal voltage started from 2.88 V when the state of charge is zero % and reached 4.64V at 100% state of charge during charging cycle, and for discharging cycles as the state of charge assumed to be 100 %, the terminal voltage was 4.5 V then decreased to 2.8 V when the state of charge became zero.

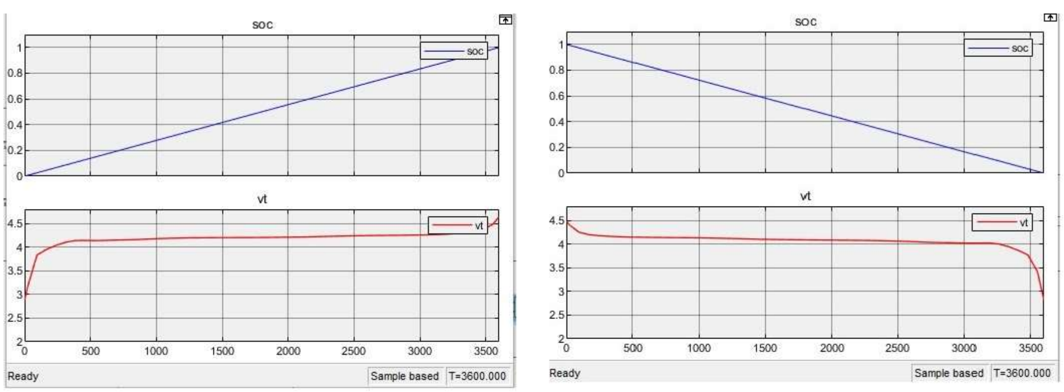



**Figure 4.14.** *Simulink scope results for SOC & Vt (left for charging cycle, right for discharging cycle) I=3 A*

Figure 4.15 shows the relationship between the SOC and the terminal voltage obtained as a result of (Appendix C) when the current assumed to be 3 A.

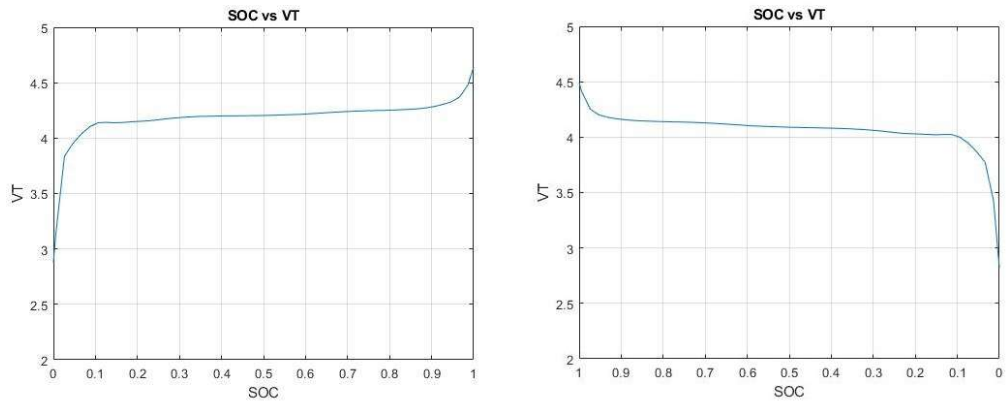



**Figure 4.15.** *SOC vs VT (left during charging cycle, right during discharging cycle) I=3 A*

Then, changing the input value (I=4 A), the Simulink result represented in Figure 4.16 for charging and discharging cycles, the terminal voltage started from 3.04 V when the state of charge is zero % and reached 4.74V at 100% SOC during charging cycle, and for discharging cycles as the state of charge assumed to be 100 %, the terminal voltage was 4.54 V then decreased to 2.9 V when the state of charge became zero.

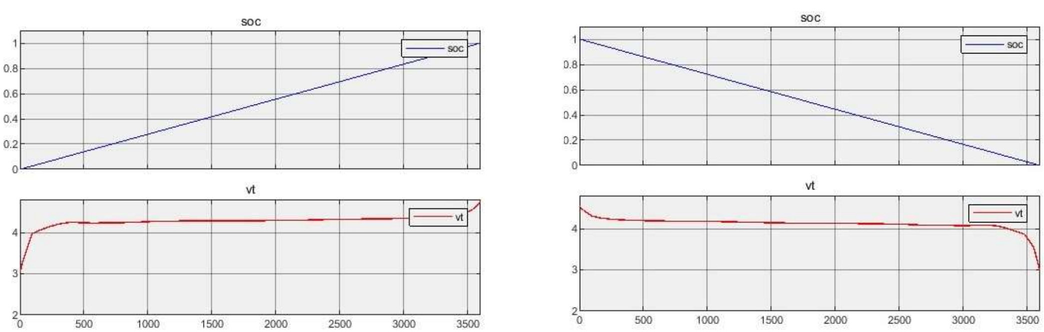



**Figure 4.16.** *Simulink scope results for SOC & Vt (left for charging cycle, right for discharging cycle) I=4 A*

Figure 4.17 shows the relationship between the SOC and the terminal voltage obtained as a result of (Appendix C) when the current assumed to be 3 A.

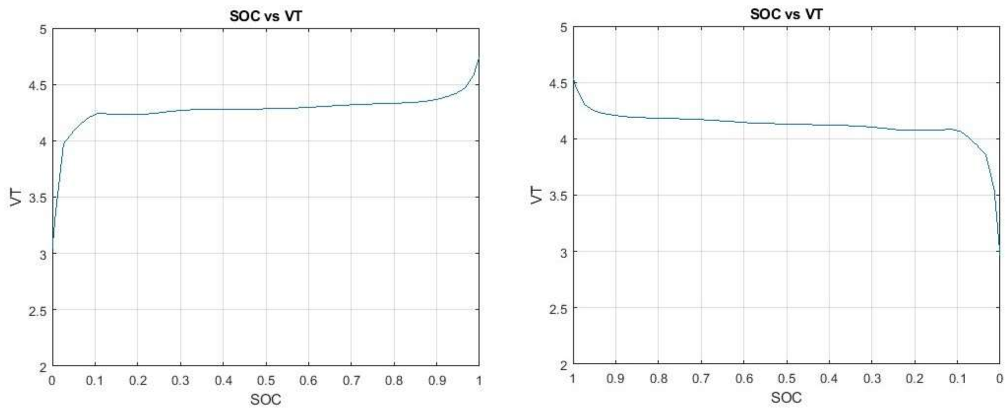



**Figure 4.17.** *SOC vs VT (left during charging cycle, right during discharging cycle) I=4 A*

From the results above, the effect of the input current is noted, for example when the input current is higher (=3) the terminal voltage reached 4.64 V when the state of charge is 100%, rather than 4.48 V when the state of charge is 100% at current value of (1.53 A) and that's due to ohms law ($V = I * R$) which means the terminal voltage is increasing when the current is increasing during charging cycle and vice versa during discharging cycle even though the value of charging and discharging resistance is slightly changing in its value.

### 4.4. Coulomb Counting Method for SOC estimation

Coulomb counting (CC) is a technique for estimating the SOC that utilizes the battery charge and discharge current and then integrates it over an interval of time. While knowing or assuming the previous estimated state of charge via a mathematical equation is preferable, the equation's parameters such as current, battery capacity, time, and initial state of charge must be known beforehand:

$$SoC_t = SoC_0 \pm \frac{1}{C}\int_0^t I(t)dt \quad (4.4.1)$$

There are several factors that affect the accuracy of Coulomb Counting method including temperature, battery history, discharge current, and cycle life.

#### 4.4.1. Methodology

Hence, by NASA (National Aeronautics and Space Administration )website https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository/,/,[38], which contains datasets for battery measurements in the form of Matlab m-files, based on experiments on Li-Ion batteries. Charging and discharging at different temperatures.

Records the impedance as the damage criterion. The data set was provided by the Prognostics CoE at NASA Ames, these experiments were conducted bu using a Li-Ion battery with 4.2V at fully charged (100% of SOC ),and 3.7V fully discharged (0% of SOC), the battery has a capcaity if 1.34 AH, in addition to 4.8 V as charging voltage and 2 Amp charging and discharging current , the results were saved as MATLAB files, in our research we have used a file named B0056 (downloaded from previously mentioned website ) in order to apply Coulomb Counting method and calculate the final state of charge SOC in both cases (charging and discharging). By using current integration formulas (3.41,3.42), This file contains the necessary information (252 cycles) to apply those formulas in Matlab in the purpose of calculating the SOC.

By creating a matlab script (code) shown in Appendix D ,to extract all data from (B0056 m.file) and applies the coulomb counting method formulas, that code calculates the battery state of charge in both cases (charging & discharging).

$$SOC_{new} = SOC_{initial} - \frac{1}{C}\int_{t1}^{t2} I_{discharge}\, dt \quad (4.4.2)$$

for discharging case, and for charging case

$$SOC_{new} = SOC_{initial} + \frac{1}{C}\int_{t1}^{t2} I_{discharge}\, dt \quad (4.4.3)$$

The flow chart shown in figure (4.18) is illustrating the procedure (Algorithm) of battery state of charge estimation based on Coulomb Counting method.

This algorithm has two parts: charging part and discharging part, in order to apply equation (4.4.2) and (4.4.3) the initial state of charge ($SOC_{initial}$) is assumed to be zero for charging case and 100 for discharging case.

This method shows that the battery voltage measured (terminal voltage) during charging cycles  is increasing while the state of charge is increasing with slight variety due to the chaging in temperature which casued by the impedance of the battery’s internal resistance , but in opposite style during discharging cycles.

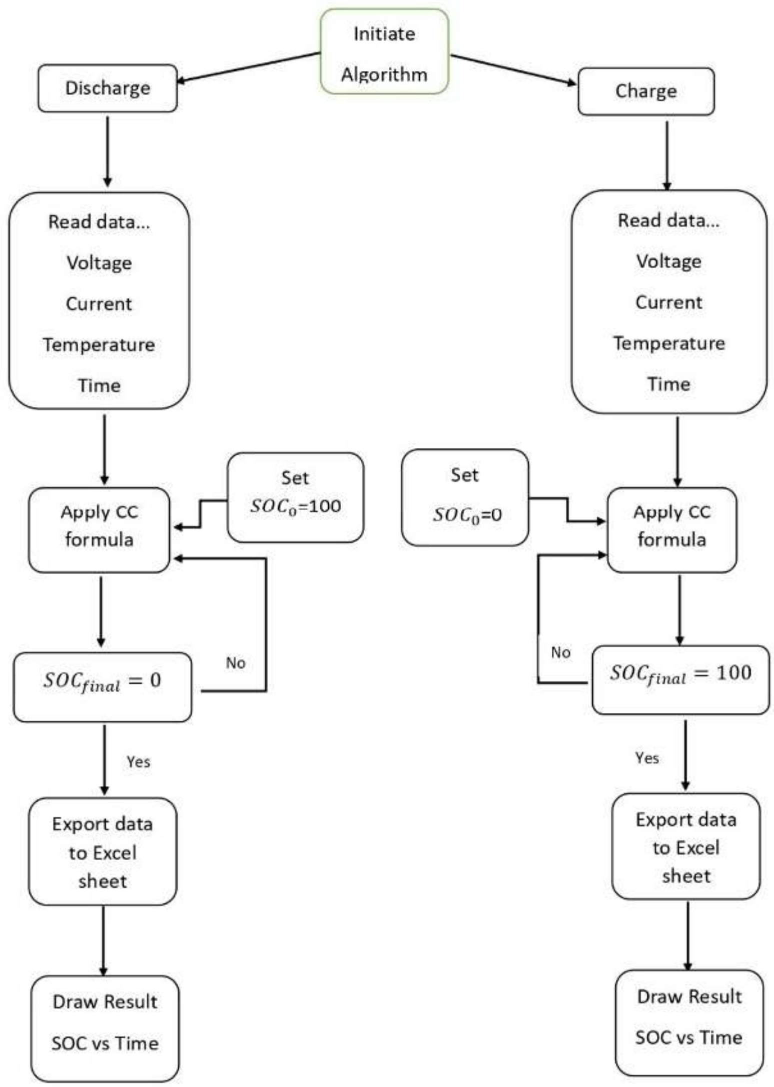



**Figure 4.18.** *Flow Chart of Coulomb Counting method*

### 4.4.2. Results

The experiment's results are saved in Excel sheets named "charge" for charging cycles and "discharge" for discharging cycles, but due to the large size of excel sheet for both cases (about 236623 rows and 7 coluomns), a portion of each part is attached as a figure, as shown in Figures 4.19 , 4.20 respectively.

Regrarding discharging cycle, the data (previously saved in the excel sheet) to apply the CC formula some values are considered such as the load current that started from

1.99 A then drops down to 0.004 A for more than 39 minutes as a consuming time for this application process, as well as the SOC that started from 99.99% the drops down as well to 0 %, rather the voltage meaured (battery voltage) droped from 3.83 V to 2.7 V, furthermore, the results of this part are shown in Figure 4.21 with red lines,

Regarding the charging process, to apply the CC formula the charging current values are considered in addition to the charging time as represented as (time) in the previously save excel sheet, it is noticed that the charging current started from 1.57 A until it becomes 0.0351 A, which means the SOC started from zero percent and reached 90 % for more than 100 minutes, the voltage increment is noticed here as well, in other meaning the voltage begin from 3.8 V and went up till it reached almost 4.2 V, the results of this part are shown in Figure 4.21 with green lines.

| Voltage_Measured | Current_Measured | Temp_Measured | Current_Charge | Voltage_Charge | Time | SoC |
|---|---|---|---|---|---|---|
| 3.682071878 | -0.00111899 | 5.936650831 | 0.0001 | -0.01 | 0 | 0 |
| 3.999290211 | 1.496382967 | 5.943098231 | 1.5017 | 4.803 | 0.000703056 | 0.07855495 |
| 4.006730329 | 1.494709036 | 5.940606634 | 1.5017 | 4.816 | 0.001384722 | 0.154720042 |
| 4.012288597 | 1.49676947 | 5.942540267 | 1.5017 | 4.816 | 0.002074722 | 0.231816247 |
| 4.017307666 | 1.495099381 | 5.969375853 | 1.5017 | 4.829 | 0.002773611 | 0.30990564 |
| 4.021789347 | 1.496724834 | 5.973679199 | 1.5017 | 4.829 | 0.003472222 | 0.387963996 |
| 4.026023221 | 1.497971538 | 5.967535704 | 1.5023 | 4.829 | 0.004179722 | 0.467047125 |
| 4.029701155 | 1.497270698 | 5.975842833 | 1.5017 | 4.841 | 0.004865556 | 0.543677774 |
| 4.0330335 | 1.499121835 | 6.002946144 | 1.5023 | 4.841 | 0.005555556 | 0.620804783 |
| 4.036236317 | 1.494779938 | 6.023371515 | 1.5017 | 4.841 | 0.006245833 | 0.697932025 |
| 4.038959638 | 1.498078912 | 6.020102136 | 1.5017 | 4.841 | 0.006931389 | 0.774531636 |
| 4.041918476 | 1.49725009 | 6.019978616 | 1.5017 | 4.854 | 0.007621667 | 0.851658879 |
| 4.044661332 | 1.497086181 | 6.020586402 | 1.5017 | 4.854 | 0.008324722 | 0.930213829 |
| 4.047289046 | 1.497212913 | 6.013211284 | 1.5023 | 4.854 | 0.009023611 | 1.008334423 |
| 4.049936281 | 1.496588946 | 6.050733362 | 1.5023 | 4.854 | 0.009722222 | 1.086423967 |
| 4.052126645 | 1.497033639 | 6.059123146 | 1.5023 | 4.854 | 0.010421111 | 1.16454456 |
| 4.054372677 | 1.497647962 | 6.067007041 | 1.5017 | 4.854 | 0.0111025 | 1.240678615 |
| 4.056601105 | 1.495833114 | 6.062110919 | 1.5017 | 4.854 | 0.0117925 | 1.31777482 |
| 4.05883161 | 1.496565715 | 6.060114346 | 1.5017 | 4.867 | 0.012473889 | 1.393908875 |
| 4.06085635 | 1.497933756 | 6.064512433 | 1.5017 | 4.867 | 0.013159722 | 1.470539523 |

**Figure 4.19.** *Output of MATLAB code for Coulomb Counting method (Charging Cycle)*

| Voltage_Measured | Current_Measured | Temp_Measured | Current_Charge | Voltage_Charge | Time | SoC |
|---|---|---|---|---|---|---|
| 3.838722882 | -0.001188893 | 6.293379384 | 0.0004 | 0 | 0 | 0 |
| 3.838476061 | 0.000194843 | 6.307098522 | 0.0004 | 3.853 | 0.002621667 | 99.99986646 |
| 3.309742937 | -1.993708007 | 6.355488553 | 1.9982 | 2.183 | 0.005438333 | 99.28314417 |
| 3.28005591 | -1.993403818 | 6.439267769 | 1.9982 | 2.175 | 0.008038333 | 98.62155436 |
| 3.255597624 | -1.994241113 | 6.561227091 | 1.9982 | 2.156 | 0.010633611 | 97.96116616 |
| 3.233244905 | -1.992083904 | 6.689295118 | 1.9982 | 2.137 | 0.013237778 | 97.29851611 |
| 3.211776383 | -1.992629363 | 6.832782315 | 1.9982 | 2.117 | 0.015829167 | 96.63911747 |
| 3.19007284 | -1.995292422 | 6.962671417 | 1.9982 | 2.098 | 0.0184375 | 95.97540718 |
| 3.167949228 | -1.994512644 | 7.110802225 | 1.9982 | 2.078 | 0.021041667 | 95.31275714 |
| 3.144744097 | -1.99312895 | 7.242766446 | 1.9984 | 2.057 | 0.023632778 | 94.65336318 |
| 3.119997413 | -1.993871581 | 7.400486367 | 1.9982 | 2.029 | 0.026232778 | 93.99177338 |
| 3.094059045 | -1.99347643 | 7.551662249 | 1.9982 | 2.003 | 0.028836944 | 93.32912333 |
| 3.066795265 | -1.992148594 | 7.696788867 | 1.9984 | 1.977 | 0.031449722 | 92.66421558 |
| 3.04058662 | -1.99497205 | 7.85654841 | 1.9982 | 1.951 | 0.034053889 | 92.00156553 |
| 3.017186921 | -1.993049809 | 8.029610638 | 1.9982 | 1.928 | 0.036640556 | 91.34336849 |
| 2.99912309 | -1.993526038 | 8.178486128 | 1.9982 | 1.908 | 0.039244722 | 90.68071845 |
| 2.987980358 | -1.992983313 | 8.359489452 | 1.9982 | 1.896 | 0.041840278 | 90.02025956 |
| 2.982525532 | -1.992946184 | 8.529605555 | 1.9982 | 1.891 | 0.044427222 | 89.36199184 |
| 2.981444082 | -1.994586757 | 8.681710263 | 1.9982 | 1.89 | 0.0470225 | 88.70160364 |
| 2.983310555 | -1.993972591 | 8.854429925 | 1.9984 | 1.892 | 0.049618056 | 88.04107865 |

**Figure 4.20.** *Output of MATLAB code for Coulomb Counting method (Discharging cycle)*

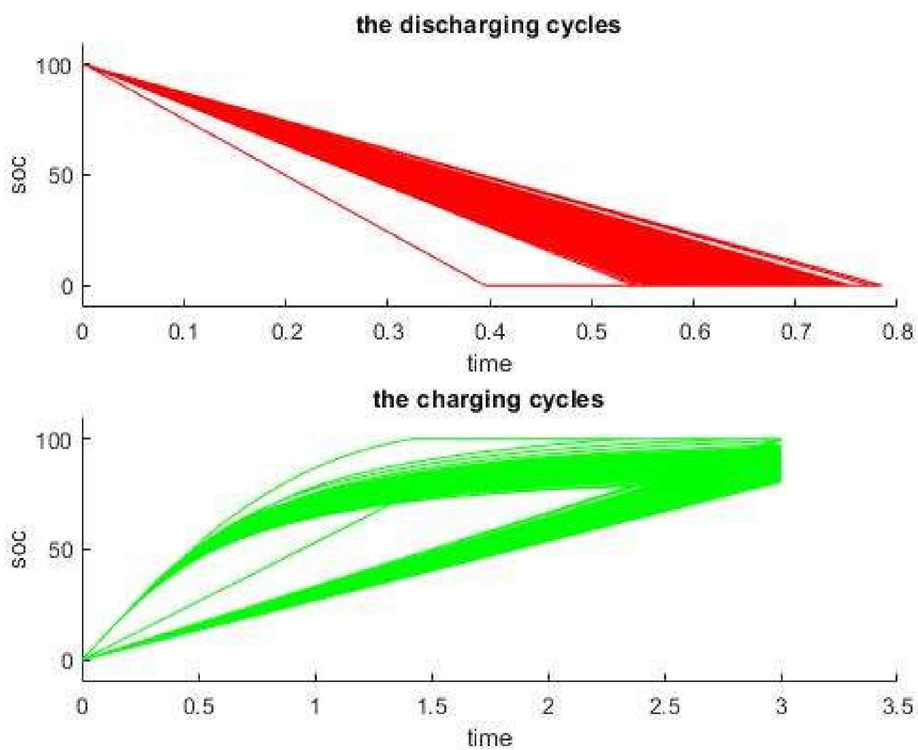



**Figure 4.21.** *SOC vs t (time) for charging and discharging cycles*

Figure 4.21 demonstrate the the results of (Appendix D) as the results of the MATALB code that generated to be used in this thesis, this figure shows the obtained final SOC with repect to the time, the diversity of the lines whether in red lines (discharging cycles) or green lines (charging cycles) are due to the changing of the charging current and discharging current vaules that saved in the excel sheet as mentioned above.

Due to BMS prinicples, the SOC did not go over 100%, or the battery being over charged (in other meaning) during charging process cycle, neither droped lower than 0 % during discharging process cycle.

### 4.5. Discussion of the Results

#### 4.5.1. Kalman Filter

- The input of the system which is the current is constant.
- Increasing the input value an increment in terminal voltage is noted.
- Proportionally relationship w.r.t the terminal voltage and the input current is noted as well.
- The time is decreasing oppositely for the cell to reach either 100% state of charge or 0 % for both input values, for example if the input current assumed to be 1.53 A, it took 100 minutes to reach 100% state of charge, in other meaning it took 100 minutes for the terminal voltage to reach 1.2 V, rather it took approximately 58 minutes to reach the same amount of terminal voltage 1.2 V when the current is assumed to be 3 A during charging process.
- This method has small error during SOC estimation process due to the state space modeling of the circuit.

#### 4.5.2. Voltage-Based method

- The input of the system which is the current is constant
- The effect of the input current is noted, in other meaning when the input current is higher (=3) the terminal voltage reached 4.64 V when the state of charge is 100%, rather than 4.48 V when the state of charge is 100% at current value of (1.53 A).
- Due to ohms law $(V = I * R)$ , the terminal voltage is increasing when the current is increasing during charging cycle and vice versa during discharging cycle even though the value of charging and discharging resistance is slightly changing in its value.
- The circuit parameters such as charging /discharging resistance, and open circuit voltage values obtained by experiment on a battery by measurement, thus this method has an error.

#### 4.5.3. Coulomb Counting method

- The input current value is variable in every cycle during charging and discharging processes.
- The error of this method depends on the pre-data set and the application of MATLAB software.
- There are several factors that affect the accuracy of this method including temperature, battery history, discharge current, and cycle life.

Table 6., shows the advantage and disadvantage of each method used in this thesis.

### 4.6. Comparison

| Method | Advantages | Disadvantages |
|---|---|---|
| *Kalman Filter* | - The circuit parameters have fixed values therefore this method is an accurate method.<br>- This method is online, dynamic, and Accurate if not affected by noise.<br>- This method can be used when the load is connected to the circuit if the input current is constant.<br>- The estimation accuracy is high in the case of considering the error.<br>- does not depend on the initial SOC value<br>- Good estimation accuracy under constant current conditions. | - The system model equations are linear, which is not realistic in many real-life situations.<br>- Initial and/or final value of the terminal value must be known before estimating the final SOC.<br>- This method can't be used directly because it requires high complex math equations.<br>- The estimation accuracy depends on the accuracy of the model.<br>- This method is limited to linear systems<br>- It is not suitable for practical applications. |
| *Voltage Based* | - SOC can be obtained directly from the terminal voltage as there is linear proportional to SOC.<br>- The circuit model is simply and applicable on every battery type. | - This method can be used when there is no load is connected to the circuit.<br>- Accuracy of this method depends on the accuracy of parameters measurement. |
| *Coulomb Counting* | - This method in used on Li-Ion batteries only, but it can be used in all type of batteries<br>- This method can be used when load is connected.<br>- Application of this method is easy, simple and reliable.<br>- fast estimation speed, low requirements for controller hardware and storage. | - Initial SOC is mandatory to estimate current SOC<br>- Time interval and charging/discharging current have to be known in order to apply this method.<br>- Inaccurate current measurements accumulate to large errors, whereas accurate current measurement is expensive.<br>- İt is heavily dependent on the accuracy of the initial SOC value. |

***Table 6.*** *Comparsion between the methods used in this thesis*

# 5. CONCLUSION

The state of charge is an important characteristic for any battery management system it is a fundamental issue for battery utilization because it is not only describes the battery's remaining capacity, but it also protects it, prevents overcharging or overdischarging, and extends its life. As a result, it is a critical parameter for a control strategy, it also allows the application to implement logical control techniques in order to fulfill the goal of energy conservation.

In this thesis, a model that can precisely represent the behavior of a battery under various situations is used to estimate the SOC. Some of these SOC estimation methods are used in this thesis, including the Coulomb Counting Method, which is considered the most frequent method, as well as the Voltage-Based Method, in addition to Kalman Filter method.

By comparing the various methods, all methods rely on the battery's parameters and specifications; consequently, the SOC estimation technique is dependent on the battery's model, whether it is mathematical equations or state space.

Certain initial conditions must be known prior to applying any method, including the initial state of charge like in the Coulomb Counting method, as it is completely dependent on it, as well as the battery's voltage, referred to as terminal voltage, and internal resistance, in order to calculate the final state of charge, as is the case with the voltage-based method.

With regards to the Kalman Filter method, the battery parameters must be known in advance in order to create a dynamic system, as the output of the system is dependent on the system's previous and/or future inputs at any point in time.

a relationship between the battery's state of charge and its open circuit voltage is observed, but the nature of this relationship varies depending on the method used;

As a result, a comparsion between the methods used in this thesis is made.

### 5.1. Future work

To order to identify the best SOC estimation method, an extensive investigation on existing SOC estimation methods must be carried out, by focusing on their benefits and limitations.

Matter of fact, researchers have proposed a plethora of SOC estimation methods, many of which require a trade-off between computational complexity and implementation cost, therefore, in the future , more attention must performed to develop a non-complex SOC estimation algorithm which is possible to implement on BMS.

It is recommended that the choice of electric battery model should be made supported the specified accuracy and therefore the available computation power.

It is important to notice that the temperature dependence of model parameters weren't considered during this work, Future studies can include energy balance equations within the models to include temperature information and its effects on the system.

A very significant recommendation for future work includes the study of battery aging and its effects on the battery cell.

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# APPENDIX A. MATLAB CODE FOR SOC ESTIMATION VIA KALMAN FILTER

```
format long;
%Value for resistors and capacitors
Csurface=82.11;
Cbk=88372.83;
Re=0.00375;
Rs=0.00375;
Rt=0.002745;
K=1/(Cbk*(Re+Rs));
L=1/(Csurface*(Re+Rs));
N=(Re*Rs)/(Re+Rs);
%State variable matrices
A=[-K K 0 ; L -L 0 ; (-K+L) 0 (K-L) ];
B=[K*Re; L*Re;
K* (0.5*Rs-Rt-N)+ L*(0.5*Re+Rt+N)]
C=[0 0 1 ];
D=[0]
% For Kalman filter:
A=[1-K K 0 ; L 1-L 0 ; (-K+L) 0 1+(K-L) ]
B=[K*Re; L*Re;
K* (0.5*Rs-Rt-N)+ L*(0.5*Re+Rt+N)]
C=[0 0 1 ]
Tc=1;
A=A*Tc;
B=B*Tc;
C=C;
% Sample time=-1 for discrete model
Plant = ss(A,[B B],C,0,-1,...
'inputname',{'u' 'w'},...
'outputname','y');
Q = 1; R = 1;
[kalmf,L,P,M] = kalman(Plant,Q,R);
kalmf = kalmf(1,:);
kalmf
K = A;
L = [B B 0*B];
c = [C;C];
N = [0 0 0;0 0 1];
P = ss(K,L,c,N,-1,...
'inputname',{'u' 'w' 'v'},...
'outputname',{'y' 'yv'});
% Parallel connection of outputs ye and y
sys = parallel(P,kalmf,1,1,[],[]);
% Close loop around input #4 and output #2
SimModel = feedback(sys,1,4,2,1);
% Delete yv from I/O list
SimModel = SimModel([1 3],[1 2 3]);
SimModel.inputname
jj =  [0:60000];
t=jj.';
u = ones(60001,1);
u(:) =input ('I'); % Current for charge/discharge
n = length(t);
randn('like',0)
w = sqrt(Q)*randn(n,1);
v = sqrt(R)*randn(n,1);
```

```
[out,x] = lsim(SimModel,[w,v,u]);
y0=input('y0'); %This is initial terminal voltage
y = out(:,1)+y0; % true response,
ye = out(:,2)+y0; % filtered response
yv = y + v; % measured response
figure(1); %Figure 1
plot(t,ye,'b-'), grid on;
xlabel('time (s)'),
ylabel('Cell terminal Votage (Vo)')
legend('Vo')
%Kalman filter response
figure(2); %Figure 2
plot(t,y-ye,'b-'), grid on;
xlabel('time (s)'), ylabel('Error')
legend ('Estimated Err')
%Calculate Errors
MeasErr = y-yv; %Measurement error
MeasErrCov= ...
sum(MeasErr.*MeasErr)/length(MeasErr);
EstErr = y-ye; %Estimated error
EstErrCov = ...
sum(EstErr.*EstErr)/length(EstErr);
%Display onto screen
MeasErrCov; %Measurement error
EstErrCov; %Estimated error
% calculating open circuit voltage OCV %
vt=ye; % terminal voltage estimated by KF%
% calculating state of charge SOC  from OCV %
ocv=ye+u(:)*Rt; % OCV=terminal voltage-I*R drop% %I=1.53,3,4 current%


%During Charging process %
 for j=1:length(ocv)
    if (j==ye(end))
        soc=1;
    else
  ocv=ye+u(:)*Rt;   % u(:)=1.53
  a0=y0;
  a1=ye(end);
  soc=(ocv-a0)/a1;
  soc(soc>1)=1;
    end
  end
  figure (3)
  plot (soc,ye)
  xlabel('SOC')
  ylabel('Terminal Voltage')
  legend ('SOC')
  grid on

    % For Discharging process  %
   a1=ye(end); % terminal voltage at soc=0 %
 a0=y0;     % terminal voltage at soc=1%
for j=1:length(ocv)
     if (j==ye(end))
      soc=0
   else
soc=(ocv-a1)/a0;
```

```
 soc(soc<0)=0;
     end
 end
figure(4)
plot(soc,ye)
set(gca, 'XDir','reverse')
xlabel('SOC')
ylabel('Terminal Voltage')
legend('SOC')
grid on
```

**APPENDIX B. EXCEL SHEET FOR BATTERY PARAMETERS USED IN VOLTAGE-BASED METHOD FOR SOC ESTIMATION [36].**

| State of Charge (%) | Open Circuit Voltage (V) | Charge Resistance (Ohms) | Discharge Resistance (Ohms) |
|---|---|---|---|
| 0 | 2.4 | 0.16 | 0.14 |
| 0.01 | 2.86404 | 0.1512 | 0.129 |
| 0.02 | 3.33456 | 0.1424 | 0.12383 |
| 0.03 | 3.47124 | 0.13569 | 0.09468 |
| 0.04 | 3.5586 | 0.12084 | 0.08038 |
| 0.05 | 3.62364 | 0.11534 | 0.07532 |
| 0.06 | 3.6762 | 0.11237 | 0.07257 |
| 0.07 | 3.72036 | 0.11039 | 0.07059 |
| 0.08 | 3.7584 | 0.10885 | 0.06894 |
| 0.09 | 3.7902 | 0.10742 | 0.06707 |
| 0.1 | 3.81708 | 0.10522 | 0.06498 |
| 0.11 | 3.83568 | 0.10236 | 0.06256 |
| 0.12 | 3.84504 | 0.09939 | 0.06025 |
| 0.13 | 3.8508 | 0.09675 | 0.05772 |
| 0.14 | 3.85596 | 0.09444 | 0.05552 |
| 0.15 | 3.861 | 0.09235 | 0.05343 |
| 0.16 | 3.867 | 0.09059 | 0.05145 |
| 0.17 | 3.87528 | 0.08905 | 0.04947 |
| 0.18 | 3.88308 | 0.08773 | 0.04793 |
| 0.19 | 3.88956 | 0.08641 | 0.04639 |
| 0.2 | 3.89496 | 0.0852 | 0.04485 |
| 0.21 | 3.89976 | 0.0841 | 0.04364 |
| 0.22 | 3.9048 | 0.08333 | 0.04254 |
| 0.23 | 3.90828 | 0.08278 | 0.04188 |
| 0.24 | 3.9132 | 0.08267 | 0.04155 |
| 0.25 | 3.91788 | 0.08268 | 0.04144 |
| 0.26 | 3.92184 | 0.08278 | 0.04133 |

| | | | |
|---|---|---|---|
| 0.27 | 3.92652 | 0.083 | 0.04155 |
| 0.28 | 3.92964 | 0.08311 | 0.04166 |
| 0.29 | 3.93192 | 0.08333 | 0.04188 |
| 0.3 | 3.93552 | 0.08334 | 0.04199 |
| 0.31 | 3.93828 | 0.08335 | 0.0421 |
| 0.32 | 3.94092 | 0.08336 | 0.0421 |
| 0.33 | 3.94296 | 0.08311 | 0.04221 |
| 0.34 | 3.94644 | 0.08289 | 0.0421 |
| 0.35 | 3.9486 | 0.08256 | 0.04199 |
| 0.36 | 3.9498 | 0.08212 | 0.04166 |
| 0.37 | 3.95256 | 0.08179 | 0.04166 |
| 0.38 | 3.95436 | 0.08146 | 0.04144 |
| 0.39 | 3.95616 | 0.08091 | 0.04122 |
| 0.4 | 3.95796 | 0.0808 | 0.04111 |
| 0.41 | 3.95904 | 0.08058 | 0.04111 |
| 0.42 | 3.9588 | 0.08025 | 0.04111 |
| 0.43 | 3.96048 | 0.08014 | 0.041 |
| 0.44 | 3.96144 | 0.07992 | 0.041 |
| 0.45 | 3.9624 | 0.07981 | 0.041 |
| 0.46 | 3.96324 | 0.0797 | 0.041 |
| 0.47 | 3.96372 | 0.07959 | 0.041 |
| 0.48 | 3.9648 | 0.07937 | 0.041 |
| 0.49 | 3.96588 | 0.07915 | 0.04089 |
| 0.5 | 3.96636 | 0.07916 | 0.041 |
| 0.51 | 3.96792 | 0.07904 | 0.04089 |
| 0.52 | 3.969 | 0.07893 | 0.04089 |
| 0.53 | 3.97092 | 0.07882 | 0.04089 |
| 0.54 | 3.97296 | 0.0786 | 0.04078 |
| 0.55 | 3.97356 | 0.0787 | 0.04078 |
| 0.56 | 3.97512 | 0.0786 | 0.04078 |
| 0.57 | 3.97704 | 0.07849 | 0.04078 |
| 0.58 | 3.97872 | 0.07838 | 0.04078 |

| | | | |
|---|---|---|---|
| 0.59 | 3.97944 | 0.07839 | 0.04078 |
| 0.6 | 3.98112 | 0.0783 | 0.04078 |
| 0.61 | 3.9858 | 0.07827 | 0.04078 |
| 0.62 | 3.98724 | 0.07838 | 0.041 |
| 0.63 | 3.98964 | 0.07838 | 0.041 |
| 0.64 | 3.99192 | 0.07838 | 0.04111 |
| 0.65 | 3.99432 | 0.07838 | 0.04122 |
| 0.66 | 3.99636 | 0.07838 | 0.04111 |
| 0.67 | 3.99876 | 0.07849 | 0.04133 |
| 0.68 | 4.00032 | 0.07849 | 0.04133 |
| 0.69 | 4.00224 | 0.0786 | 0.04144 |
| 0.7 | 4.00452 | 0.0786 | 0.04155 |
| 0.71 | 4.00572 | 0.07882 | 0.04166 |
| 0.72 | 4.0068 | 0.07883 | 0.04166 |
| 0.73 | 4.008 | 0.07904 | 0.04177 |
| 0.74 | 4.00884 | 0.07915 | 0.04199 |
| 0.75 | 4.00992 | 0.07926 | 0.04199 |
| 0.76 | 4.01028 | 0.07937 | 0.0421 |
| 0.77 | 4.01052 | 0.07948 | 0.04221 |
| 0.78 | 4.01088 | 0.07959 | 0.04232 |
| 0.79 | 4.0116 | 0.07981 | 0.04243 |
| 0.8 | 4.01244 | 0.08003 | 0.04254 |
| 0.81 | 4.01245 | 0.08025 | 0.04276 |
| 0.82 | 4.01364 | 0.08058 | 0.04298 |
| 0.83 | 4.01448 | 0.08069 | 0.04309 |
| 0.84 | 4.01508 | 0.08113 | 0.04331 |
| 0.85 | 4.0158 | 0.08146 | 0.04353 |
| 0.86 | 4.01628 | 0.08201 | 0.04386 |
| 0.87 | 4.01784 | 0.08267 | 0.04419 |
| 0.88 | 4.01928 | 0.08344 | 0.04463 |
| 0.89 | 4.02108 | 0.08454 | 0.04518 |
| 0.9 | 4.02264 | 0.08597 | 0.04584 |

| | | | |
|---|---|---|---|
| 0.91 | 4.02516 | 0.08773 | 0.04672 |
| 0.92 | 4.02708 | 0.09037 | 0.04793 |
| 0.93 | 4.03128 | 0.0918 | 0.0487 |
| 0.94 | 4.03584 | 0.094 | 0.0498 |
| 0.95 | 4.04376 | 0.0962 | 0.0509 |
| 0.96 | 4.05624 | 0.0984 | 0.052 |
| 0.97 | 4.07772 | 0.1006 | 0.0531 |
| 0.98 | 4.11816 | 0.1028 | 0.0542 |
| 0.99 | 4.19436 | 0.105 | 0.0553 |
| 1 | 4.32 | 0.1072 | 0.0564 |

## APPENDIX C. MATLAB CODE FOR VOLTAGE-BASED METHOD

***Part 1 Before Simulink***

```
%% Define the Battery Capacity
i=input('i')
Q=i*3600;

%% Read Excel Dataset
Battery_Data  = xlsread('Battery_Parameters.xlsx',1);
SOC           = Battery_Data(:,1);
OCV           = Battery_Data(:,2);
R_Charging    = Battery_Data(:,3);
R_Discharging = Battery_Data(:,4);

%% Plot SOC Vs. OCV1
figure;
plot(SOC, OCV); xlabel('SOC'); ylabel('OCV [V]'); title('SOC Vs. OCV')
xlim([0 1])
ylim([2.2 4.4])
grid on

%% Model Simulation with current vaules of 1.53. 3 A
% Define the Input Current
i = i;
soca=0;
socb=1;
sim('Project5');
```

***Part 2 After Simulink***

```
T=table(Terminal_Voltage.signals.values,State_Of_Charge.signals.values
);
writetable(T,'SimResults.xls');
data = readtable('SimResults.xls');    % read  file as table
data.Properties.VariableNames = {'TerminaVoltage','SoC'};
writetable(data,'SimResults.xls');   % write back modified data to
excel file
[v,T,vT]=xlsread('SimResults.xls');
t=v(:,1);y=v(:,2);
figure(1)
plot(y,t)
set(gca, 'XDir','reverse')
title('SOC vs VT')
xlabel('SOC')
ylabel('VT')
axis([0 1 2 5])
grid on
```

## APPENDIX D. MATLAB CODE FOR CC METHOD

```
clc
clear all
load('B0056.mat');
n=0;C=[];VM=[];CM=[];TM=[];CC=[];VC=[];T=[];socM=[];
n1=0;C1=[];VM1=[];CM1=[];TM1=[];CC1=[];VC1=[];T1=[];socM1=[];
for i=1:252

    Type=B0056.cycle(i).type;
    if strcmp(Type,'discharge')==1
        SOC=100;
        Voltage_measured=B0056.cycle(i).data.Voltage_measured;
        n=size(Voltage_measured);
        C=[C i*ones(1,n(2))];
        VM = [VM Voltage_measured];
        Current_measured=B0056.cycle(i).data.Current_measured;
        CM = [CM Current_measured];
        Temperature_measured=B0056.cycle(i).data.Temperature_measured;
        TM=[TM Temperature_measured];
        Current_charge=B0056.cycle(i).data.Current_load;
        CC=[CC Current_charge];
        Voltage_charge=B0056.cycle(i).data.Voltage_load;
        VC=[VC Voltage_charge];
        Time=B0056.cycle(i).data.Time/3600;
        T=[T Time];
        Capacity=B0056.cycle(i).data.Capacity;
        for j=1:length(Current_charge)
            if (j == 1)
                SOC0 = 100;

                State =100;
            else

             State =State  -((Current_charge(j))*(Time(j)-Time(j-
1))*100./Capacity);
             if State>=0
                 SOC(j)=State;
             else
                 SOC(j)=0;
             end
            end
        end
        socM = [socM SOC];

    elseif strcmp(Type,'charge')==1
        SOC1=0;
        Voltage_measured1=B0056.cycle(i).data.Voltage_measured;
        VM1 = [VM1 Voltage_measured1];
        n1=size(Voltage_measured1);
        C1=[C1 i*ones(1,n1(2))];
        Current_measured1=B0056.cycle(i).data.Current_measured;
        CM1 = [CM1 Current_measured1];

Temperature_measured1=B0056.cycle(i).data.Temperature_measured;
        TM1=[TM1 Temperature_measured1];
        Current_charge1=B0056.cycle(i).data.Current_charge;
        CC1=[CC1 Current_charge1];
        Voltage_charge1=B0056.cycle(i).data.Voltage_charge;
```

```
        VC1=[VC1 Voltage_charge1];
        Time1=B0056.cycle(i).data.Time/3600;
        T1=[T1 Time1];
        Capacity1=1.344;
        %B0056.cycle(i).data.Capacity;
        for j=1:length(Current_charge1)
            if (j == 1)
                SOC0 = 0;
                SOC1(j)=0;
                State1 =0;

            else
                State1 =State1  +((Current_charge1(j))*(Time1(j)-
Time1(j-1))*100./Capacity1);
                if State1<=100
                    SOC1(j)=State1;
                else
                    SOC1(j)=100;
                end
            end
        end
        socM1 = [socM1 SOC1];

    end
end
%/ In this part I'm trying to know all the cycle in the charge part
and in
%/ the discharge part
%/ I will save any cycle of the discharge part in the NC vector
%/ I will save any cycle of the charge part in the NC1 vector
%/   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
nc=size(C);
NC=[C(1)];
for i=1:nc(2)-1
    if C(i+1)~=C(i)
        NC=[NC C(i+1)];
    end
end
nc1=size(C1);
NC1=[C1(1)];
for i=1:nc1(2)-1
    if C1(i+1)~=C1(i)
        NC1=[NC1 C1(i+1)];
    end
end
%/ The first Excel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A=[ VM', CM',TM',CC',VC',T'];
A(1:end,end+1)=socM;
a=strcat('B0006.cycle(', num2str(i-5),').discharge.xlsx');
xlswrite(a,A);
data=A;
data = readtable(a);     % read Excel file as table
data.Properties.VariableNames =
{sprintf('%20s','Voltage_Measured'),.....
    sprintf('%-20s','Current_Measured'),...
    sprintf('%-20s','Temp_Measured'),...
    sprintf('%-20s','Current_Charge'),......
```

```
    sprintf('%-20s','Voltage_Charge'),...
    sprintf('%-20s','Time')...
    ,sprintf('%-20s','SoC')};

% data.Properties.VariableNames = {'Voltage_Measured'
'Current_Measured' 'Temp_Measured' 'Current_Charge' 'Voltage_Charge'
'Time' 'SoC'};
writetable(data,a)    % write back modified data to excel file
[num,txt,raw] = xlsread(a); %% 'B0006.cycle(252).charge.xlsx'
[v,T,vT]=xlsread(a);

% The second Excel %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

B=[ VM1', CM1',TM1',CC1',VC1',T1'];
B(1:end,end+1)=socM1;
b=strcat('B0006.cycle(', num2str(i-5),').charge.xlsx');
xlswrite(b,B);
data1 = readtable(b);    % read Excel file as table
data1.Properties.VariableNames =
{sprintf('%20s','Voltage_Measured'),.....
    sprintf('%-20s','Current_Measured'),...
    sprintf('%-20s','Temp_Measured'),...
    sprintf('%-20s','Current_Charge'),......
    sprintf('%-20s','Voltage_Charge'),...
    sprintf('%-20s','Time')...
    ,sprintf('%-20s','SoC')};
writetable(data1,b)    % write back modified data to excel file
[num1,txt1,raw1] = xlsread(b); %% 'B0006.cycle(252).charge.xlsx'
[v1,T1,vT1]=xlsread(b);

%ploting%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

nnc=size(NC);
x=cell(nnc(2));y=cell(nnc(2));
for i=1:nnc(2)
for j = nc(2)-2
  if C(j)==NC(i)
   x{i}=[x{i} v(:,6)];
   y{i}=[y{i} v(:,7)];
  end
end
end

nnc1=size(NC1);
x1=cell(nnc1(2));y1=cell(nnc1(2));
for i=1:nnc1(2)
for j = nc1(2)-2
  if C1(j)==NC1(i)
   x1{i}=[x1{i} v1(:,6)];
   y1{i}=[y1{i} v1(:,7)];
  end
end
end
subplot(2,1,1);
hold on
for i=1:nnc(2)
  plot(x{i},y{i},'r')
end
ylim([-10 110]);
```

```
xlabel('time')
ylabel('soc')
title('the discharging cycles')
hold off
subplot(2,1,2);
hold on
for i=1:nnc1(2)
  plot(x1{i},y1{i},'g')
end
ylim([-10 110]);
xlabel('time')
ylabel('soc')
title('the charging cycles')
hold off
```