PROJECT REPORT ON

SIMULATION OF SOC ESTIMATION OF RECHARGEABLE BATTERIES

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF

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IN

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POWER SYSTEM ENGINEERING

UNDER

ASSAM SCIENCE AND TECHNOLOGY UNIVERSITY

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CANDIDATE'S DECLARATION

I, hereby declare that the work presented in the dissertation "**SIMULATION OF SOC ESTIMATION OF RECHARGEABLE BATTERIES**" to be accorded the degree of "MASTER OF TECHNOLOGY" in Electrical Engineering, with specialization in "POWER SYSTEM ENGINEERING", submitted to the Department of Electrical Engineering, Assam Engineering College, Guwahati, is an authentic record of my own work carried out under the supervision and guidance of Dr. Purobi Patowary, Professor, Department of Electrical Engineering, Assam Engineering College, Guwahati. The matter embodied in this project has not been submitted by me for the award of any other degree.

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CERTIFICATE FOR APPROVAL

This is to certify that the project work entitled "**SIMULATION OF SOC ESTIMATION OF RECHARGEABLE BATTERIES**" **,** undertaken by Chinmoy Jyoti Sivananda (Roll No. PG-E-004), a M.Tech. 3rd semester student of the Department of Electrical Engineering, Assam Engineering College, Guwahati-13, has been carried out by him during the academic year 2022-23 under my supervision and guidance.

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ABSTRACT

Battery is the most widely used energy storage device. Despite its ever increasing importance, many challenges remain unsolved to characterize and manage the battery. Among them, one fundamental issue is the estimation of state of charge (SoC)..

Information on SoC can be used to control charging and discharging process of the batteries. A good SoC estimation offers many advantages such as longer battery life, better battery performance and increased reliability of battery pack. There are several methods for determining SoC. Some of the popular methods are Coulomb counting, Voltage estimation and Impedance measurement method. There have been many attempts in literature to estimate SoC by synthesizing circuit models based on measured voltage and current at battery terminals. The final goal of any SoC algorithm is to predict the remaining capacity accurately. Developing efficient yet accurate SoC estimation algorithms remains a challenging task.

This project aims at developing a novel method to estimate the SoC and remaining runtime of a rechargeable battery which overcomes the drawbacks of existing methods. The proposed method is based on renowned Coulomb Counting technique. The proposed method predicts the SoC by Coulomb Counting method and corrects it using PI controller by employing a closed loop to estimate actual SoC. The proposed method is simple and easy to implement. The SoC as well as remaining runtime are estimated accurately.

Based on the new method, a model is developed using MATLAB/SIMULINK. The code corresponding to develop model is dumped in a target PC and is run in real time for online estimation of SoC. The required parameters such as voltage and current at the battery terminals are acquired by target PC and SoC is estimated. Estimated SoC and remaining runtime are used for control the charging and discharging process of the battery

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LIST OF ABBREVIATIONS

ACU	-	Adaptive Control Unit
AIO	-	Analog Input Output
CC	-	Constant Current
CV	-	Constant Voltage
CCCV	-	Constant Current Constant Voltage
DAQ	-	Data Acquisition
DIO	-	Digital Input Output
EDL	-	Electric Double Layer
EMF	-	Electro Motive Force
EoD	-	End of Discharge
GUI	-	Graphical User Interface
GUIDE	-	GUI Development Environment
LAN	-	Local Area Network
NI	-	National Instruments
OCV	-	Open Circuit Voltage
OVP	-	Over Potential
PCI	-	Peripheral Component Interconnect
PXI	-	PCI Extensions for Instrumentation
REDOX	-	Reduction Oxidation
RTSI	-	Real Time System Integration
SCPI	-	Standard Commands for Programmable Instrumentation
SCXI	-	Signal Conditioning Extensions for Instrumentation
SoC	-	State of Charge
TCP/IP	-	Transmission Control Protocol / Internet Protocol

NOTATION

ε	-	Error Signal
η	-	Over Potential
C_{TL}	-	Long-Time Capacitance
C_{TS}	-	Short-Time Capacitance
I_{bat}	-	Battery Terminal Current
K_P	-	Proportional Constant of PI Controller
K_I	-	Integral Constant of PI Controller
OCV_{EoD}	-	OCV at the End of Discharge
Q_{nom}	-	Nominal Capacity of the Battery
R_{ser}	-	Battery Series Resistance
R_{TL}	-	Long-Time Resistance
R_{TS}	-	Short-Time Resistance
SoC_{cc}	-	SoC Estimated by Coulomb Counting Technique
SoC_{cf}	-	Correction Factor in SoC
SoC_e	-	Actual Value of Estimated SoC
SoC_{EoD}	-	SoC at the End of Discharge
SoC_i	-	Initial SoC
T_r	-	Remaining Runtime
$V_{bat,meas}$	-	Measured Terminal Voltage of the Battery
$V_{bat,model}$	-	Terminal Voltage of the Battery Model

Chapter 1

Introduction

1. BATTERIES

The modern society relies completely on the fossil fuels such as natural gas, coal and oil for its energetic needs. Their reserves are however limited and the environmental concerns are nowadays haunting the society. The utilization of energy in a sustainable way is the only pursuable solution to cope with these problems. Thus, the conversion and storage of energy is becoming necessary step for global efficiency of the energy generation and utilization process. Battery is the most widely used energy storage device. An electric battery is a device that converts chemical energy directly into electrical energy. Battery powered applications have become ubiquitous in the modern society. The recent rapid expansion in the use of these applications creates a strong demand for fast deployment of battery technologies at an unacceptable rate.

1.1 Construction

An electric battery is one or more electrochemical cells connected in series (or) parallel (or) series-parallel combination.

1.1.1 Electrochemical Cell

An electrochemical cell is a device capable of delivering electrical energy from chemical reactions (or) facilitating chemical reactions through the introduction of electrical energy. The main parts of an electrochemical cell include:

(a) Two half cells
(b) Electrolyte and
(c) Electrodes

(a) Half Cells

Each half cell consists of a conductive electrode surrounded by a conductive electrolyte. The two half cells may use same electrolyte, (or) they may use different electrolytes. A salt bridge is often employed to provide ionic contact between two half cells with different electrolytes to prevent the solutions from mixing and causing unwanted side reactions. The construction of an electrochemical cell is shown in Figure 1.

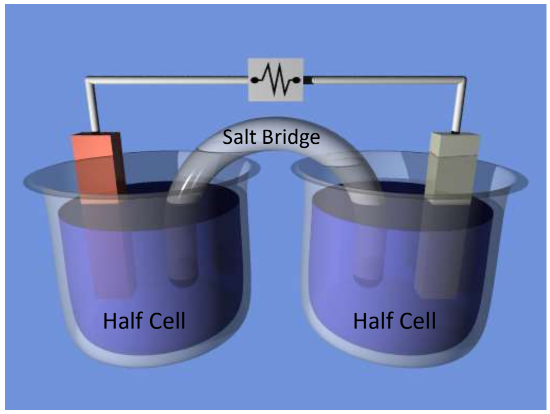

Figure 1: Electrochemical Cell Construction

(b) Electrolyte

An electrolyte is a substance containing free ions that make the substance electrically conductive. The most typical electrolyte is an ionic solution, but molten electrolytes and solid electrolytes are also possible. Commonly, electrolytes are solutions of acids, bases (or) salts. Electrolyte solutions are normally formed when a salt is placed into a solvent such as water and the individual components dissociate due to the thermodynamic interactions between solvent and solute molecules, in a process called "salvation". For example, when table salt (i.e.) "NaCl", is placed in water, the salt dissolves into its component ions, according to the dissociation reaction given below.

$$NaCl_{(S)} \longrightarrow Na^{+}_{(aq)} + Cl^{-}_{(aq)} \quad (1.1)$$

Furthermore, some gases may act as electrolytes under conditions of high temperature (or) low pressure. Electrolyte solutions can also result from the dissolution of some biological and synthetic polymers, termed polyelectrolyte, which contain charged functional groups. Molten salts can also act as electrolytes as well. For instance, when Sodium Chloride is molten, it conducts electricity.

(c) Electrodes

An electrode is an electrical conductor. An electrochemical cell contains two electrodes with one in each half cell. An electrode in an electrochemical cell is referred to as either an "Anode" (or) a "Cathode". The anode is defined as electrode at which electrons leave the cell and oxidation occurs. In contrast, the cathode is defined as the electrode at which electrons enter the cell and reduction occurs. An electrode may become either anode (or) the cathode depending on the direction of current through the cell.

1.2 Helmholtz Layer

The Helmholtz layer also called as "Double Layer" (DL) (or) "Electric Double Layer" (EDL) is a structure that appears when an electrode is placed into an electrolyte. Figure 2 shows an example of Helmholtz layer.

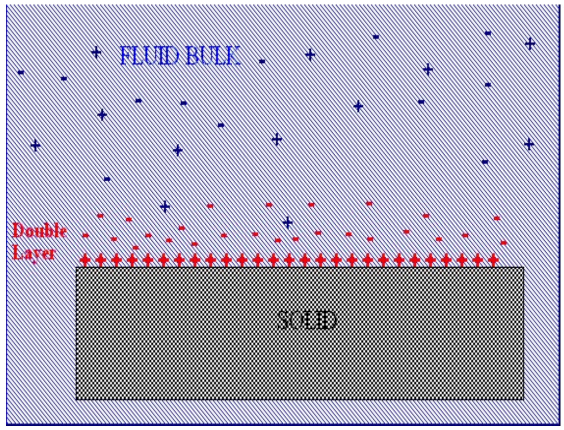

Figure 2: Helmholtz Layer

The EDL refers to two parallel layers of charge surrounding the electrode. The first layer (i.e.) the surface charge (either positive or negative), comprises ions absorbed directly onto the electrode due to a host of chemical reactions. The second layer comprises ions attracted to the surface charge due to Coulomb force, electrically screening the first layer. The second layer is loosely associated with the electrode, because it is made up of free ions which move in the electrolyte under the influence of electric attraction and thermal motion rather than being firmly anchored. The EDL plays an important role in the operation of batteries. The entire chemical reaction that occurs in an electrochemical cell occurs in this EDL.

1.3 REDOX Reaction

REDOX reaction stands for "Reduction-Oxidation" reaction that describes all the chemical reactions that occur in a battery. The term REDOX comes from the two concepts of reduction and oxidation. "Oxidation" is chemical reaction in which an atom loses its electrons and "Reduction" is a chemical reaction in which an atom gains electrons.

$$\text{Oxidant} + e^- \longrightarrow \text{Product} \qquad \text{(Reduction)} \qquad (1.2)$$

(Electrons Gained; Oxidation Number Decreases)

$$\text{Reductant} \longrightarrow \text{Product} + e^- \qquad \text{(Oxidation)} \qquad (1.3)$$

(Electrons Lost; Oxidation Number Increases)

Figure 3 shows an illustration of REDOX reaction.

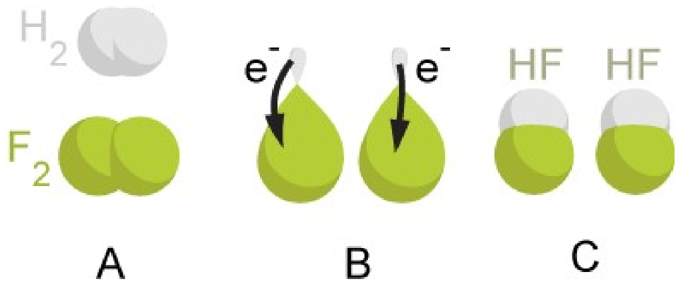

Figure 3: REDOX Reaction

1.4 Principle of Operation

An electric battery is a device that converts stored chemical energy directly to electric energy. It consists of a number of electrochemical cells, each consisting of two half cells connected in series by a conducting electrolyte. One half cell includes an electrode and an electrolyte. In the REDOX reaction that powers the battery, reduction occurs to cat ions at the cathode and oxidation occurs to anions at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Some cells use two half cells with different with different electrolytes. A separator between half cells allow ions to flow, but prevents mixing of electrolyte as shown in Figure 4.

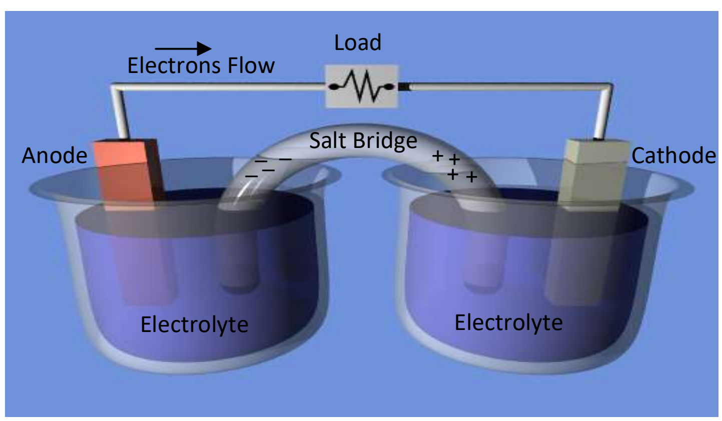

Figure 4: Battery Principle of Operation

Each half cell contains a conductive electrode and a surrounding conductive electrolyte separated by a naturally occurring Helmholtz layer (or) EDL. Chemical reactions within this layer momentarily pump electric charges between the electrode and the electrolyte, resulting in a potential difference between them. The typical anode reaction involves a metal atom in the electrode being dissolved and transported as a positive ion across the double layer, causing the electrolyte to acquire a net positive charge while the electrode acquires a net negative charge. The growing potential difference creates an intense electric field within the double layer, and the potential rises in value until the field halts the net charge-pumping reactions.

Each half cell has an EMF, determined by its ability to drive electric current from the interior to the exterior of the cell. The net EMF of the cell is the difference between the EMFs of its half cells. Therefore, if the half cells of have EMFs "E_1" and "E_2", then the net EMF of cell is given by,

$$\text{Net EMF} = E_1 - E_2 \tag{1.4}$$

The reaction at the positive electrode (or) anode is given by,

$$A_{(Red+)} \longrightarrow B_{(Ox+)} + n\,e^- \tag{1.5}$$

The potential developed at this electrode is given by,

$$E_{(eq+)} = E_{(0+)} + \left[\frac{RT}{nF}\right] \ln \frac{(a_{ox+})^B}{(a_{red+})^A} \tag{1.6}$$

The reaction at the negative electrode (or) cathode is given by,

$$A_{(Red+)} \longrightarrow B_{(Ox+)} + n\,e^- \tag{1.7}$$

The potential developed at this electrode is given by,

$$E_{(eq-)} = E_{(0-)} + \left[\frac{RT}{nF}\right] \ln \frac{(a_{ox-})^C}{(a_{red-})^D} \tag{1.8}$$

Then, the overall potential of the cell is given by,

$$E_{(eq,bat)} = E_{(eq+)} - E_{(eq-)} = E_{(0+)} - E_{(0-)} + \left[\frac{RT}{nF}\right] \ln \frac{(a_{ox+})^B (a_{red-})^D}{(a_{red+})^A (a_{ox-})^C} \tag{1.9}$$

Where, $a_i = \gamma .\ C_i = \dfrac{\gamma .\ m_i}{\text{Volume}}$ (1.10)

γ = Activity Coefficient

m_i = Molar amount of the species

1.5 Classification of Batteries

Batteries are broadly classified into two types:

(a) Primary (or) Disposable Batteries

(b) Secondary (or) Rechargeable Batteries

1.5.1 Primary Batteries

A primary battery is a battery in which electrochemical reaction is not reversible. A common example of a primary battery is the disposable battery. In a primary battery, the reactants cannot be restored to their initial position and capacity. Primary batteries use up the active materials in one (or) both of their electrodes. Primary batteries are intended to be used once and discarded. They can produce current immediately on assembly. Generally, these batteries have higher energy densities and are used extensively in low drain applications. Primary batteries are commonly used in portable devices that have low current drain.

Some examples of primary batteries are Alkaline battery, Aluminum battery, Silver Oxide battery, Zinc Carbon battery, Zinc Air battery, Zinc Chloride battery, Lithium battery, Mercury battery etc.

1.5.2 Secondary Batteries

Secondary battery also called as "Rechargeable Battery" is a battery in which the electrochemical reactions are electrically reversible. These batteries can be recharged by applying an electric current, which reverses the chemical reactions that occur during its use. These batteries are designed to be recharged and used multiple times. These batteries must be charged before use. Rechargeable batteries come in many shapes and sizes as shown in Figure 5.

Figure 5: Secondary (or) Rechargeable Batteries

During charging, the positive active material is oxidized, producing electrons, and the negative material is reduced, consuming electrons. These electrons constitute the current flow in the external circuit. The energy used to charge rechargeable batteries usually comes from a battery charger using AC mains electricity. Chargers take from a few minutes (rapid chargers) to several hours to charge a battery. Every rechargeable battery chemistry supports a different charging method. For instance, a rechargeable Lead Acid battery should be charged with a constant voltage. Charging process plays an important role in preserving the life cycle of the battery. So, over charging (or) reverse charging a rechargeable battery may lead to its damage (or) reduction in its life cycle.

Rechargeable batteries have lower total cost of use and environmental impact than disposable batteries. They have higher initial cost, but can be recharged very cheaply and used many times. These batteries are used in both high and low drain applications. Rechargeable batteries are used for automobile starters, portable consumer devices, light vehicles such as motorized wheelchairs, golf carts, electric bicycles, and electric forklifts, tools and uninterruptible power supplies. Emerging applications in hybrid electric vehicles and electric vehicles are driving the technology to reduce cost and weight and increase lifetime. Some examples of rechargeable batteries are Lead acid, Nickel Cadmium, Nickel Metal Hydride, Lithium ion, Lithium Polymer, Silver Zinc, Nickel Iron, Lithium Titanate, Lithium Sulphur etc.

1.6 Rechargeable Batteries – Types and Comparison

Rechargeable batteries come in many shapes and sizes ranging from a button cell to megawatt systems. These batteries are available with various chemistries. Some of the commonly used chemistries include:

(a) Lead Acid Battery
(b) Nickel Cadmium (NiCd) Battery
(c) Nickel Metal Hydride (NiMH) Battery
(d) Lithium Ion (Li-ion) Battery
(e) Lithium Polymer (Li-Pol) Battery
(f) Silver Zinc (Ag-Zn) Battery

The above listed chemistries are compared in Table 1.

Table 1: Comparison of Various Rechargeable Batteries

S.No	Feature		Lead Acid	NiCd	NiMH	Li-ion	Li-Pol	Ag-Zn
1	Cell Voltage (V)		2.1	1.2	1.2	4.1	4.1	1.86
2	Specific Energy (MJ/Kg)		Low	Low	Moderate	High	High	Very High
3	Cost		Moderate	Low	Low	High	Very High	Very High
4	Load Current	Peak	5C	20C	5C	2C	2C	30C
		Best Result	0.2C	1C	0.5C or Lower	1C or Lower	1C or Lower	2C to 3C
5	Self Discharge Rate (Per Month)		Very Low	Moderate	Very High	Low	Low	Negligible
6	Memory Effect		No	Yes	Yes	No	No	No
7	Operating Temp.(˚C)		-20 to 60	-40 to 60	-20 to 60	-20 to 60	0 to 60	-30 to 60
8	Internal Resistance		Low	Low	Moderate	High	High	Very Low
9	Efficiency (%)		70 to 92	70 to 90	62 to 70	80 to 90	85 to 95	94 to 98
10	Recharge Life (Cycles)		500 to 800	1300 to 1500	500 to 1000	1000 to 1200	800 to 1000	>4000
11	Environmental Impact		More	More	Less	Very Less	Very Less	Very Less
12	Overcharge Tolerance		More	Moderate	Less	Very Less	Less	Less
13	Maintenance Req. (Days)		90 to 180	30 to 60	60 to 90	Not Required	Not Required	Not Required

Chapter 2 explains about the State of Charge (SoC), factors affecting SoC and various methods for determining SoC with their merits and demerits.

Chapter 3 explains the proposed method for SoC estimation and its implementation.

Chapter 4 explains the MATLAB/Simulink modelling of Coulomb Counting and the proposed method along with the simulation results.

Chapter 5 explains the hardware test bench developed for validating Coulomb Counting and the proposed method.

Chapter 6 explains the various tests performed, test results and comparison of test results.

Chapter 7 gives the conclusion of work done and its future scope.

Chapter 2

State of Charge

2. STATE OF CHARGE

Battery is the most widely used energy storage device. Since its invention, it has become a common power source for various household and industrial applications. Despite its ever-increasing importance, many challenges remain unsolved to characterize and manage the battery. Among them, one fundamental issue is the estimation of state-of-charge (SoC).

2.1 What is SoC?

State of Charge (SoC) of a battery indicates the capacity remaining inside the battery. SoC is usually expressed in percentage. If SOC is 100%, it indicates that the battery is fully charged. If SoC is 0%, it indicates that the battery is empty. The SoC of a battery is simply calculated as,

$$\mathrm{SoC} = \mathrm{SoC_i} - \frac{\int I \, dt}{Q_{nom}} \tag{2.1}$$

Where, SoC_i = Initial SoC

Q_{nom} = Nominal Capacity of the battery

I = Current flowing through the battery

The magnitude of current is taken as positive for discharging process and negative for charging process.

SoC determination is an increasingly important issue in battery technology. A precise knowledge of SoC provides additional control over charging and discharging process, which can be employed for better utilization of stored energy. Accurate SoC determination for battery powered applications is also important for user convenience. A good SoC estimation leads to longer battery life, better utilization of stored energy and increased reliability of the battery pack.

SoC has strong dependency on temperature and age of the battery. The terminal voltages, operating currents and surface temperatures are the direct measurable parameters of a battery. But, the complex inter-relationship between these parameters makes SoC estimation an intricate task. Many attempts have been made in literature to estimate SoC accurately. Developing efficient yet accurate SoC estimation algorithms remains a challenging task.

2.2 Factors Affecting SoC

There are three factors that affect the accurate SoC estimation of a battery.

- Temperature
- Ageing
- Self-discharge

2.2.1 Temperature Effect on SoC

The chemical reactions that occur in a battery are temperature dependent. So, the SoC of a battery is affected by its operating temperature. The operating temperature of a battery is decided by current flowing in (or) out of the battery. As the temperature varies, the SoC of a battery also varies. The operating temperature of a battery is a major factor that affects its SoC estimation. So, in order to determine the SoC of a battery accurately, the estimation algorithm should incorporate the temperature effect.

2.2.2 Ageing Effect on SoC

When the battery is being used repeatedly, the performance of the battery deteriorates. There is a separate parameter to monitor the effects of this aging which is known as the State of Health (SoH) of the battery. As the battery ages, the nominal capacity of the battery decreases and the impedance of the battery increases. This is because of the sulfate formation on the plates of the electrodes in the battery which decreases the net concentration of the electrolyte concentration in the battery. This reduces the full-charge capacity of the battery which in turn affects the SoC calculations. Since the nominal capacity of a battery has a direct relation with the SoC, it affects SoC estimation. The impedance with increases with age also effects the SoC estimation of a battery.

2.2.3 Self-discharge Effect on SoC

Self-discharge is a phenomenon in batteries in which internal chemical reactions reduce the stored charge of the battery without any connection between the electrodes. In addition to the charge being put into and taken out of the battery during the normal charge - discharge process, the continuing long term effect of self discharge consuming the available energy in the cell must also be taken into account. This becomes more significant the longer the periods between charging. Self-discharge decreases the shelf-life of batteries and causes them to have less charge than expected when actually put to use. Since the self-discharge of a battery is abnormal behaviour, it also affects the SoC estimation.

2.3 SoC Estimation Methods

There are three methods existing in literature for SoC estimation of a battery.

- Direct Measurements
- Book-Keeping Systems
- Adaptive Systems

2.3.1 Direct Measurements

The direct measurement method is based on a reproducible and pronounced relation between a measured battery variable and the SoC. This battery variable should be electrically measurable in the practical set-up. Examples of such battery variables are battery terminal voltage "V" and battery impedance "Z". Most relations between battery variables depend on the temperature "T". Therefore, besides the voltage (or) the impedance, the battery temperature should also be measured. The relation "f_T^d" is between the measured battery variable and the SoC, can be stored in the system. The basic principle for SoC estimation based on direct measurement is shown in Figure 6.

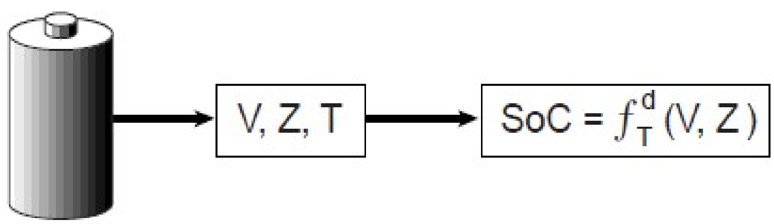

Figure 6: SoC Estimation by Direct Measurements Method

The SoC of a battery can be estimated by using the following relation,

$$SoC = f_T^d (V, Z) \tag{2.2}$$

Advantages

- The main advantage of a system based on direct measurement is that it does not have to be continuously connected to the battery. The measurements can be performed as soon as the battery has been connected, after which the SoC can be directly inferred from the relation "f_T^d".
- The direct measurement method is very easy to implement.
- The direct measurement method is applicable to any kind of battery chemistry.

Disadvantages

- Difficult to obtain the function "f_T^d", which can describe the relation between measured battery variable and the SoC under all applicable conditions.
- Doesn't account for the age the age of the battery.
- Continuous battery monitoring and SoC estimation is not possible.
- Battery's operation should be interrupted in order to determine SoC.

2.3.2 Book-Keeping Systems

Book-Keeping systems are based on current measurement and integration. This method is also known as "Coulomb Counting" method, which literally means "counting the charge flowing into (or) out of the battery. This yields an accurate SoC estimation when all the charge applied to the battery can be retrieved under any condition and at any time. The basic principle for SoC estimation based on book-keeping system is shown in the Figure 7.

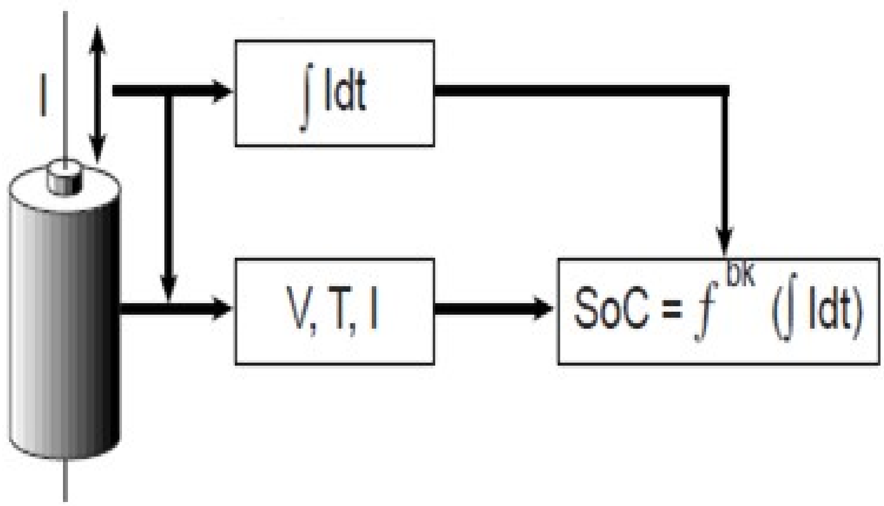

Figure 7: SoC Estimation Based on Coulomb Counting Method

The SoC of a battery can be estimated by using the following relation,

$$SoC = SoC_i - \frac{\int I \ dt}{Q_{nom}} \quad (2.3)$$

Where, SoC_i = Initial SoC

Q_{nom} = Nominal Capacity of the battery

I = Current flowing through the battery ("+" for discharging and "-" for charging)

Advantages

- This method yields accurate SoC estimation with flawless current measurement.
- This method is very easy to implement.
- This method can be applied to any kind of battery chemistry.
- Continuous monitoring and online estimation of battery SoC is possible with this method

Disadvantages

- Results in a large error due a small flaw in current measurement as the error gets integrated.
- SoC is estimation is affected by change in "Q_{nom}" with age.
- Results in error if the initial SoC is not estimated properly.

2.3.3 Adaptive Systems

The main problem in designing an accurate SoC indication system is the unpredictability of both battery and user behaviour. Battery behaviour depends strongly on conditions, including age, some of which may be unanticipated. Moreover, spread in behaviour of batteries of the same type and batch makes life more difficult. A possible solution is to add adaptivity to a system based on direct measurement, book-keeping or a combination of the two. The basic principle of adding adaptivity to a SoC estimation system is depicted in Figure 8.

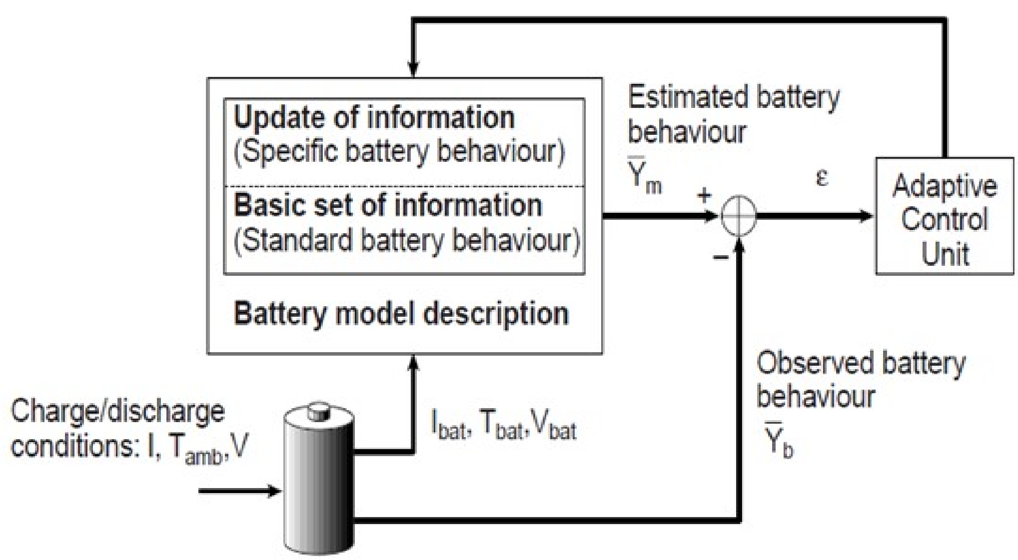

Figure 8: SoC Estimation Using Adaptive Systems

The measured battery variables I_{bat}, T_{bat} and V_{bat} are the inputs of this model, which estimates battery behaviour in the form of output vector Y_m on the basis of these inputs. Vector Y_m contains at least the SoC, but could also contain additional battery variables, such as an estimated value of the battery impedance. Another possibility would be to estimate the battery voltage on the basis of the I_{bat} and T_{bat} measurements, and to compare this estimated value with the measured value V_{bat}. This method may use direct measurement method (or) book-keeping method (or) a combination of the two. The system starts with a basic set of information, which describes standard battery behaviour for the type of battery concerned.

Adaptivity of the model is based on a comparison of Y_m with observed battery behaviour in the form of vector Y_b. This comparison is made whenever possible. It results in an error signal "ε", which is input to an Adaptive Control Unit (ACU). The unit updates the information in the model by updating parameter values or even by changing the model description. As a result, the model is adapted on the basis of behaviour specific to the battery to which the system is connected and the error between estimation and observation is minimized.

Advantages

- SoC can be estimated accurately considering the age, temperature and some other unanticipated conditions.
- The nominal capacity and the battery parameters are estimated with age and temperature.
- Online estimation of SoC is possible.
- Adaptivity can be added and SoC can be estimated for any kind of battery chemistry.

Disadvantages

- Adaptivity is very difficult to implement.
- Needs strong hypothesis on battery model.
- Large amount of memory is required in real world applications.

Chapter 3

Proposed Method

3. THE PROPOSED METHOD FOR SoC ESTIMATION

SoC estimation is an increasingly important issue in battery technology. This thesis presents a new algorithm for SoC estimation of a rechargeable battery. The proposed method estimates the SoC of a battery based on book-keeping, direct measurement and model-based approaches.

3.1 The Proposed Method

The SoC estimated from Coulomb counting can include a large error due to flaws in terminal current measurement and/or initial SoC estimation. To recalibrate the SoC estimated by Coulomb counting method, a method combining Coulomb counting, direct measurement and model-based approach is proposed. The block diagram of the proposed method is shown in Figure 9.

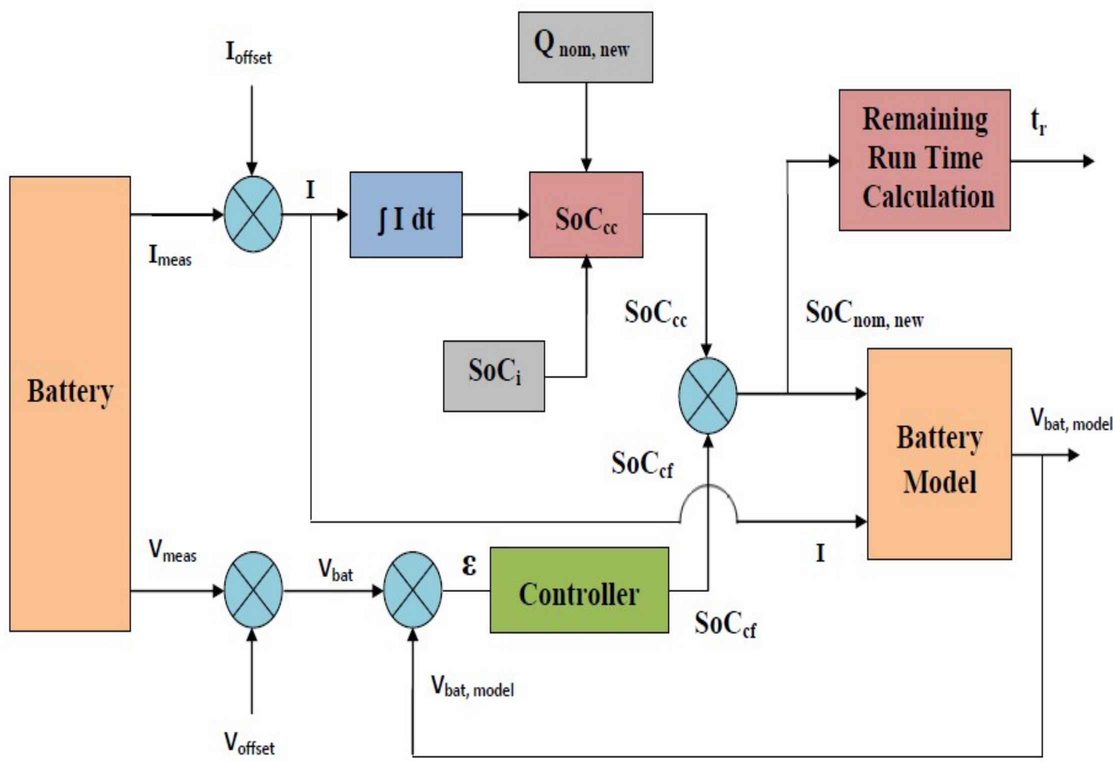

Figure 9: Block Diagram of the Proposed Method

The measured current and voltage at the battery terminals are summed with an offset to obtain accurate measurement values. The measured current "I" is integrated with time. The procedure for obtaining "SoC_i" is explained in the next section. Then the SoC is estimated using Coulomb Counting method as explained by equation 2.1. The corresponding Open-

Circuit Voltage (OCV) for the SoC estimated by Coulomb counting method is obtained from an OCV-SoC relationship. The procedure for obtaining OCV-SoC relationship is explained in the next section.

The voltage "OCV (SoC)" and battery current "I" are applied to the battery model and terminal voltage "$V_{bat,\ model}$" is obtained. The proposed battery model is explained in the next section. The parameters of the battery model such resistances and capacitances change with age and temperature. The procedure for capturing parameters of the battery model is also explained in the next section.

The terminal voltage obtained from the battery model (i.e.) "$V_{bat,\ model}$" is compared with the measured terminal voltage "V_{bat}". The error "ε" in the terminal voltage is processed by a controller producing a correction factor "SoC_{cf}". This correction factor is summed with the SoC determined from Coulomb counting method to estimate the accurate state-of-charge "SoC_e". The method for designing and tuning a controller is presented in the next section.

3.2 Implementation

The implementation of proposed method is explained in the following subsections.

3.2.1 OCV – SoC Relationship

The state-of-charge (SoC) of battery has a pronounceable relationship with its open-circuit voltage (OCV). A typical OCV-SoC curve for Li-Io cell is shown in Figure 10.

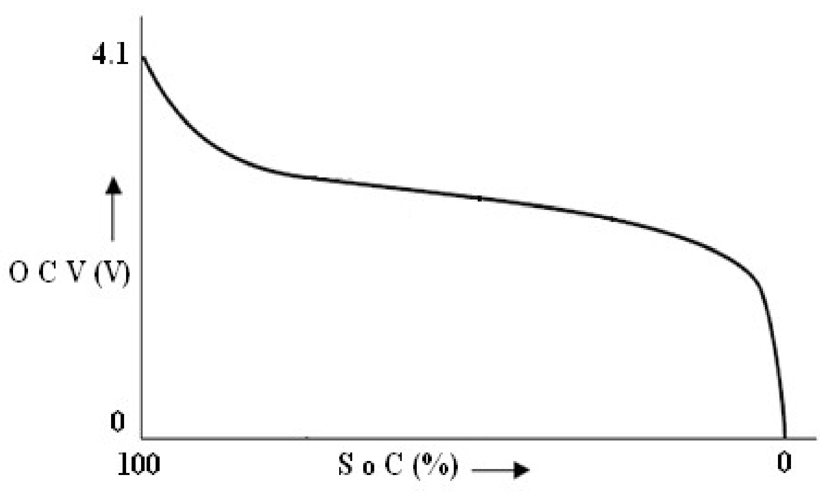

Figure 10: OCV – SoC Curve of Li-Ion Cell

The OCV – SoC relationship can be determined from a discharge test. During the test, battery is discharged with a constant C-rate for certain period and is allowed to rest for some time interval. This allows battery to stabilize its internal chemical reaction after the discharge. Then, the voltage is measured across the battery terminals which is equal to the battery's OCV. The test is performed until the OCV reaches the End-of-Discharge (EOD) voltage. From the test data obtained, the relation between SoC and OCV can be obtained from any of the available curve-fitting techniques.

$$OCV = f\,(SoC) \tag{3.1}$$

3.2.2 Battery Model

There are many models available in literature for battery modeling. An accurate, intuitive and comprehensive battery model is proposed as shown in Figure 11. The self-discharge of a battery is usually represented by a resistor. But, the battery considered for this project is a Li-Polymer battery. Since, the self-discharge of a battery is usually negligible; this resistor is neglected for the analysis.

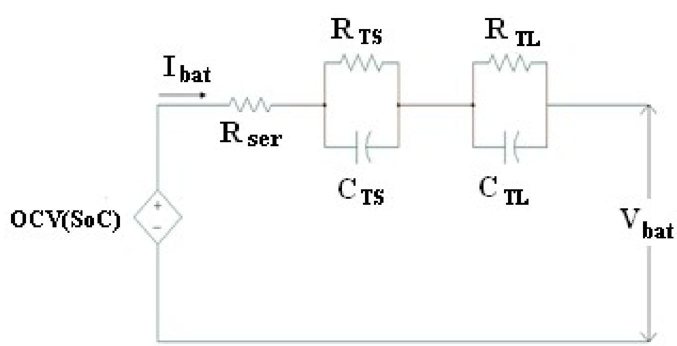

Figure 11: The Proposed Battery Model

The proposed battery model consists of a dependent voltage source "OCV (SoC)", a series resistance "R_{ser}" and two parallel RC circuits to represent the dynamics of the battery. The series resistance represents the resistance of electrodes and contacts. The first RC circuit "R_{TS}" and "C_{TS}" represent the short-time transient resistance and capacitance respectively. The second RC circuit "R_{TL}" and "C_{TL}" represent the long-time transient resistance and capacitance respectively. The voltage source is modeled as dependent source because the voltage developed depends on the charge present inside the battery. With no current flowing through the battery, the OCV is equal to the terminal voltage of the battery.

The model parameters can be obtained from a discharge test using pulse current profile as shown in Figure 12.

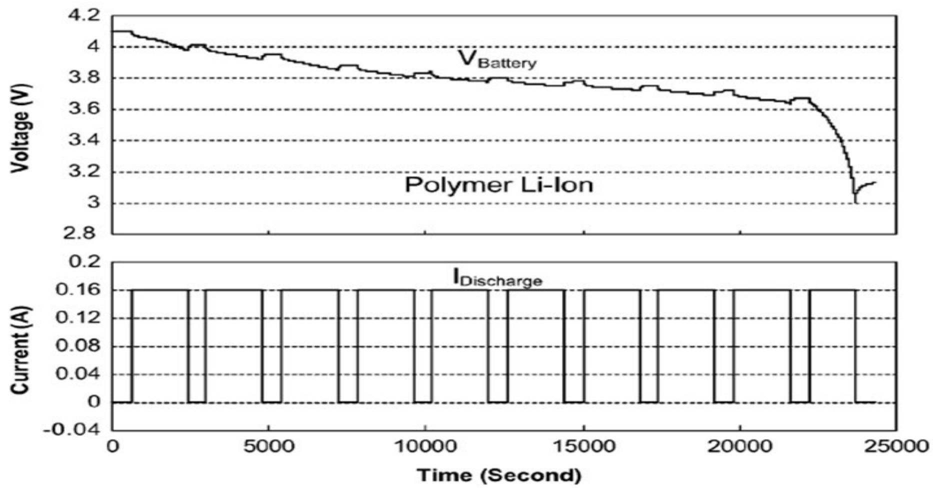

Figure 12: Li-Polymer Terminal Voltage and Current with Pulse Profile

Whenever a battery discharges with pulse current, there will be a plunge in its voltage profile as shown in Figure 13.

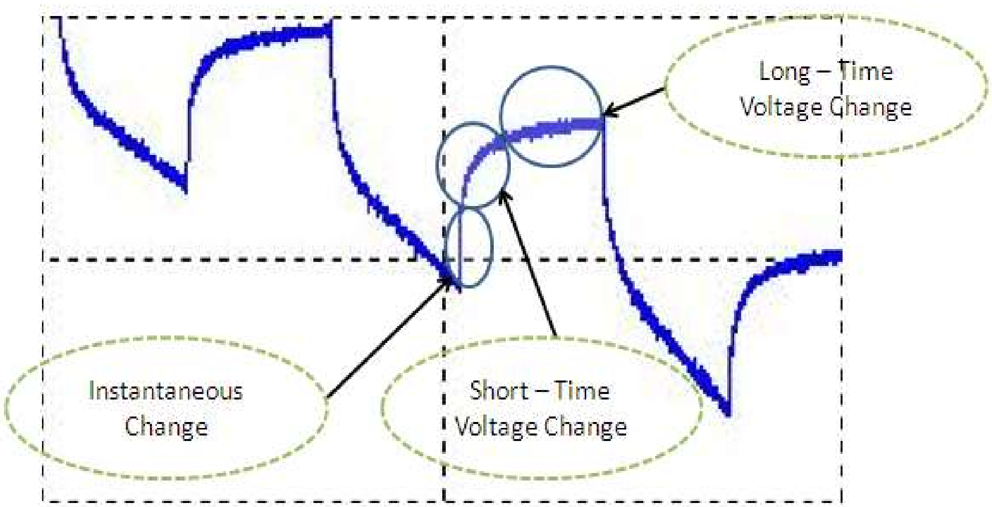

Figure 13: Voltage Profile Due to Pulse Discharge Current Profile

The voltage profile of a battery when discharged with a pulse current profile can be used to determine the parameters of a battery by using the following relations.

Series Resistance

The series resistance of a battery is given by,

$$R_{ser} = \frac{\text{Instantaneous Voltage Change } (\Delta V_{inst})}{\text{Change in Battery Current } (\Delta I_{bat})} \tag{3.2}$$

Short-Time Transient Resistance

The short-time transient resistance is given by,

$$R_{TS} = \frac{\text{Short-Time Voltage Change } (\Delta V_{TS})}{\text{Change in Battery Current } (\Delta I_{bat})} \tag{3.3}$$

Short-Time Transient Capacitance

The short-time transient capacitance is given by,

$$C_{TS} = \frac{\text{Short-Time Constant } (T_{TS})}{\text{Short-Time Transient Resistance } (R_{TS})} \tag{3.4}$$

Long-Time Transient Resistance

The long-time transient resistance is given by,

$$R_{TL} = \frac{\text{Long-Time Voltage Change } (\Delta V_{TL})}{\text{Change in Battery Current } (\Delta I_{bat})} \tag{3.5}$$

Long-Time Transient Capacitance

The long-time transient capacitance is given by,

$$C_{TL} = \frac{\text{Long-Time Constant } (T_{TL})}{\text{Long-Time Transient Resistance } (R_{TL})} \tag{3.6}$$

3.2.3 Battery Model Terminal Voltage

From the equation 3.1, the OCV corresponding to the "SoC_{cc}" estimated by Coulomb Counting method is determined. This OCV acts as input voltage to the battery model as shown in Figure 14.

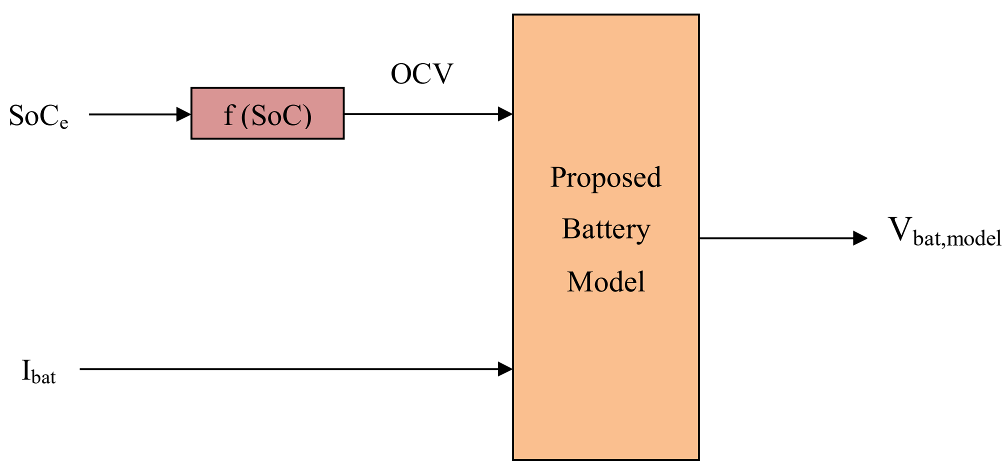

Figure 14: Determination of Battery Model Terminal Voltage

The OCV along with the measured battery current "I_{bat}" is used for determining the battery terminal voltage "$V_{bat, model}$" which is given by,

$$V_{bat,\ model} = OCV\ (SoC) - \{[R_{ser}+K_1+K_2] * I_{bat}\} \qquad (3.7)$$

Where,

$K_1 = \dfrac{R_{TS}}{1 + S\ R_{TS}\ C_{TS}}$

$K_2 = \dfrac{R_{TL}}{1 + S\ R_{TL}\ C_{TL}}$

$I_{bat} =$ Battery Current

The magnitude of battery current is taken as positive for discharging and negative for charging. When the battery current is zero (ie) in equilibrium state, the OCV is equal to its terminal voltage. The total potential drop that occurs in a battery due to its impedance is also known as "Over Potential" (OVP) denoted by "η" which is given by,

$$\eta = [R_{ser}+K_1+K_2] * I_{bat} \qquad (3.8)$$

3.2.4 Controller

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs.

The PID controller calculation involves three separate parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.

In the absence of knowledge of the underlying process, a PID controller is the best controller. By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID controller for control does not guarantee optimal control of the system or system stability.

Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral value may prevent the system from reaching its target value due to the control action.

The controller used here is a PI controller. The battery terminal voltage "$V_{bat,\ model}$" obtained by eq.(3.7) is compared with the actual measured voltage "$V_{bat,\ meas}$". The error generated by this comparison is processed by controller and the corresponding correction factor is added to the SoC estimated by Coulomb Counting method to determine the actual value of SoC i.e. "SoC_e". The process of comparison and updating the SoC continues till the error reduces to zero.

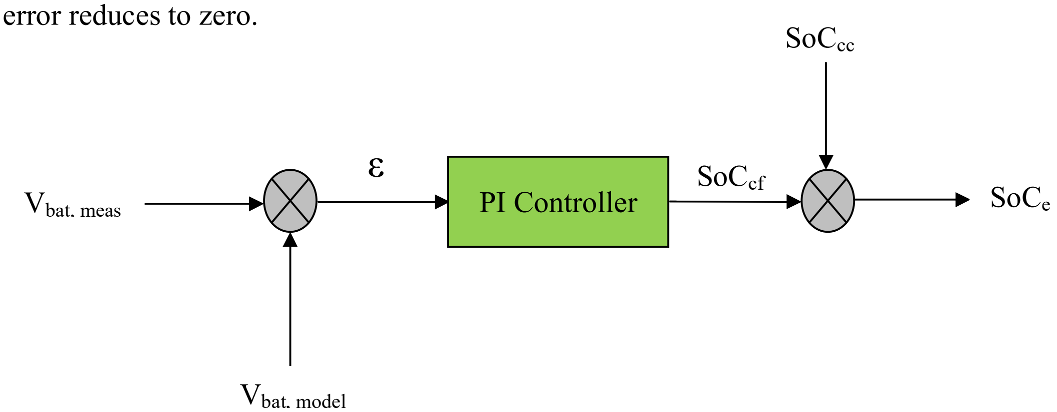

Figure 15: PI Controller in Proposed Algorithm

The error signal produced is given by,

$$\varepsilon = V_{bat,\ meas} - V_{bat,\ model} \tag{3.9}$$

The actual SoC estimated i.e. SoC_e is given by,

$$SoC_e = SoC_{cc} + SoC_{cf} \tag{3.10}$$

The correction factor produced by the PI controller is given by,

$$SoC_{cf} = G_c(s).\ \varepsilon \tag{3.11}$$

Where, $G_c(s)$ = Transfer Function of the PI Controller

For instance, the SoC estimated by Coulomb Counting method "SoC_{cc}" is higher than the true value of SoC, and then the OCV calculated as a function SoC will be higher. So, this leads to a higher calculated value of battery terminal voltage "$V_{bat\ ,model}$". When "$V_{bat\ ,model}$" is compared with actual measured value "$V_{bat,\ meas}$", the error will be negative and the corresponding correction factor produced by the PI controller will also be negative. This correction factor is summed up with "SoC_{cc}" value which reduces the estimated SoC i.e. "SoC_e". This process repeats until the value of error reaches zero and the value of SoC reaches a steady state value.

If the SoC estimated by Coulomb Counting method "SoC_{cc}" is lower than the true value of SoC, and then the OCV calculated as a function SoC will be lower. So, this leads to a lower calculated value of battery terminal voltage "$V_{bat,\ model}$". When "$V_{bat,\ model}$" is compared with actual measured value "$V_{bat,\ meas}$", the error will be positive and the corresponding correction factor produced by the PI controller will also be positive. This correction factor is summed up with "SoC_{cc}" value which increases the estimated SoC i.e. "SoC_e". This process repeats until the value of error reaches zero and the value of SoC reaches a steady state value.

The PI controller is tuned as per the requirements such as settling time and steady state error. This is done by using "Simulink Response Optimization" toolbox which is available in MATLAB/Simulink. The tuned parameters thus obtained are used in the MATLAB/Simulink model during simulation.

3.2.5 Remaining Runtime (T_r)

The remaining runtime "T_r" is the time after which terminal voltage of the battery falls below the "End-of-Discharge" (EoD) voltage. The remaining runtime determines the time for which the battery can be discharged. The battery can be discharged beyond this time which is usually called as "Deep Discharge" which decreases the life of the battery. In order to improve battery life, estimating the remaining runtime is a good practice. Consider the discharge curve of battery as shown in Figure 16.

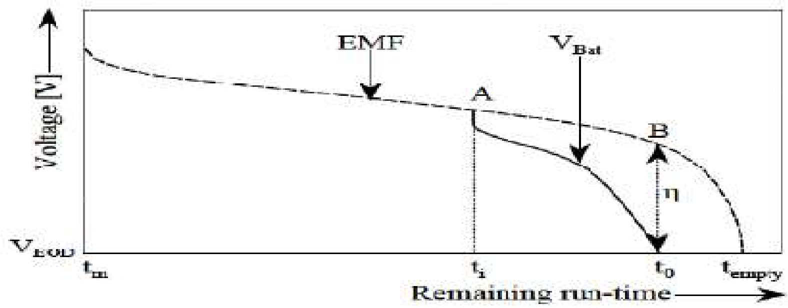

Figure 16: Remaining Runtime Estimation

Let the present operating point be "A" and "B" is the operating point at which the terminal voltage falls below the EoD voltage as shown in the figure 3.8. Then, the remaining runtime of a battery can be determined from the knowledge of estimated SoC i.e. "SoC_e", over potential "η" and the battery discharge current "I_{bat}". The OVP for a discharge current "I_{bat}" is given by,

$$\eta(I_{bat}) = \eta_{ser}(I_{bat}) + \eta_{TS}(I_{bat}) + \eta_{TL}(I_{bat}) \quad (3.12)$$

Where,

η_{ser} = OVP due to R_{ser}

η_{TS} = OVP due to R_{TS}

η_{TL} = OVP due to $_{RTL}$

For a known EoD voltage and measured OVP, the OCV can be calculated as,

$$OCV_{(EoD)} = V_{(EoD)} + \eta(I_{bat}) \quad (3.13)$$

The corresponding SoC at the EoD is given by,

$$SoC_{(EoD)} = f\,(OCV_{(EoD)}) \quad (3.14)$$

Then, the remaining runtime "T_r" is calculated as,

$$T_r = \frac{[SoC_e - SoC_{(EoD)}] * Q_{nom}}{I_{bat}} \quad (3.15)$$

Where,

Q_{nom} = Nominal Capacity of the Battery

$SoC_{(EoD)}$ = SoC at End of Discharge (EoD)

I_{bat} = Battery Current

SoC_e = Actual estimated SoC

Chapter 4

Matlab/Simulink Modelling

4. MATLAB/SIMULINK MODELLING

The algorithm proposed and discussed in the previous chapter is modeled using MATLAB/Simulink tool. This chapter explains the modeling of proposed algorithm using MATLAB/Simulink tool. This chapter also provides the simulation results for Coulomb Counting technique and proposed technique for pulse discharge current profile.

4.1 Modelling and Simulation

The simulation is the manipulation of model in such a way that it operates on time or space to compress it, thus enabling one to perceive the interaction that would not otherwise be apparent because of their separation in time or space.

Modeling and Simulation is a discipline for developing a level of understanding of the interaction of the parts of a system and of the system as a whole. A model is a simplified representation of the actual system intended to promote understanding. The model is good model or not depends on the extent to which it promotes the understanding. All the models are simplification of reality, there is always trade off level of details included in the model.

A simulation refers to computerized version of the model run over time to study the implication of the defined interactions. Simulations are generally iterative in the development.

The MATLAB/Simulink is an environment for multi-domain simulation and model based design for dynamic and embedded systems. This tool supports for customizable set of libraries for design, simulation and testing.

4.2 MATLAB/Simulink Model of Coulomb Counting Method

The MATLAB/Simulink model of Coulomb Counting technique is shown in Figure 17. The capacity of the battery is considered to be 44Ah. The initial SoC is assumed to be 100%. A discharge current of pulse profile with a magnitude of 10A is assumed as shown in Figure 18. The model is simulated for 20000 seconds and the SoC and remaining runtime are estimated as shown in Figure 19 and Figure 20.

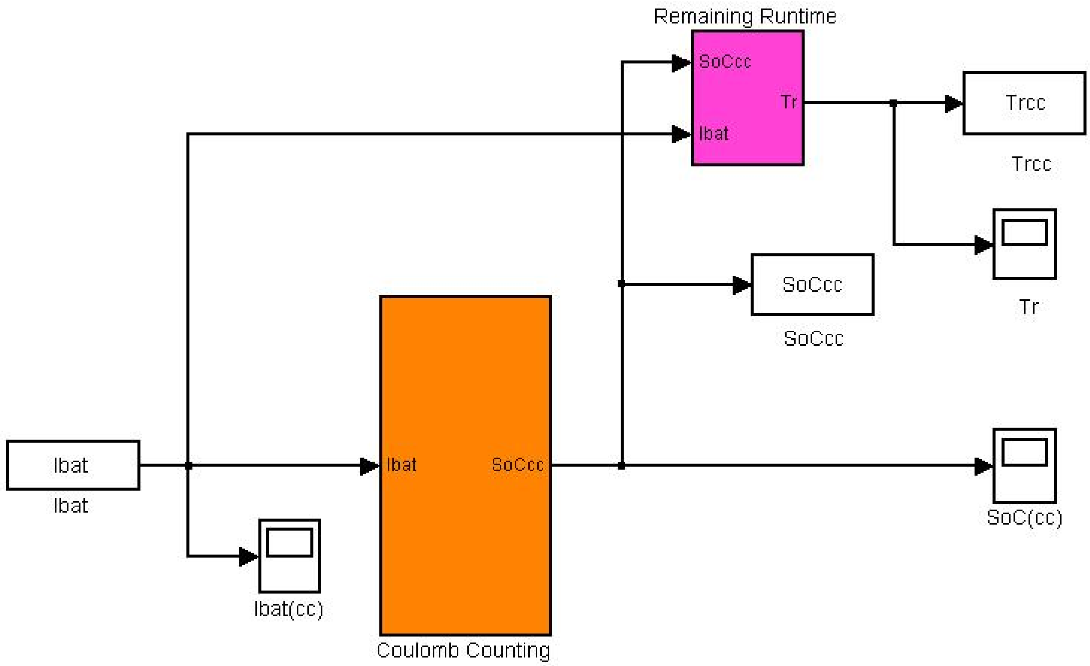

Figure 17: MATLAB/Simulink Model of Coulomb Counting Method

4.2.1 Simulation Results for Coulomb Counting Method

The discharge current profile is of pulse type as shown in the Figure 18.

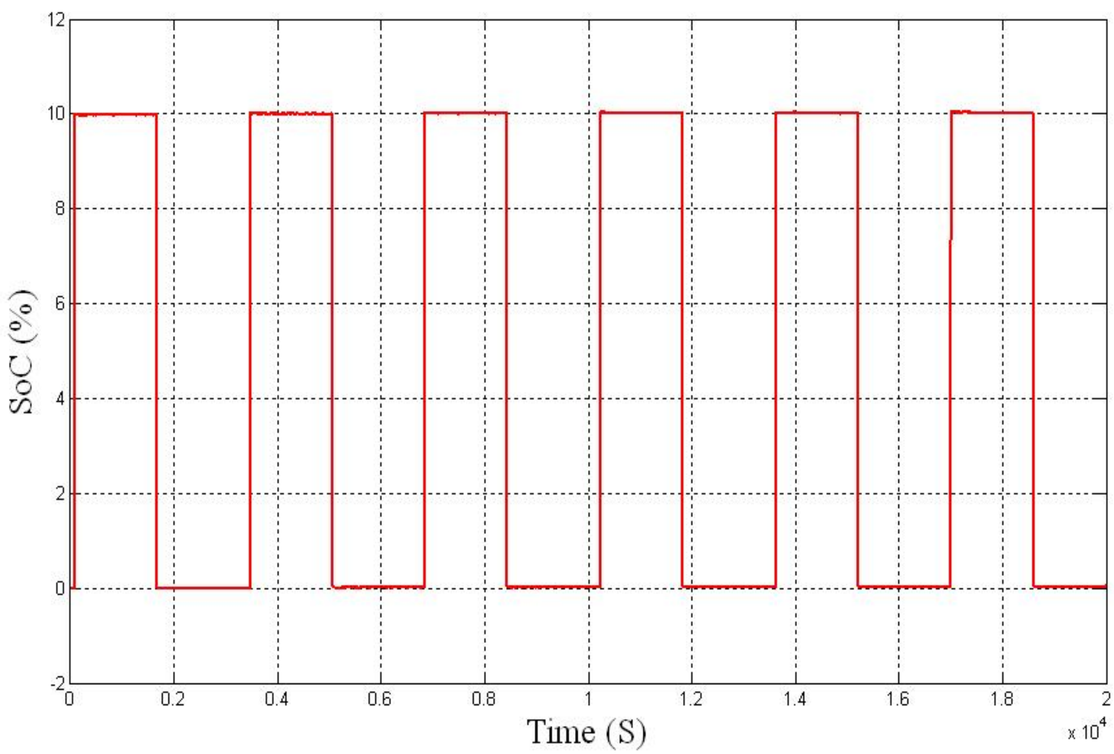

Figure 18: Simulation Results for Battery Current Profile

The simulation result for SoC estimated by Coulomb Counting method is shown in Figure 19.

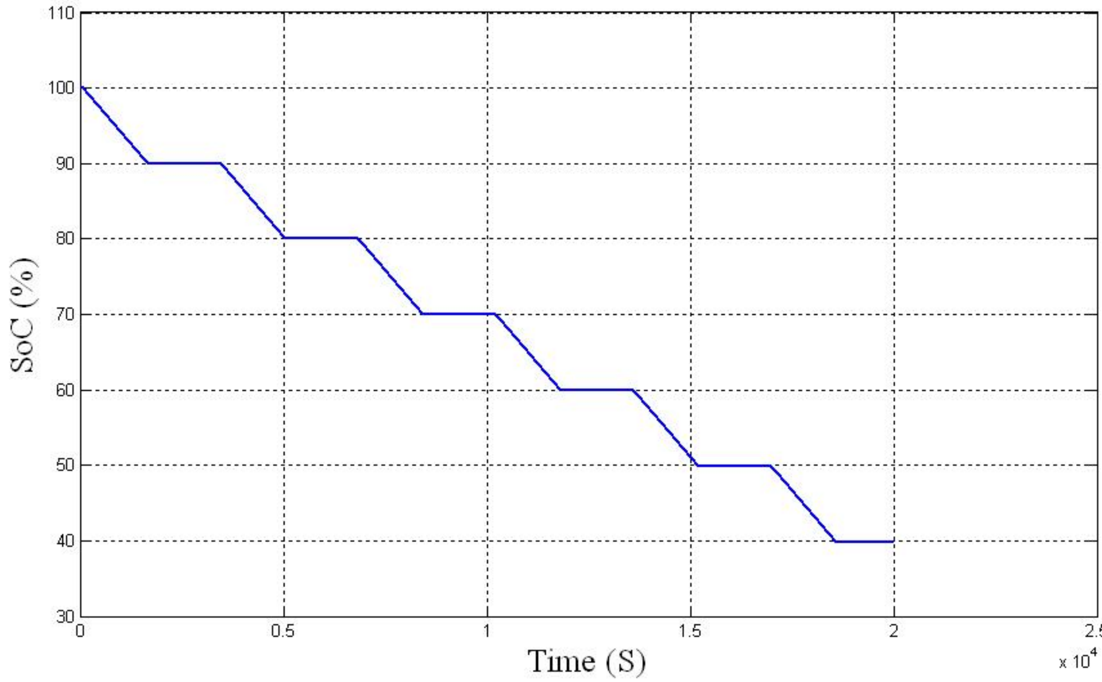

Figure 19: Simulation Result for SoC Estimation by Coulomb Counting Method

The simulation result for remaining runtime estimated by Coulomb Counting method is shown in Figure 20.

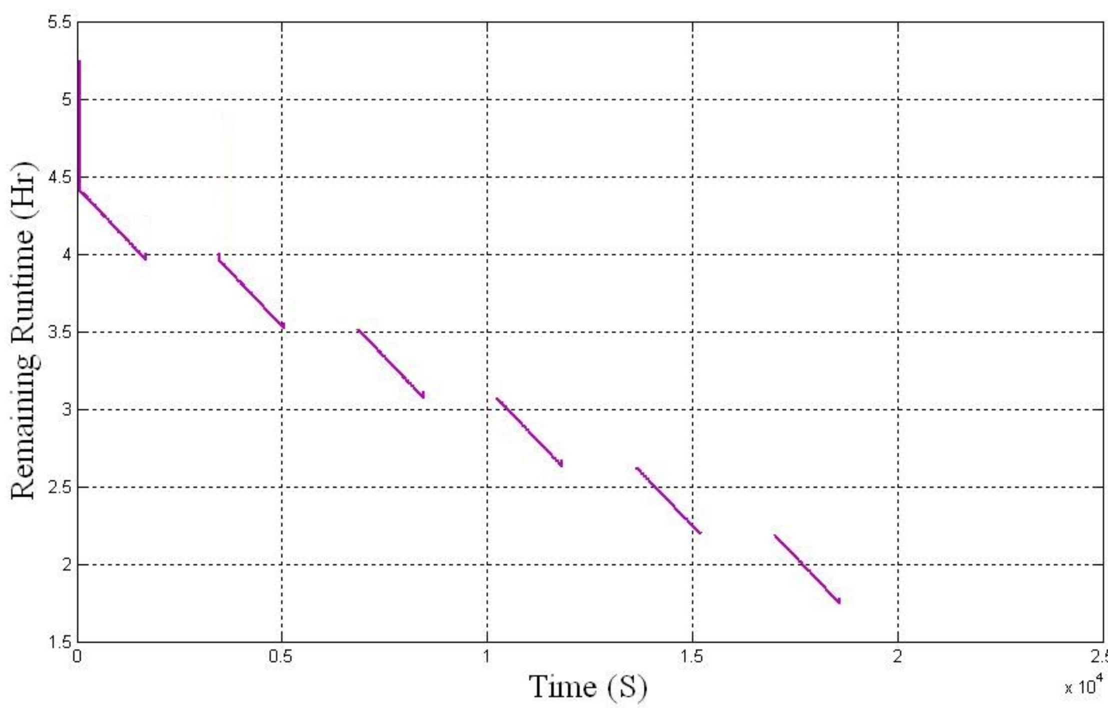

Figure 20: Simulation Result for Runtime Estimation by Coulomb Counting Method

4.3 MATLAB/Simulink Model of the Proposed Method

The MATLAB/SIMULINK model of Coulomb Counting technique is shown in Figure 21. The controller employed is a PI controller. The battery model parameters are obtained from discharge tests as explained in Section 3.2.2 and tabulated in **Error! Reference source not found.**. The correction factor obtained from the controller is summed up with the SoC obtained from Coulomb Counting technique. From the estimated SoC, the remaining runtime is estimated as explained in Section 3.2.5.

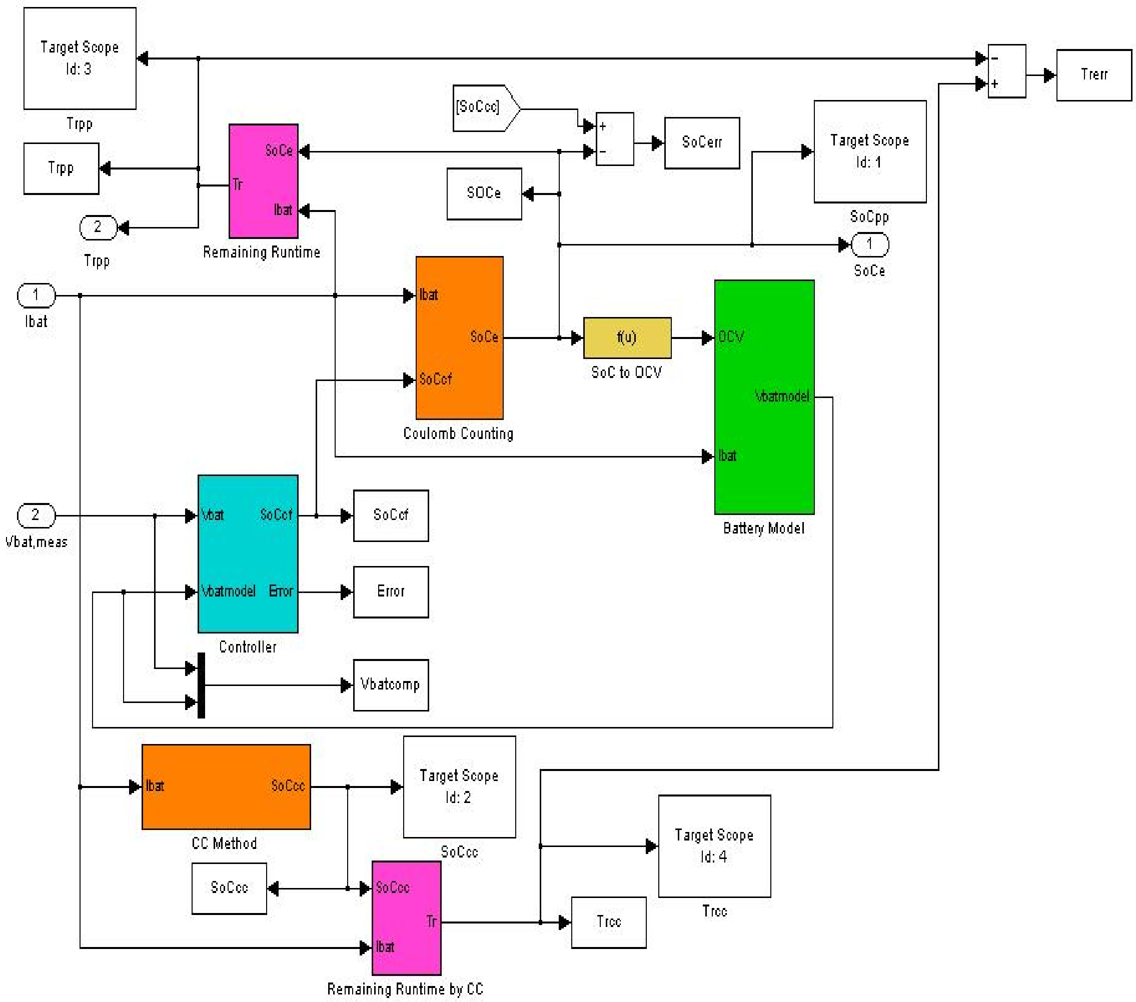

Figure 21: MATLAB/Simulink Model of Proposed Method

The proportional and integral constants of the PI controller are obtained by tuning. The tuning of these parameters is done using the Simulink Response Optimization toolbox. The above model is run in real-time where the battery current and voltage are acquired from the hardware test bench explained in the next chapter. Then, the SoC and remaining runtime are estimated online.

Chapter 5

Conclusion and future scope

5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

With the rising importance for battery, both in the automotive industry and the energy sector, it is of critical importance to develop more accurate algorithms for SOC estimation of the battery. This thesis presents a novel technique for SoC estimation of the battery where the SoC estimated by Coulomb Counting method is corrected using the battery model and a PI controller. The proposed method has an advantage of estimating SoC accurately even if there is an error in determining initial SoC and flaws in current measurement.

Based on experimental results obtained from battery testing, the battery equivalent model parameters are estimated. Then the proposed estimation technique is employed for the estimation of SoC which is further used in order to compute the remaining runtime of the battery. The SoC estimation technique was implemented for a battery current of pulse profile, and results for Coulomb Counting method and the proposed method are discussed in detail in chapter 6.

From the estimation results, we find that the SoC estimated from Coulomb Counting and the proposed technique has a maximum error of 12%. It is observed that there is a difference of 0.7Hr in the remaining runtime estimated by Coulomb Counting and the proposed technique. An error of 0.15Hr and 0.4Hr is observed in the estimated remaining runtime by the proposed and Coulomb Counting methods respectively when compared with the actual time. The advantage of this method is that it predicts the SoC by Coulomb Counting method and corrects it using a PI controller by employing a closed loop. Hence, this method can be employed in battery monitoring algorithms for the online estimation of SoC and remaining runtime (T_r) for many applications.

5.2 Future Scope

The novel method proposed is only a beginning in the online-estimation of SoC and remaining runtime. It is not an end in itself. In this estimation technique, the battery health is assumed to be 100% always. That is, the aging factor of the battery was not taken into account and hence the deterioration in the values of battery model parameters was not taken into consideration. Hence, the dependence of the battery model parameters with the cycle number ’n’ needs to be developed which will result in a non-linear model. Hence incorporating the effect of aging factor on the battery parameters is possible and a challenging sophistication that can be brought to this algorithm.

In addition, we have assumed that the operating temperature of the battery is constant; this is not true in practice. SoC as well as the battery model parameters has strong dependence on operating temperature. Hence, developing control logic for sensing temperature and also modifying the algorithm to allow the estimation of SoC even for various operating temperatures would be a more advanced sophistication in the model.

Hence, we conclude that the proposed method in the thesis is a new progress in the estimation of SoC and remaining runtime. However, more interesting and challenging sophistication can be added to the proposed method for a more precise and efficient battery monitoring

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