Modeling Lithium-Ion Rechargeable Battery System

by

Kausillyaa Rajakumar

Dissertation submitted in partial fulfillment

of the requirements for the

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Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

DR VIJANTH SAGAYAN ASIRVADAM

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

I hereby declare that the project titled "**Modeling Lithium-Ion Rechargeable Battery System"** is my own work and to the best of my knowledge. Any contribution made to the research by others, with whom I have worked for this project, explicitly acknowledged in the thesis.

I also certify that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic is acknowledged.

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KAUSILLYAA RAJAKUMAR

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ABSTRACT

Battery-powered electronics devices have become well-verse in the current society. The rapid growth of the use of portable devices such as portable computers, personal data assistants, cellular phones and Hybrid Electrical Vehicles (HEVs) creates a strong claim for fast deployment of the battery technologies at an extraordinary rate. The design of a battery-power-driven device requires many battery-management features, including charge control, battery-capacity monitoring, remaining run-time information and charge-cycle counting. Portable energy storage devices such as batteries are needed when the need in mobility increase. Compare to other batteries, lithium battery has the highest power density, energy density and the longest cycle life. Lithium batteries have been highly used as a choice of rechargeable battery for portable consumer electronic tools. The main objective is to develop a battery management system model to ensure that optimum use is made of the energy inside the battery powering the portable device and that the risk of damage to the battery is prevented. This is achieved by simulating the battery's charging and discharging process. Modeling a battery management system by studying the charging and discharging characteristic curve of the lithium-ion battery is being proposed in this research project. This battery management model will construct a charging and discharging curves which will show different percentage of charges and discharge rate when it is connected to various loads. This model can further study on testing the other parameters effect towards the performance of the battery using the existed constructed model.

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Abbreviations & Nomenclature

V_{bat}	=	Battery output voltage [V]
V_{oc}	=	Battery open-circuit voltage [V]
Z_{eq}	=	Battery equivalent internal impedance [Ω]
I_{bat}	=	Battery current [A]
$\Delta E(T)$	=	Temperature correction of the potential [V]
SOC	=	State of charge
SOC_{init}	=	Initial state of charge
C_{usable}	=	Usable battery capacity [Ah]
T	=	Temperature [^{o}C-^{o}K]
t		Storage time [months]
Q_n	=	Change in state of charge of battery negative electrode
N	=	Cycle number
k_1	=	Coefficient for the change in SOC of battery negative electrode [cycle^{-2}]
k_2	=	Coefficient for the change in SOC of battery negative electrode [cycle^{-1}]
k_3	=	Coefficient for the change in R_{cycle} [Ω/cycle$^{1/2}$]
CCF	=	Capacity correction factor
C_{init}	=	Initial battery capacity [Ah]
E_{Batt}	=	Nonlinear voltage (V)
E_0	=	Constant voltage (V)
Exp(s)	=	Exponential zone dynamics (V)
K	=	Polarization constant (Ah^{-1}) or Polarization resistance (Ohms)
i*	=	Low frequency current dynamics (A)
i	=	Battery current (A)
it	=	Extracted capacity (Ah)

Q	=	Maximum battery capacity (Ah)
A	=	Exponential voltage (V)
B	=	Exponential capacity $(Ah)^{-1}$

Chapter 1

Introduction

1.1 Background Studies

The current innovation relates commonly to the field of Battery Management Systems (BMS), and more specifically it related to the control system to control and monitor the charging of the rechargeable batteries. Today, the typical effort to conserve precious reserves of fossil fuels and to reduce emissions of air pollutants are being achieved by the invention of electrically powered vehicles in daily usage. Electric vehicles (EV) rely upon a battery pack consist of consistent recharging battery connected in series and management to maintain the batteries to charge optimum in order to provide motive force for the vehicle (Jose T. Baer et al. 1997)

The conventional Battery Management Systems provide a battery model by only using state of charge (SOC) as a state variable in order to accurately reproduce the charging and discharging curves. In the present invention, a step taken to improvise the accuracy of the curve graph value obtained and to combine both charging model and discharging model into one single simulation using the same method.

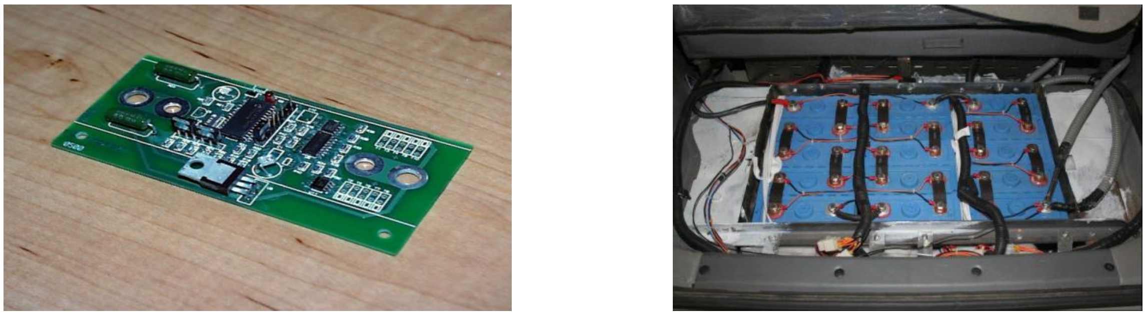

Figure 1: Battery Management System

The rechargeable batteries are essentially being used to provide power for only a few hours. Once the battery's power discharged (depleted), the robot/batteries must be connected to a recharger via human intervention. So in cases as such the battery management is essential need to control the load on the battery or by isolating/disconnecting the battery from the load such as robots if the load cannot be controlled.

Lithium based rechargeable batteries were first demonstrated in the 1970's. At the present days, lithium batteries gained much wider usage. It enables the technology in many applications such as mobile phones, laptops, PDA, cameras and other consumer electronic products. However, in high power applications, they hardly use it except some R&D projects because of costly and safety concern.

Figure 2: Product of Lithium-Ion Battery in existing market

1.2 Problem Statement

Lithium-ion battery is a type of rechargeable battery that currently being commonly used in electronic devices and electric vehicles. Whereas, Battery Management System (BMS) plays an important role in keeping track on the key parameters such as voltage, current, and internal/ambient temperature of the batteries during its charging and discharging period. In current research, to test the battery's charging and discharging property, we have to use the conventional method by conducting experiment in lab using scope box which consumes time. Thus, to overcome this problem, the battery management system model simulation is generated.

1.3 Objective

The main objectives that be achieved for this research project are as follow:

a) Determination of appropriate battery model to be used for the Battery Management System.
b) Build a complete block diagram models for Lithium-Ion battery using Matlab Simulation.

1.4 Scope of Study

In order to complete this research project, the suitability characteristics of lithium-ion battery for battery model construction have to be determined. Further to that, a model of Battery Management System will be constructed by using the Matlab-Simulation approach. The proposed model will improvise the existing non-linear battery model by constructing a merged model to study both charging and discharging characteristic of lithium-ion battery using fixed parameters.

1.4.1 The relevancy of the project

In this project we will be focusing on constructing the non-linear battery model by studying the charging and discharging property of the battery. Studies states the property of the battery changes when the battery being charged and discharged with the existence of load. Thus it will be highly beneficial for the researcher if there basic battery model is constructed as a reference point. Furthermore the result model can be used as reference by future researcher to conduct their test on different parameter of the battery. Plus, battery management system is a field that being highly looked into for power management purpose.

1.4.2 Feasibility of the project within scope and time frame

The project is divided into two sections. The first section will basically be on finding, collecting, and reading of journals, technical papers, and books of the research topic. In this section one, the non-linear battery model is being identified to be used to study the charging and discharging characteristic of the lithium ion battery.

The second section of the project will be mainly is to construct the charging and discharging model of the lithium ion battery using MATLAB-Simulink Software. Once the two separate models can be converged; it will be merged into one model where it could be used as a reference model by future researcher to test on their parameters. The discharging model has being constructed during the FYP 1. While the charging and the merged model will be completed during FYP 2.

Chapter 2

Literature Review and Theory

2.1 Literature Review on Lithium Ion Battery

Batteries are the most common electrical energy storage devices in electrical vehicles. The performance of a battery when it is connected to a load or a source is based on the chemical reactions inside the battery. The chemical degrade with time and usage that reflect the gradual reduction in the energy storage capacity of the battery. The battery depreciation process needs to be reduced by conditioning the battery in a suitable manner by controlling it's charging and discharging profile, even various load conditions. In general, battery life time will be diminished when the battery is operated under a wide range of thermal conditions. Batteries are safe, despite reports of explosion of failure, when used with a power conditioning system that incorporates safety features and automatic shutdown. Basically there are two aspects taken into consideration to enhance battery performance. Firstly is the capability of the battery itself, which it depends on the material of the battery been constructed and the making process. Secondly is the Battery Management System (BMS) (K.W.E. Cheng et al. 2011)

Lithium-ion battery is a family of the rechargeable battery type. It is one of the most common types of rechargeable batteries used for portable electronic devices and electric vehicle. Lithium battery is chosen as one of the best energy densities, higher power density, and has long cycling life compare to Lead-Acid battery and Nickel Metal Hydride battery. Lithium battery also has no memory effect and low self discharge when it is not in use. Due to these characteristics, lithium-ion battery has come into people's attention more frequently. Table 1 are results that been obtain by Li Siguang et al. 2009 to compares the parameters and the characteristics of lithium-ion battery to other 2 types of batteries. Thus, the parameters of lithium-ion battery are greater compare to Lead-Acid battery and Nickel Metal Hydride battery.

Table 1: Comparison parameters of different type of battery

Category of battery	Energy density (Wh/kg)	Power density (W/kg)	Cycle life (time)	Cost ($)
Lead-acid	30~50	200~400`	400~600	120~150
NiMH	50~70	150~300	>800	150~200
Lithium	120~140	250~450	1200	150~180

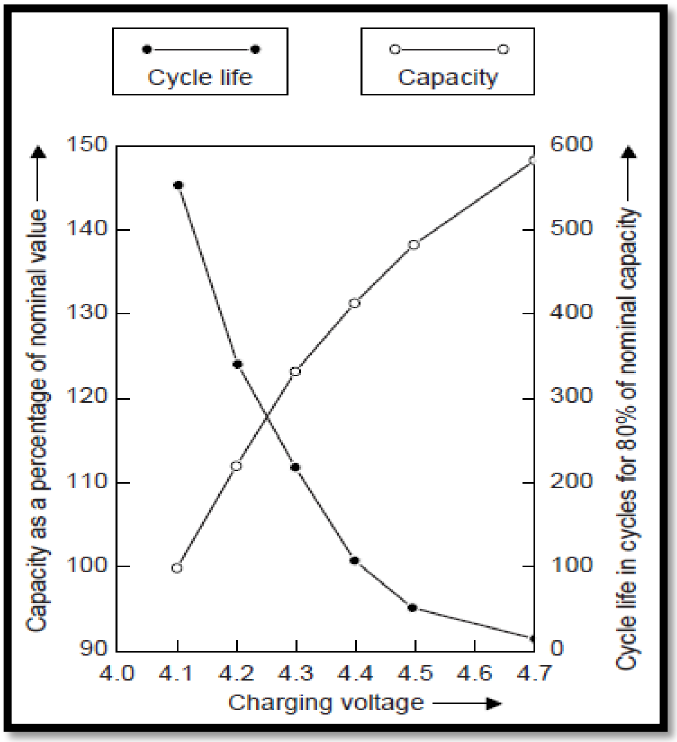

Figure 3: Maximum battery capacity and cycle life as a function of a battery voltage for Li-Ion Battery

Above figure illustrates that the higher this voltage, the higher the maximum battery capacity and the lower the cycle life will be. Around 4.1 to 4.2 V, a 100 mV increase in battery voltage yields a 12% capacity increase, but a sharp decrease in cycle life of 200 cycles.

The best description of the nature of chemical batteries can be found in Per Bro and Sam Levy's book entitled, *"Quality and Reliability Methods for Primary Batteries."* They claimed that ***"batteries are unique…….living, dynamic systems that respond to their environment….not observed by with other electrical components**."* Lithium is the lightest of metals and it can floats on water. The greatest electrochemical potential in it makes it one of the most reactive of metals with high energy and power densities. With these features it has been used in high power battery applications such as automotive and standby power. (Charles J Scuilla et al. 2007)

The construction of lithium-ion battery includes a negative electrode, a positive electrode, separator between the electrodes, and electrolyte for submerging the electrodes. The negative electrodes is made of active materials including at least one lowly graphitizes carbon material and least one highly graphitized carbon material and least one highly graphitized carbon material. The positive electrode made of active materials including lithium ion, transition metal ion and polyanion (Cheng-Hua FU et al. 2010).

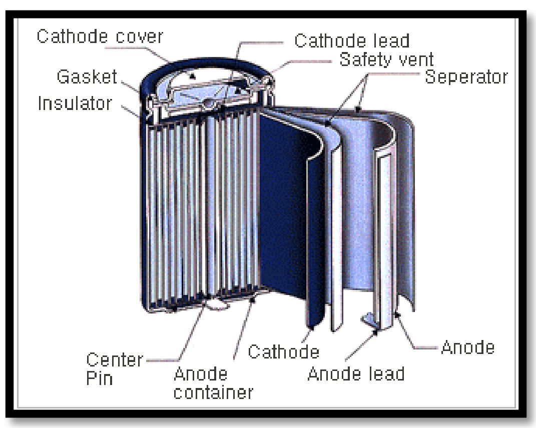

Figure 4 : Structure of Lithium-Ion Battery

2.2 Literature Review on Battery Management System

Battery Management System is defined as a control or management unit plurality of rechargeable batteries. An ideal BMS will be energy efficient, drawing as little power as possible, effective at realizing the full capacity of the batteries through effective balancing and ensure that the batteries are not being damaged by over charging, discharging or excessive current load or discharge.

2.2.1 Why Battery Management System needed?

An intelligent battery management system is needed because the battery chargers presently in use are shortening the life of entire sets of batteries. Proper charging and discharging of a battery can significantly lengthen its life and also produce more efficient use of the battery.

2.2.2 Functions of Battery Management System

The increased interest in electric vehicles and electronic devices, Battery Management System has become one of the chief components. Battery monitoring is vital for the electric vehicles and electronic devices, because the safety, operation and the life span of the battery depends on the battery management system. Battery Management Systems (BMS) handle all monitoring, control and balancing and safety circuitry of the battery packs and control systems. Battery Management Systems effectively monitors the cell voltages, balances the voltages between the cells to maintain a constant pack voltage, and manages its charging and discharging. Besides that, the other important feature of Battery Management System is to protect the system from over-voltage and over-current conditions for packs of cells in series. It also monitor system temperatures, handles power saving, and interact with external controllers to provide system feedbacks (Grant Gothing et al. USA).

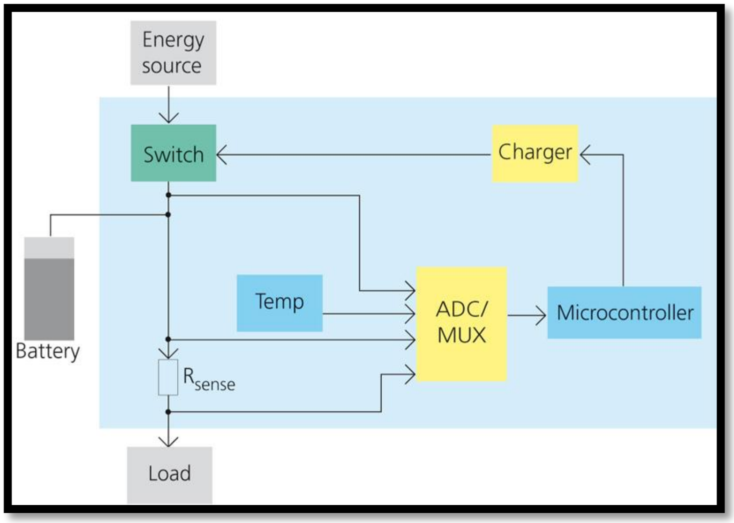

Figure 5 : General Architecture of a Battery Management System

2.3 Lithium Ion Battery (Theory Approach)

The positive active material is oxidized, producing electrons, and the negative material is reduced, consuming electrons during the charging period. In the external circuit, these electrons constitute the current flow. In lithium ion cells, the electrolyte may serve as a simple buffer for internal ion flow between the electrodes. A battery charger using AC mains electricity is being used to charge rechargeable batteries, though some are equipped to use a vehicle's 12-volt DC power outlet. Charging period takes from a few minutes to several hours to charge a battery. Approximately 14 hours or more will be needed to complete a full charge whereas for slow chargers without voltage- or temperature-sensing capabilities will charge at a low rate. Rapid chargers can typically charge cells in two to five hours, depending on the model, with the fastest taking as little as fifteen minutes. There are multiple ways of detecting when a cell reaches full charge (change in terminal voltage, temperature, etc.) to stop charging before harmful overcharging or overheating occurs by the fast chargers. The fastest chargers often incorporate cooling fans to keep the cells from overheating.

The cell consists of five regions which include a negative-electrode current collector made of copper, a porous composite negative insertion electrode, a porous separator, a porous composite insertion electrode and positive-electrode current collector made of aluminum. The active materials particles held together by a binder and a suitable filler material such as carbon black to produce composite electrodes. The negative electrode is fully lithiated and the positive electrode is ready to accept lithium ions when discharge about to begin. During discharge, the lithium ions deintercalate from the negative electrode particles and the solution phase, while in the positive electrodes region lithium ions in the solution phase, while in the positive electrode region lithium ions in the solution phase intercalate into the LiCoO2 particles. This drives lithium ions from the negative electrode to the positive electrode into gradient concentration. During discharge, the cell voltage decreases as the equilibrium potentials and over potentials of the two electrodes are strong functions of the concentrations of lithium on the surface of the electrode particles. After the voltage drop to 3.0V, the cell has reached to end of discharge period.

Lithium metal oxides for storing the lithium ions are the medium for the positive electrodes. The negative carbon electrode is made up of petroleum coke or graphite. The electrolytes are salt that dissolved in an organic solvent. The Li-ion batteries operating voltage is critical and over-discharging results in fast aging and may cause fire or even exploding batteries.

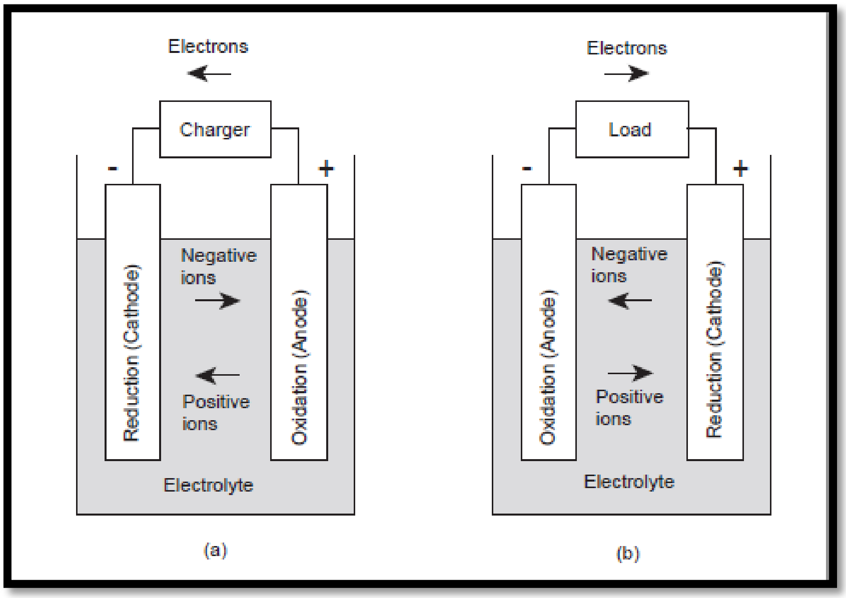

Figure 6 : Electrochemical operation of battery during charging (a) and discharging (b)

2.3.1 Over charge affects the battery performance

The process of charging a battery after it being fully charged is called overcharge. The positive state of charge is higher than the negative on design. Thus this resulted in oxygen generation in positive can composite, through separator, with Cd generated in negative. The internal pressure will not rise in normal state of the battery. Compare to cases where the charge current is high or the charge time is so long, and the generated oxygen cannot be used up in time, there will be some quality defect risen such as internal pressure rising, battery distortion, leakage and so on. Meanwhile its performance will decline.

2.3.2 Over discharge affects the battery performance

The state of over-discharge will occur when the discharge is continuous though the battery the cell's voltage reaches a designed value, which means the battery has discharge the stored capacity. The end voltage can be identified through end discharge current. Over discharge may cause to the malfunction of the battery, especially at heavy current or repeated over discharge. Over discharge can make cell inner pressure raise, and causes the reliability of the materials both in positive and negative electrode will be damaged.

Chapter 3

Methodology

3.1 Research Methodology & Project Activities

Different findings and methodologies are gathered from the research work of other researchers and to be incorporated in this project. First and foremost, various journals and technical papers were read through the get the general understanding on the project. It is also needed to identify the objective of this project and to come up with a proven method to simulate the model.

The main topic that study need to be done will be on the principal characteristic of the lithium-ion batteries. All the principal characteristic of the lithium battery need to be identified and the criteria to differentiate it been other batteries should be known. Other research need to be done on the modeling of Battery Management Systems. There are mainly three types of battery models; experimental, electrochemical and electric-circuit based (O.Tremblay et al. 2007). Experimental and electrochemical models are not recommended to represent cell dynamics for the purpose of state-of-charge (SOC) of the battery. Electric circuit-based models are recommended as it can be useful to represent electrical characteristic if the batteries.

Table 2: Comparison of different model of Battery Management System

Technique	Field of application	Advantages	Drawbacks
Simplest Electric Model (Durr Mattias et al. 2006)	Ideal voltage source in series with an internal resistance	Simple construction, Low cost	Does not take account of the battery SOC Only discharge curve being produced
Warburg Impedance Model (E.Kuhn et al. 2006)	Open circuit voltage in series with resistance and parallel RC circuit (E.Karden et al.1997)		The identification of all the parameters of this model is based on a complicated technique called spectroscopy
Shepherd Model (Shepherd et al. 1965)	An equation developed to describe the electrochemical behaviour of a battery directly in terms of terminal voltage, open circuit voltage, internal resistance, discharge current and state of charge.	Can be applied for charge and discharge model	Causes algebraic loop problem in closed loop simulation of modular models (Gregory et al. 2004)
Non- Linear Battery Model	Battery models with only SOC as state as state of variable	Similar to Shepherd's Model but it does not produce an algebraic loop	

Thus, the non-linear battery model is being used in the proposed project. This model uses SOC as a state of variable to produce the charging and discharging curve. The chosen model is constructed using several assumptions such as:

a) The internal resistance is supposed to be constant during charge and discharge cycle and does not vary with the amplitude
b) The model's parameter are deduced from the discharge characteristics and assumed to be the same for charging
c) The capacity of the battery does not change with the amplitude of the current
d) The temperature does not affect the model's behavior
e) The self-discharge of the battery is not represented.
f) The battery has no memory effect

In order to obtain a physical charging and discharging curve, a system need to be created using the charging and discharging equation. The objective of the project is obtain when the right equation being determined for the lithium-ion battery, because the model of charging and discharging will change base on the type of battery used. The battery model will be built based on some specific assumption and limitations. Once all the calculation procedure has been identified, it needs to be translated into simulation blocks using computation software of MATLAB to be converge. The equivalent circuit of the battery is shown below:

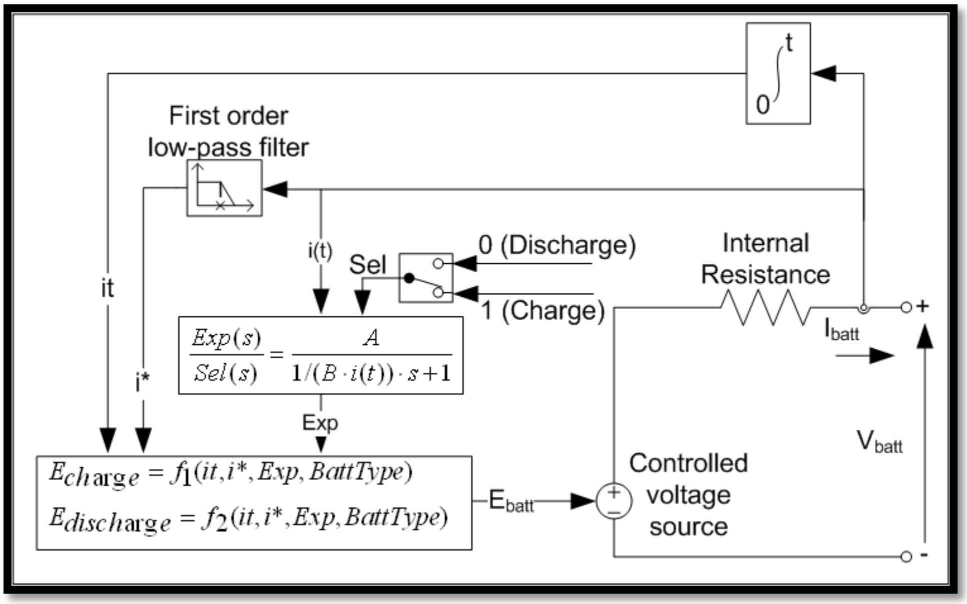

Figure 7 : Non- Linear Battery Model

Lithium-Ion Model:

Discharge Model (i* > 0)

$$f_1(it, i*, i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \qquad (1)$$

Charge Model (i* < 0)

$$f_2(it, i*, i) = E_0 - K \cdot \frac{Q}{it-0.1.Q} \cdot i * -K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \qquad (2)$$

The models limitations are as per below:

a) The minimum no-load battery voltage is 0 V and the maximum battery voltage is not limited. (O.Tremblay et al. 2007)
b) The minimum capacity of the battery is 0 Ah and the maximum capacity is not limited. (O.Tremblay et al. 2007)

3.2 Tools Required

In order to complete this project, the end product would be modeling of this Battery Management Systems in the computation software. The software is needed to translate the calculation procedure into simulink-blocks. The software chosen is computation software of MATLAB-Simulink.

This software was developed by Mathworks. This software is a commercial tool for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. Simulink is widely used in control theory and digital signal processing for multi-domain simulation and Model-Based Design. The calculation method of the model will be changed into block diagrams this software.

3.3 Work Flow

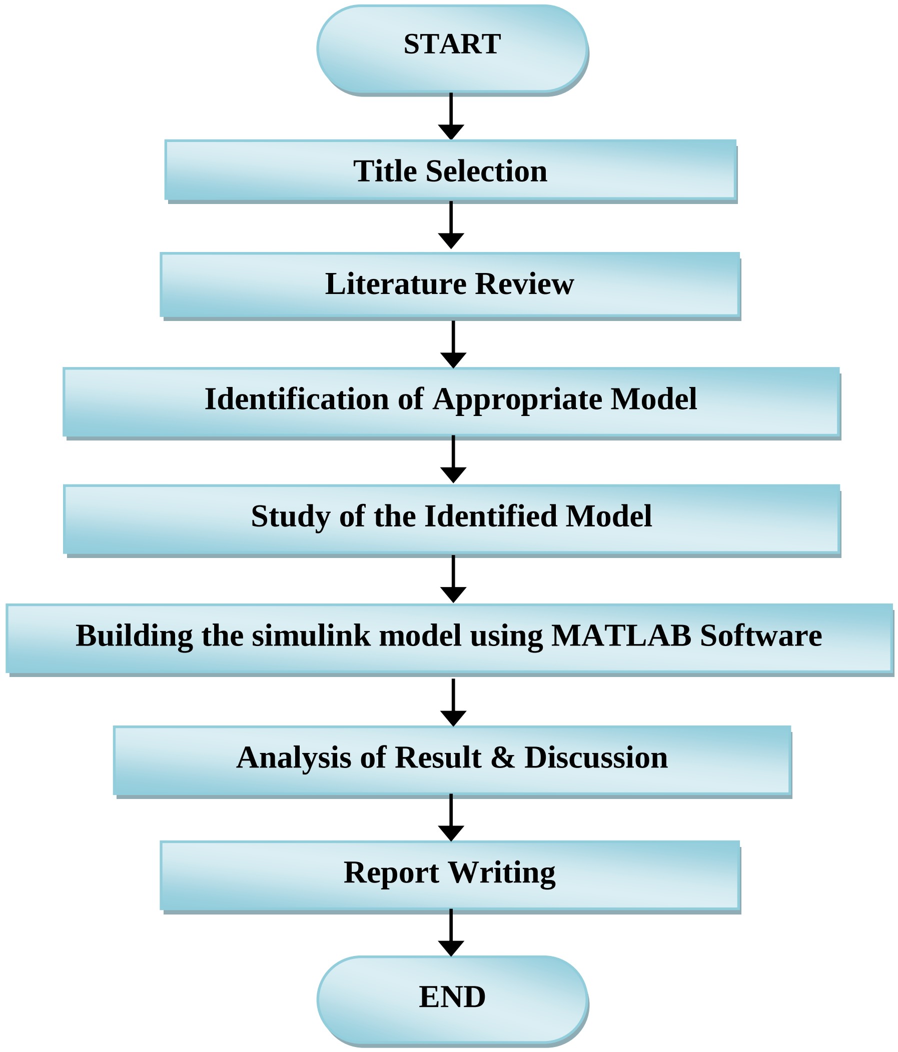

Figure 8: Project Activities Flow Chart

3.4 Activities/Gantt Chart and Milestones

Table 3: Gantt Chart of Weekly Task for Semester 1 & 2

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
	FINAL YEAR PROJECT 1															
1	Selection of Project Topic								Mid Semester Break							
2	Preliminary Research Study															
3	Submission of Extended Proposal						28/2									
4	Literature Review on Selected Topic															
5	Proposal Defense															
6	Viva: Project Defense and Progress Evaluation									08/3 - 21/3						
7	Report Preparation															
8	Submission of Interim Draft Report															16/4
9	Submission of Interim Report															23/4

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
	FINAL YEAR PROJECT 2															
10	Submission of Progress Report									9/7						
11	Draft Report													08/08		
12	Final Report (Soft Cover)														15/08	
13	Technical Paper														15/08	
14	Viva															28/08
15	Final Report (Hard Cover)															10/09

Processes

Chapter 4

Result and Discussion

4.1 Simulation Setup

A charging and discharging system for the different type of battery models created based on equation for charging and discharging equation. The equation differs from one battery to another. As for this project we use the lithium ion charging and discharging equation (1) and (2).

Discharge Model (i* > 0)

$$f_1(it, i*, i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \quad (1)$$

Charge Model (i* < 0)

$$f_2(it, i*, i) = E_0 - K \cdot \frac{Q}{it-0.1.Q} \cdot i* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \quad (2)$$

4.2 Battery Discharge

Before start the modeling process, certain parameters required by the system has being finalized to be inserted into the model. The parameters mentioned are as per below

Table 4 : Battery parameters (Discharge)

Parameters Type	**E_0(V)**	**R(ohm)**	**K(V)**	**A(V)**	**B $(Ah)^{-1}$**
Lithium-Ion Battery	3.7348	0.09	0.00876	0.468	3.5294

Battery open circuit voltage is used to calculate the battery's output voltage. The resulting voltage drop from the battery equivalent internal impedance and the temperature correction of the battery potential. The battery output voltage expressed as:

$$V_{bat} = V_{OC} - i_{bat} \times Z_{eq} + \Delta E(T) \qquad (3)$$

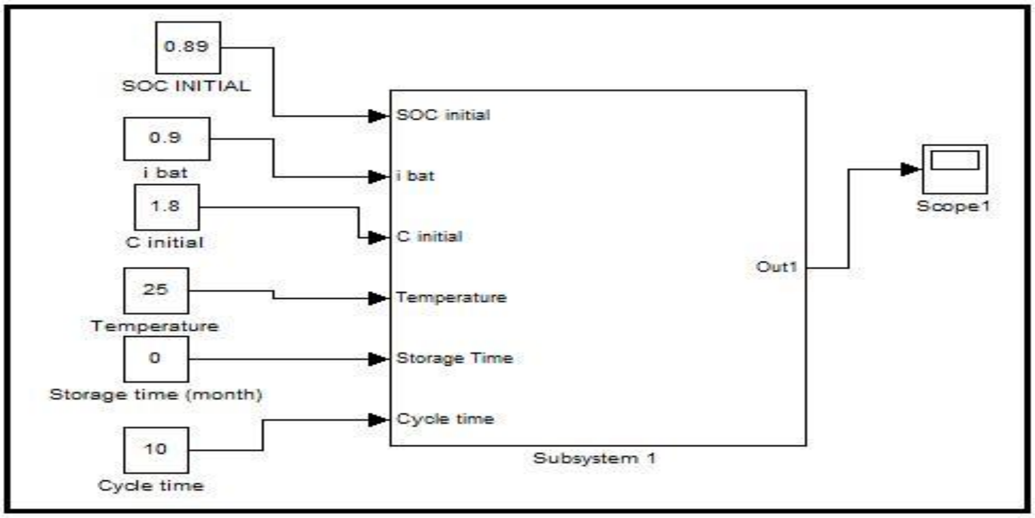

Figure 9 : Simulation Block Diagram of the Main System (Discharge)

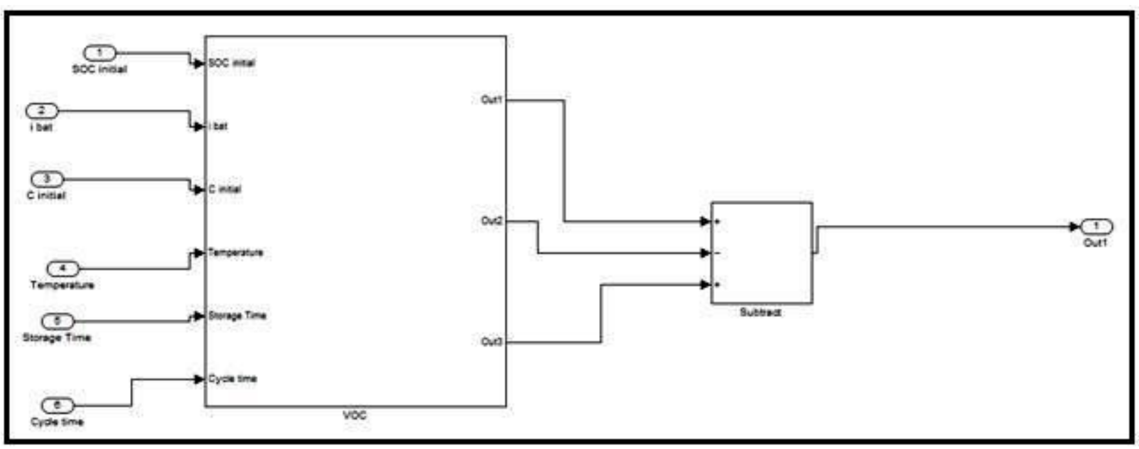

Figure 10 : Simulation Block Diagram for Subsystem 1

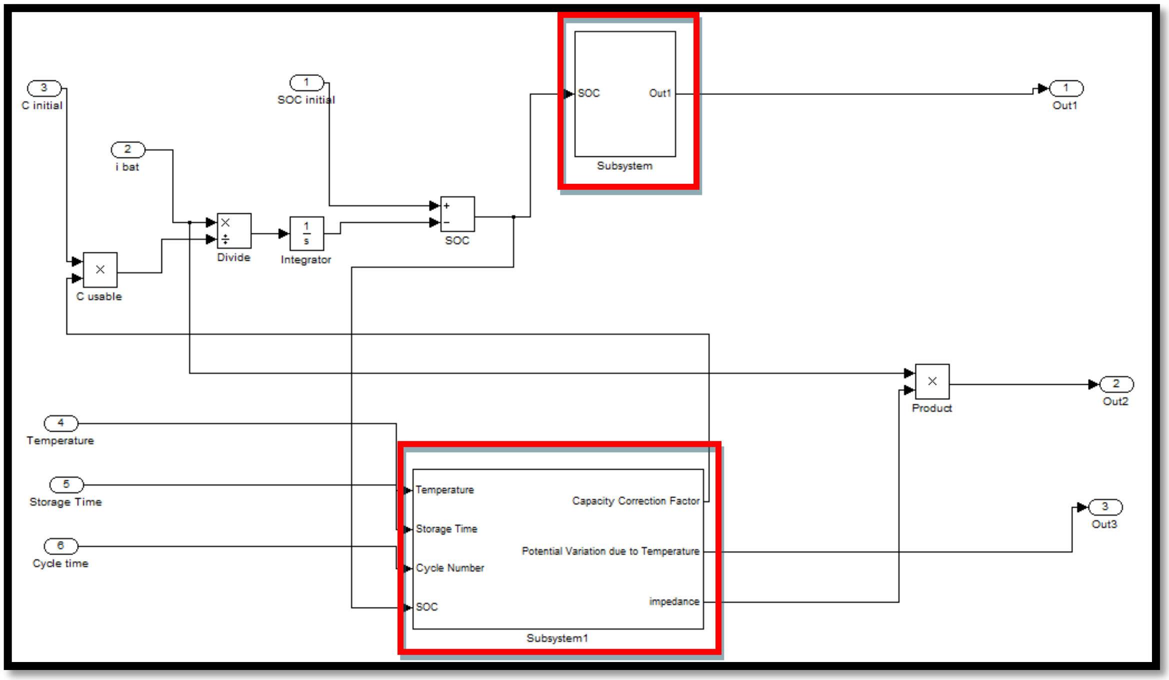

Figure 11 : Simulation Block Diagram for Voltage Open Circuit

4.2.1 The battery open circuit voltage

The difference of electrical potential between two terminals of a battery when there is no external load connected is known as battery open circuit voltage. The value of open circuit voltage can be calculated as below:

$$V_{OC}(SOC) = -1.301 \times \exp(-35 \times SOC) + 3.685 + 0.1256 \times SOC - 0.1178 \times SOC2 + 0.321 + SOC3 \quad (4)$$

The battery SOC can be expressed as:

$$SOC = SOC_{int} - \int (i_{bat} / C_{usable}) dt \quad (5)$$

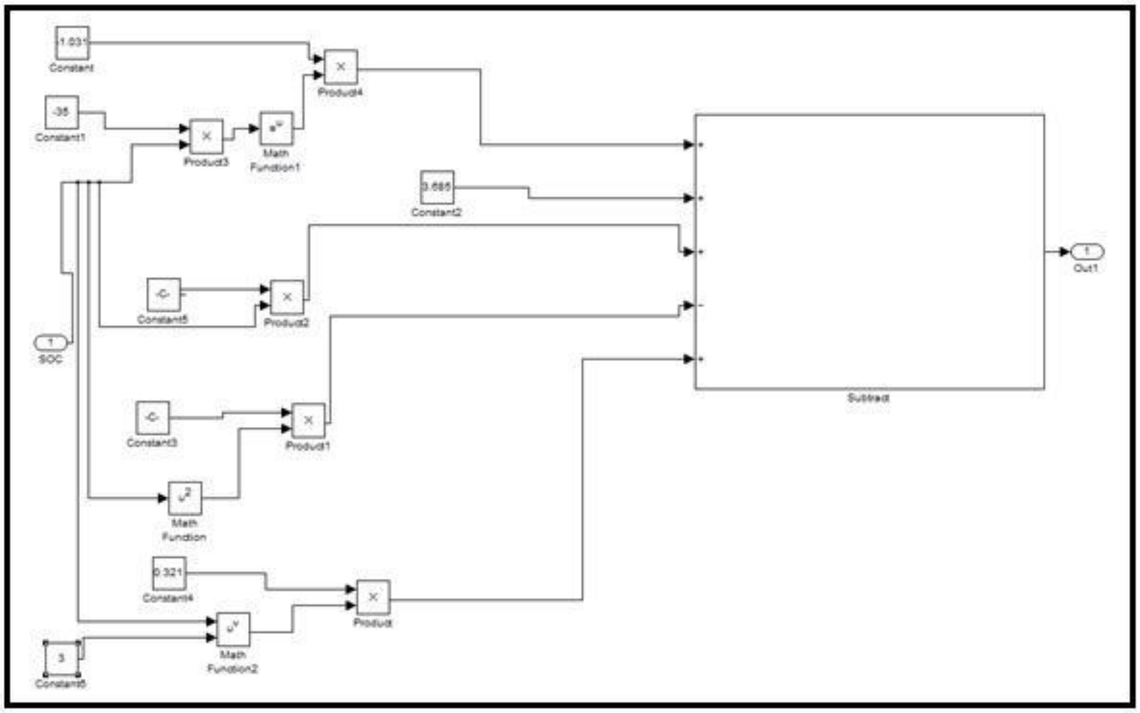

Figure 12 : Simulation Block Diagram for Voltage Open Circuit dependent in battery SOC (Subsystem)

4.2.2 The effect of capacity fading

Capacity fading is known as the irreversible loss in usable capacity of a battery due to temperature, cycle number and time. The capacity correction factor can be calculated as:

$$CCF = 1 - (Calendar\ life\ losses + cycle\ life\ losses) \quad (6)$$

Then the remaining usable battery capacity defined as:

$$C_{usable} = C_{initial} \times CCF \quad (7)$$

During the battery is not in use, the calendar life losses of a battery consist of storage losses. The percentage of storage losses are as per below

$$\%\ storage\ loss = 1.544 \times 10^7 \times \exp\left(\frac{40498}{8.3143 \times T}\right) t \quad (8)$$

Life cycle losses:

Table 5 : Values of the coefficients dependent on cycling temperature

Cycling temperature (°C)	$k_1\ cycle^{-2}$	$k_2\ cycle^{-1}$	$k_3\ cycle^{-\frac{1}{2}}$
25	8.5×10^{-8}	2.5×10^{-4}	1.5×10^{-3}
30	1.6×10^{-6}	2.9×10^{-4}	1.4×10^{-3}

k_1 = capacity losses that increase rapidly during adverse condition such as cycling at high temperature (Erdinc et al.2009)

k_2 = factor to account for capacity losses under usual conditions of cycling (Erdinc et al.2009)

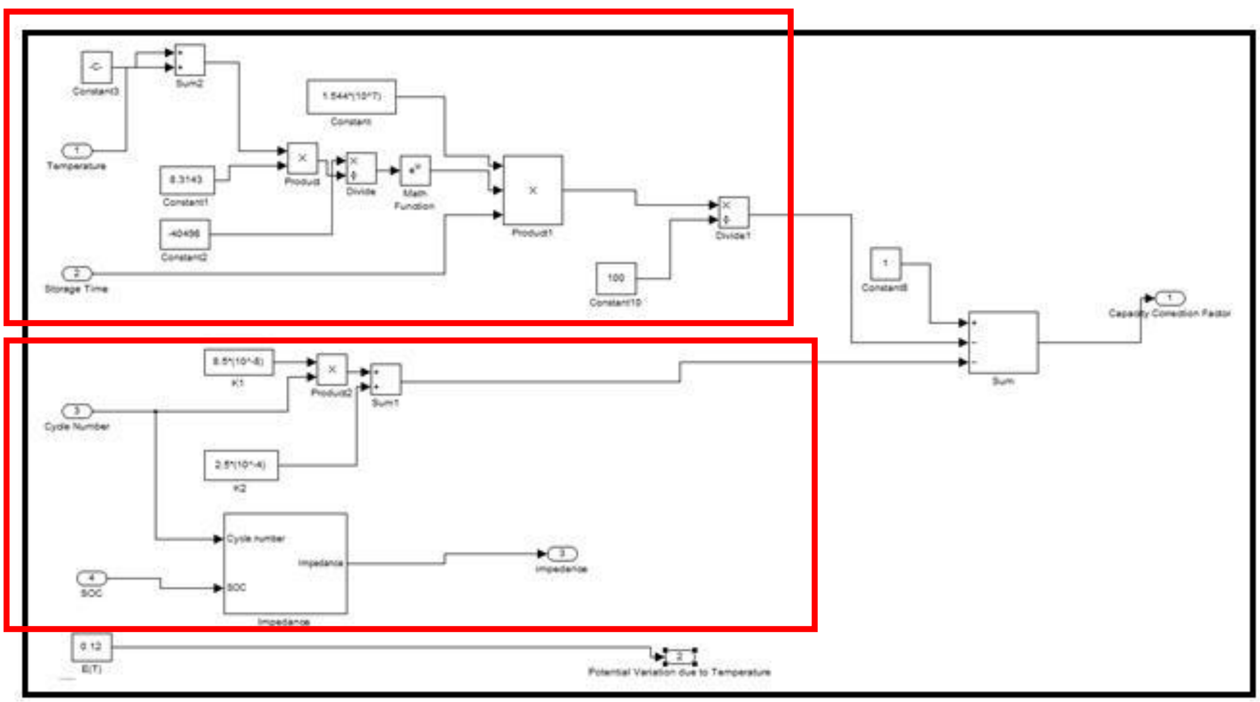

Figure 13 : Simulation Block Diagram for Subsystem 1

4.2.3 Variable equivalent internal impedance of battery

The battery equivalent internal impedance consists of a series of resistor composed of R_{series} and R_{cycle} and two RC network composed of $R_{transient_L}$, $C_{transient_L}{'}$ $R_{transient\_S}$, and $C_{transient\_S,}$. R_{series} is accountable for instantaneous voltage drop in battery terminal voltage (Erdinc et al.2009). Meanwhile, the other component of series resistor $R_{cycle}$is meant to define the increase in the battery resistance with cycling. The components of RC networks are responsible for short and long-time transient’s inn battery impedance. The $R_{transient\_S}$, $C_{transient\_S,}$ $R_{transient_L}$ and $C_{transient_L}$ (Erdinc et al.2009) value is calculated, due to battery SOC as:

$$R_{series}\,(SOC) = 1.562\ \times \exp(-24.37 \text{ x SOC}) + 0.07446 \tag{9}$$

$$R_{transient\_S}(SOC) = 0.3208 \text{ x} \exp(-29.14 \text{ x SOC}) + 0.04669 \tag{10}$$

$$C_{transient\_S}(SOC) = 752.9 \text{ x} \exp(-13.51 \text{ x SOC}) + 703.6 \tag{11}$$

$$R_{transient_L}(SOC) = 6.603 \text{ x} \exp(-155.2 \text{ x SOC}) + 0.04984 \tag{12}$$

$$C_{transient_L}(SOC) = -6056 \text{ x} \exp(-27.12 \text{ x SOC}) + 4475 \tag{13}$$

$$R_{cycle} = k_3 \times N^{\frac{1}{2}} \tag{14}$$

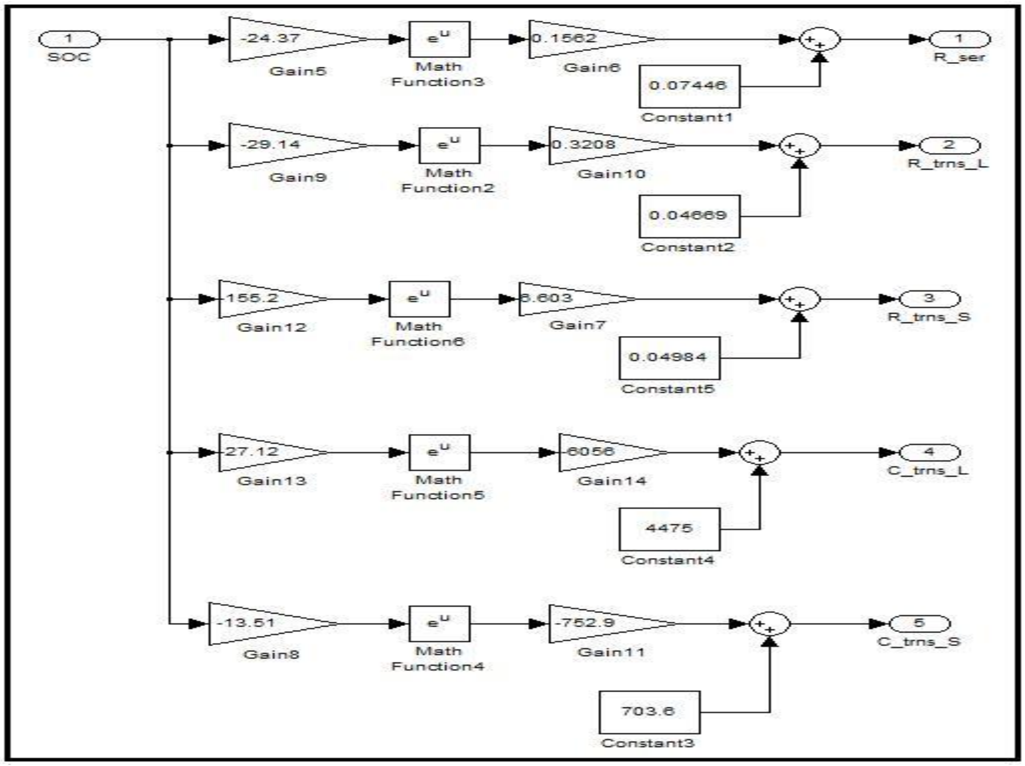

Figure 14: Simulation Block Diagram for Impedance

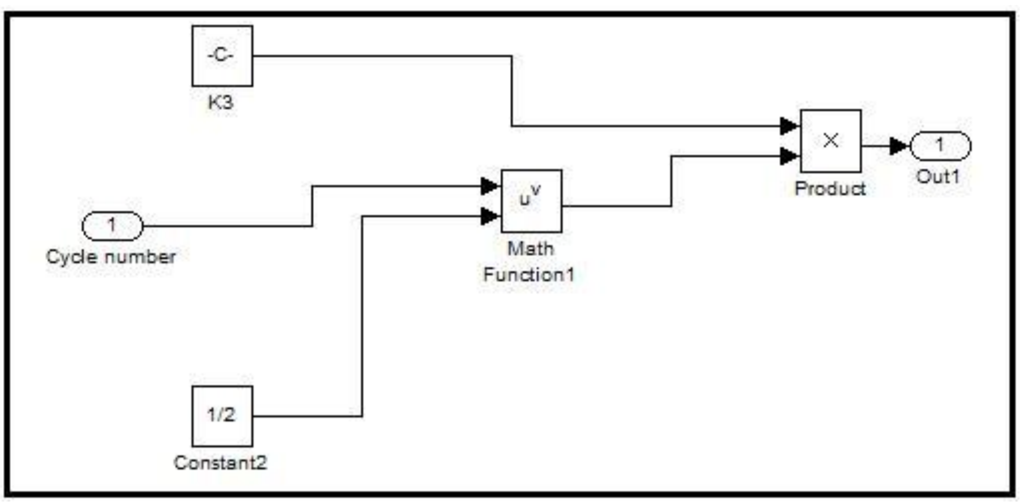

Figure 15 : Simulation Block Diagram for R cycle

4.3 Charging

For the charging process, it is always assumed that the battery will be charged to reach its 100% capacity before its usage. During charging period, commonly the battery will not be connected to any load. It will be only connected directly to the charging system. Thus, the charging period will not produce any losses in voltage due to temperature, capacity fade or from internal resistance. However, every battery has its own life time. The chemical composite of the battery decides the internal losses of the battery. The higher the frequently of the battery being charged and discharged the shorter the life span of the battery. This is because research shows that, each time the battery being charged, the life span of the battery will reduce by one cycle. Besides that, if the battery being charged while the load is being connected, the battery will not reach its maximum capability of charges (less than 100% of charges) , due to some voltage of will be donated to the load.

Below is the parameter that will be used during the simulation of the charging model. However certain assumption is made during the model is being constructed

a) The battery is not connected to any load during charging period and it is assumed no losses produced during charging period
b) The battery is being charged for the 1st cycle only.

Table 6: Battery parameters for charging

Parameters Type	E_0(V)	Q(Ah)	K(V)	A(V)	B $(Ah)^{-1}$	I(A)	Amp
Lithium-Ion Battery	3.7348	10	0.01875	0.468	3.5294	0.2	0.2

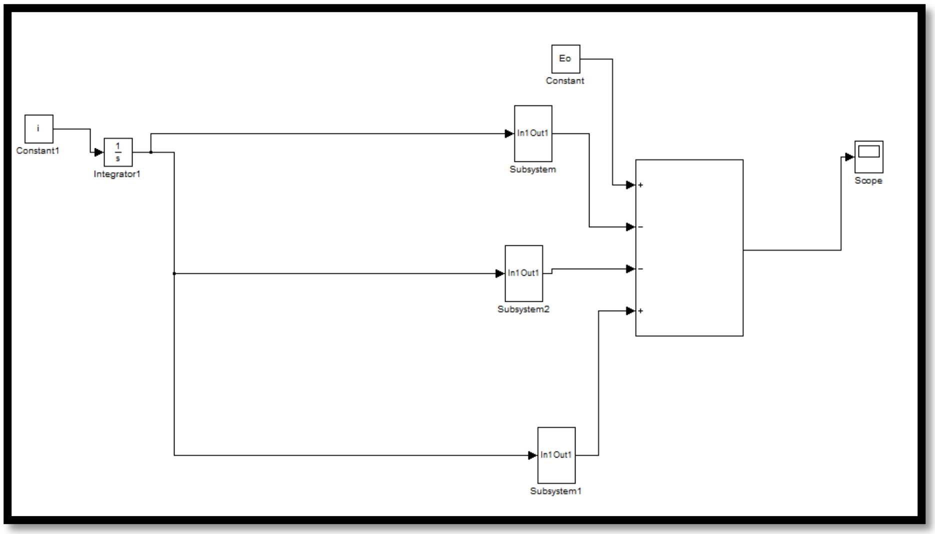

Figure 16 : Simulation Block Diagram of the Main System (Charging)

4.3.1 Subsystem 1

Following are the equation for the Subsystem 1 in the charging model :

$$Subsystem\ 1 = k\left(\frac{Q}{(it+0.1)Q}\right)i \tag{14}$$

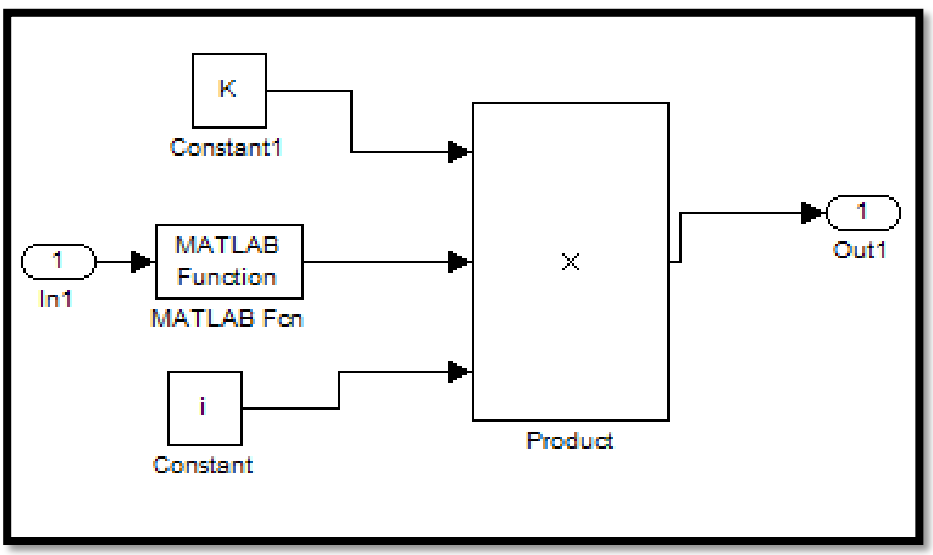

Figure 17: Simulation Block Diagram of the Subsystem 1

4.3.2 Subsystem 2

Following are the equation for the Subsystem 2 in the charging model :

$$Subsystem\ 2 = k\left(\frac{Q}{Q-it}\right)it \qquad (15)$$

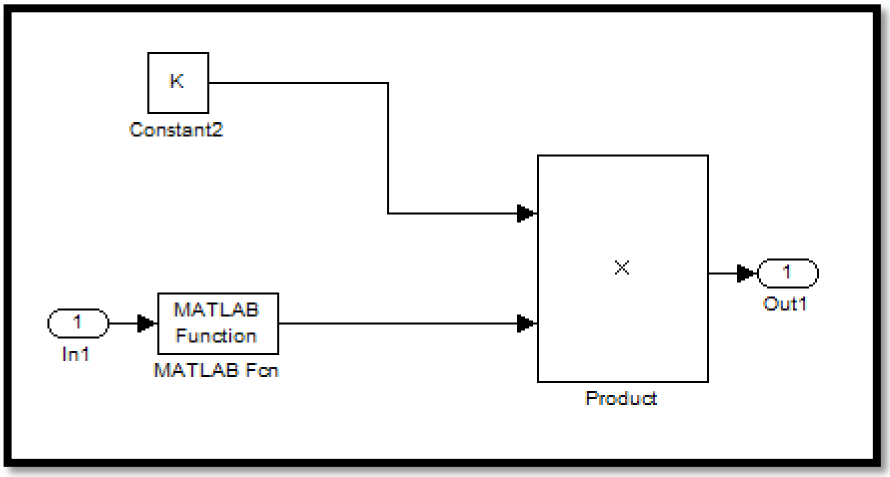

Figure 18 : Simulation Block of the Subsystem 2

4.3.3 Subsystem 3

Following are the equation for the Subsystem 3 in the charging model :

$$Subsytem\ 3 = A * \exp(-B * it) \qquad (16)$$

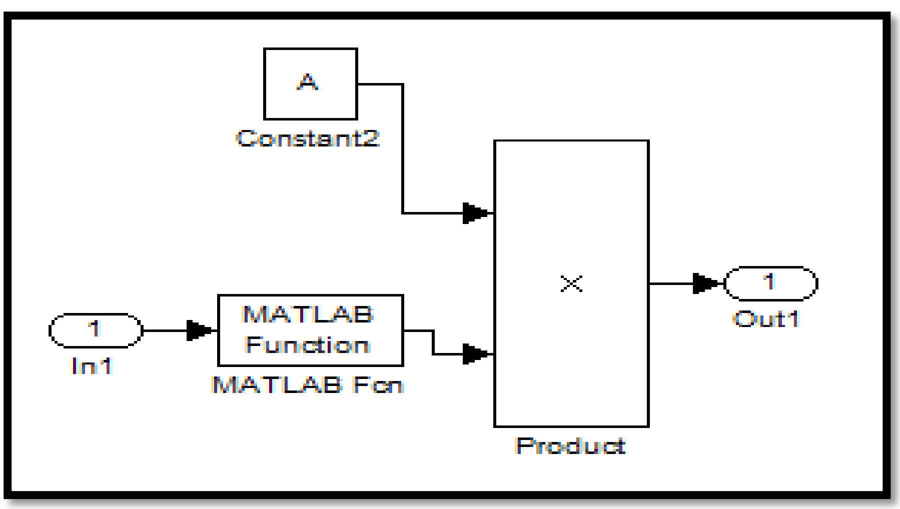

Figure 19 : Simulation Block Diagram of the Subsystem 3

4.4 Results and Discussion

4.4.1 Discharge

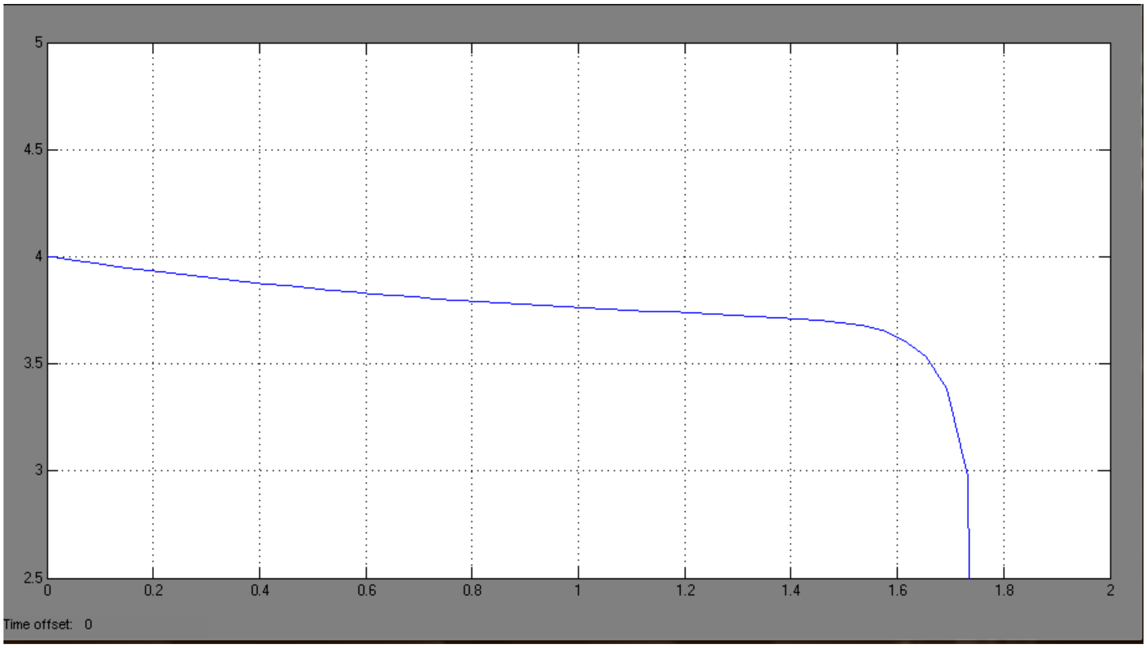

Figure 20 : Discharge Curve with SOC initial 0.89 (10 cycle time) & current value 0.9A

Figure 20, above shows the result from the discharging simulation of lithium ion battery. The battery is discharged at 4.2V and it discharging period completes at 1.7Ah. The model is being supplied with the current rate of 0.9A. At the time of t=0.2Ah, the battery discharges quickly until it reaches 3.8V. Then the battery discharge at a constant value of 3.6V from t=0.4Ah till it reaches t=1.4Ah. Later if the battery was continuously discharged, the voltage of the battery will drop below the battery's voltage. Whereas Figure 21, Figure 22 and Figure 23 shows the result of discharge simulation curve after the model is been discharge with the existence of load. The battery in Figure 21 discharges at 4.0V and its discharging period completes at t=1.9Ah. The battery is being connected to a load value of 0.94 ohm, current value of 0.95 A. At the time of t=0.3Ah, the battery discharges rapidly. At the time rate of t=0.5Ah till t=1.5Ah, the battery discharges at a constant rate of 3.5V. After the time rate of 1.5Ah the battery discharges continuous, and its voltage drop below its voltage level.

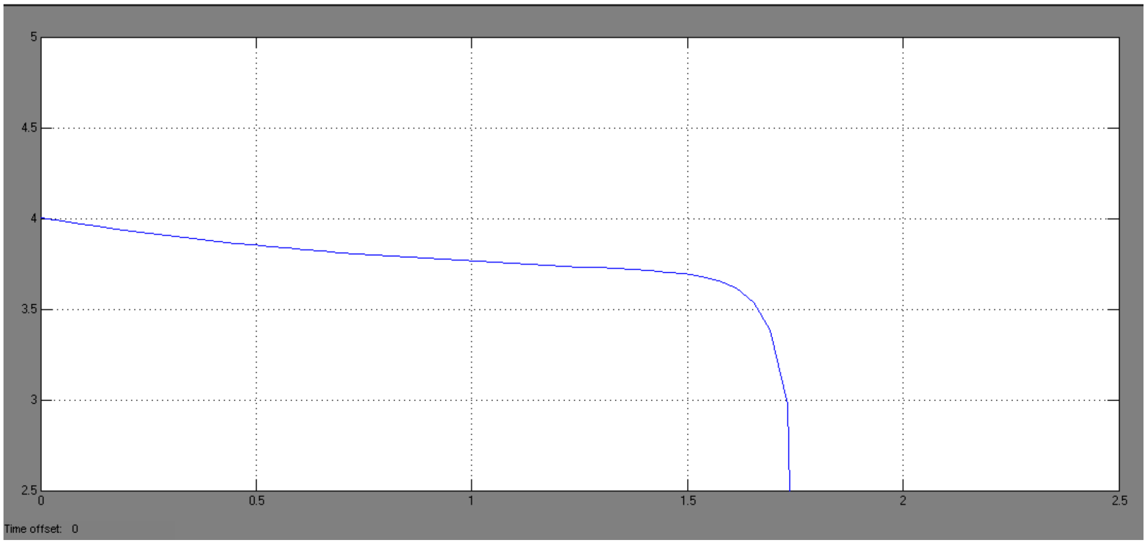

Figure 21 : Discharge Curve with SOC initial 0.89 (10 cycle time) with load 0.94 ohm

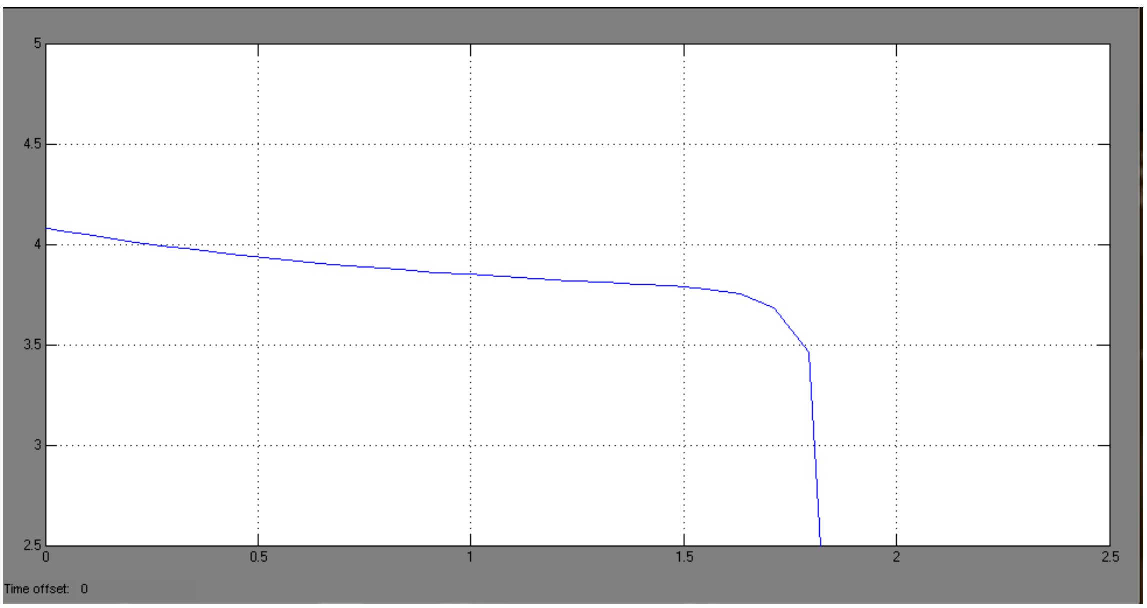

Figure 22 : Discharge Curve with SOC initial 0.89 (10 cycle time) with load 1.04 ohm

Meanwhile, the battery in Figure 22 discharges at 4.1V and its discharging period completes at t=1.7Ah. The battery is being connected to a load value of 1.04 ohm, current value of 0.85 A. At the time of t=0.5Ah, the battery discharges rapidly. At the time rate of t=0.5Ah till t=1.5Ah, the battery discharges at a constant rate of 3.7V. After the time rate of 1.5Ah the battery discharges continuous, and its voltage drop below its voltage level.

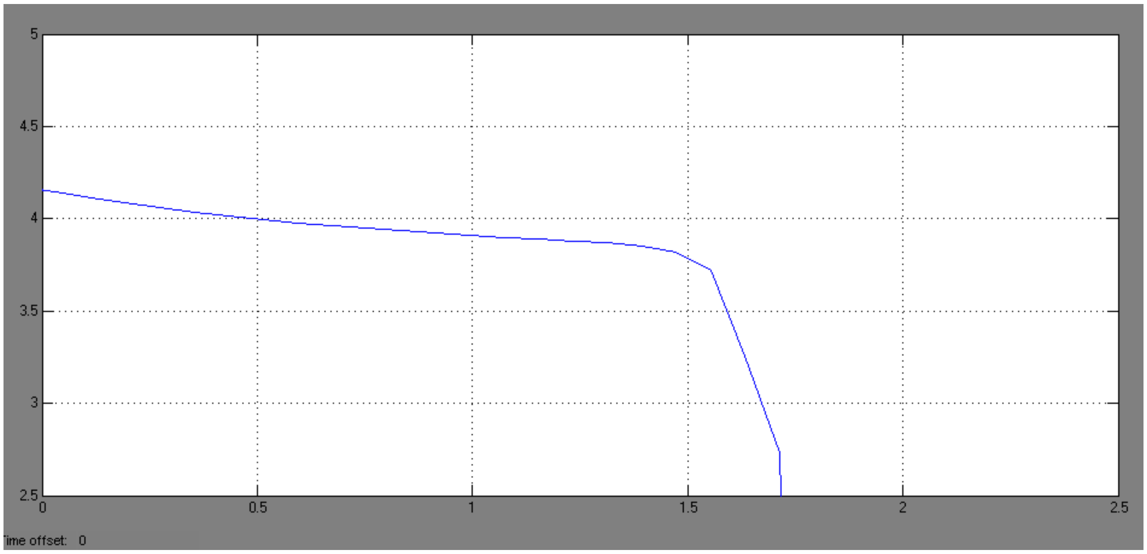

Figure 23: Discharge Curve with SOC initial 0.89 (10 cycle time) with load of 1.11 ohm

Finally, the battery in Figure 23 discharges at 4.3V and its discharging period completes at t=1.6Ah. The battery is being connected to a load value of 1.11 ohm, current value of 0.80 A. At the time of t=0.5Ah, the battery discharges rapidly. At the time rate of t=0.5Ah till t=1.2Ah, the battery discharges at a constant rate of 3.8V. After the time rate of 1.2Ah the battery discharges continuous, and its voltage drop below its voltage level. Figure 24, shows the overall comparison of the being discharged with different load. Table 7 shows the results obtain from the discharge period. It is summarized that the higher the load value (resistance), the lower its discharge capacity.

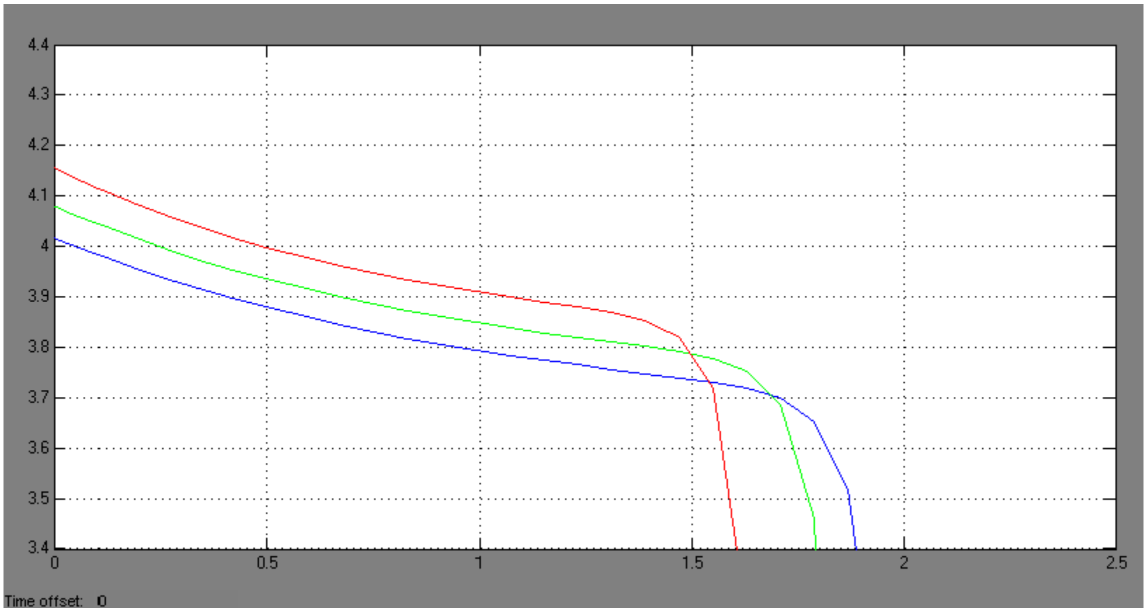

Figure 24 : Comparison of discharge curves with different loads

Table 7: Comparison of discharge curve using varies load

LINE	CURRENT (A)	LOAD (ohm)	DISCHARGE CAPACITY (Ah)
1	0.80	1.11	1.60
2	0.85	1.04	1.70
3	0.95	0.94	1.90
4	1.50	0.60	0.8

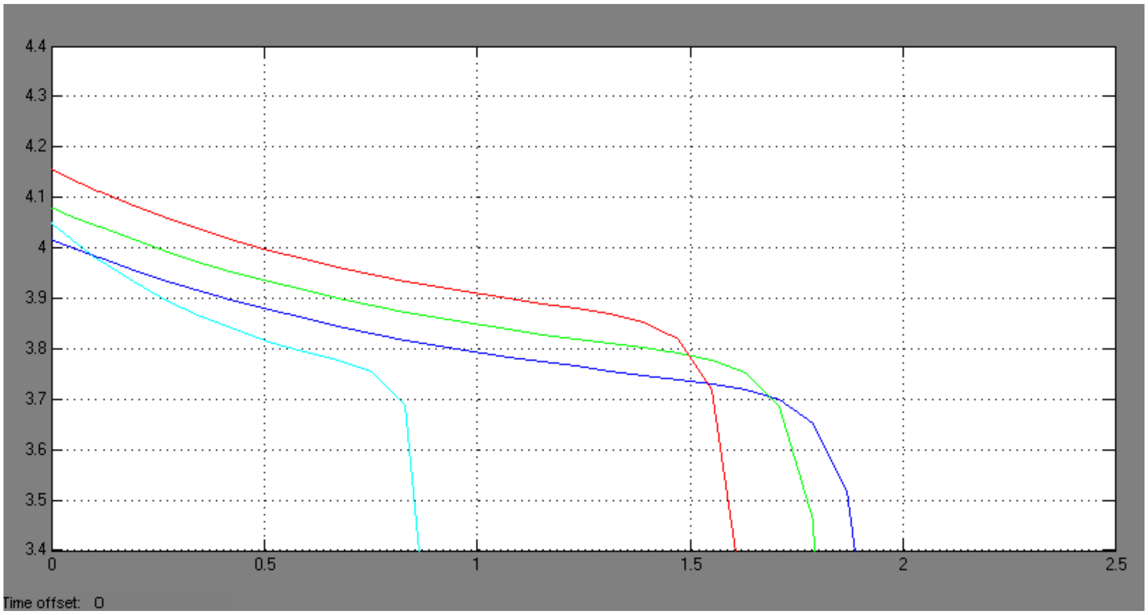

Figure 25 : Over-discharge curve (Line 4) due to heavy current supply

Line 4 in figure 25 shows the effect of over-discharge due to heavy current supply to the battery. The battery discharges immediately after it being used. The battery starts to discharge at 4.05V and its discharging period completes at t=0.7Ah. The battery is being connected to a load value of 0.6 ohm, current value of 1.5 A. The battery rapidly discharges from t=0Ah, and fast discharge at t=0.6Ah until its voltage drop below the voltage level. This shows the battery has reached its malfunction level (damage) where it lose its storage capability

4.4.2 Charging

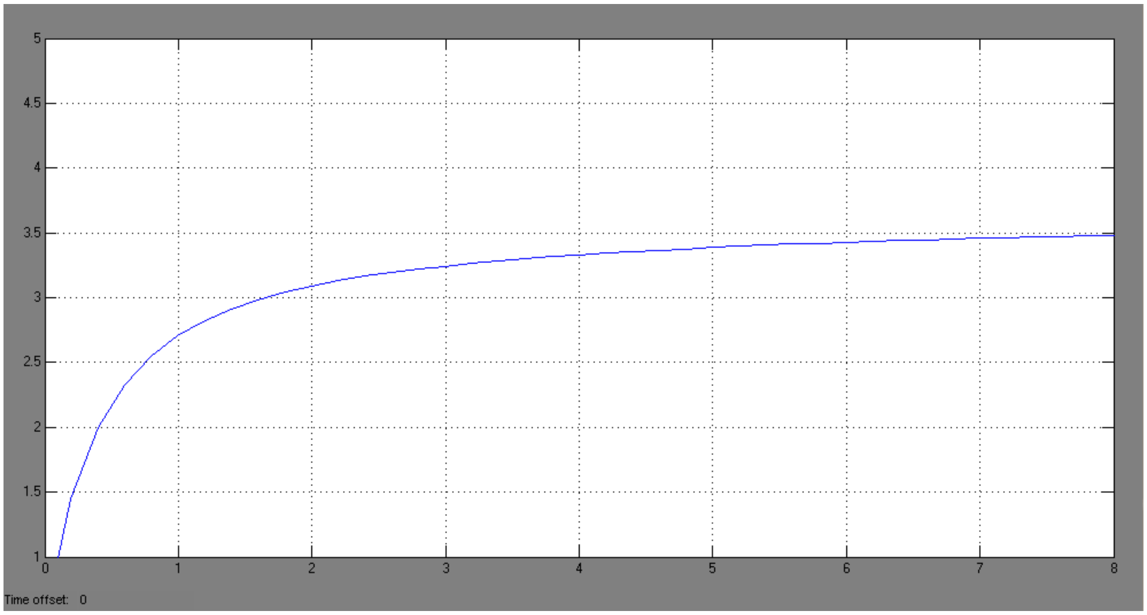

Figure 26 : Charging Curve with current value of 0.2A

Figure 26 shows the battery is charged at the constant voltage of 3.7348V and current of 0.2A is being supplied to the simulation. The simulation process produces a smooth charging curve as per figure above. The battery reaches its maximum charge voltage in its t=4Ah. Therefore, the lithium ion battery requires a short period to reach its maximum charge level. Whereas, Figure 27 and Figure 28 are batteries which has been connected to load before starts is charging process. Battery in Figure 22 is being charged at the constant voltage of 3.7348V and the current value is being varied to 0.4A. The battery reaches its maximum charge state when t=0.4Ah. Meanwhile in figure 28, the battery also being charged with a constant voltage of 3.7348V and supplied with current value of 0.6A. Results shows, the battery reaches its maximum charge state when t=0.65A.

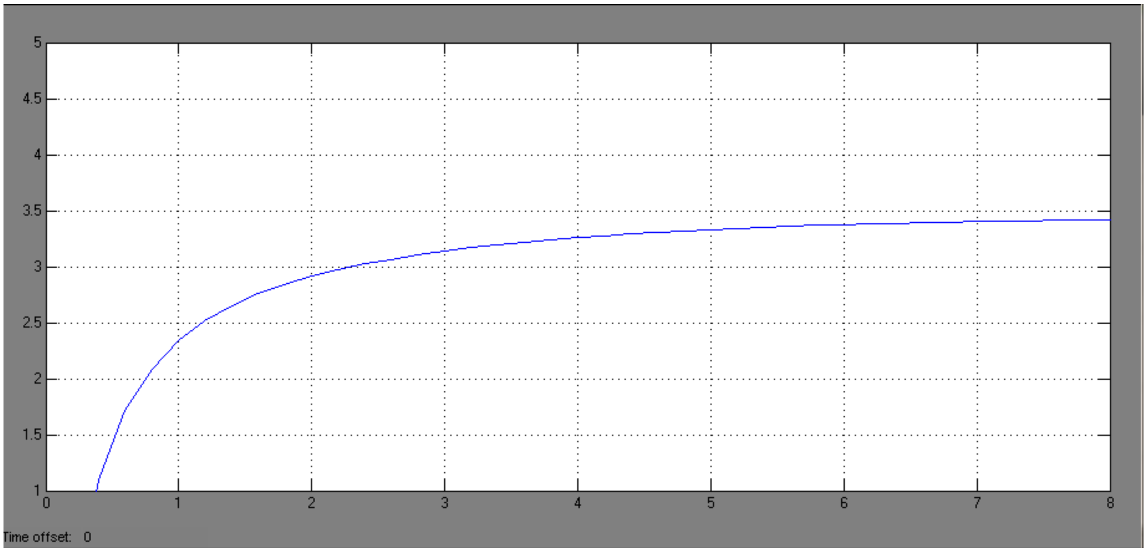

Figure 27 : Charging Curve with current value of 0.4A

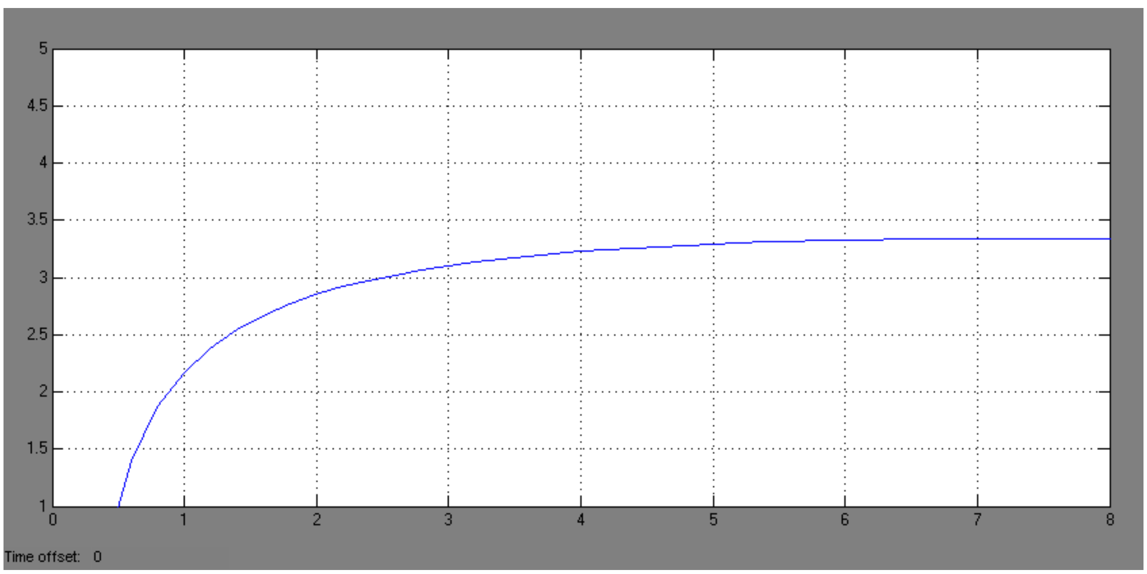

Figure 28: Charging Curve with current value of 0.6

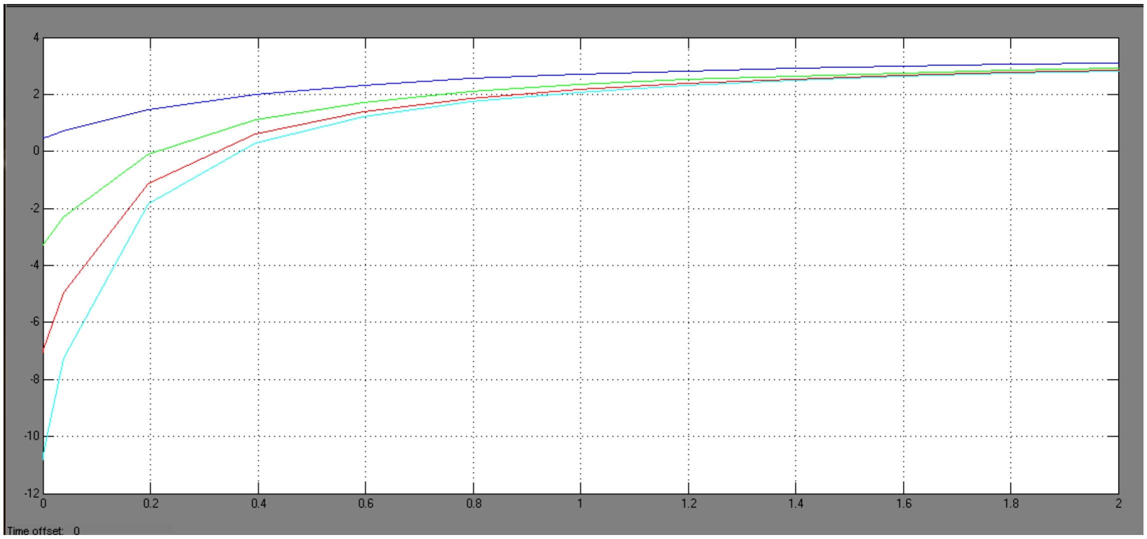

Figure 29 : Comparison of charging curves with varies voltage

Table 8 : Comparison of charging curve using varies load

Line	**CURRENT (A)**	**LOAD (ohm)**	**CHARGE TIME** (Ah)
1	0.2	18.65	0.2
2	0.4	9.32	0.4
3	0.6	6.22	0.6
4	1.5	2.49	Negative value

Figure 30, shows the overall comparison of charging curve using different load value. Table 7 shows the results obtain from the charging time. It is summarized if the lithium battery is fixed with a load during its charging period, it will delay the charging period of the battery. The higher the load value, the slower it takes for the battery to get charged. Meanwhile the Line 4 in figure 30 refers the effect of over-discharge due to heavy current supply to the battery. The battery is being charged at the constant voltage of 3.7348V and the current value is fed up to 1.5A. Result shows that, the charging curve was not obtained perfectly. This shows the sign of the over-charge due occurs in the battery. Over-charge occurs due to continual charge of battery with high current supply or continual charge of the phone though the battery has not discharged completely. Both these actions lead to the increase of internal pressure and temperature of the battery's material which ends with battery distortion.

Chapter 5

Conclusion and Recommendation

So far from the study and research done, the objectives set have been achieved. Firstly, the appropriate battery for portable device and electric vehicle been identified. The lithium-ion battery is to be chosen as the best compares to lead-acid battery and nickel metal hydride because it is one of the best energy densities, no memory effect, long cycling life and a slow loss of charge when it is not in use.

Next, would be the selection of the appropriate battery model. The model chosen would be non-linear battery model whereby the model only uses state of charge (SOC) as a state variable. This mode was selected because in order to accurately reproduce the charging and discharging curve with based on assumption that been identified. This project is based on the calculation of the charging and discharging equation using the model chosen. Once the calculation procedure is identified, the following step will be to translate the calculation procedure into block diagrams using the computation software of MATLAB-Simulink. Soon the model build has been tested by connect it to various load to charging and discharging simulation.

Therefore, this research is carried out to identify the time required for charging and discharging of the lithium battery. The charging time with higher load takes longer than the charging time low loads. Continues charging of the battery on higher current (beyond the battery's intake capacity), will lead the battery to damage due to over-current. Whereas, the discharging time with higher load is faster compare to lower loads. Over-discharge state occurs when the discharge is continuous though the battery the cell's voltage reaches a designed value. Over-discharge occurs when the battery malfunctions or repeatedly charged or the battery is discharged with heavy current.

Over-discharge cause the temperature of the battery increase and cause to material of the battery damage.

In nutshell, lithium battery is chosen to be the best because it is one of the best energy density, no memory effect, long life cycle and slow loss of charge. The property if the lithium-ion battery changes when the battery being charged and discharged with the existence of load, thus it important to study the optimum load a battery could support throughout its usage period to avoid malfunctions. Besides that, the constructed battery model could be reused in the future to study other property effect such as, temperatures, storage time and state of charge effect to the battery’s charging and discharging characteristic.

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