CAPACITY STUDY
OF LITHIUM ION BATTERY
FOR HANDPHONES

By

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FINAL YEAR PROJECT FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK

November 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained here have not been undertaken or done by unspecified sources or persons.

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Khalid Khairulanam b. Mohd Ramli

ABSTRACT

This project is to study about the capacity of various types of lithium-ion (Li-ion) batteries for handphones. The battery models developed from this project is using MATLAB/Simulink. The model has been developed in order to investigate the output characteristics of lithium-ion batteries. Dynamic simulations are carried out, including the observation of the changes in battery terminal output voltage under different temperature, cycling conditions, storage time. The changes that this project is focused on are the capacity of the battery. Simulation results are obtained and compared with the real result. Higher temperature seems to have high effect on the calendar life loss and cycle life loss of the battery. The first chapter is to explain to the reader the problem statement, objectives and scope of study. The second chapter is the literature review for the reader to understand about lithium-ion battery. The third chapter explains the methodology used by the author, as well as the MATLAB block diagram that the author has made to simulate the result. The fourth chapter is where the author reveals the simulation result as well as discussing the result and comparing it to other result. The fifth and last chapter is where the author conclude his findings and make suitable recommendation to advance the project. The simulation of this project has been proven effective and operational.

ACKNOWLEDGEMENTS

First and foremost, thank you god for letting me breath to finish this report. I would like to thank my supervisor of this project, Assoc. Prof. Dr. Mumtaj Begam Kasim Rawthar for the valuable guidance and advice.

Finally I would like to thank my family and friends for their great support and help when I am learning MATLAB Simulink.

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CHAPTER 1

INTRODUCTION

1.1 Background

Batteries directly contribute to the advancement of technologies ranging from portable electronics to the fuel efficient vehicles. Among the various existing rechargeable batteries, lithium-based batteries appear to occupy a prime position in various aspects.

Lithium-ion battery is currently widely used in the market for portable electronic device. One of it is hand phones. This project is to find out the capacity for various types of lithium-ion batteries for hand phones. It also aims to investigate the effect of multiple factor such as temperature, storage time and cycle number to the capacity of Li-ion batteries.

The difference between cheap batteries and expensive batteries depends on the material used for the anode and cathode. Different materials have different capacities and lifetimes.

1.2 Problem Statement

Capacity is an important attribute for a battery. Higher capacity means that the battery will last longer.

The problem is, we don't know what factor affect the battery's capacity. What would be the ideal operating temperature? Does using the battery reduces its capacity? How can we reduce the rate of capacity reduction?

1.3 Objective

The objective for this project is to investigate the effect of multiple factor such as temperature, storage time and cycle number to the capacity of Li-ion batteries.

1.4 Scope of Study

This project scope of study is limited to Li-ion battery for hand phone only. The scope of investigation is limited to capacity only, although if there are other characteristics needed to investigate the capacity, it will also be researched.

CHAPTER 2

LITERATURE REVIEW

2.1 History of lithium ion battery

1970s - First proposed by M.S. Whittingham. Whittingham used titanium(II) sulfide as the cathode and lithium metal as the anode [1].

1983 - Michael Thackeray, John Goodenough, and coworkers identified manganese spinel ($MgAl_2O_4$) as a cathode material. Spinel showed great promise, since it is a low-cost material, has good electronic and lithium ion conductivity, and possesses a three- dimensional structure which gives it good structural stability. Although pure manganese spinel fades with cycling, this can be overcome with additional chemical modification of the material. Manganese spinel is currently used in commercial cells.

1989 - Arumugam Manthiram and John Goodenough (University of Texas) at Austin showed that cathodes containing polyanions, eg. sulfates, produce higher voltages than oxides due to the inductive effect of the polyanion.

1991 - First commercial lithium-ion battery was released by Sony. The cells used layered oxide chemistry, specifically lithium cobalt oxide. These batteries revolutionized consumer electronics.

1996 - Akshaya Padhi, John Goodenough and coworkers identified the lithium iron phosphate ($LiFePO_4$) as cathode materials for lithium-ion batteries. $LiFePO_4$ is superior for large batteries for electric automobiles and other energy storage applications such as load saving, where safety is important. It is currently being used for most lithium-ion batteries powering portable devices such as laptop computers and power tools.

2002 - Yet-Ming Chiang and his group at MIT published a paper in which they showed a dramatic improvement in the performance of lithium batteries by boosting the material's conductivity by doping it with aluminum, niobium and zirconium.

2004 -Chiang increased performance by utilizing iron-phosphate particles of less than 100 nm in diameter. This miniaturized the particle density by almost a hundredfold, increased the surface area of the electrode and improved the battery's capacity and performance.

2.2 Basic understanding of lithium ion battery

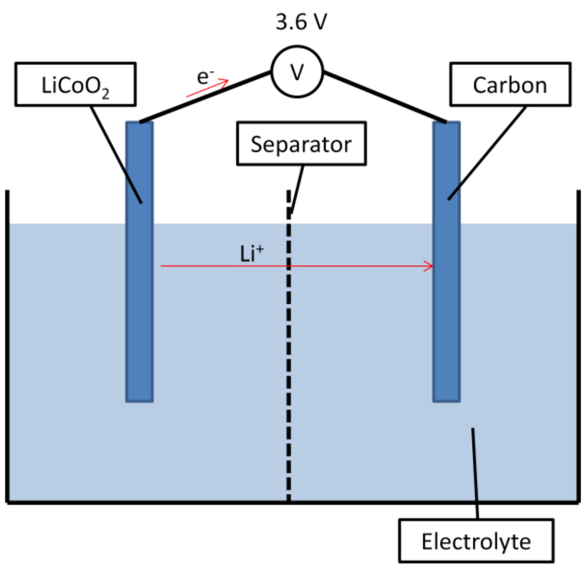

Figure 1 : Li-ion battery cell during charging

A lithium-ion battery is a type of rechargeable battery in which lithium ions move from the anode to cathode during discharge, and from the cathode to the anode when charged. With respect to the figure above, $LiCoO_2$ is the anode and carbon is the cathode.

When the battery charges, ions of lithium move through the electrolyte from the positive electrode to the negative electrode and attach to the carbon.

During this time, electrons will move from $LiCoO_2$ to the carbon. This movement of electrons create current at opposite direction of the electron. During discharge, the lithium ions move back to the $LiCoO_2$ from the carbon and electrons will travel from carbon to $LiCoO_2$

The figure above shows the movement of lithium ions and electrons during charging process. After 1 charge and 1 discharge, it is called 1 cycle.

After a Li-ion battery is charged, and it is discharged, there is some portion of lithium that will be stuck at the carbon (this is called dead lithium). Due to this, after every cycle, the Li-ion battery capacity will drop a little bit. A good Li-ion battery can still work until 200 cycles.

Transfer of 1 electron will give 96500 coulomb of charge.

$$I = \frac{dQ}{dt} = \frac{96500}{60 \times 60} = 26.8Ah$$

Therefore, 1 electron will give 26.8Ah of current.

And to calculate the battery capacity:

$$\frac{26.8}{mass} \; Ah/kg$$

This is called the capacity of Li-ion battery.

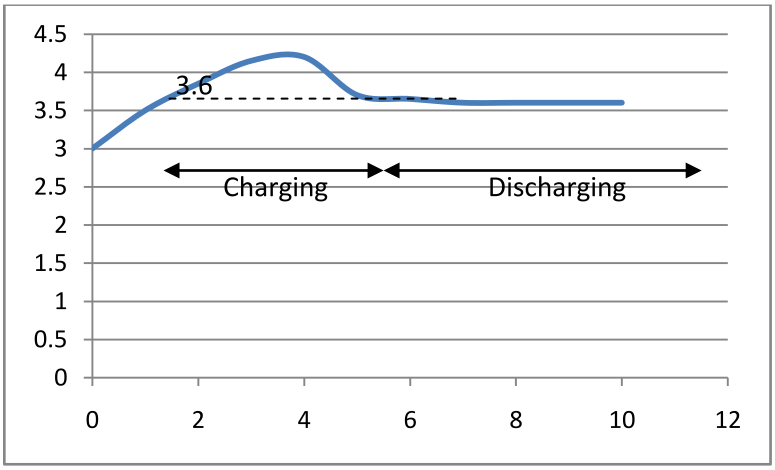

Figure 2 : Voltage characteristics for Li-ion battery cell

From the graph, the operating voltage for Li-ion battery is 3.6V. Generally, the operating voltage is assumed to be 3V.

2.3 Cathode Materials

Table 1 : Characteristics for cathode material [1]

Cathode Material	**Average Voltage**	**Gravimetric Capacity**	**Gravimetric Energy**
$LiCoO_2$	3.7 V	140 mAh/g	0.518 kWh/kg
$LiMn_2O_4$	4.0 V	100 mAh/g	0.400 kWh/kg
$LiNiO_2$	3.5 V	180 mAh/g	? kWh/kg
$LiFePO_4$	3.3 V	150 mAh/g	0.495 kWh/kg
Li_2FePO_4F	3.6 V	115 mAh/g	0.414 kWh/kg
$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$	3.6 V	160 mAh/g	0.576 kWh/kg
$Li(Li_aNi_xMn_yCo_z)O_2$	4.2 V	220 mAh/g	0.920 kWh/kg

2.4 Anodes Material

Table 2 : Characteristics for anode material [1]

Anode Material	Average Voltage	Gravimetric Capacity	Gravimetric Energy
Graphite, LiC6	0.1-0.2 V	372 mAh/g	0.0372-0.0744 kWh/kg
Titanate, Li4Ti5O12	1-2 V	160 mAh/g	0.16-0.32 kWh/kg
Si (Li4.4Si)	0.5-1 V	4212 mAh/g	2.106-4.212 kWh/kg
Ge (Li4.4Ge)	0.7-1.2 V	1624 mAh/g	1.137-1.949 kWh/kg

2.5 Li-ion Battery Cell

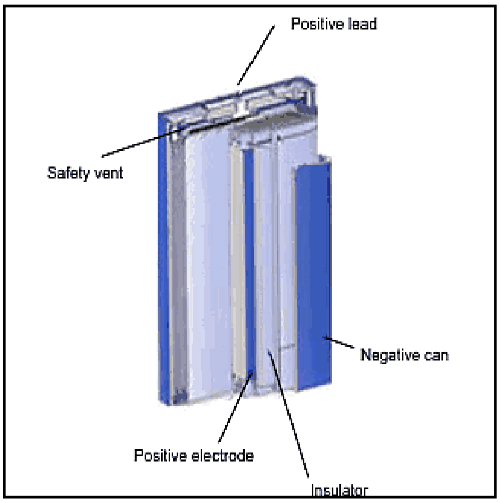

Figure 4: Handphone Li-ion battery [2]

Figure 3 : Li-ion battery structure [2]

This is the structure of a general lithium ion battery cell. Positive electrode (cathode) material is made from $LiCoO_2$ and the negative electrode (anode) material is made from carbon.

Figure 5 : A laptop Li-ion battery [3]

Figure 6 : An inside look of the laptop battery[3]

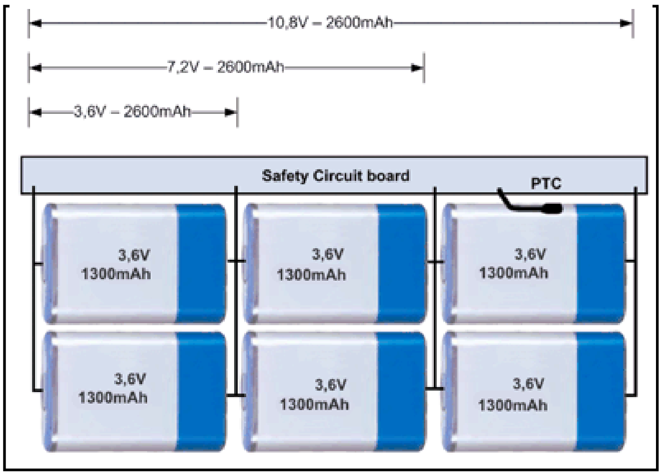

Figure 7 : Circuit diagram of the laptop battery [3]

Take note that inside the laptop battery, there is a safety circuit board. This is to control the voltage of the charger when the battery is charging. A Li-ion battery will be irreversibly damaged if charged above 4.3V and below 3V (per cell). This safety circuit board is also used to stop the operation of the Li-ion battery whenever it is dangerous. Li-ion battery can be explosive if mistreated.

2.6 Advantages of Li-ion Batteries

- Best energy to weight ratio compared to other type of batteries. This is why Li-ion battery is used for almost all portable device.
- They hold their charge. A lithium-ion battery pack loses only about 5 percent of its charge per month, compared to a 20 percent loss per month for NiMH batteries.
- They have no memory effect, which means that we do not have to completely discharge them before recharging, as with some other battery chemistries. Nickel cadmium batteries have memory effect.
- When not in use, Li-ion batteries has slow loss of charge. The loss of charge is approximated to be 5% per month.
- Lithium-ion batteries can handle hundreds of charge/discharge cycles before the battery will be unusable.

2.7 Disadvantages of Li-ion batteries

- They start degrading as soon as they leave the factory. They will only last two or three years from the date of manufacturing whether you use them or not.
- They are extremely sensitive to high temperatures. Heat causes lithium-ion battery packs to degrade much faster than they normally would.
- If you completely discharge a lithium-ion battery, it is ruined.
- A lithium-ion battery pack must have an on-board computer to manage the battery. This makes them even more expensive than they already are.
- Irreversibly damaged if (generally) charged under 3V or above 4.3V.
- There is a small chance that, if a lithium-ion battery pack fails, it will burst into flame.

2.8 Li-ion battery applications

Because Li-ion battery has the best energy to weight ratio among other batteries, Li-ion batteries is used in small, portable electronics mainly. Below is a list of Li-ion battery applications.

- Artificial pacemakers and other implantable electronic medical devices.
- PDA.
- Watches.
- Thermometer.
- Calculator.
- Computer and communication backup battery.
- Digital camera.
- Laptop.
- Remote car lock.
- Handphones.
- Other portable electronics.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

In the figure below is the project flow.

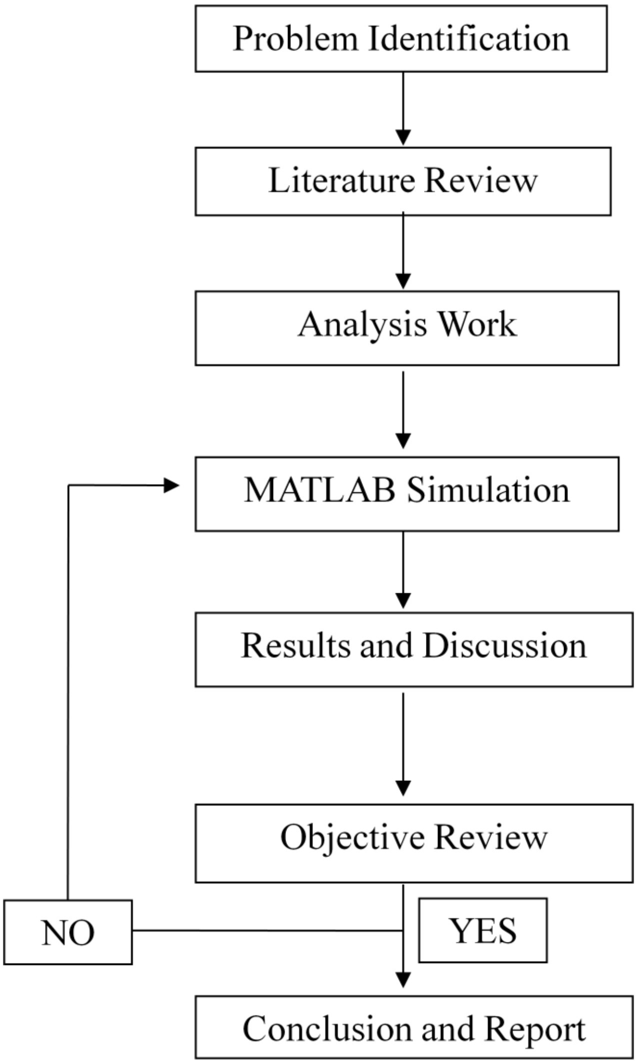

Figure 8 : Project flow

Problem identification is the first step where a problem has been identified like in the problem statement. After that the scope of study and objectives is defined. Literature review is done after that to learn more about this project and to strengthen knowledge about the Li-ion battery.

Next is the analysis work where the important equations and data were gathered to do the simulation. To gather data, most of the references used is taken from the Institute of Electrical and Electronics Engineers (IEEE) website.

After that, the equations and data were implemented in the MATLAB, mainly by building a function block to get the correct result. After the result is obtained, the result is checked with the literature review to make sure that the result is correct and acceptable.

When the objectives has been met, conclusions and recommendations are written and this project is then finalized.

3.2 Simulation

Simulation is using Mathworks MATLAB Simulink. The objective of simulation is to simulate the expected result which is Li-ion battery charging/discharging characteristics. In Simulink, the battery block can be found in section Electrical Sources under SimPowerSystems toolbox.

3.3 Li-ion Charging/Discharging Characteristics

The equation for Li-ion charging/discharging characteristics is:

Discharge Model ($i^* > 0$)

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

Charge Model ($i^* < 0$)

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

Figure 9 : Li-ion charging/discharging equation [4]

where

E_{Batt} = Nonlinear voltage (V)

E_0 = Constant voltage (V)

Exp(s) = Exponential zone dynamics (V)

Sel(s) = Represents the battery mode. Sel(s) = 0 during battery discharge, Sel(s) = 1 during battery charging.

K = Polarization constant (Ah^{-1}) or Polarization resistace (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 $(Ah)^{-1}$

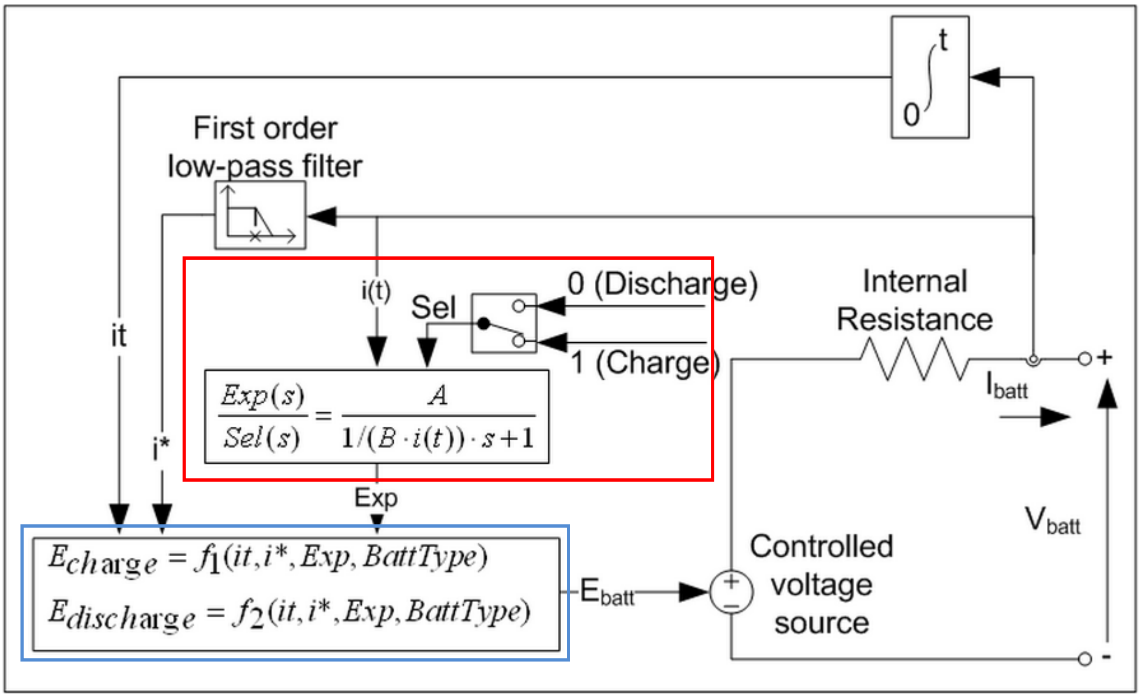

Figure 10 : Generic Battery Block [4]

The figure above is the generic battery block for the simulation of battery. Since we only focus on Lithium-Ion battery, we didn't need the function block marked in the red block (Laplacian block). That block is only used when simulating Lead-Acid, Nickel-Cadmium and Nickel-Metal-Hydride model.

The blue block is the discharge/charging equation from Figure 9.

Table 3 : Battery Parameters [5]

Type Parameters	**Lead-Acid** 12V 1.2Ah	**Nickel-Cadmium** 1.2V 1.3Ah	**Lithium--Ion** 3.6V 1Ah	**Nickel-Metal-Hydrid** 1.2V 6.5Ah
$E_0(V)$	12.6463	1.2505	3.7348	1.2848
R (Ω)	0.25	0.023	0.09	0.0046
K (V)	0.33	0.00852	0.00876	0.01875
A (V)	0.66	0.144	0.468	0.144
B $(Ah)^{-1}$	2884.61	5.7692	3.5294	2.3077

This is the battery parameters that is already calculated from Tremblay's paper. The only variable that we can change without changing the characteristic of the battery is current (I) and battery capacity (Q).

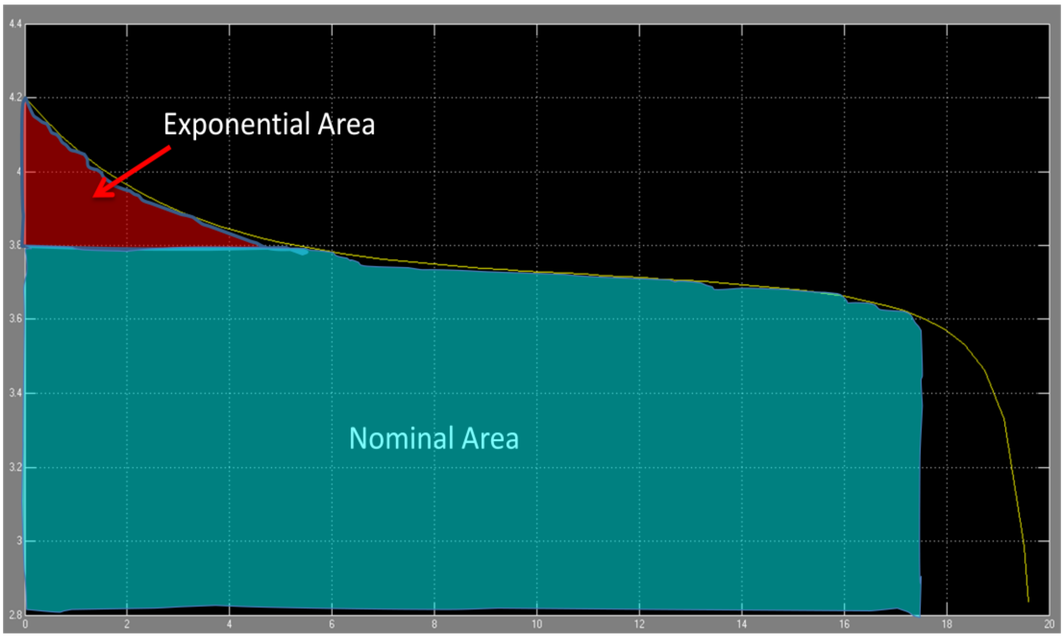

Figure 11 : Discharge curve nominal and exponential area

The figure above shows the area where the battery is usable which is during exponential and nominal area. Take note that normally the nominal voltage for Li-ion battery is 3.6V. When the battery is no longer in nominal area, it might not be usable anymore until it has been charged again.

3.4 Function Block for MATLAB Discharging Equation

Discharge Model (i* > 0)

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

Figure 12 : Discharge model equation [4]

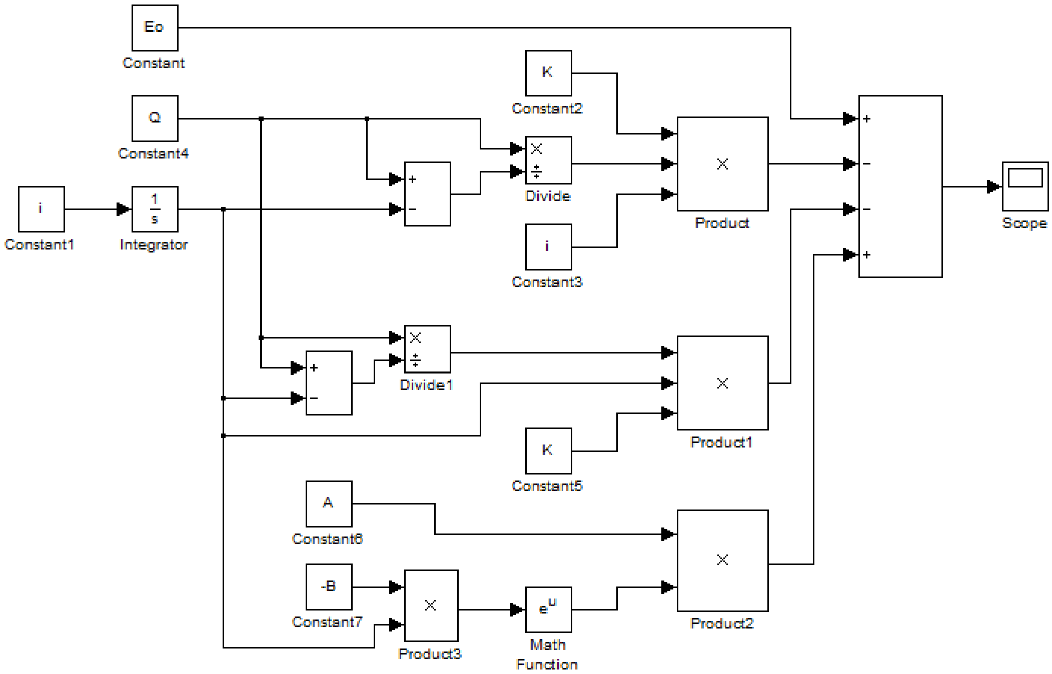

Figure 13 : Function block for the MATLAB equation

Figure 13 shows the function block for the MATLAB equation. An integrator is used to get the 'it' term in the equation. Product block calculates the term for the red term in the equation. Product1 block calculates the term for the green term in the equation. Product2 block calculates the term for the blue term in the equation. The battery parameters is taken from Table 3.

3.5 Function Block for Tremblay's Discharging Equation

This equation is taken from Tremblay, Dessaint and Dekkiche paper titled "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles" [5].

$$E = E_0 - K\frac{Q}{Q - it} + A\exp(-B \cdot it)$$

Figure 14 : Discharging equation [5]

This equation is simpler than MATLAB website equation since one term is ignored which is the red block in figure 12.

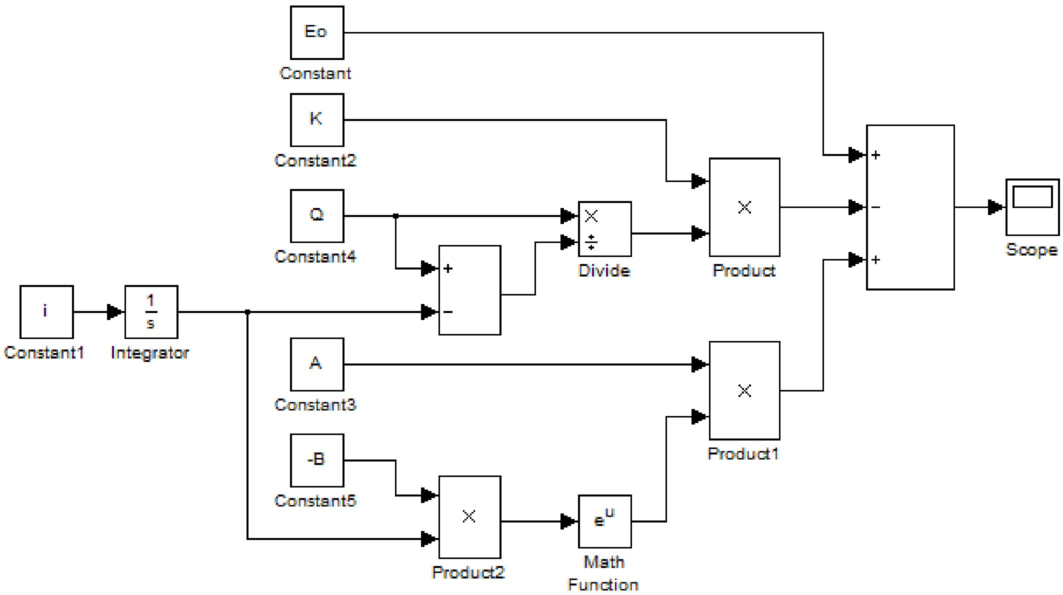

Figure 15 : Function block

Figure 15 shows the function block for the equation. Product block calculates for the term in the red rectangle. Product2 block calculates for the term in the green rectangle. The battery parameters is taken from Table 3.

3.6 Function Block for Charging Characteristic

Charge Model (i* < 0)

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

Figure 16 : Charging Equation [4]

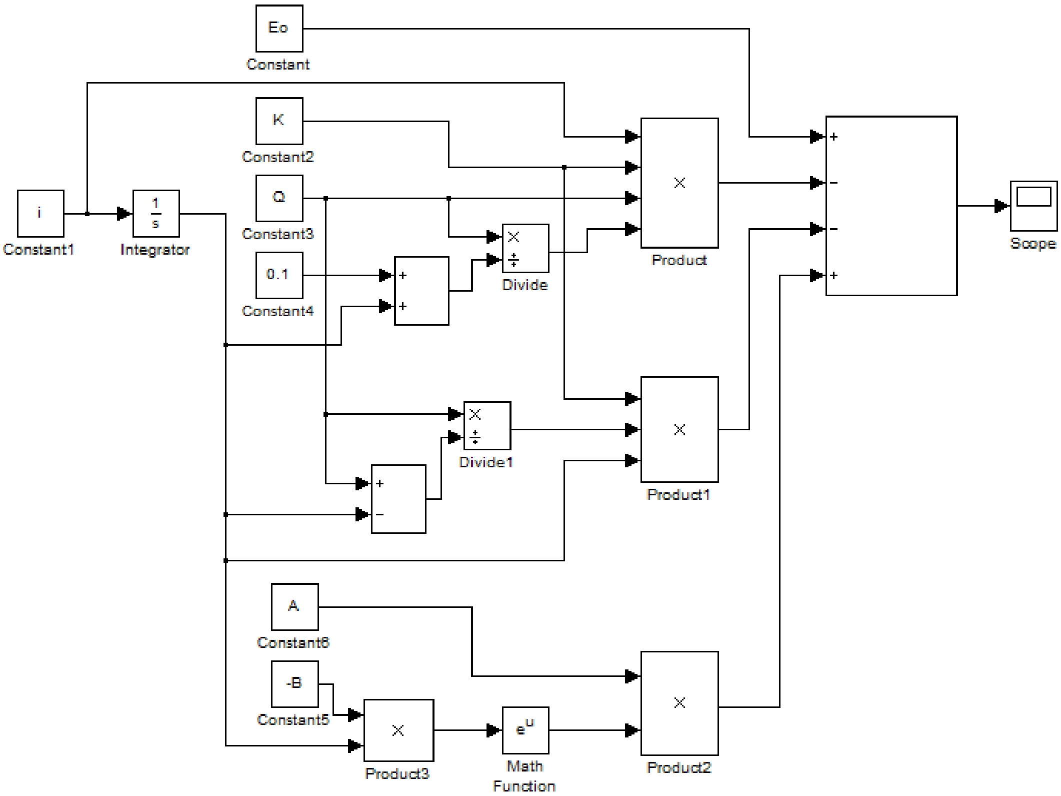

Figure 17 : Charging equation function block

Figure 17 shows the charging equation function block. Product block calculates the term in the red block. Product1 block calculates the term in the blue block and Product2 block calculates the term in the green block. The battery parameters is taken from Table 3.

3.7 Discharging Characteristics with Capacity Fading

The equation for discharging is using the MATLAB Li-ion discharging equation (Figure 12). Capacity fading refers to the irreversible loss in the usable capacity of a battery due to time, temperature and cycle number. Because of that, modeling the capacity fading is important in determining the battery remaining life.

The irreversible loss causing capacity fading is associated with degradation of the battery, and the loss occurs whether the battery is inactive (calendar life losses) or exercised (cycle life losses) [6]. Both the calendar and cycle life losses of a battery appear to be linear with time and dramatically increase with increasing temperature [7].

Therefore the effect of temperature must be considered while modeling the capacity fading for a battery. The calendar and cycle life losses lead to a capacity correction factor to determine the remaining usable battery capacity. The capacity correction factor can be calculated as [8]

$$\textbf{CCF = 1 - (Calendar life losses + Cycle life losses)} \quad (1)$$

Then the remaining usable battery capacity can be defined as [8]

$$\mathbf{C_{usable} = C_{initial} \times CCF} \quad (2)$$

where C = battery capacity (Ah), also known as Q in previous equation.

The calendar life losses of a battery consist of storage losses occurring when the battery is not used. The percentage of storage losses can be expressed as [6,7]

$$\%\ \boldsymbol{storage\ loss} = \mathbf{1.544 \times 10^{7}} \times \boldsymbol{t} \times \mathbf{exp}\left(\frac{\mathbf{-40498}}{\mathbf{8.3143} \times \boldsymbol{T}}\right) \quad (3)$$

where T = temperature (Kelvin)

t = storage time (months)

It is a valid assumption to consider that the only variable related with the other component of capacity fading, cycle life losses, is the negative electrode state of charge (SOC). The rate of change in negative electrode SOC is dependent on cycle number and temperature can be represented as [7].

$$\frac{d\theta n}{dN} = k_1 N + k_2 \quad (4)$$

where the coefficient k_1 accounts for capacity losses that increase rapidly during adverse conditions such as cycling at high temperature, and k_2 is a factor to account for capacity losses under usual conditions of cycling.

The values of k_1 and k_2 can be referred to the table below. It is interesting to notice that k_2 doesn't change much due to temperature. The variations of negative electrode SOC can be considered for simulating the cycle life losses [7].

Table 4 : Values of the Coefficients Dependent on Cycling Temperature [7]

Cycling temperature [°C]	k_1 [cycle^{-2}]	k_2 [cycle^{-1}]
25	8.5×10^{-8}	2.5×10^{-4}
50	1.6×10^{-6}	2.9×10^{-4}

3.8 Block Diagram for Discharging Characteristics with Capacity Fading

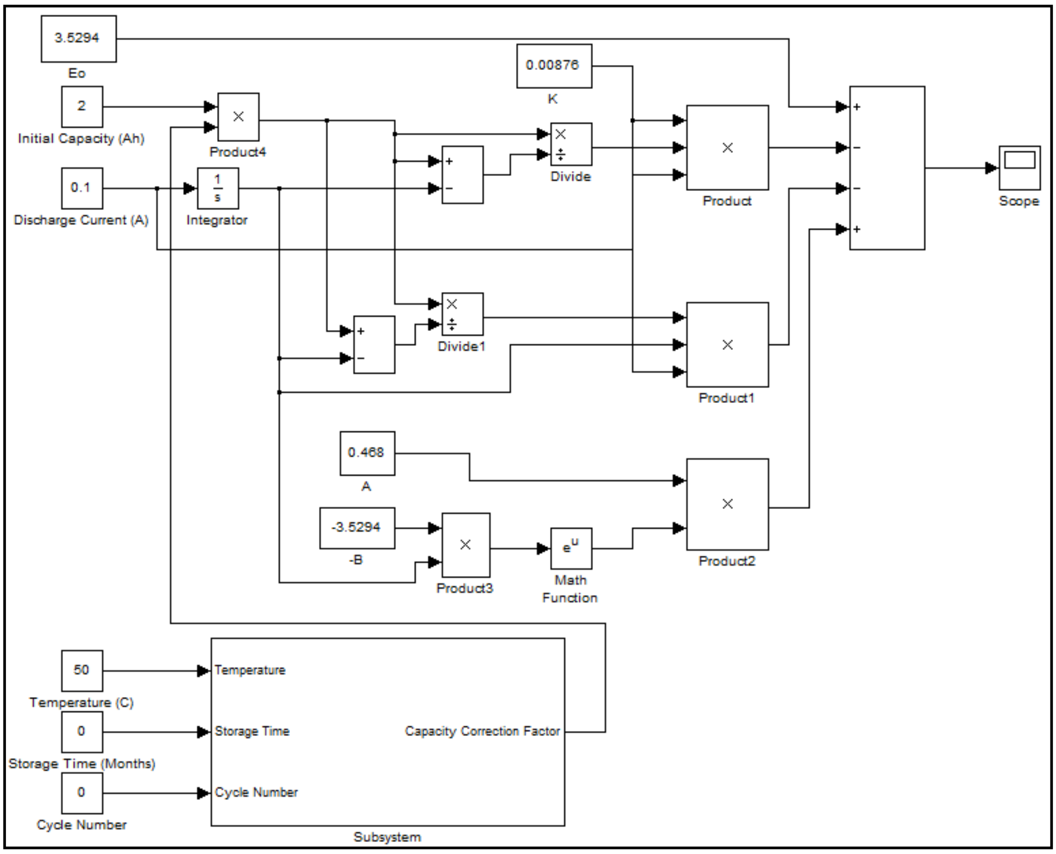

Figure 18 : Overall dynamic model of lithium-ion battery

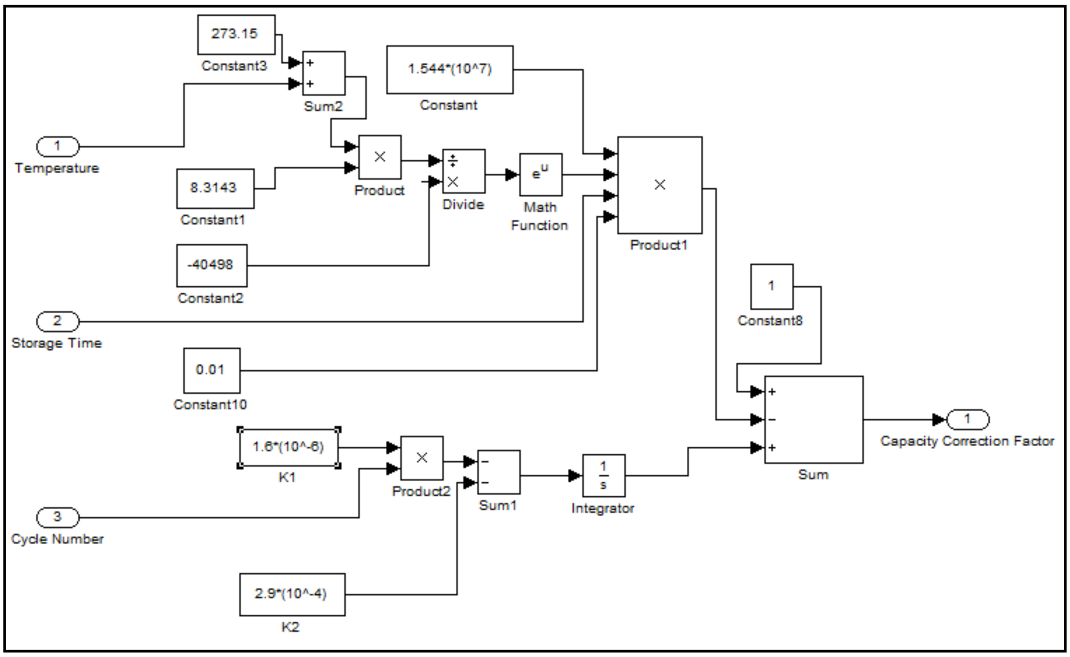

Figure 19 : Capacity Correction Factor Subsystem

For the overall dynamic model of lithium-ion battery, we are using the block diagram from Figure 13, however the only difference is that there is a new block to calculate the capacity correction factor (CCF). CCF is then multiplied with the initial capacity, to calculate equation (2).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Result for Discharging Characteristic

This is the comparison of MATLAB and Tremblay's equation for discharging curve.

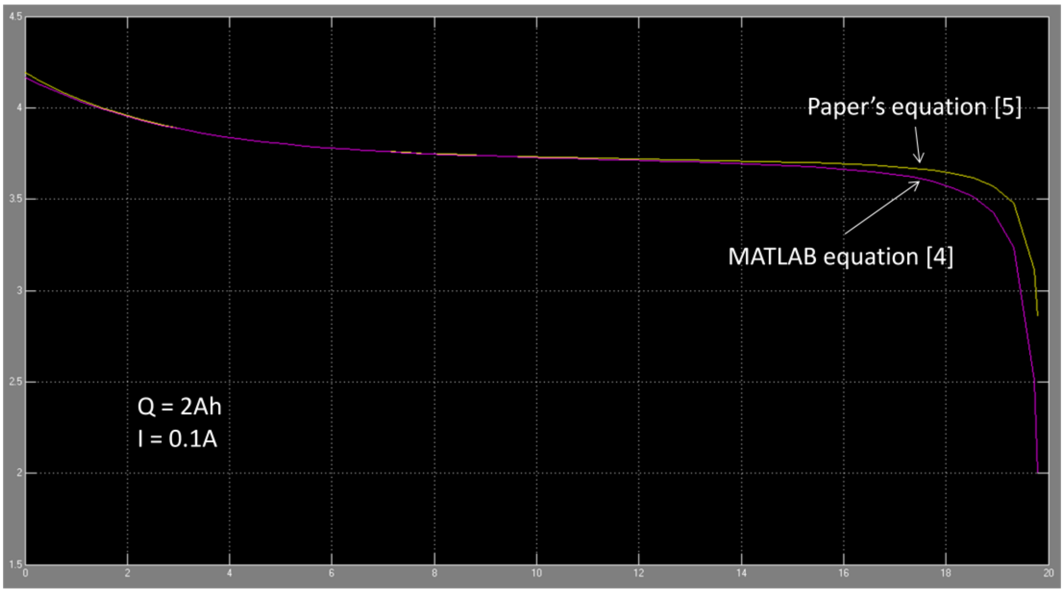

Figure 20 : Discharging curve for both equation [Voltage(V) vs time (hours)]

Both of the equation can simulate the discharging curve for the Li-ion battery successfully. However, from the discharging curve above, the curve from the paper is more favorable for this simulation since the battery can stay above nominal voltage (3.6V) longer.

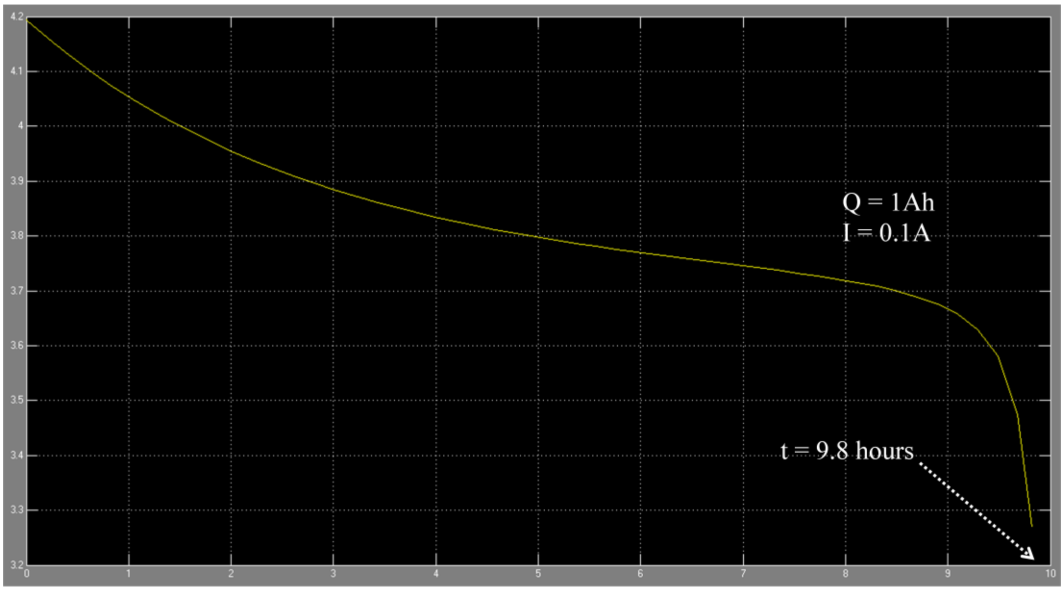

Figure 21 : Simulation result with Q = 1Ah and I = 0.1A [Voltage(V) vs time (hours)]

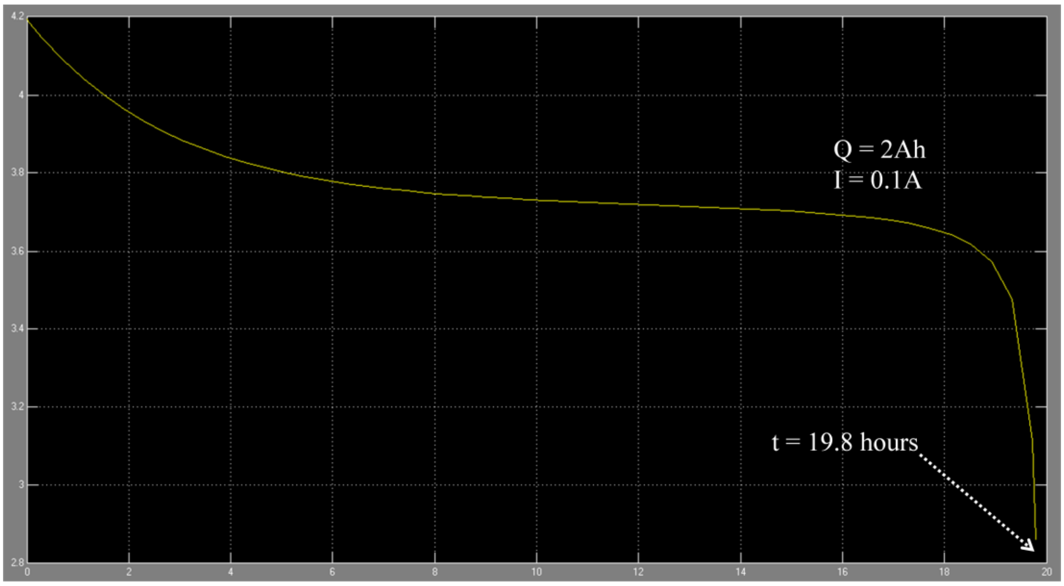

Figure 22 : Simulation result with Q = 2Ah and I = 0.1A [Voltage(V) vs time (hours)]

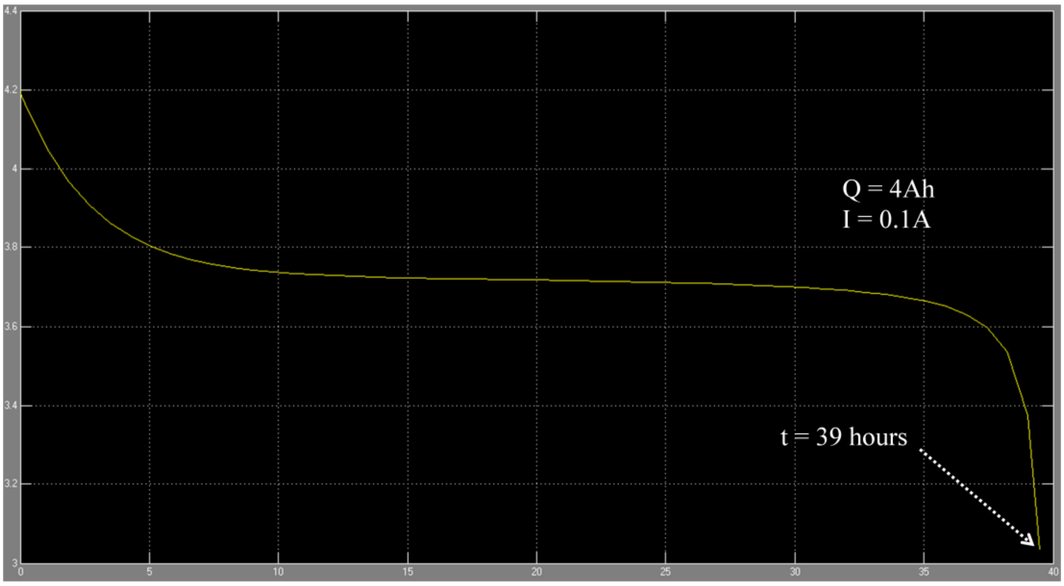

Figure 23 : Simulation result with Q = 4Ah and I = 0.1A [Voltage(V) vs time (hours)]

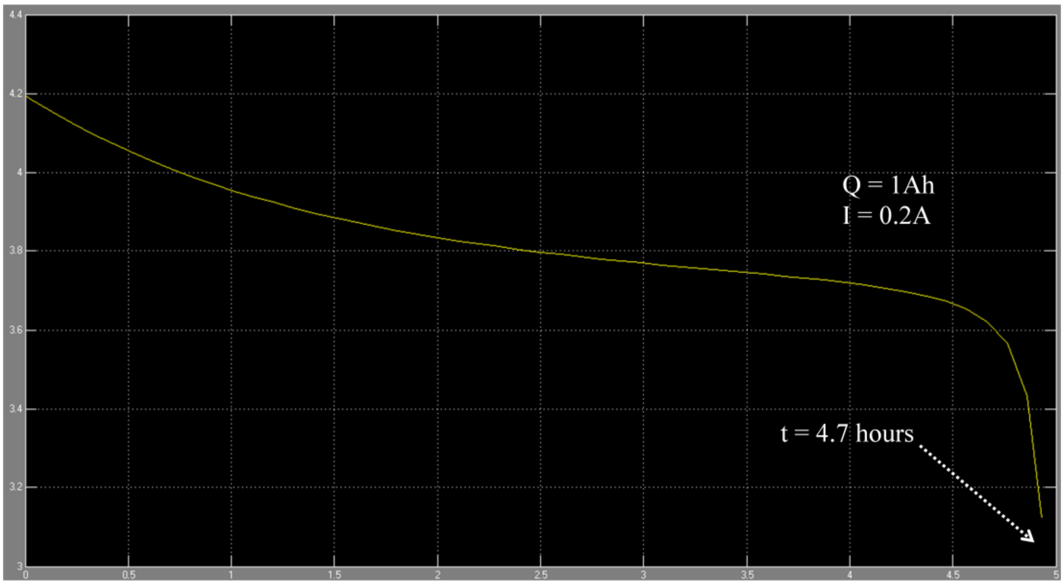

Figure 24 : Simulation result with Q = 1Ah and I = 0.2A [Voltage(V) vs time (hours)]

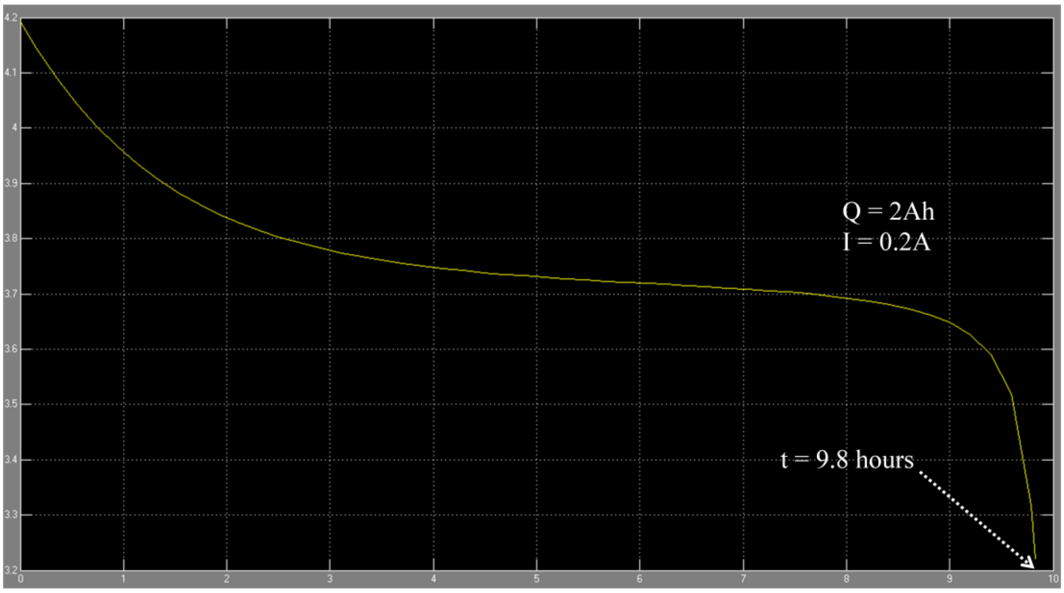

Figure 25 : Simulation result with Q = 2Ah and I = 0.2A [Voltage(V) vs time (hours)]

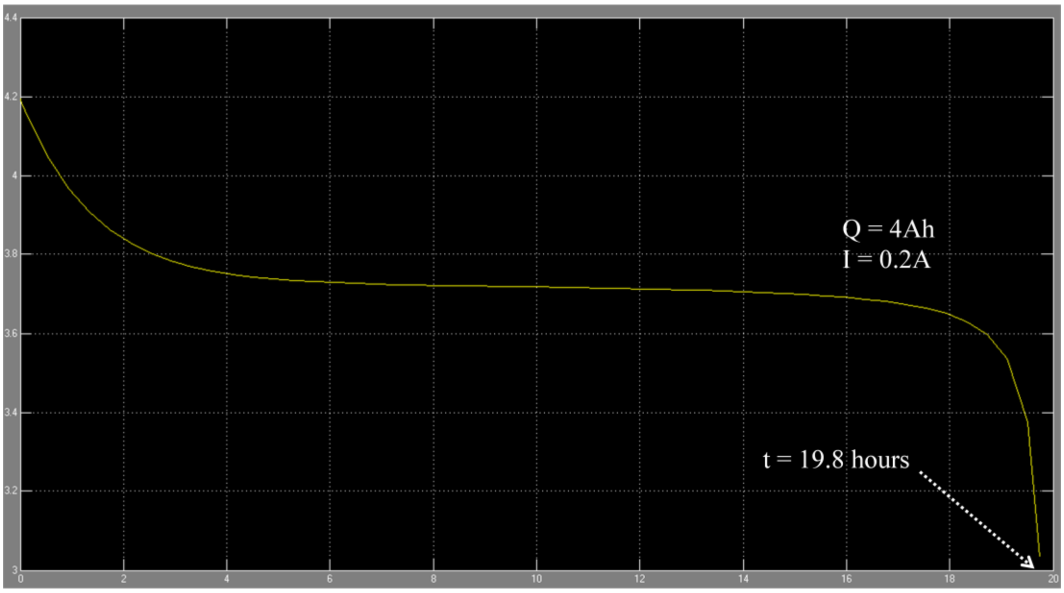

Figure 26 : Simulation result with Q = 4Ah and I = 0.2A [Voltage(V) vs time (hours)]

Table 5 : Discharge characteristics for different amount of I and Q

I (A)	Q (Ah)	Fully Discharge Time (hours)
0.1	1	9.8
	2	19.7
	4	39.0
0.2	1	4.7
	2	9.5
	4	19.7

The result in Figure 18 until Figure 23 is obtained by simulating the block diagram of Figure 13 which is the MATLAB equation.

From the table above we can see that if we double the capacity (Q) the time it takes to fully discharge will be doubled too. And if we double the current absorbed from the battery, the time to fully discharge will be shortened by the factor of 2.

This proves that higher capacity battery can store more charges in them because the discharge time is higher. The discharge time has linear relationship with the capacity of the battery. Thus, higher capacity battery is better than lower capacity battery.

4.2 Simulation Result for Charging Characteristic

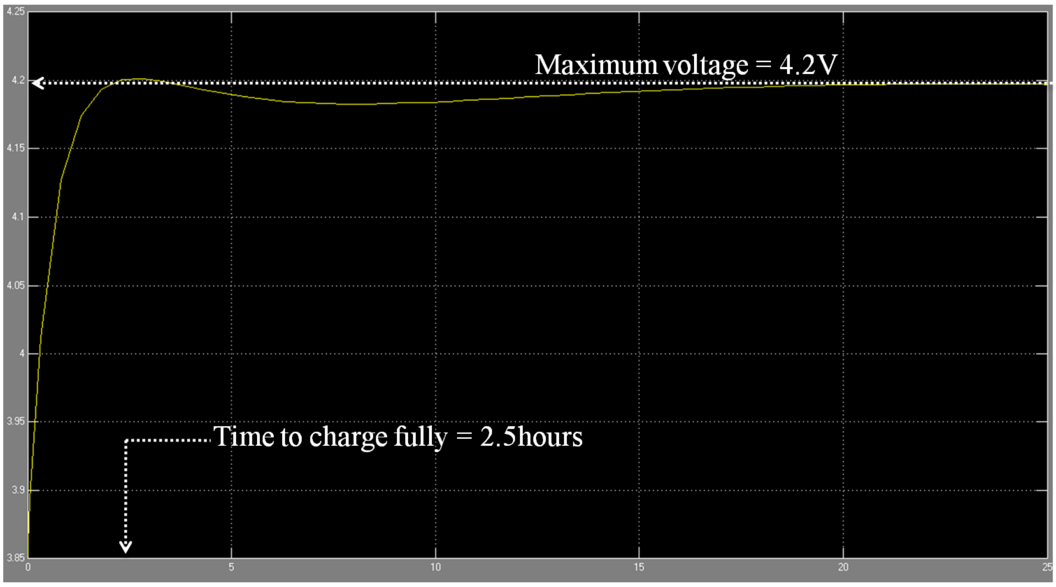

Figure 27 : Simulation Result for Charging Characteristic [Voltage(V) vs time (hours)]

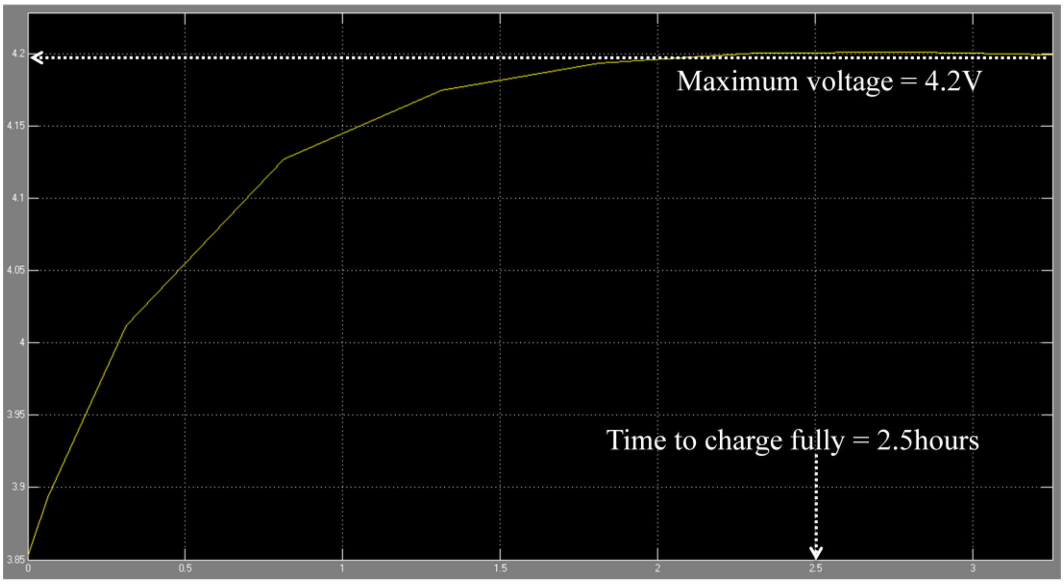

Figure 28 : Zoomed Simulation Result until t = 3.5 Hours [Voltage(V) vs time (hours)]

From the result, it is proven that the battery characteristic is identical to the battery in the discharging simulation since both batteries has maximum voltage of 4.2V.

4.3 Result for Different Temperature

For this simulation the constant is discharge current = 0.1A, initial capacity = 2.0Ah and storage time = 0 months.

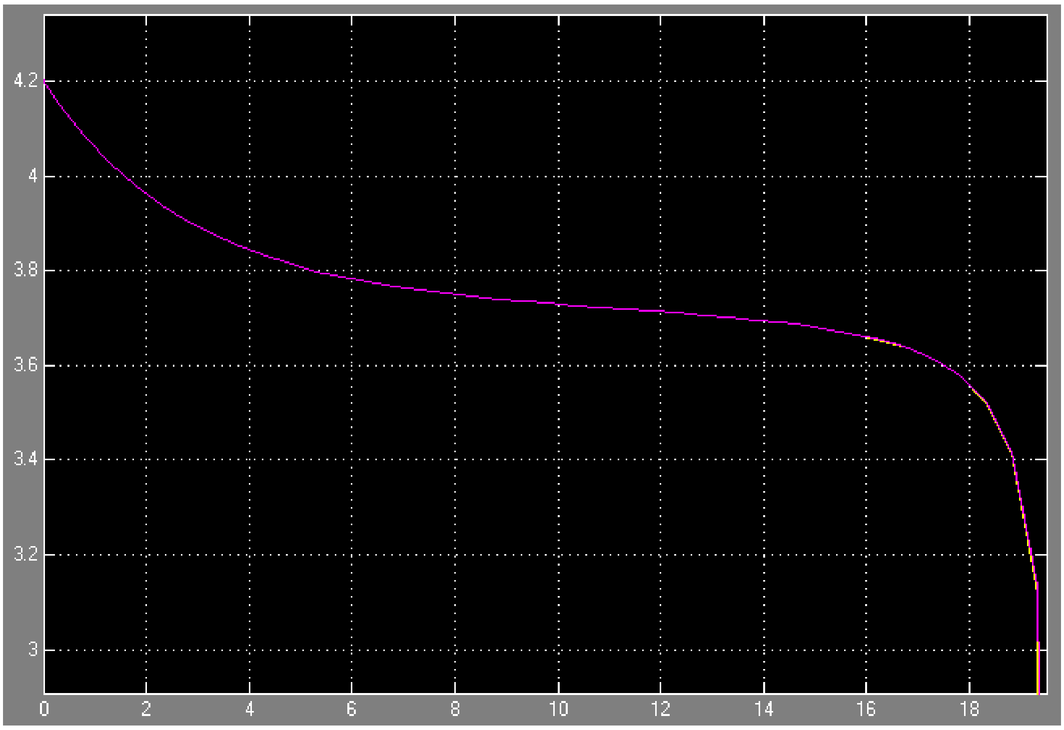

Figure 29 : Discharge Characteristics For 25ºC and 50ºC for First Discharge [Voltage(V) vs time (hours)]

From the graph, we can see that there is no difference between the discharge curve when the battery is in the first discharge. The time to discharge the battery for both temperature is approximately 19.3 hours.

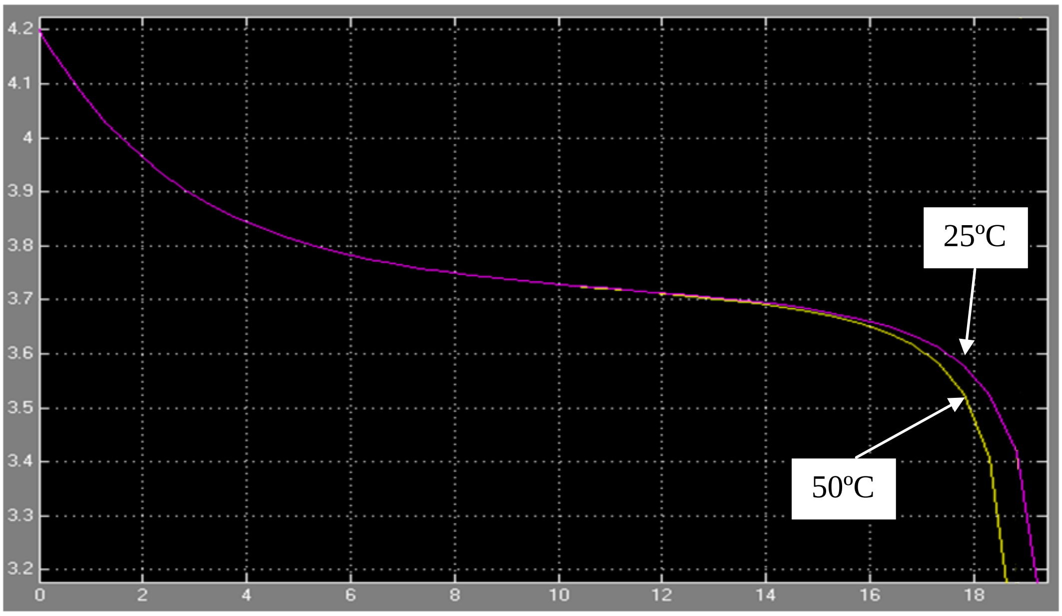

Figure 30 : Discharge Characteristics For 25ºC and 50ºC For 100th Discharge [Voltage(V) vs time (hours)]

However, for the 100th discharge curve, the difference between 25ºC and 50ºC can be seen from the curve. The time to discharge the battery for 25ºC is approximately 19.2 hours and the time to discharge the battery for 50ºC is approximately 18.2 hours.

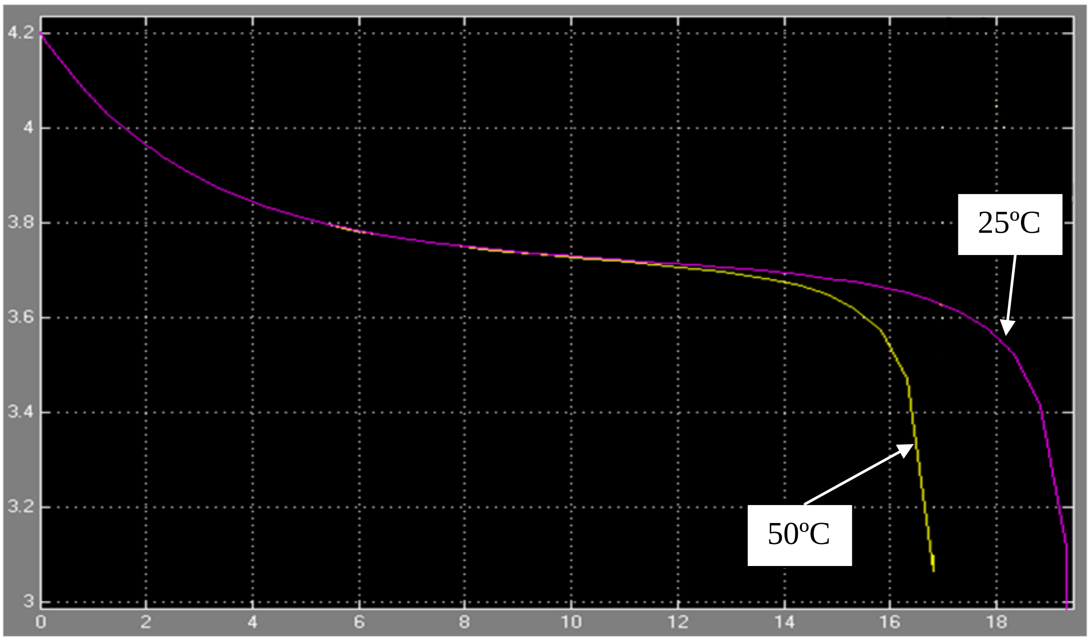

Figure 31 : Discharge Characteristics For 25ºC and 50ºC for 500th Discharge [Voltage(V) vs time (hours)]

For 500th discharge, the time to discharge the battery for 25ºC temperature is still about the same as 100th discharge which is 18.8 hours. However, the time to discharge the battery for 50ºC operating temperature has dropped significantly to 16.8 hours from 18.2 hours at 100th discharge. The difference of discharge time between 25ºC and 50ºC is significantly higher now. The time to discharge the battery for 25ºC is significantly longer than 50ºC.

Table 6 : Summary of Simulation for Different Temperature

Cycle Number	Time to Fully Discharge (hours)	
	25ºC	50ºC
0	19.3	19.3
100	19.2	18.2
200	19.1	17.7
300	19.0	17.5
400	18.9	17.3
500	18.8	16.8

From the table above, we can conclude that battery running at higher temperature will result in significant reduction of its capacity compared to running at lower temperature. For 25ºC, the capacity of the battery has not changed much even though it has already run 500 cycle. This is because the coefficient of k_1 for 25ºC (8.5 x $10^{-8)}$ is too low compared to 50ºC (1.6 x 10^{-6}).

As a conclusion, it is better to run a battery in lower temperature to make sure that the capacity fading effect of the battery is lower.

4.4 Simulation for Different Storage Time

Storage time refers to the time when the battery is inactive. For this simulation the constant is discharge current = 0.1A, initial capacity = 2.0Ah and the battery is in its first discharge.

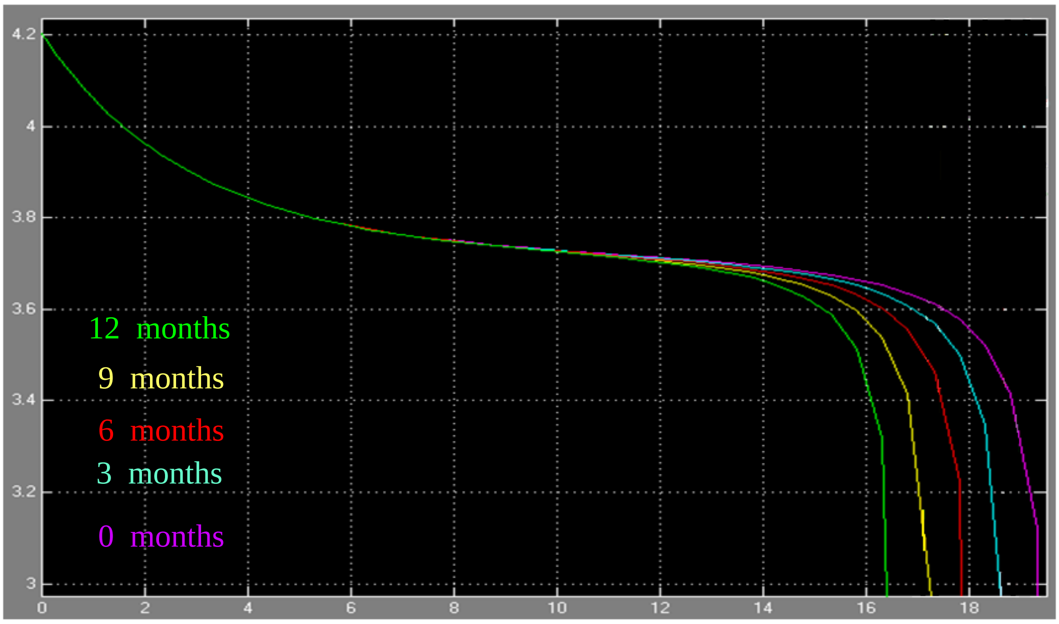

Figure 32 : Discharge Characteristics for Storage Time 0-12 months for temperature 25ºC [Voltage(V) vs time (hours)]

Storage time is associated to the calendar loss time, which is the capacity loss due to inactivity of the battery. Inactive in this context means that the battery is not discharged or charged. The next graph will show the curve of the battery stored in 50ºC. However it is more realistic to assume that the battery is stored in 25ºC because it is the room temperature.

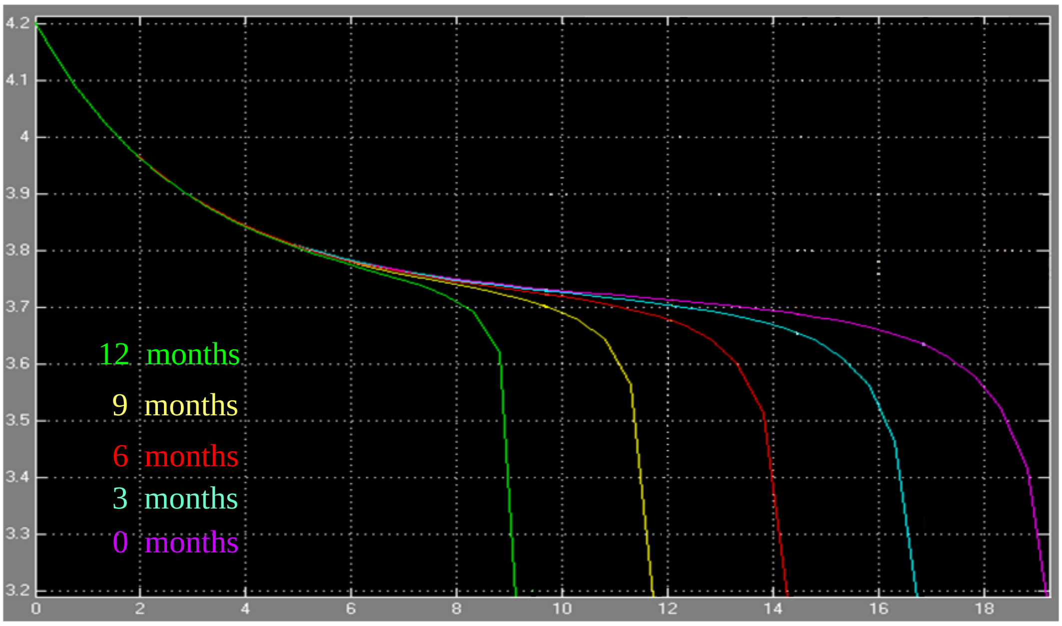

Figure 33 : Discharge Characteristics for Storage Time 0-12 months for temperature 50°C [Voltage(V) vs time (hours)]

From the graph above, we can see that storing the battery in higher temperature room will result in capacity loss greater than storing in lower temperature room.

Please refer to Table 6 below for the summary of the battery discharge time.

Table 7 : Summary of Simulation for Different Storage Time

Storage time (months)	Time to fully discharge (hours)	
	25ºC	50ºC
0	19.33	19.2
3	18.60	16.7
6	17.85	14.2
9	17.25	11.7
12	16.40	9.1

Storing a Li-ion battery without using it will result in greater capacity loss than using the battery (cycling). The factor that contributes to capacity loss is the temperature. Higher storage temperature will result in higher capacity loss due to calendar loss time.

So it is better to use a battery than storing it. If we must keep a spare battery as a backup battery, it is better to store it in someplace dry and has low temperature.

4.5 Simulation for Different Cycle Number

For this simulation the constant is discharge current = 0.1A, initial capacity = 2.0Ah and the storage time = 0. The temperature is assumed at 50ºC because when a battery is running, the temperature will surely rise due to heat generated from the battery.

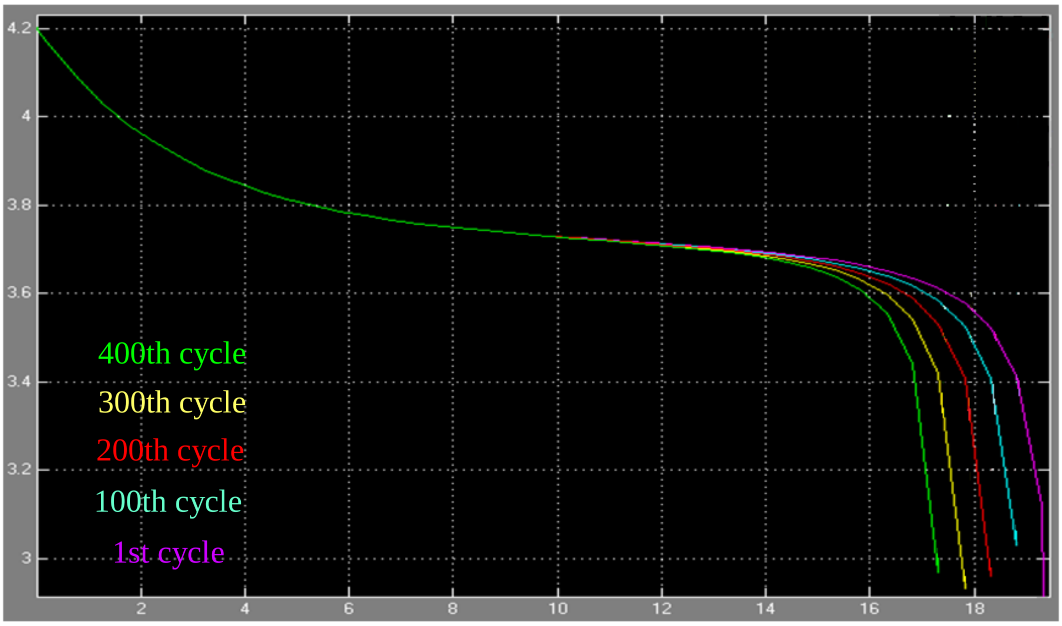

Figure 34 : Discharge Characteristics for Cycle Number 0-400 [Voltage(V) vs time (hours)]

Table 8 : Summary of Simulation for Different Cycle Number

Cycle Number	Time to Fully Discharge (hours)
0	18.8
100	18.2
200	17.7
300	17.5
400	17.3
500	16.8

From the table above, it is proven that the battery capacity will decrease over time when the battery went through a lot of charge/discharge cycles during its lifetime.

However, it is interesting to note that the time to fully discharge the battery at 500th cycle is higher than not using it for 12 months at 50ºC. So it is better to use a battery rather than letting it being inactive so that the capacity loss is lower.

4.6 Comparison with Experimental Data

This graph is a data from an experiment of charging and discharging cycle for $Li_2Co_2(MoO_4)_3$ battery. The experiment is done up until the 20th cycle.

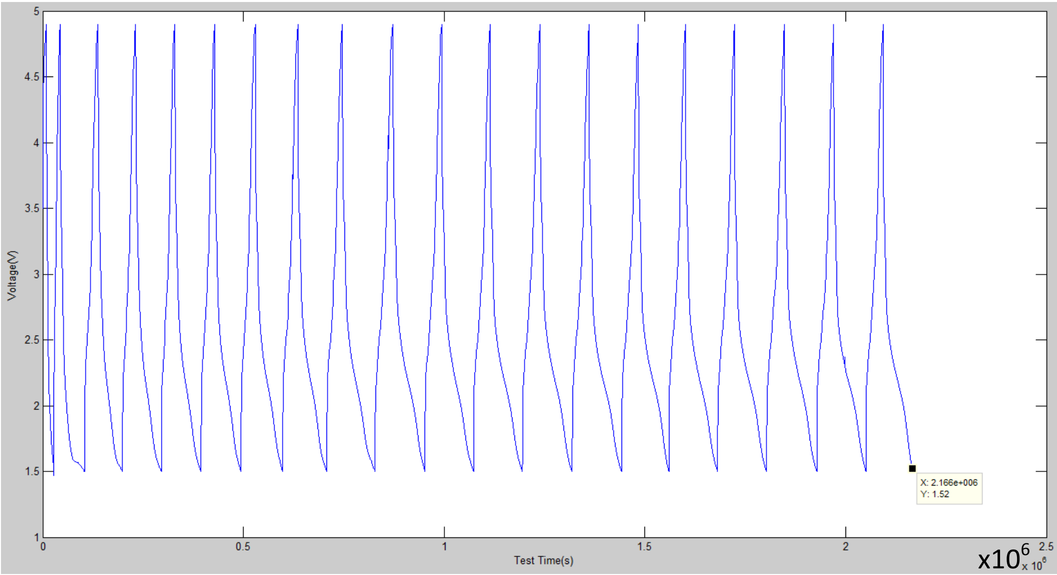

Figure 35 : Charging/Discharging curve for $Li_2Co_2(MoO_4)_3$ battery

The figure above shows the charging and discharging curve for the first cycle until the 20th cycle of the battery.

Table 9 : Summary of Charging/discharging Cycle for $Li_2Co_2(MoO_4)_3$ Battery

Cycle Number	Time to completely discharge	
	In seconds	In hours
2	81000	22.500
5	80600	22.389
10	79500	22.083
15	77000	21.389
20	75000	20.833

In table 9 we can see that as the cycle number increases, the time to completely discharge the battery is decreased a little bit. This proves that the capacity of the battery has been reduced due to cycle life losses.

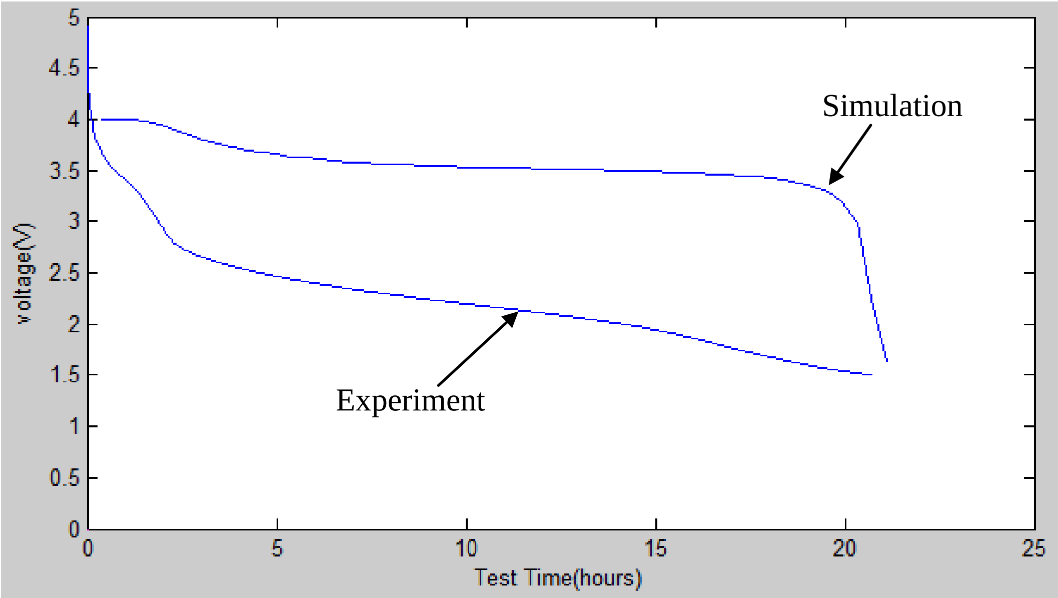

Figure 36 : Comparison between Experiment Data and Simulation Data for 20th Cycle

From the graph above, we can see that the capacity of the battery for experiment data and simulation data is about the same even though the voltage curve for experiment data and the simulation data is not the same. Thus, this confirms that the battery model proposed in this project is working properly.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Li-ion battery usage has been growing rapidly in the last decade. The demand for Li-ion battery has risen due to many portable electronics has come out in the market.

In this project, a model of lithium-ion battery considering the effect of temperature and capacity fading is discussed. The simulation results shows that the developed model can truly reflect the output characteristic of lithium-ion battery.

The developed model is able to evaluate the battery performance under several different temperatures, storage time, current and cycle number.

Higher capacity battery is always better than lower capacity battery because it can last longer than the lower capacity battery. A battery with 2Ah capacity can last approximately twice than a battery with 1Ah capacity if the temperature, cycle number and storage time is the same.

For the temperature effect to the battery capacity, higher temperature has higher effect to the capacity fading of the battery. This effect is applicable to both the calendar loss and cycling time capacity loss of the battery.

So it is always better to operate a Li-ion battery in lower temperature and it is also better to store a Li-ion battery in lower temperature area.

As the battery goes through more cycles is its lifetime, a little bit of the battery capacity will be loss due to cycle life losses. This capacity loss is irreversible, meaning that after some time, we should buy a new battery to replace the old one. However to reduce the capacity loss due to cycle life, operate the battery in lower temperature. Higher operating temperature will significantly increase the cycle life losses of the battery.

Letting the battery inactive will also result in the loss of capacity for the battery. Worse than that, from the simulation result, calendar life losses is always higher than cycle life losses. So it is better to use the battery rather than letting it become inactive. To reduce the calendar life losses, it is advisable to store the battery at lower temperature because from the simulation result, higher temperature will result in greater calendar life losses to the battery.

The simulation for this project is also compared with real experiment data. Even though the discharge curve is not exactly the same, but the capacity is about the same so the battery model in this project is supposed to work correctly.

5.2 Recommendation

For the future advancement of this project, the work that has to be done is the new MATLAB block to consider the effect of different cathode and anode materials, and how they effect on the capacity of the battery.

This is because to use the model with a certain cathode material, for this project block we have to calculate manually the mass per mole of the negative electrode. Maybe in the future in the MATLAB block there is a lookup table to relate between the material and its mass per mole.

For buying a battery, it is recommended to buy a battery with higher capacity because higher capacity battery can last longer.

When operating a battery, to reduce the cycle life losses, operate the battery in low temperature. For large scale Li-ion battery, it is preferable for the battery to have heat sinks on it to reduce its temperature, thus prolonging its life.

It's better if we only buy a Li-ion battery when only needed. This is because due to inactivity the battery's capacity will reduce over time. If a battery is must be bought as a backup battery, store it in a dry, cool place to make sure the battery's capacity calendar life loss is reduced.

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APPENDICES

APPENDIX A

FYP 1 GANTT-CHART

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								Mid-semester break							
2	Submission of Preliminary Report															
3	Literature Review															
4	Submission of Progress Report															
5	Seminar															
6	Simulation															
7	Submission of Interim Report															
8	Oral Presentation									After exam week						

APPENDIX B

FYP 2 GANTT-CHART

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Simulation on Effect of Temperature	■	■	■	■				Mid Sem Break								
2	Submission of Progress Report 1				■												
3	Simulation of Storage Time					■	■	■		■							
4	Submission of Progress Report 2									■							
5	Simulation of Cycling										■	■	■	■			
6	Poster Presentation													■			
7	Comparison with Real Data														■	■	■
8	Submission of Draft Report															■	
9	Submission of Final Report																■
10	Oral Presentation	After Exam Week															