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UNIVERSITI TEKNOLOGI PETRONAS

"LITHIUM-ION BATTERY DISCHARGING CURRENT CHARACTERISTICS. MODELING APPROACH"

by

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LITHIUM-ION BATTERY DISCHARGING CURRENT CHARACTERISTICS. MODELING APPROACH

by

CHELLADURAI A/L SINKARAM

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PERAK

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DECLARATION OF THESIS

Title of thesis	LITHIUM-ION BATTERY DISCHARGING CURRENT CHARACTERISTICS. MODELING APPROACH

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I would like to devote my thesis to my parents who taught me that knowledge is the key to success. To my beloved wife Ms. Kavitha who taught me the meaning of success.

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ABSTRACT

Battery-powered electronics devices have become ubiquitous in the modern society. The recent rapid expansion of the use of portable devices (e.g. portable computers, personal data assistants, cellular phones, shavers, etc) and Hybrid Electrical Vehicles (HEVs) creates a strong demand for fast development of the battery technologies at an unprecedented rate. With growing usage of portable electronics it has become important in the recent decades to find an energy storage device which has high specific power with minimum charging timing. Currently the most widely used power source for the portable electronic devices is Lithium- Ion batteries as it has high voltage, power density and high cycle time. Lithium batteries have now taken their place as the rechargeable battery of choice for portable consumer electronics equipment's. The main objective is to develop a dynamic lithium-ion battery discharging model. It is very important to develop a battery model to study the behavior of the battery for different operation condition. Lithium-ion battery models capture the characteristics of life batteries and can be used to predict their behavior under various operating condition. The model accounts all dynamic characteristics of the lithium ion battery, includes nonlinear open circuit voltage, current, temperature, cycle number and storage time depended capacity to transient response. Simulation results are obtained and results compare with theoretical results. The simulation also carried out under different load current, temperature, cycle number and capacity the changes in the battery terminal voltage and remaining capacity is monitored. The battery model is developed by using MATLAB/Simulink.

ABSTRAK

Bateri peranti elektronik telah menjadi sentiasa ada dalam masyarakat moden. Pengembangan pesat penggunaan peranti mudah alih (contohnya komputer mudah alih, pembantu data peribadi, telefon bimbit, pencukur, dll) dan Kenderaan Hibrid Elektrik (HEVs) baru-baru ini mewujudkan permintaan yang kukuh untuk pembangunan pesat teknologi bateri pada kadar yang tidak disangka. Dengan penggunaan yang semakin meningkat elektronik mudah alih, ia telah menjadi penting dalam beberapa dekad kebelakangan ini untuk mencari peranti penyimpanan tenaga yang mempunyai kuasa tinggi khusus dengan masa minimum mengecas. Pada masa kini, sumber kuasa yang paling banyak digunakan untuk peranti mudah alih elektronik adalah Litium-Ion bateri kerana ia mempunyai voltan yang tinggi, ketumpatan kuasa dan masa kitaran tinggi. Bateri litium kini telah mengambil tempat, sebagai bateri boleh dicas semula pilihan untuk pengguna mudah alih peralatan elektronik. Objektif utama adalah untuk membangunkan model bateri lithium-ion yang dinamik menunaikan. Ia adalah sangat penting untuk membangunkan model bateri untuk mengkaji tingkah laku bateri untuk keadaan operasi yang berbeza. Model bateri litium-ion menangkap ciri-ciri bateri kehidupan dan boleh digunakan untuk meramalkan tingkah laku bateri di bawah pelbagai keadaan operasi. Model yang mencakupi semua ciri-ciri dinamik bateri litium-ion, termasuk linear voltan litar terbuka, arus, suhu, kitaran bilangan dan masa penyimpanan bergantung kapasiti untuk sambutan fana. Keputusan simulasi yang diperolehi akan dibandingkan dengan keputusan teori. Simulasi juga dijalankan di bawah beban yang berbeza semasa, suhu, kitaran bilangan dan kapasiti perubahan dalam voltan terminal bateri dan kapasiti baki dipantau. Model bateri dibangunkan dengan menggunakan MATLAB/Simulink.

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LIST OF ABBREVIATIONS

SOC	State of Charge
DC	Direct current
AC	Alternating current
CLF	Calendar Life Losses
CLL	Cycle Live Losses
DOD	Depth of Discharge
Li-ion	Lithiun-ion
HEV	Hybrid Electrical Vechile
NiMH	Nickel Metal Hydride
NiCd	Nickel Cadmium

NOMENCLATURE

V_o	=	Battery output voltage [V]
V_{oc}	=	Battery open-circuit voltage [V]
Z_T	=	Total internal impedance of the battery [Ω]
I_L	=	Load current [A]
$\Delta E(T)$	=	Temperature correction of the potential [V]
SOC_{initi}	=	Initial state of charge
C_{usable}	=	Usable battery capacity [Ah]
T	=	Temperature [°C-°K]
t		Storage time [months]
Q_{usable}	=	Remaining usable battery capacity
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} [$\Omega/cycle^{1/2}$]
CCF	=	Capacity correction factor
C_{init}	=	Initial battery capacity [Ah]
Exp(s)	=	Exponential zone dynamics (V)
K_{0t}	=	Acceleration factor
E	=	Active region
R_s	=	Series resistor [Ω]
R_c	=	Cycle resistor [Ω]
RC	=	Transient
R_{T_S}	=	Short transient resistor [Ω]
R_{T_L}	=	Long transient resistor [Ω]
C_{T_S}	=	Short transient capacitor [Ω]
C_{T_L}	=	Long transient capacitor [Ω]
Z_T	=	Total impedance [Ω]
X_C	=	Inductive capacitance [Ω]

Z_{T_S} = Short Transient Impedance [Ω]

Z_{T_L} Long Transient Impedance [Ω]

C = Capacitor (F)

f = Frequency (H_Z)

CHAPTER 1

INTRODUCTION

1.1 Introduction to batteries

Since the dawn of civilization world has become increasingly addicted to electricity due to its utmost necessity for human life. The demand for electricity operated devices led to a variety of different energy storage systems which are chosen depending on the field of application. Among the available stationary power sources, advanced batteries substantially impact the areas of energy storage, energy efficiency and advanced vehicles.

The electronic devices such as laptop, digital camera, camcorders, etc have become portable in size owing to the rechargeable battery technologies which provide the power for the effective operation of the portable device [1]. The invention of batteries has opened new horizons in the field of portable electronic devices [2]. The electronic devices such laptop, become miniature in size due to rechargeable batteries like lithium ion, Nickel cadmium, Nickel Metal hydride and Lead acid, which provide the power source for their effective operation [3].

In general, batteries are device that translate the energy of electrochemical reactions directly into electricity. But this simple definition greatly understates the pervasive role of batteries in our life. Batteries are effcient ways to make electricity portable. Since conversion of heat is not involved, the thermodynamic efficiency can be at least twice that of a thermal power plant. Practical energy efficiencies reaching 90% are possible for electrochemical energy storage systems.The first battery was demonstrated nearly 200 years ago (in year 1800) and battreries have been extensively researched since then [4].

Batteries come in a varity of shapes and size. Some are small enough to fit on a computer circuit board while others are large enough to power a submarine [5].

There are batteries that are used once and thrown away and there are batteries that are recharged and reused thousands of times. Some batteries are used several times everday while othres might sit for ten to twenty years before they are ever used. Obvoiusly for such a diversity of uses, a varity of battery types is necessary. But all of them work from the same basic priciple [6].

1.1.1 Birth of primary and secondary batteries

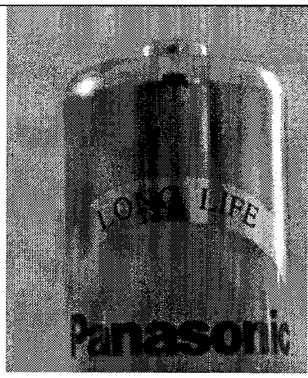
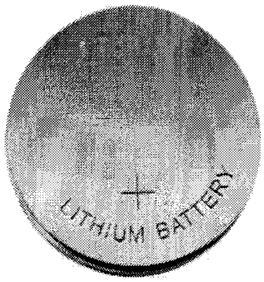
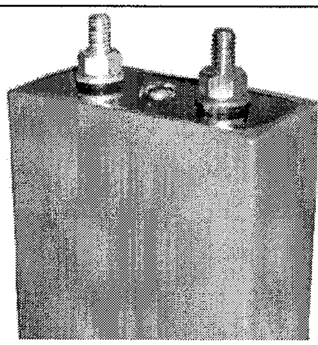
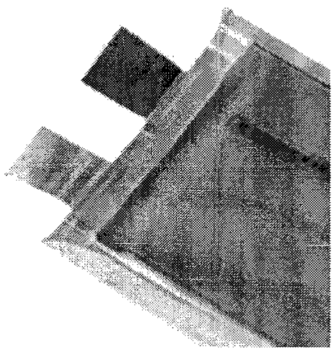
Most historians date the invention of batteries to about 1800 when experiments by Alessandro Volta resulted in the generation of electrical current from chemical reactions between dissimilar metals. The original voltaic pile zinc and silver disks and a separator consisting of porous non-conducting materials saturated with sea water. When stacked, a voltage could be measured across each silver and zinc disk. Experiments with different combination of metals and electrolytes continued over the next 60 years. Even though large and bulky, the voltaic piles provided the only practical source of electricity in the early 19th century. They were the original primary battery.

Johann Ritter first demonstrated the elements of a rechargeable battery in 1802, but rechargeable batteries remained a laboratory curiosity until the development, much later in the century of practical steam-driven dynamos to recharge them. During the first half of the 19th century, experiments continued with a varity of electrochemcial couples (combnations of positive and negative electrodes materials and electrolyte). Finally about 1860, the ancestors of todays primary and secondary batteries were developed [7] .

1.2 Types of battries cells

The first batteries for the commercial use were introduced in 1800. There are few sizes and shapes of battery available for the commercial use. There are cylindrical cell, button cell and prismatic cell. Table 1.1 shows the type of cell and the application [8].

Table 1.1: Distinguishing features of a lithium-ion battery [8]

Type of cells	Picture	Year Invented	Application
Cylindrical Cell		1907	-Digital camera -Power tools -Medical instruments -Laptops
Button Cell		1980	-Cordless telephone -medical device
Prismatic cell		1990	-Portable device range from 400mAh -2,000mAhg
Pouch Cell		1995	-Portable electronic devices.

1.3 Problem statement

The rapid growth and use of miniature devices such as Portable Computers, Personal data assistants and Cellular Phones, and Hybrid Electrical Vehicles creates a strong claim for fast development of the battery technologies at extorting rates. Therefore it is timely and extremely important to develop battery models which will enable the study of Li-ion battery characteristics when operated under various conditions reflecting corresponding variations in the discharge performance relating to capacity, current delivered by the battery, voltage, etc.

1.4 Motivation of work

The invention of batteries has opened new horizons in the field of portable electronic devices. New technologies such as laptop heavily depend on battery packs. As the devices become miniature in size, portable power source are required to provide them with adequate electricity for their effective operation. The pursuit of efficient and environmentally safe energy storage system is the rechargeable lithium-ion battery, which is recognized currently as a top contender for energy storage solutions. It is important to study the characteristics of the battery for various discharging condition. Therefore, it is crucial to develop a dynamic discharging Lithium-ion battery model to analyze the characteristic of the battery when it is connected to various types of load. Modeling of lithium-ion batteries and simulating the results to reveal the battery characteristics is important in order to visualize the real time batteries.

Experimentally, many works have been carried out to predict the characteristics of the battery. Nevertheless, this thesis is intended in developing a dynamic lithium-ion discharging model and simulation is carried out as voltage profiles for various values of initial State Of Charge (from here on referred to an SOC_{initi} in this thesis), cycle number, capacity, load current and temperature

1.5 Objectives

The thesis by to addressing the following objectives:

a) To build a dynamic discharge block diagram model for Lithium-Ion battery using MATLAB/ Simulation.

b) To investigate the effect of temperature, storage time and cycle number on the performance of Lithium-ion batteries and the remaining capacity of the battery after discharge for various loads currents.

1.6 Scope of Research

This research investigates the performance of Lithium-ion battery for various discharging conditions. It will focus on remaining usage time and voltage profile for the various parameters such as (Initial State of charge) SOC_{initi}, load current, cycle number, capacity and temperature.

1.7 Outlines of the Thesis

Chapter 1 briefly discusses the different between primary and secondary battery and also discusses the history of the lithium ion battery. The research problem considered or this work is introduced and a brief description of the problem studied.

In Chapter 2, a brief history about the lithium-ion battery are presented. The basic characteristics of Li-ion different type of battery model and also discussed the advantage and disadvantage of the models reported by several researchers in the past are reviewed.

A dynamic lithium-ion battery is developed; to meet the objective of this work is given in Chapter 3.

The results are presented and discussed in Chapter 4. The effects of various factors on lithium ion batteries are analyzed briefly.

Finally, the conclusions and recommendations are given in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Battery

Most of the electronic gadgets heavily depend on battery packs. As the devices become miniature in size, portable power source are required to provide them with adequate electricity for their effective operation in the ICT (Information and communication technology) environment. The pursuit of efficient and environmentally safe energy storage system is the rechargeable lithium-ion battery, which is recognized currently as a top contender for energy storage solutions [9]. In 1991, SONY Corporation introduced to the lithium-ion batteries with high energy density, high operating voltage levels and long cycle life, to fulfill the needs of portable electronic market and is in extensive use till date [10]. Ultimately, the family of lithium-ion battery plays an ever greater role in all aspects of our life. Figure 2.1 [10] shows the lithium-ion battery in hand phone. Figure 2.2 [10] shows the lithium-ion battery internal structure. Figure 2.3 show the, inside look of the laptop battery [10]. The battery contains six cells, which four cells connected in parallel to increase the voltage to 14.4V and two cells is connected in series to increase their capacity from 2400mAh to 4800mAh [8].

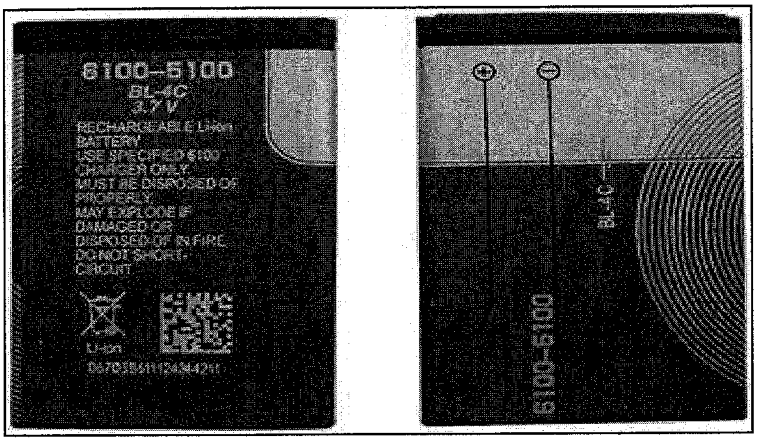


Figure 2.1: Lithium-ion battery in hand phone [8]

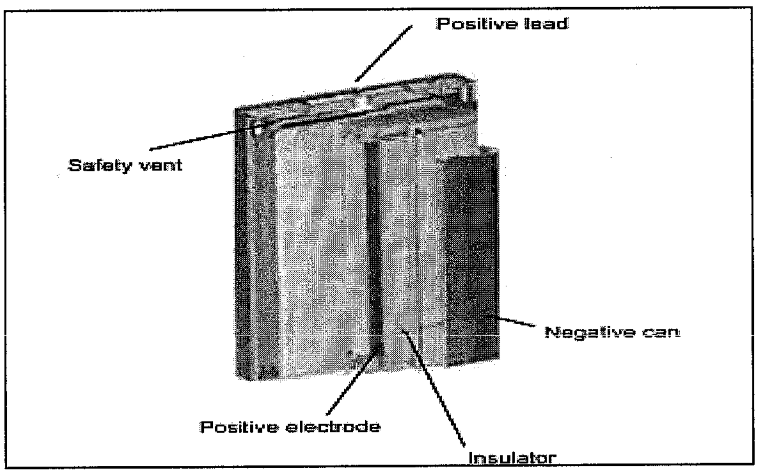


Figure 2.2: Li-ion battery structure [8]

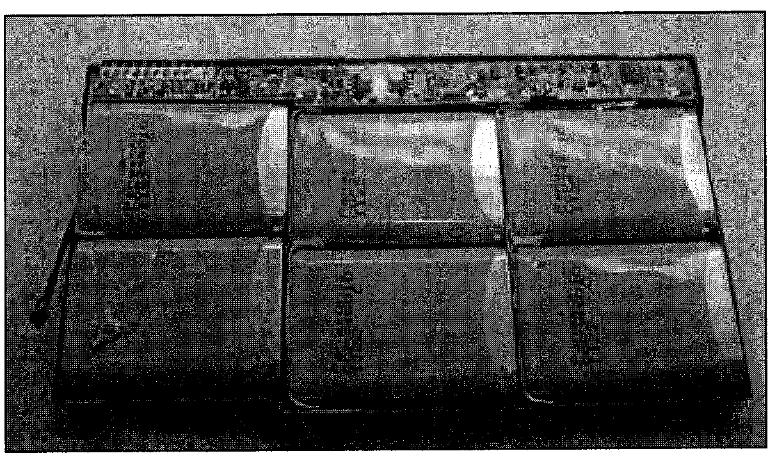


Figure 2.3: An inside look of the laptop battery [8]

2.2 Differences between primary and secondary rechargeable battery

Primary batteries are non-rechargeable and are used once and replaced. The chemical reactions that supply current in them are irreversible [11]. They contain only a fixed amount of the reacting compounds and are discharged only once. If the educts are consumed by discharging, the battery cannot be used again. Figure 2.4 shows the internal structure of a primary battery [8].

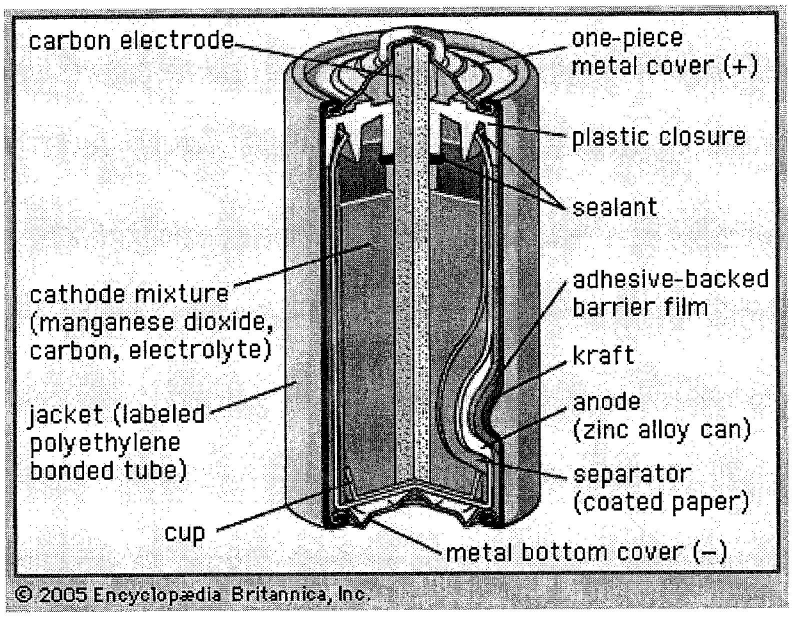


Figure 2.4: Internal structure of primary battery [8].

Secondary batteries can be recharged and reused. They use reversible chemical reactions. By reversing the flow of electricity, the chemical reactions are reversed to restore the active material that had been depleted and the stored electrochemical energy can be used again. The process should be reversible hundreds or even thousands of times, so that the life time is lengthened. This is a fundamental advantage, especially with regard to the important aspects of the purchasing costs, which are normally much higher than those of primary batteries.

Secondary batteries are also known as rechargeable batteries, storage batteries or accumulators. (Besenhard, 1989) [12]. Table 2.1 shows various rechargeable batteries and the year in which they were invented [4].

Table 2.1: Various batteries invented since ancient days [4]

Name of the battery system	Year
Voltaic pile: silver zinc	1800
Daniel cell: copper zinc	1836
Plante: rechargeable lead-acid cell	1859
Leclanche: carbon zinc wet cell	1868
Gassner:carbon zinc dry cell	1888
Commercial flashlight, D cell	1898
Junger: nickel cadmium cell	1899
Neumann: sealed NiCd	1946
Alkaline, rechargeable NiCd	1960s
Lithoum, sealed lead asid	1970s
Nickel metal hydride (NiMH)	1990
Lithium-ion	1991
Rechargeable alkaline	1992
Lithium-ion polymer	1999

2.3 Classification of rechargeable batteries

Various battery chemistries are evaluated not only on the merit of long talk time but also with respect to operational costs, self-discharge and load characteristics [13]. Table 2.2 [14] provides the characteristics of different kinds of rechargeable battery technologies.

Table 2.2: Characteristics of rechargeable batteries [14]

Characteristic	Lead Acid	NiCd	NiMH	Li-ion	Li-ion Polymer
Gravimetric energy density	30-50 (Wh/kg)	45-80 (Wh/kg)	60-120 (Wh/kg)	110-160 (Wh/kg)	100-180(Wh/kg)
Cell voltage (nominal)	2V	1.25V	1.25V	3.6V	3.6V
Maintenance Requirement	3-6 months	1-2 months	2-3 months	Not required	Not required
Self-discharge /month	5%	20%	30%	10%	Nil
Fast charge time	8-16 h	1 h typical	2-4 h	2-4 h	2-4 h
Discharge temperature	-20 to 60 °C	-40 to 60 °C	-20 to 60 °C	-20 to 60 °C	0 to 60°C
Internal resistance (mΩ)	<100 12V pack	100-200 6V pack	150-300 6V pack	150-300 7.2V	25-75[2]
Overcharge tolerance	High	Moderate	Low	Low	Low
Charge Temperature	-20 to 50°C	0 to 45°C	0 to 45°C	0 to 45°C	0 to 45°C
Safety requirements	Thermally stable	Thermally stable	Thermally stable	Protection circuit mandatory	Protection circuit mandatory
Toxicity	Very high	Very high	Low	Low	Low
Dischrage cutoff voltage (v/cell)	1.75	1.00	1.00	2.50-3.00	2.50-3.00

2.3.1 Lead acid batteries

Lead acid batteries were the first rechargeable batteries introduced for commercial use. Besides its low energy density amongst the rechargeable batteries, lead (*Pb*) toxicity is of more concern due to its environmentally unfriendliness. Such batteries are used when weight is of little concern.

2.3.2 Nickel Cadmium (NiCd) batteries

For many years, nickel cadmium (NiCd) was the only practical rechargeable battery for portable radios, cell phones, laptop computers and video cameras. The need for increased talk time in mobile communication devices demanded the development of alternative battery chemistries. In addition, the negative publicity about the memory phenomenon and concerns Cd disposal caused equipment manufacturers to seek alternatives. Thus emerged yet another rechargeable battery system, Nickel Metal hydride.

2.3.3 Nickel Metal Hydride (NiMH) batteries

Once hailed as a superior battery system to NiCd batteries in a number of areas, Nickel metal hydride (NiMH) batteries also have limited energy density, are relatively heavy and pose serious environmental concerns. They suffer from a high self-discharge rate and limited cycle life. Ultimately, they fail to provide the universal battery solution for the twenty first century. Shorter than expected service life remains a major complaint [14].

2.4 Lithium ion batteries

Lithium-ion batteries are considered to be the best choice especially for the fast moving commercial market. Maintenance free an advantage that no other battery chemistry can claim, Li-ion batteries are the preferred choice for many applications because they offer a small size and long runtime as well as high voltage level, 3.6V per cell compared to other rechargeable battery technologies. There is no lithium metal and such batteries are safe, if used properly. They offer a low self-discharge rate, the overall specific energy (110-160 Wh/kg) [15] is impressive and an excellent cycle life (between 300 to 500 cycles) is obtained [4]. This system is used in both consumer and defense application such as cellular telephone and notebook computer.

But this battery system is not without problems. A relatively rapid aging process, even if the battery is not in use, limits the life to some extent. In addition to containing the liquid electrolyte which is flammable under abuse condition, Li-ion cells must have a rigid metal housing, adding considerable weight to multi cell packs (Lithium polymer). Such batteries remain expensive. The operating temperature conditions base problem and as well. However, research has been going on in full swing and researchers have succeeded to reduce the drawbacks although not fully less costly versions of rechargeable lithium ion batteries for use in electric and hybrid vehicles.

Depth of the discharge (DOD) will determine the cycle count of the battery. If the DOD is low than, the battery will be lost for longer time [8]. Table 2.3 compares the number of discharge/charge cycles the Li-ion cells can deliver at various DOD levels before the battery capacity drops to 70 percent [8]. Another problem with lithium-ion battery is storage temperature. When the lithium ion battery is stored at a temperature of 30°C, it's suffered from stress. When a battery is fully charged (4.2V), exposed to high temperature and stored in a full state-of-charge (SOC) for time, is more stressful than cycling. Table 2.4 demonstrates capacity loss as a function of temperature and SOC [8]. As the temperature is increase the remaining usable capacity is reduce for the two different value of SOC [16].

Table 2.3: Comparison between depth of discharge and cycle number [8]

Depth of discharge	Discharge cycle
100% DoD	300-500
50% DoD	1200-1500
25% DoD	200-2500
10% DoD	3750-4700

Table 2.4: Capacity loss as a function of temperature and SOC [8]

Temperature	40% Charge	100% Charge
0^0C	98%	94%
25^0C	96%	80%
40^0C	85%	65%
60^0C	75%	60%

Table 2.5 shows as how the discharge cycle and full charge capacity charges with respect to cell voltage [8]. It is seen from Table 5 that a reduction of 0.10 V/cell doubles the cycles time with a corresponding charge in capacity . Figure 2.5 shows the capacity of the lithium-ion battery for different cycle time [8]. The remaining capacity in the battery always depends to the number of cycle. Increasing the cycle time will reduce the remaining capacity [17] and also reduce cell voltage.

Table 2.5: Comparison between cell voltage and cycle time [8]

Charge level (V/cell)	Discharge cycle	Capacity at full charge
4.30V	150-250	110%
4.20V	300-500	100%
4.10V	600-1000	90%
4.00V	1200-2000	70%
3.92V	2400-4000	50%

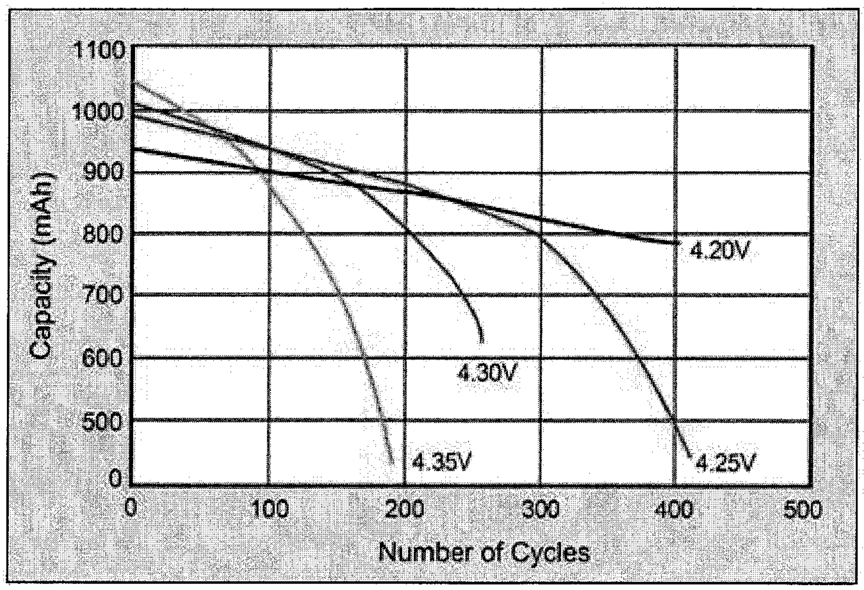


Figure 2.5: Remaining capacities for the different cycle number [8]

2.5 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 [18].

1983 - Michael Thackeray, John Good enough, 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 - AkshayaPadhi, 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.

2.5.1 Lithium primary batteries

A lithium primary battery (non-rechargeable) is composed of lithium metal or a lithium aluminum alloy as an electrode (anode) and a transition metal dioxide such as MnO_2 as a positive electrode (cathode). Such batteries do not have to put up with the design constraints that rechargeable lithium batteries do, indicating that they have more capacity and lower self-discharge rates (0.5% per year). Due to the organic liquids that need to be used for electrolytes, primary lithium batteries typically have high internal impedance, limiting their maximum current to surprisingly low values.

2.5.2 Rechargeable lithium batteries

Lithium anodes have been among the most heavily utilized in secondary (rechargeable) battery systems due to a very high negative potential of lithium combined with a low equivalent weight. Number of rechargeable lithium batteries have been developed and demonstrated in prototype cells such as Li/TiS_2 and Li/MnO_2. In the mid-1970s, rechargeable lithium systems using this concept were introduced to the market.

The positive electrode usually exhibits sufficient cycle ability due to the reversible insertion mechanism but the periodic dissolution and deposition of lithium, during cycling of the negative electrode is a severs problem. Cycling of metallic lithium is associated with extensive shape changes imposing limitation on metallic lithium anode.

The well-known surface dendrites are formed upon repeated charging and discharging cycles as reported by Abraham and Brummer (1983) [19]. This ultimately leads to reduced efficiency, failure, and even explosion [20]. Formation of dendrites on lithium metal anode during repeated charging and discharging cycles and cell explosion is illustrated in the Figure 2.6 [4].

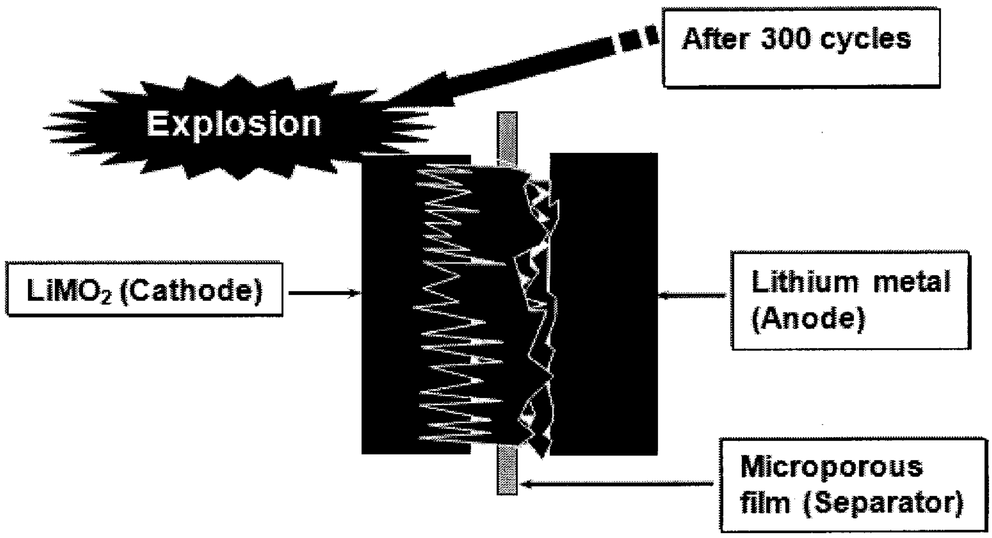


Figure 2.6: Diagram illustrating the formation of dendrites on the surface of lithium metal anode.

In addition to the inherent instability of lithium metal, especially during charging , its violent reaction with air and moisture makes its use hazardous.

Due to these limiting factors in using metal lithium, research shifted to nonmetallic lithium batteries using lithium-ions, in which the metallic lithium is replaced by a lithium intercalation compound. The intercalation compounds used in lithium-ion batteries are capable of intercalating lithium-ions reversibly at very low voltage.

Although slightly lower in energy density than lithium metal, the lithium-ion is safe improved cycle life, provided certain precautions are met when charging and discharging. Today, the lithium- ion is the fasted growing battery chemistry [14].

2.6 Rechargeable lithium ion batteries

The latest trend today battery research is focused on lithium- ion chemistry so much, so that one could presume that all portable devices would be powered with lithium-ion batteries. In many ways, lithium-ion is superior to nickel and lead based chemistries and the application for lithium–ion batteries are growing as result. The lithium–ion chemistry is continually optimized and tailored for a variety of application. Table 2.6 shows the distinguishing features of a lithium-ion battery [4].

Table 2.6: Distinguishing features of a lithium-ion battery [4]

Parameters	**Lithium-ion**
Weight	Light
Size	Small
Maintenance	Free
Run time	Long
Self-discharge rate	Low
Technology	Advanced
Cycle life	Excellent
Safety	Safe and reliable
Voltage	High
Energy density	High
Power	High
Memory effect	No
Environmentally	Friendly

2.6.1 Insertion electrode materials

A wide area of ambient-temperature rechargeable batteries includes insertion electrode materials due to the reason that electrochemical insertion (or electro insertion) reactions are intrinsically simple and reversible [21].

2.6.2 Positive electrode (cathode) materials

Materials containing lithium-ions and that can be used as cathode active materials must be capable of reinserting lithium-ions during charge and inserting lithium-ions during discharge without undergoing appreciable changes in lattice volume. Such materials are generally called insertion cathodes. The layered materials such as lithium cobalt oxide ($LiCoO_2$) and lithium nickel oxide ($LiNiO_2$) and spinel lithium manganese oxide ($LiMn_2O_4$) are widely studied as insertion cathodes. The layered $LiMO_2$ is shown in Figure 2.7. It is seen that the layers of lithium lie between slabs of cobalt and oxygen, which are arranged in octahedral [43]. Table 2.7 shows the characteristics for cathode materials [18].

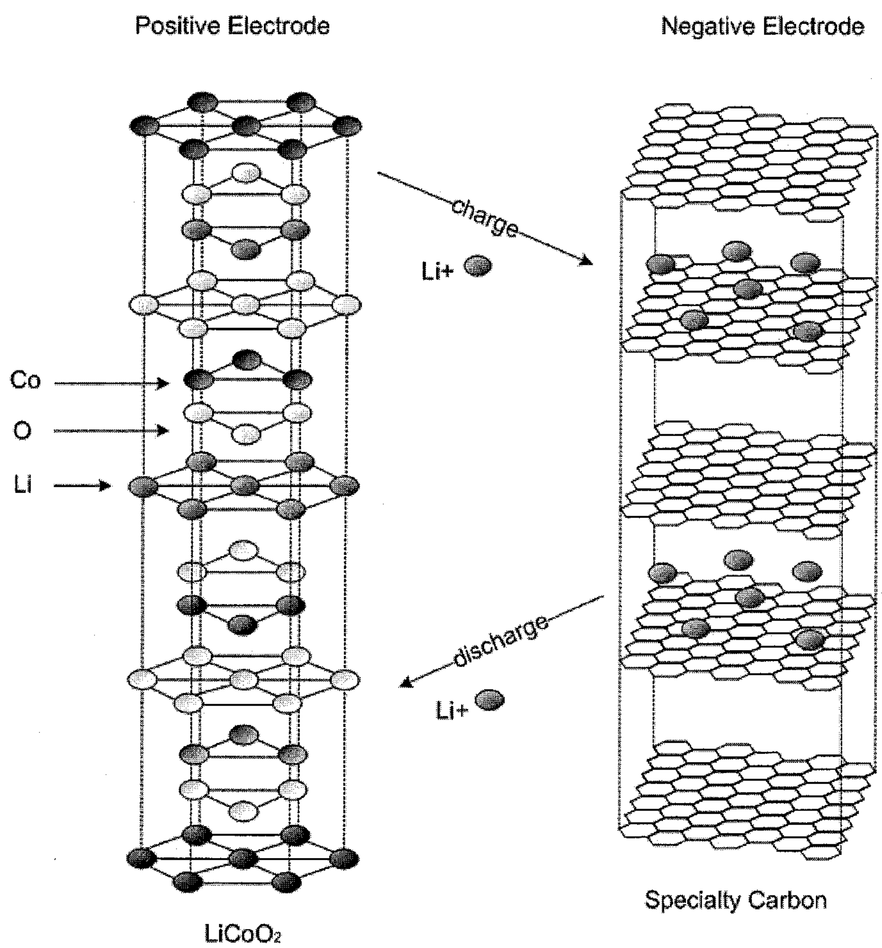


Figure 2.7: Crystal structure of LiMO2 oxides emphasizing the layered nature [4]

Table 2.7: Characteristics if cathode materials [18]

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

2.6.3 Negative electrode (anode) material

From the very beginning of manufacturing in the second half of the nineteenth century. Carbon materials have proved to be very useful as constituents of many systems because of their high electrical conductivity and relative electrochemical stability. In order to create lithium-ion batteries with higher energy density, carbon-based materials are preferred as insertion anodes due to their lithium storage capacity and small volume expansion (10%) upon lithium insertion. These features combined safety and economic factors make carbon based anodes the commercially preferred anode materials in today' lithium-ion battery technology. Graphitic carbon is used specifically due to its high capacity, and low potential profile versus lithium. Table 2.8 shows the characteristic of anode materials [8].

Table 2.8: Characteristics of node materials [8]

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

2.6.4 Lithium- ion polymer batteries

The most recent development in lithium – based rechargeable battery technology is the lithium–ion polymer batteries exhibiting similar characteristics to the Li-ion batteries [22]. This system differentiates itself from other rechargeable systems in the type of electrolyte used. The electrolyte resembles a plastic like film that does not conduct electricity, but allows the exchange of ions (electrically charged atoms or groups of atoms). The polymer electrolyte replaces the traditional porous separator, which is soaked in non-aqueous liquid electrolytes. The dry polymer design offers simplifications with respect to fabrications, ruggedness, safety and this profile.

There is no danger of flammability because no liquid or gelled electrolyte is used. It does offer a very slim form factor but this quality is attained in exchange for slightly less energy density.

2.6.5 Working of a lithium ion battery Mechanism of charge /discharge

A typical intercalation cell consists of insertion electrodes with advantages of dimensional stability and improved chemical stability. No lithium needs to exist in this cell. Lithium is always held as a guest in one of the electrodes depending on the state of charge. The electrolyte takes no part in the electrochemical reaction expect for conveying the electro active lithium ions during discharge from high energy state in the negative electrode to a low energy state in the positive electrode while the electron pass through the external circuit with a release of energy. The opposite reaction occurs on charge, so that recharge ability depends on the reversibility of the reaction at the electrodes. The electrode undergoes a reversible topotactic redox reaction, meaning that the electrode materials act as host structures that can accommodate guest ions and electrons without destruction of the lattice.

During charge, lithium-ions are extracted from the cathode host $LiMO_2$ (M-Co, Ni, etc.) and a de-litigated phase, $Li_{-x}MO_2$ is formed. The classical inorganic view of this reaction is that the M ions absorb the charge change the valence state of the M ions changes from M^n to M^{n+1} in order to maintain the charge neutrality. The extracted lithium-ions sit in the van der Walls gap between carbon layers in the anode host forming Li_xC_6. Figure 2.8 shows the movement of lithium ions and electrons during charging process. After 1 charge and 1 discharge, it is called 1 cycle.

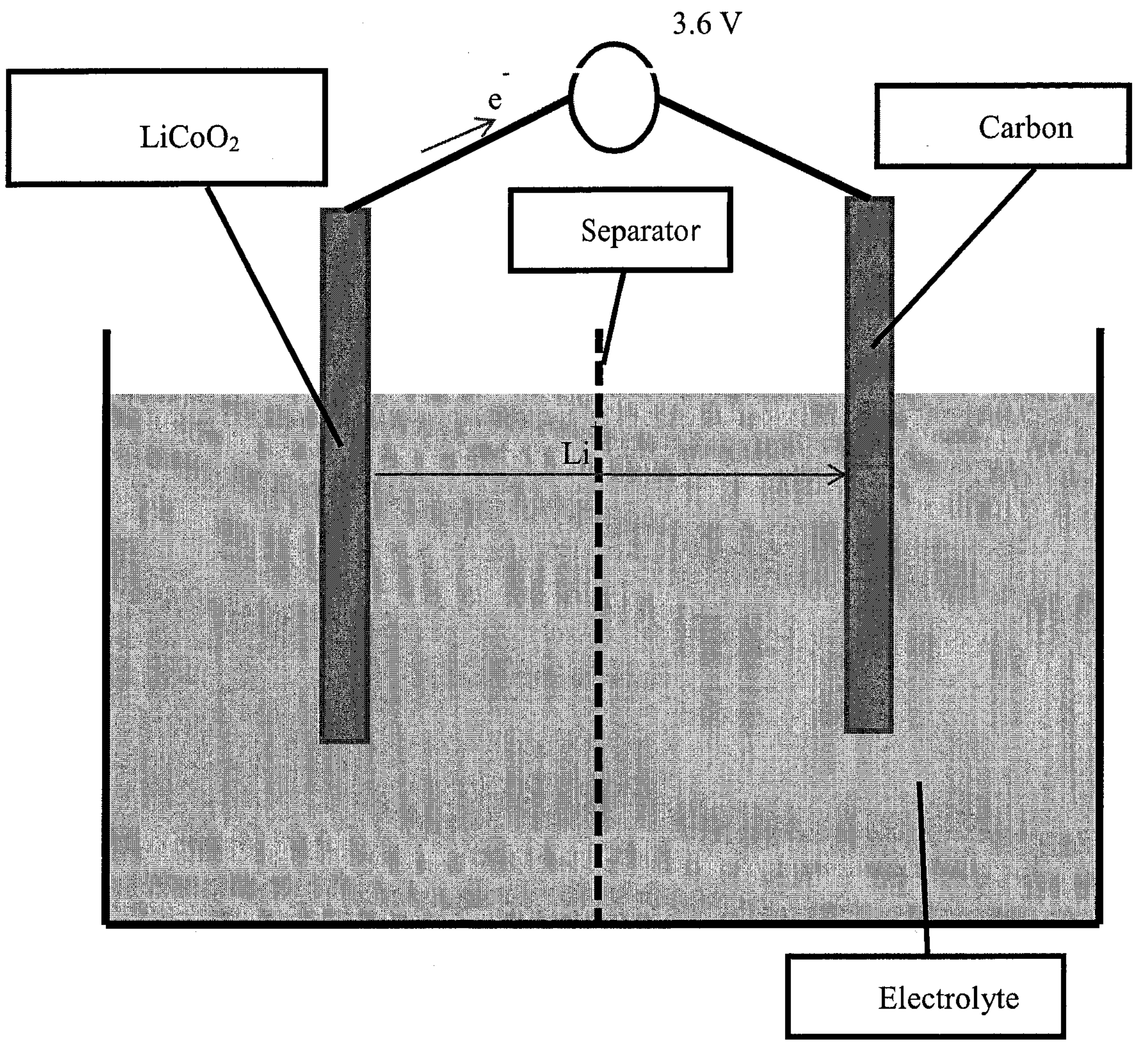


Figure 2.8 Movement of lithium ion during charging processes

2.6.6 Battery reaction

The chemical reactions for charge (extraction) and discharge (insertion) are shown below [4]:

Positive electrode ⟶ $LiMO_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_{-x}MO_2 + xLi^+ + xe^-$

Negative electrode ⟶ $C_6 + xLi^+ + xe^- \, Li_xC_6 \quad \underset{\text{Discharge}}{\rightleftarrows}$

$$\text{A cell as a whole} \longrightarrow LiMO_2 + C_6Li_{-x}MO_2 + Li_xC_6 \quad \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}}$$

2.6.7 Battery Modeling

New technologies in the modern world such as laptop will heavily depend on battery packs. It is therefore important to develop models that can conveniently be used with simulators of power systems and on-board power electronic systems [23-25]. There are basically three types of battery models, namely, electrochemical, mathematical and electric circuit-based models. Electrochemical and mathematical models are not well suited to represent cell dynamics for the purpose of state-of-charge (SOC) estimations of battery packs [16]. However, electric circuit-based models can be useful to represent electrical characteristics of batteries [26], [27]. It was found that the electrical models could give rise to an accuracy of 95% to 99%, [16]. Which make it possible to use this model conveniently to analysis the lithium-ion battery behavior under different condition and compared to other battery models [28]. The three basic models falling under the electrical models category are Thevenin, [29]-[39], impedance[35], [36] and runtime models [28], [37], [38]. Table 2.9 shows the different between the battery models [40].

2.6.8 Thevenin Based Electrical models

A Thevenin-based model shown in Figure 2.9 in the basic form uses a series resistor (R_S) and an RC parallel network (R_T and C_T) to predict battery response to transient load events at a particular state of charge (SOC), by assuming the open-circuit voltage [V_{OC} (SOC)] is constant. This assumption, unfortunately, prevents it from capturing steady-state battery voltage variations (i.e., dc response) and runtime information.

Table 2.9: Difference among three electric models [40]

Technique	Field of application	Advantages	Drawbacks
Simplest Electric Model (DurrMattias 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	None

The derivative models [29]-[34] gain improvements by adding additional components to predict runtime and dc response, but they still have several disadvantages. For example, [17] uses a variable capacitor instead of V_{OC}(SOC) to represent nonlinear open-circuit voltage and SOC, which complicates the capacitor parameter, needs the integral over voltage to obtain SOC, and gives roughly 5% runtime error and 0.4 –V error voltage for constant charge and discharge currents. For the [29] models, there is nonlinear relation between the open-circuit voltage and SOC, but it ignores the transient behavior. The [30], [31] and [33] models need additional equations to obtain the SOC and estimate runtime, and they are not implemented in circuit simulators. The [32] model adopts two constant RC parallel networks, but only works at a particular SOC and temperature condition, and the [34] model employs a complicated electrical network extracted from physical process to model open-circuit voltage (V_{OC}), which complicates the whole model. Thus, none of these Thevenin-based models can predict the battery runtime simply and accurately in circuit simulators.

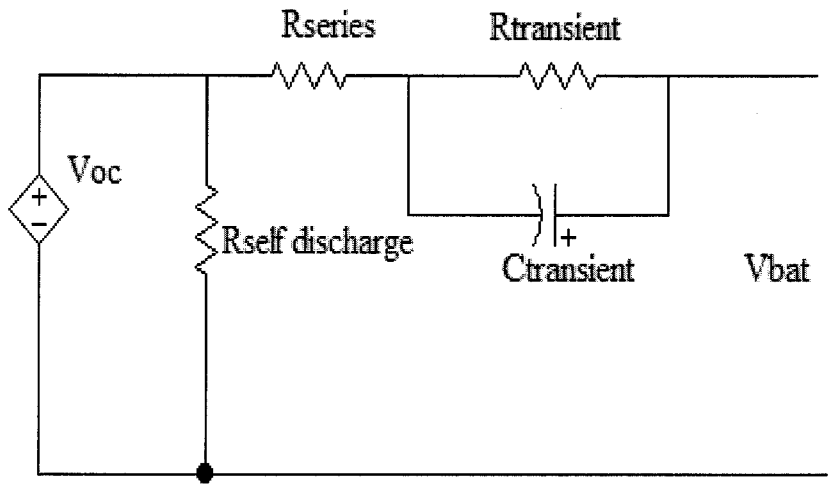


Figure 2.9: Thevenin models.

2.6.9 Impedance Based models

The Impedance-based models, shown in Figure 2.10, employ the method of electrochemical impedance spectroscopy to obtain an ac-equivalent impedance model in the frequency domain and then use a complicated equivalent network (Z_{ac}) to fit the impedance spectra. This fitting process is difficult, complex and non-intuitive. The impedance-based models also work only for a fixed SOC and temperature setting [35], and therefore they cannot predict dc response or battery runtime.

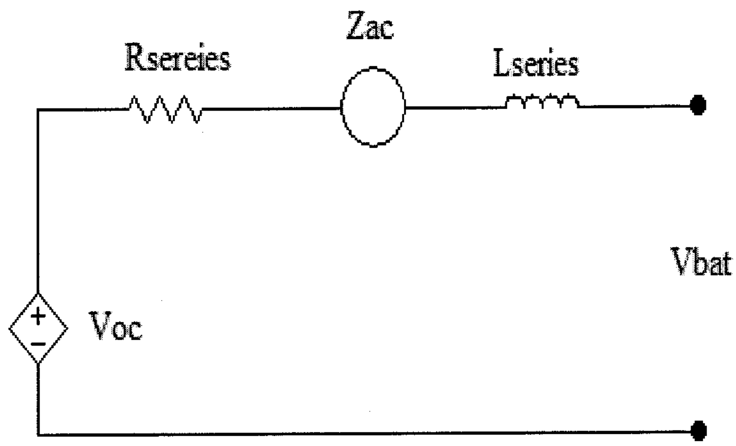


Figure 2.10: Impedance models

2.6.10 Runtime –Based model

The Runtime-based models, shown in Figure 2.11, use a complex circuit network to stimulate battery runtime and dc voltage response for a constant discharge current in SPICE-compatible simulators. [32] and [33] are continuous-time implementations in SPICE simulators and [28] is a discrete-time implementation using Very high speed integrated circuit Hardware Description Language (VHDL) code. They can predict neither runtime nor voltage response for varying load currents accurately.

Table 2.10 illustrates a brief comparison which indicates that none of these models can be implemented in circuit simulators to predict both the battery runtime and I-V performance accurately [41]. Hence, a comprehensive battery model combining the transient capabilities of Thevenin-based models, ac features of impedance-based models, and runtime information of runtime-based models is highly desired for system design, integration and optimization.

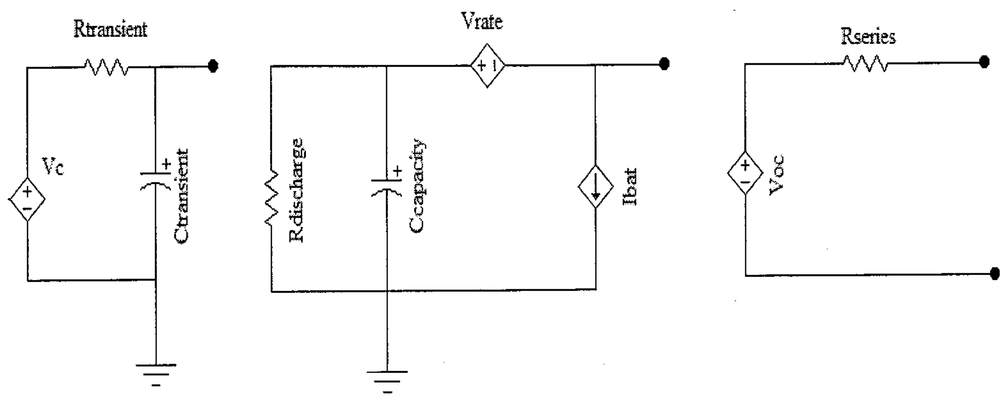


Figure 2.11: Runtime models.

Table 2.10: Comparison of the circuit models [41]

PREDICTING CAPABILITY	THEVENIN BASED MODEL	IMPEDANCEBASED MODEL	RUNTIME BASE MODEL
DC	NO	NO	YES
AC	LIMITTED	YES	NO
TRNSIENT	YES	LIMITED	LIMITED
BATTERY RUNTIME	NO	NO	YES
CAPACITY FADING	NO	NO	NO

2.7 Summary

This chapter has reviewed the types of rechargeable battery available and the characteristic of each battery. Then it proceeds to discuss, the processes charging and discharging of the lithium-ion battery and the negative materials.

The three electrical models and their difference were further discussed in this chapter. The difference is shown clearly in Table 2.10.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Model and Modelling Of Lithium-Ion Battery

Real time cycle life testing for lithium-ion batteries becomes prohibitively expensive if one considers variables that can have remarkable changes on the discharge characteristics of the battery, such as SOC, temperature, cycle number, current and capacity. Therefore it is important to develop a dynamic discharge model for the lithium-ion battery for several discharging conditions.

Open literature revealed the development of various models to study the performance of lithium-ion batteries by changing the discharging current. The models, although found useful to envisage the battery performance, yet have several drawbacks in a way or other, such as ignoring the transient behaviour [42], some models work for fixed SOC and such models were not updated giving provisions to change SOC, and some models were unable to predict battery run time [35]. The proposed model addresses such issues and accounts for the dynamic characteristics of the battery from nonlinear open circuit voltage, current, cycle number, storage time, capacity to transient response, self-discharge and temperature.

The project will be complete with modelling of Li-ion battery using computer software. The software is needed to translate the calculation procedure into simulinkblocks. The software chosen is computation software of MATLAB-Simulink with Math works. This software is a commercial tool for modelling, simulating and analysing 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 in this software.

The mathematical equation for the proposed lithium-ion battery discharge model is created based on the Thevenin electrical circuit models. The Thevenin electrical model shown in Figure 3.1, considers the effect of temperature and capacity loss on the discharge characteristic of the battery.

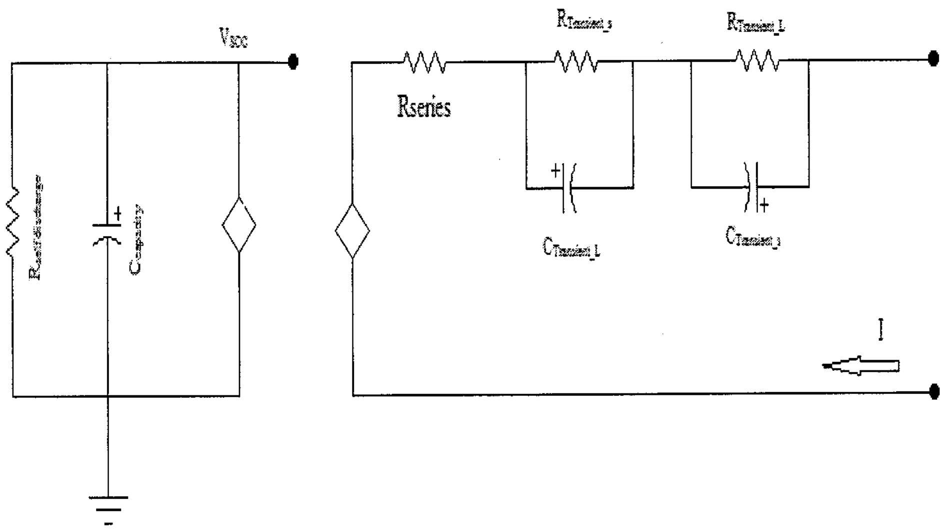


Figure 3.1: Thevenin electrical models

3.2 Battery Output Voltage

The output voltage of the lithium-ion battery (V_o) is a function of open circuit voltage and the voltage drop across the internal impedance of the battery (Z_T). The output voltage is mathematically expressed as equation 1 [43].

$$V_o = V_{oc} - (I_L \times Z_T) \quad (1)$$

where,

V_o	=	Battery output voltage
I_L	=	Load current
Z_T	=	Total internal impedance of the battery
V_{oc}	=	Battery open circuit voltage

There are several quantities that have impact on the output voltage. Such quantities are explained below.

3.3 Battery Open Circuit Voltage

The open circuit voltage of the battery V_{oc}, is the difference of electrical potential between the two terminals of a battery, when there is no external load connected. It depends upon the operating temperature, the amount of active materials in the electrodes [44], [45] or SOC (state of charge) and potential correction due to temperature changes, ΔE (T). It is known that V_{oc} is higher at room temperature (25°C) when compared to all other temperatures. The open circuit voltage is calculated using equation 2 [43]. Equation 3 is obtain from equation 2. The value of V_{oc} strongly depends on battery SOC values (state of charge).

$$V_{oc}[i(t),T(t),t] = \sum_{k=o}^{n} ck.SOC^{k}[i(t),T(t),t] + \Delta E(T) \quad (2)$$

$$V_{oc}(SOC) = -a \times e^{(-x \times SOC)} + b + c \times SOC - d \times SOC^{2} + e \times SOC^{3} + \Delta E(T) \quad (3)$$

Where, a, b, c, d, e and x are constants, the values of which are extracted from experimental results [46] and are given in Table 3.1.

Table 3.1: Contant values Voc

Parameters	Values
a	1.031
b	3.685
c	0.2156
d	0.1178
e	0.321
X	35

3.4 Battery SOC

The open circuit voltage of the battery depends upon the state of charge (SOC) of the battery which, in turn, is influenced by the initial state of charge (SOC_{initi}), load current and remaining capacity in the battery. SOC_{initi} is the percentage of initial charging of the battery (which assumes a max. value 1 if the battery is fully charged). SOC_{initi} is not a constant; it changes as the cycle number changes, its value decreases as the cycle number increases. It is determined using equation 4.

$$SOC = SOC_{initi} - \int \left(\frac{I_L}{Q_{usable}}\right) dt \quad (4)$$

Apart from SOC_{initi} on which SOC depends upon, the usable capacity (Q_{usable}) of the battery has an effect on the SOC. Usable battery capacity varies with the capacity fading or capacity losses.

3.5 The capacity fading

When lithium -ion battery is discharged from an equally charged state to the same end-of-discharge voltage, the extracted energy, called usable capacity, declines as cycle number, discharge current, and/or storage time (self-discharge) increases, and/or as temperature decreases.

It was reported that a battery is considered to be usable until reaching 80% of its initial capacity [1], [47]. Therefore modeling the capacity fading is important for predicting the remaining life of the battery. The capacity loss was found to occur when the battery is inactive. There are two types of such losses, namely, called calendar life loss (CLF) and exercised cycle life losses (CLL) [47]. Both losses are intensely affected by temperature and cycle number. The temperature and cycle number have a negative impact on the capacity losses [48]. The calendar life loss and cycle life loss lead to capacity correction factor (CCF), which is used to determine the remaining usable battery capacity. The capacity correction factor is calculated as follows.

$$CCF = 1 - (CLF + CLL) \quad (5)$$

The remaining usable battery capacity (Q_{usable}) is determined using equation (6) [49]. It is seen from eqn. 6 that Q_{usable} depends on the initial capacity of the battery (Q_{initi}).

$$Q_{usable} = Q_{initi} \times CCF \quad (6)$$

3.6 Storage losses in the Battery

It was mentioned in the previous section that the calendar life loss of the battery arises when the battery is not used. It is obvious that the storage losses will increases if the storage time increases (battery not in use for a prolonged duration). The storage losses are calculated by using equation (7) [47], [50].

$$C(t,T) = k_0 t e^{-(E/RT)} \qquad (7)$$

Where t is storage losses, T is temperature in Kelvin, k_{0t} is acceleration factor, E is active region for which the values shown in Table 3.2 are extracted from experimental results [47].

Table 3.2: Contant values of storage losses

Parameters	Values
E	1.544×10^7
k_{0t}	40498
T	(273 + T)
RT	8.3143

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 in equation 8.

$$\frac{d\theta n}{dN} = k_1 N + k_2 \qquad (8)$$

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 [47]. The values of k_1 and k_2 can be referred to the Table 3.3below [47]. 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 [47].

Table 3.3: Values of the coefficients dependent on cycling temperature [47]

Cycling temperature[°C]	K_1[cycle^{-2}]	K_2[cycle^{-1}]	K_3[Ω/cycle$^{1/2}$]
25	8.5×10^{-8}	2.5×10^{-4}	1.5×10^{-3}
50	1.6×10^{-6}	2.9×10^{-4}	1.7×10^{-3}

3.7 The variable equivalent internal impedance of Lithium –Ion battery

The battery equivalent internal impedance of the lithium ion battery consists of a series resistor composed of R_s and R_c and two RC networks composed of $R_{Tt\text{-}S}$, $C_{T\text{-}S}$, $R_{T\text{-}L}$, and $C_{Tt\text{-}L}$. The $R_s$is responsible for the instantaneous voltage drop in battery terminal voltage. The R_c is used to explain the increase in the battery resistance with cycling. The RC components are responsible for the short and long time transients in battery internal impedance. The values of the R_s and two RC networks composed of $R_{T\text{-}S}$, $C_{T\text{-}S}$, $R_{T\text{-}L}$, and $C_{T\text{-}L}$ can be calculated as below [46]. The constant values are extracted from experimental values [46] and is shown in Table 3.4 .

$$R_s = Ae^{(x_1 \times SOC)} + y_1 \tag{9}$$

$$R_{T-s} = Be^{(x_2 \times SOC)} + y_2 \tag{10}$$

$$C_{T-s} = Ce^{(-x_3 \times SOC)} + y_3 \tag{11}$$

$$R_{T-L} = D\, e^{(-x_4 \times SOC)} + y_4 \tag{12}$$

Table 3.4: Contant values of Transient

Parameters	Values
A	0.1562
B	0.3208
C	752.9
D	6.603
E	6056
x_1	24.37
x_2	29.14
x_3	13.51
x_4	155.2
x_5	27.12
y_1	0.07446
y_2	0.04669
y_3	703.6
y_4	0.04984
y_5	44.75

The cycle resistor is calculated as equation 14.

$$R_C = k_3 \times N^{1/2} \tag{14}$$

The coefficient, k_3 is shown in Table 3.3.The total internal impedance of the lithium ion battery is calculated as in the equation (15). The long and short transient impedance (Z_{T_L}& Z_{T_S}) was calculated as in equation 16

$$Z_T = R_{cycle} + R_{series} + Z_{T\_s} + Z_{T\_L}. \tag{15}$$

$$Z_{T\_L} \& Z_{T\_S} = \frac{R \times X_C}{R + X_C} \tag{16}$$

The inductive capacitance is calculating using equation 6 (17). The frequency value is use is 0.0014Hz.

$$X_C = \frac{1}{2 \times \pi \times f \times C} \tag{17}$$

It is seen from the above that there are many quantities on which the output voltage of the battery relies upon. All the quantities explained a role to play on the characteristics of the Li-ion battery. Accordingly the dynamic model for the Li-ion battery is created and is shown in Figure 3.2.

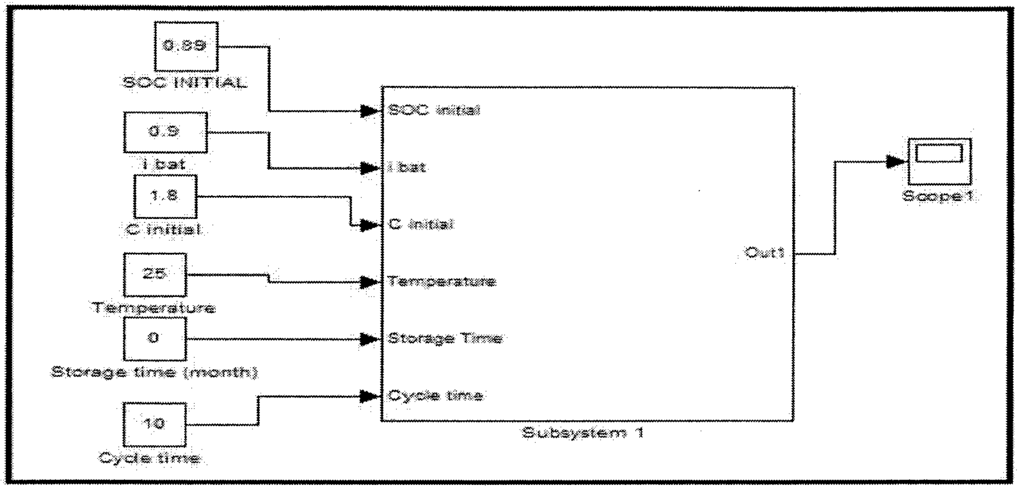


Figure 3.2: Dynamic Lithium-ion Battery Model

3.8 Summary

The model developed as explained in this metholody is used to simulate the Li-ion battery using Matlab/Simulinik and the results obtained will be explained in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter describes the simulation results obtained using the developed Li-ion battery model. The dynamic model was created using mathworks MATLAB/Simulink based on the equation as explained in the previous chapter.

There are six variables used to simulate the results in order to study the discharge charateristics Li-ion batteries with a view to understand the real time battery behaviour. They are Battery Capacity, Dischrage Current, Temperature, Storage time, Cycle number and initial State of Charge (SOC_{initi}). The prsent chapter consists of seven section. The 1st three section describe the results with regards to varifing battery capacity, discharge current, temperature and storage time respectively. The reset three section explain the role of cycle number, SOC_{initi} and load current on the dischrage charateristics of the battery. The last section coverts the validation of the simulated results.

4.2 Battery Characteristics: Varying Battery Capacity and dischrge current

The voltage profile of the Li-ion battery was simulated for various values of battery capacity and discharge current and the results are presented in this section.

A 1.8Ah battery was taken into consideration for analysis. The first cycle results at room temperature (25°C) are shown in Figure 4.1 to 4.3 for initial capacity 1Ah, 2Ah and 4Ah respectively. It is clearly seen from Figures 4.1 and 4.2 that the runtime of the battery increses from 9.22 hours to 18.81 hours. When the initial capacity is incresed from 1Ah to 2Ah. Figure 4.3 clearly shows that the flat potential regime is widened and the usable runtime of the battery rises to 36.19 hours. It is evident from these results that the battery can be safely operated for a prolonged runtime when discharged from high initial capacity values. This will be useful in designing original or real batteries.

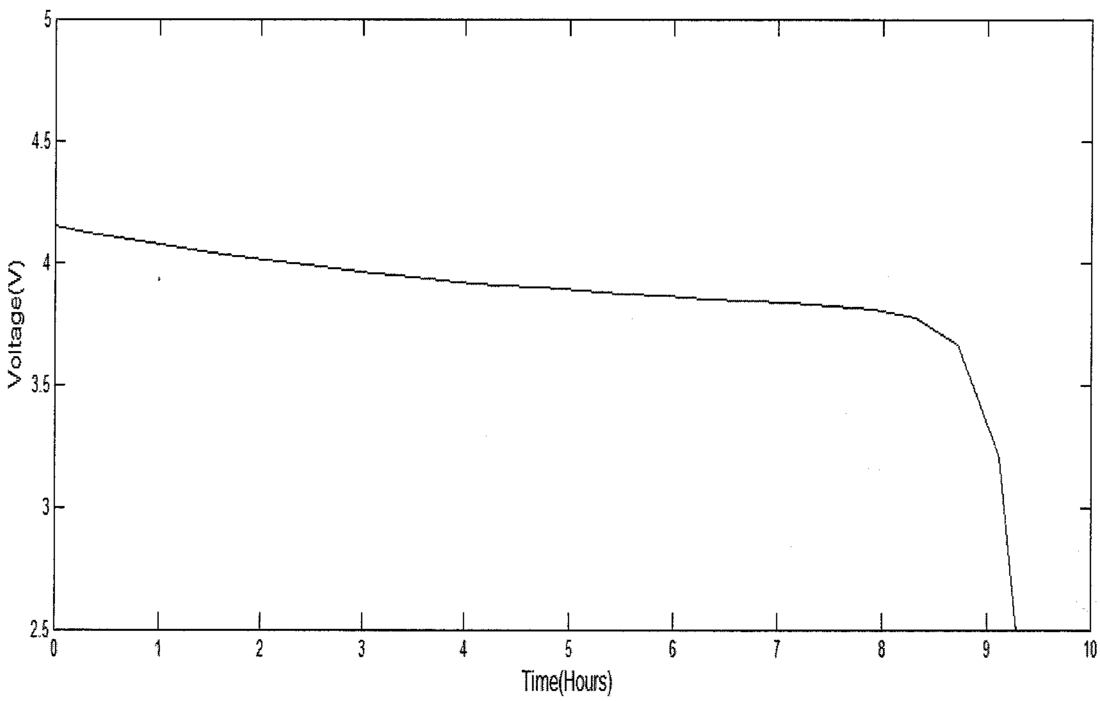


Figure 4.1: Discharge profile of Li-ion battery with Q = 1Ah and I = 0.1A

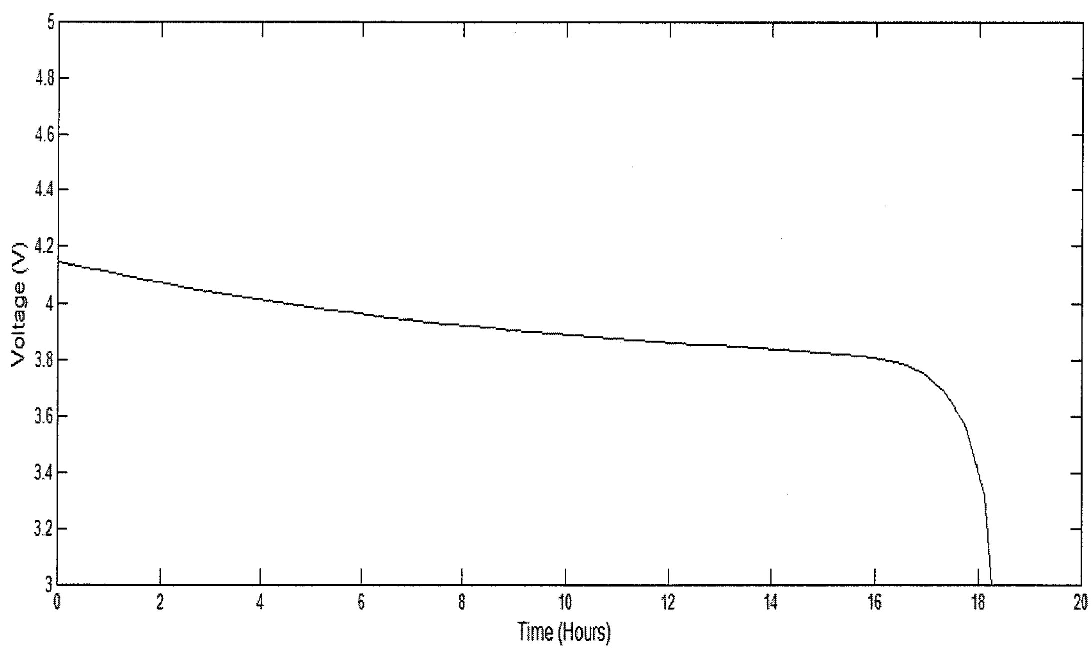


Figure 4.2: Discharge profile of Li-ion battery with Q = 2Ah and I = 0.1A

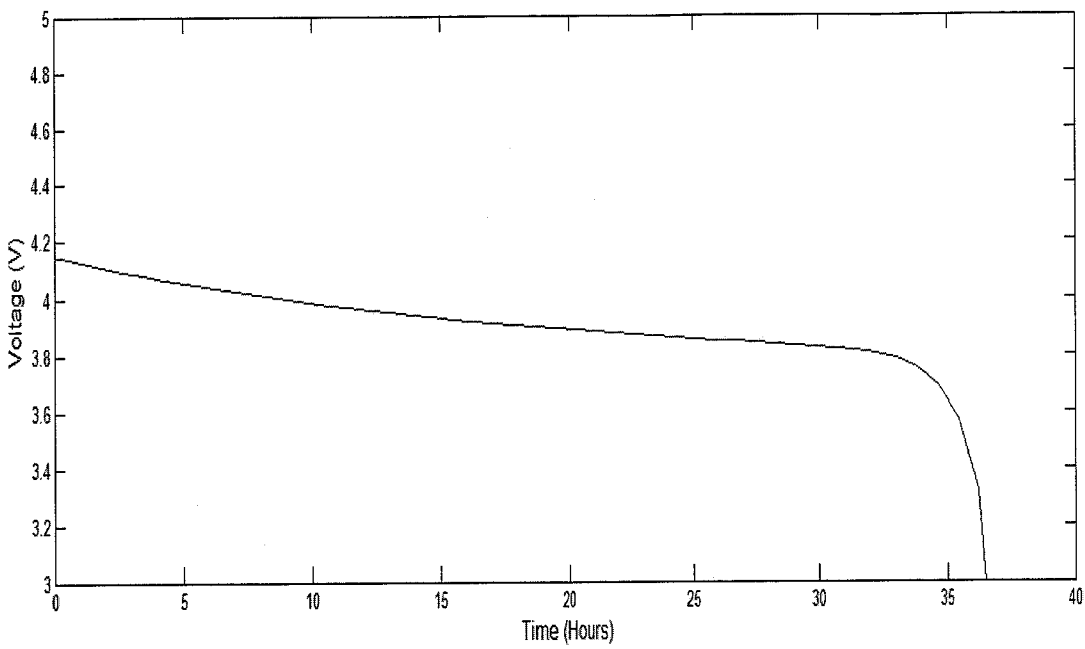


Figure 4.3: Discharge profile of Li-ion battery with Q = 4Ah and I = 0.1A

The discharge curves of the battery were also examined by changing the dischrage current from 0.1A to 0.2A, keeping the same initial capacity values of 1Ah, 2Ah and 4Ah, and the corresponding results are shown in Figure 4.4 to 4.6.

The flatness in the voltage profile is narrowed down which, in turn reduce the runtime of the battery to 4.51 hours before the voltage drops below 3.5V (Figure 4.4). However the battery runtime increases when the battery capacity increases to 2Ah as seen in Figure 4.5. It is clear from these results that the runtime of the battery can be increased by increasing the initial battery capacity. But the runtime for the same initial capacity is higher at 0.1A dischrage current when compared to 0.2A discharge current. In order to prolong the runtime, it is better to keep low discharge current. Figure 4.6 shows the discharge charateristic of the battery for an initial capacity of 4Ah with a widened flat potential regime giving rise to the runtime of almost double the value for 2Ah capacity. It is observed from there simulations results that the battery will be safe and run longer when operated at lower discharge currents and higher initial capacity. The results obtened from this simulation results are summarised in Table 4.1.

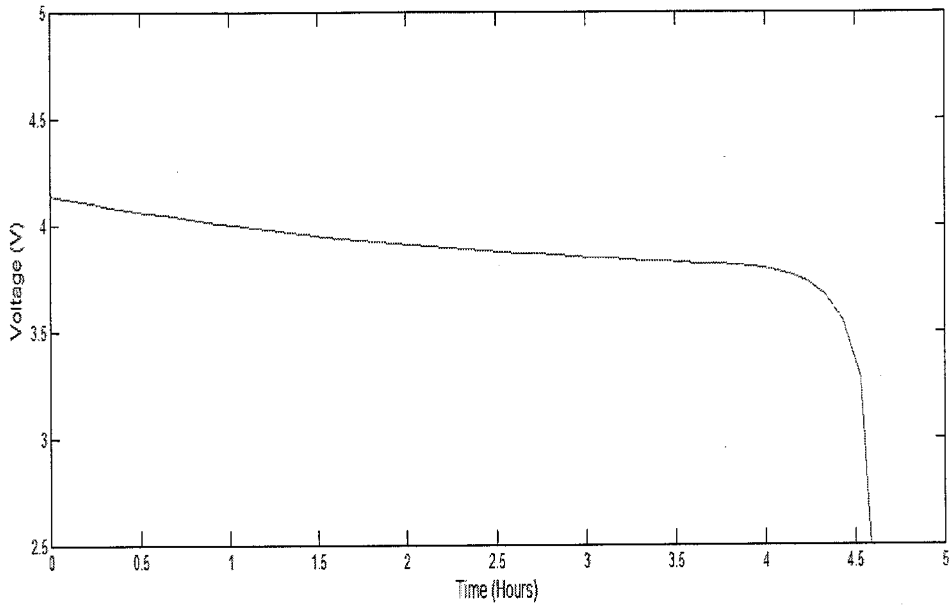


Figure 4.4: Discharge profile of Li-ion battery with Q = 1Ah and I = 0.2A

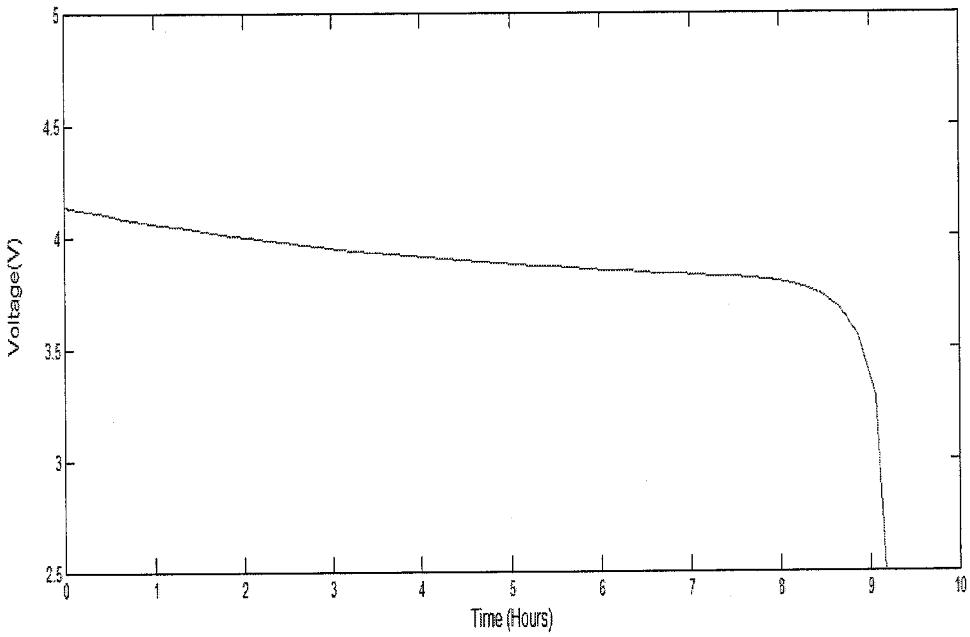


Figure 4.5: Discharge profile of Li-ion battery with Q = 2Ah and I = 0.2A

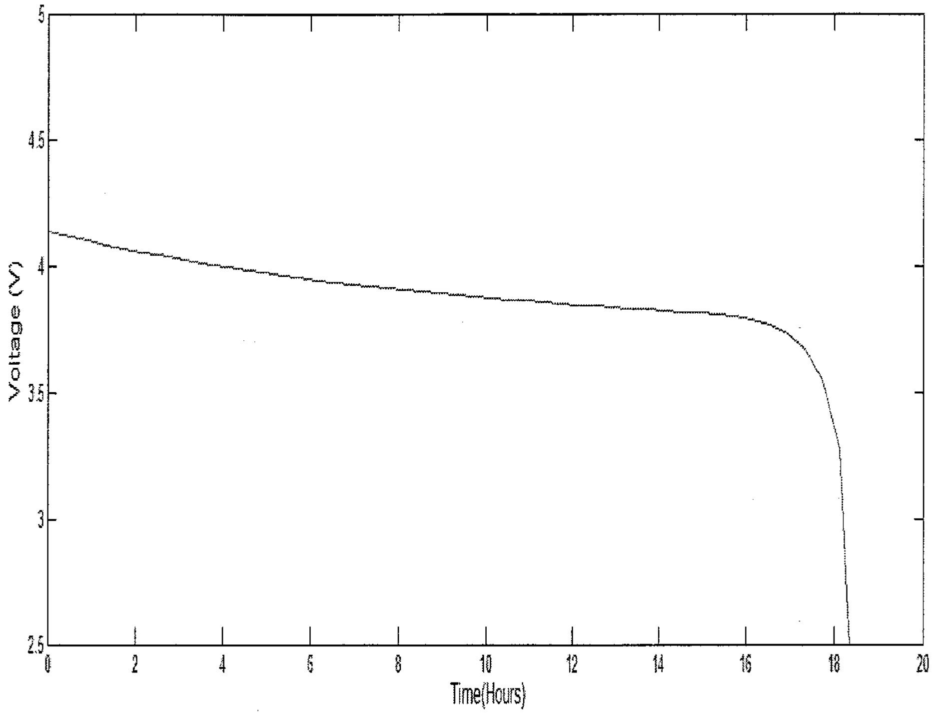


Figure 4.6: Discharge profile of Li-ion battery with Q = 4Ah and I = 0.2A

Table 4.1: Discharge characteristics for different amount of I and Q

I (A)	Q (Ah)	Remaining Capacity (Ah)
0.1	1	9.22
	2	18.81
	4	36.91
0.2	1	4.51
	2	9.16
	4	18.32

4.3 Lithium-ion battery discharge: Effect of temperature.

The lithium-ion battery can be operated over a wide range of temperature from between -20°C to 60°C. When the operating temperature of the battery is either increased or decreased from room temperature (25°C), the useful runtime of the battery will decrease [23].

A battery (Li-ion) witn the following specifications was simulated .

I_L = 0.1A

$C_{Initial}$ = 2Ah

$T_{Storage}$ = 0 Month

and the simulation results are presented in Figure 4.7 to 4.9.

It is seen from Figure 4.7 that there is no difference between the 1stcycle discharge curves at 25°C and 50°C and the time to discharge the battery for both temperatures is approximately 18.44 hours. However, for the 100th cycle discharge curve, the difference between 25°C and 50°C can be seen from the curve in Figure 4.8. The time to discharge the battery for 25°C is approximately 19.2 hours and the time to discharge the battery for 50°C is approximately 18.2 hours. For 500th cycle, the time to discharge the battery for 25°C temperature is still about the same as 100th cycle which is 18.8 hours as shown in the Figure 4.9. However, the time to discharge the battery for 50°C operating temperature has dropped significantly to 16.8 hours from 18.2 hours at 100th cycle. The difference of discharge time between 25°C and 50°C is significantly higher now. The time to discharge the battery for 25°C is significantly longer than 50°C.

The results are shown in Table 4.2. It is seen fron the table that battery running at higher temperature will result in significant reduction of its capacity compared to running at lower temperature. For 25°C, the capacity of the battery has not changed much even though it has already run 500 cycles. This is because the coefficient of k_1 for 25°C (8.5×10^{-8}) is too low compared to 50°C (1.6×10^{-6}).

It is better to run a battery at 25°C temperature to make sure that the capacity fading effect of the battery is lower.

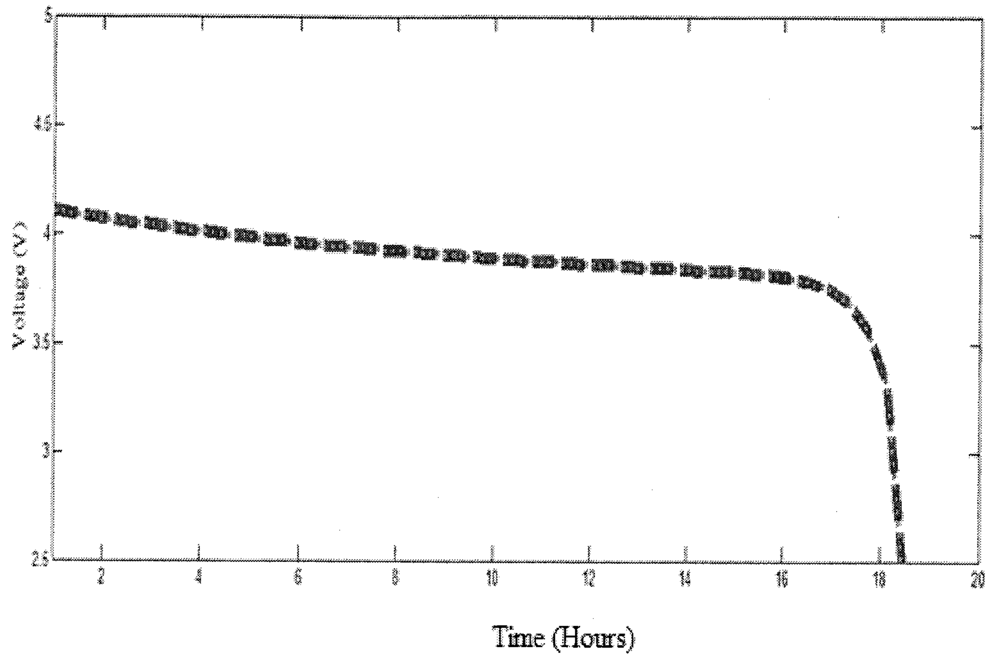


Figure 4.7: Discharge Characteristics for 25°C and 50°C for First Cycle

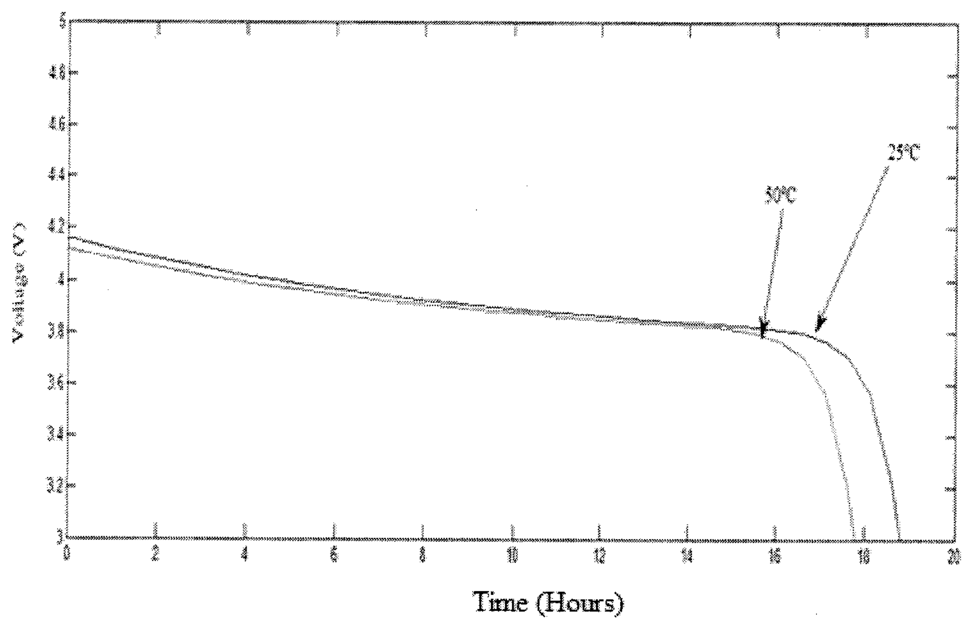


Figure 4.8: Discharge Characteristics for 25°C and 50°C For 100th Cycle

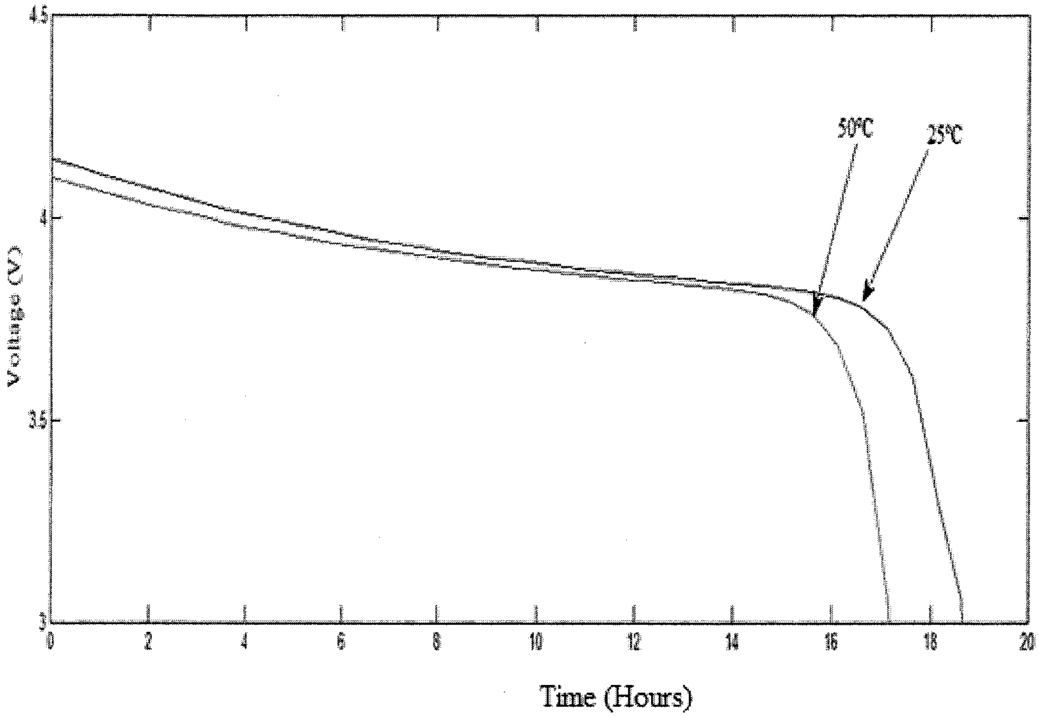


Figure 4.9: Discharge Characteristics For 25°C and 50°C for 500th Cycle [Voltage(V) vs time (hours)]

Table 4.2: Summary of Simulation for Different Temperature

Cycle Number	Time to Fully Discharge (hours)	
	25°C	50°C
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

4.4 Simulation for Different Storage Time

Storage time refers to the time when the battery is inactive or not in use. The lithium-ion battery with capacity of 2.0Ah is discharged at 0.1A current and the battery is in its first cycle. 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 connected to any load. The battery is stored at room temperature 25°C. Figure 4.10 shows the discharge curve for the battery when stored at room temperature 25°C. It is shown clearly that the storage loss increases when the storage month is increased. Figure 4.11 shows the graph when the battery is stored at temperature 50°C. From Figure 4.10 and 4.11, it is observed that the storage loss is very higher when the battery is stored at 50°C when compared to storage at low temperature at room temperature (25°C). Table 4.3 shows summary of the battery discharge time.

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 dry and having low temperature.

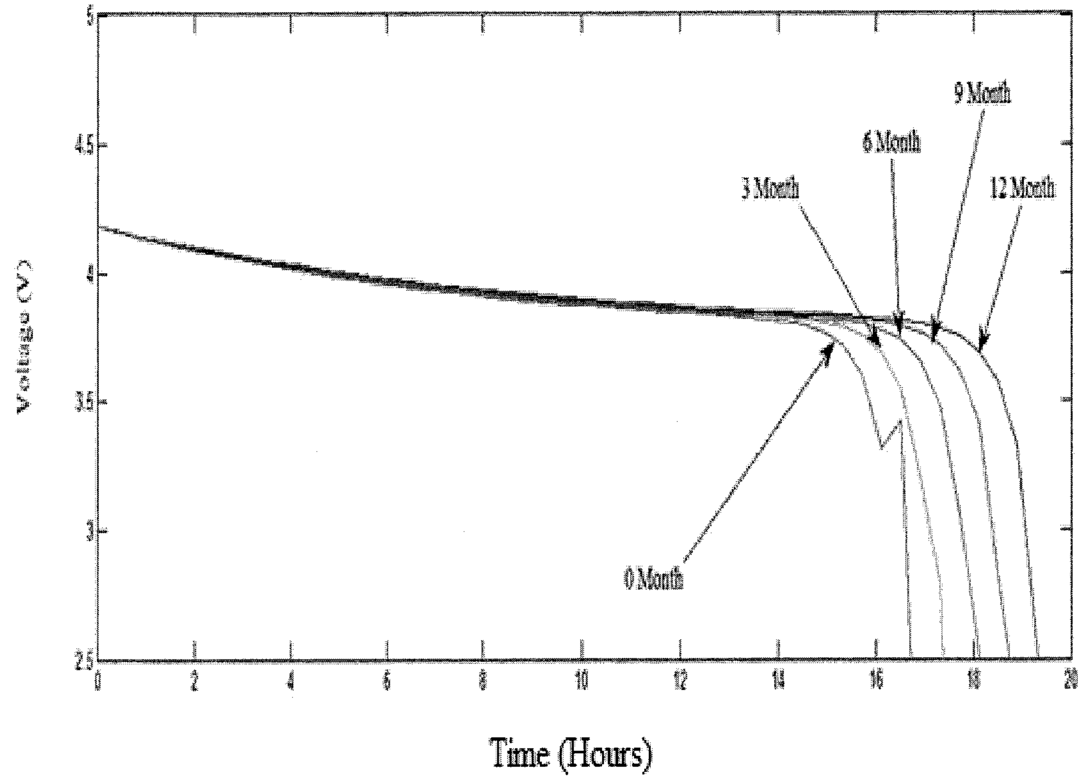


Figure 4.10: Discharge Characteristics for Storage Time 0-12 months for temperature 25°C

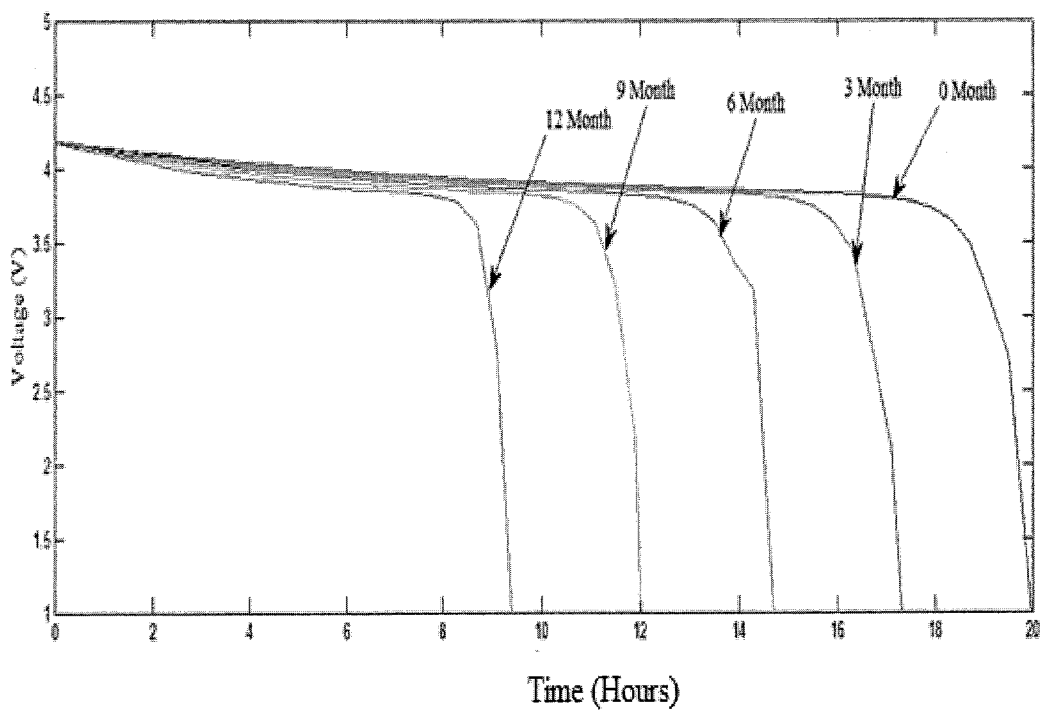


Figure 4.11: Discharge Characteristics for Storage Time 0-12 months for temperature 50°C

Table 4.3: Summary results for different storage time

Storage time (months)	Time to fully discharge (hours)	
	25°C	50°C
0	19.35	19.21
3	18.75	16.56
6	18.11	14.2
9	17.37	11.7
12	16.10	9.1

4.5 Simulation for Different Cycle Number

The battery performance is normally found to degrade gradually due to repeated cycling. A separate simulation study was performed with a view to investigate the effect of cycle number and the performance of the battery.

A 2.0Ah battery was discharged at 0.1A current for two different temperatures, 25°C and 50°C and the results are shown in Figure 4.12 and 4.13. It is visible from Figure 4.12 that the capacity gets reduce when the cycle number increases.

The capacity was found to reduce by 10% after 100 cycles. The reduction in capacity is about 32% at the end of 800 cycles. This seems to be nominal and reasonable in all batteries.

When the simulation was repeated by changing the temperature from 25°C to 50°C (Figure 4.13) the capacity was found to reduce faster. For example, after 600 cycles, the capacity was found to reduce by 61% which is almost twice the values for 25°C observation after 800 cycles. Accordingly the results are summarized in Table 4.4 and 4.5.

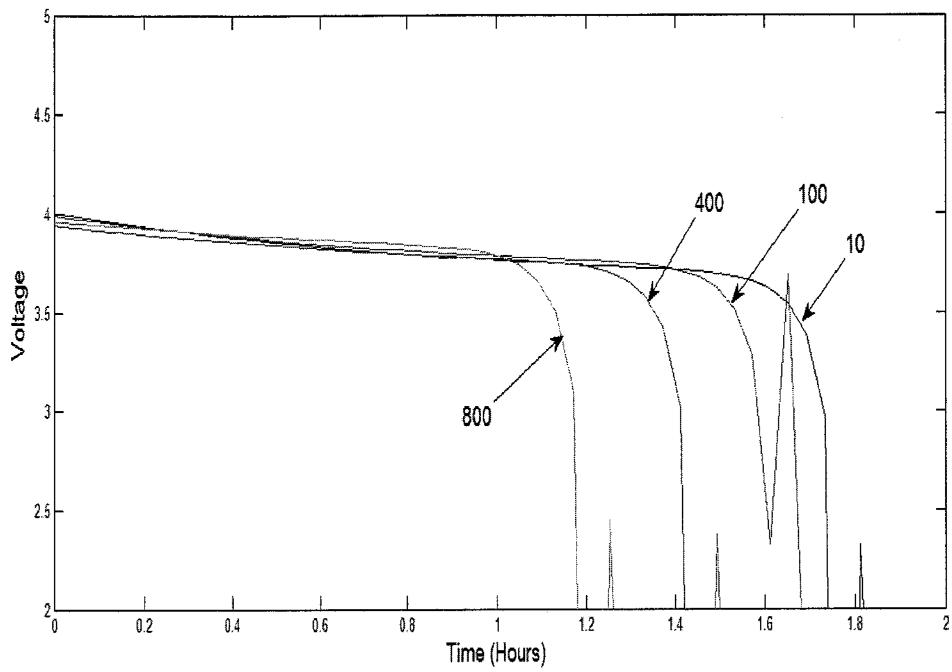


Figure 4.12: Discharge Characteristics for Different Cycle Number (25°C)

Table 4.4: Summary of Simulation for Different Cycle Number(25°C)

Cycle Number	Remaining Capacity (Ah)
0	1.78
100	1.6
400	1.5
800	1.2

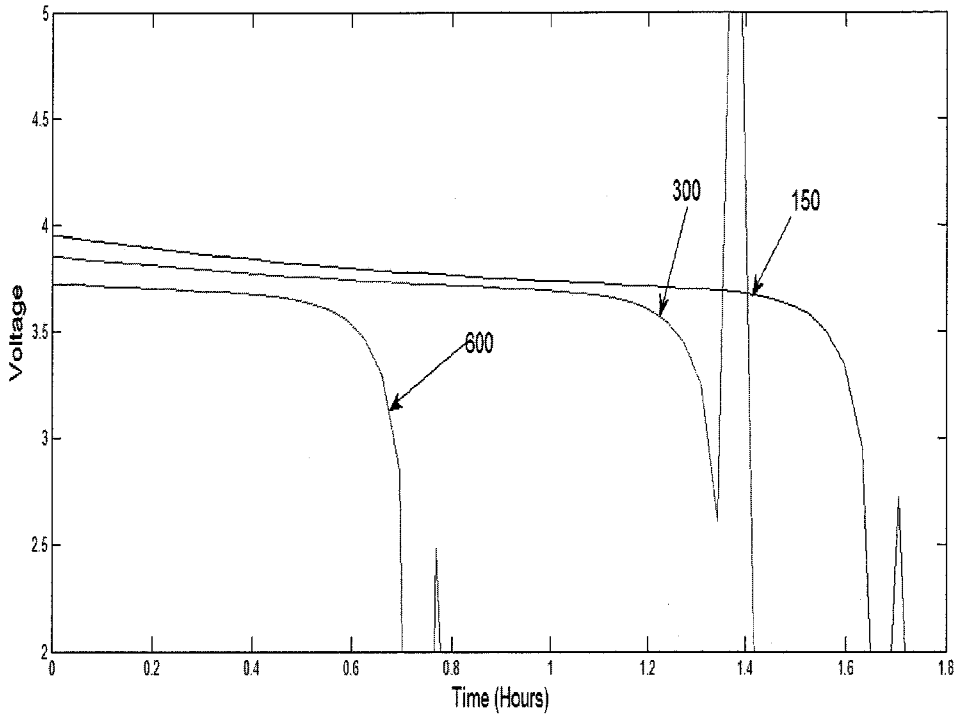


Figure 4.13: Discharge Characteristics for Different Cycle Number (50°C)

Table 4.5: Summary of Simulation for Different Cycle Number(50°C)

Cycle Number	Remaining Capacity (Ah)
150	1.63
300	1.28
600	0.7

From the Table 4.5 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.

4.6 Simulation for Various Load Current

Another simulation was performed to examine the influence of load current on the voltage characteristics of the battery and the corresponding result was compared with that of constant load profile. It was observed from this study that the discharge time for the flat potential is more (Figure 4.14) in the case of constant load current when compared to the variable load current scenario (Figure 4.15) and the results are tabulated (Table 4.6).

Table 4.6: Summary of the results for different load current

Load Current	Battery Run time (Hours)
Variable load current	1.7
Fixed load current	3.1

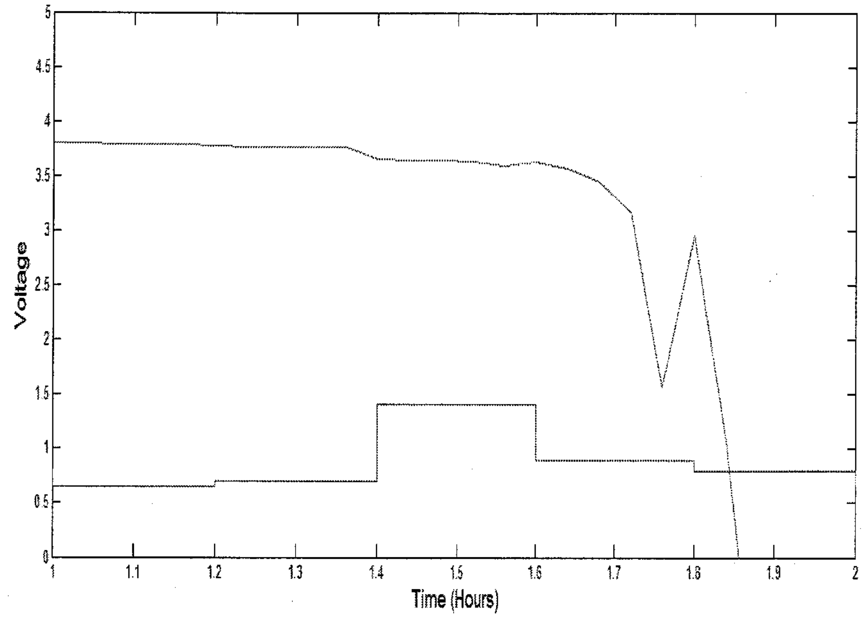


Figure 4.14: Discharge profile of Li-ion battery for variable load current

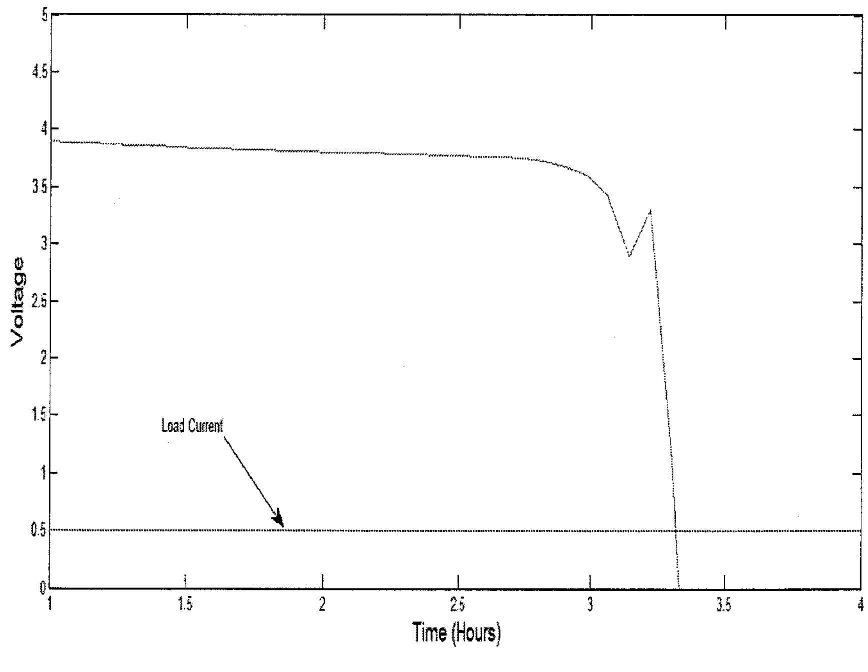


Figure 4.15: Discharge profile of Li-ion battery for fixed load current

4.7 Simulation for Various SOC_{initi}

The voltage profile of the Li-ion battery was simulated for two different values of initial State of Charge (SOC_{initi}). The results were simulated for a 1.8Ah battery with a discharge current of 0.9A at room temperature (25°C) the results are shown for the 10^{th} cycle. Figure 4.16 shows the voltage profile of SOC_{initi} as 0.89. It is seen from Figure 4.16 that the battery can retain the flat potential for 1.74 hours which represents the usable time of the battery before the voltage drop below 3.62 V.

The simulation results clearly shows that the potential flatness is a bit narrowed down when the battery is discharged from SOC_{initi} 0.84 (Figure 4.17) which, in turn, reduces the usable time to 1.64 hours refer the voltage drops below 3.5 V. These results indicate that the battery run time can be prolonged when SOC_{initi} is high. So it is desirable to set SOC_{initi} as higher possible in order to maximize the battery run time.

We also examined the voltage profile of the battery by changing the discharge current from 0.9A to 0.6. The results are depicted in Figures 4.18 and 4.19 for 0.89 and 0.84 SOC_{initi} respectively. Figure 4.18 clearly shows that the flat potential regime is widened and the usable runtime of the battery increases to 2.52 hours. On the other hand, the battery runtime is found to be 2.46 hours as seen in Figure 4.19.

It is believed that the dischrge charateristic of the Li-ion battery was inthueneed by the change in SOC_{Initi} as evideneed from the above observation. Table 4.7 shows the summary of the results.

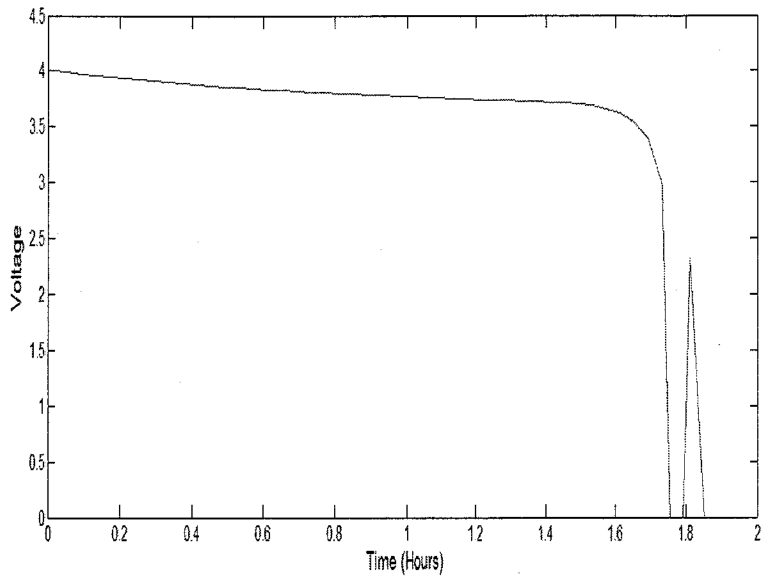


Figure 4.16: Discharge profile of Li-ion battery 0.9A and SOC initial 0.89

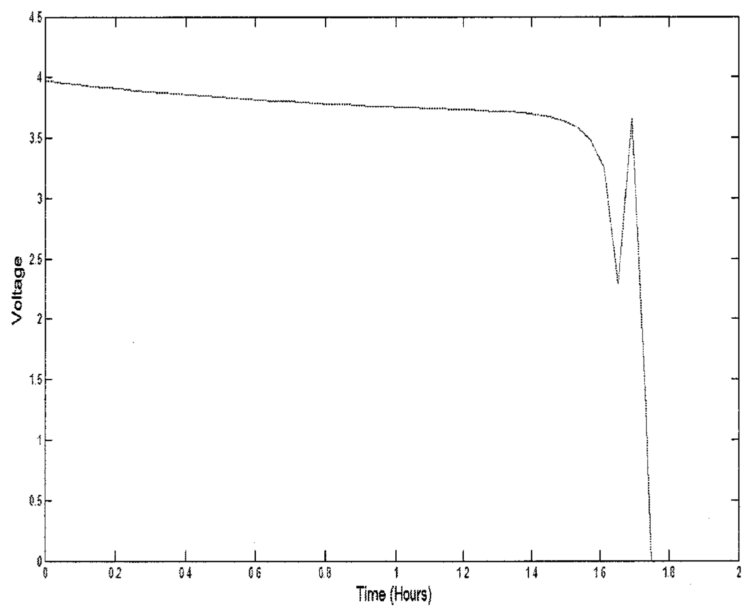


Figure 4.17: Discharge profile of Li-ion battery for 0.9A and SOC initial 0.84

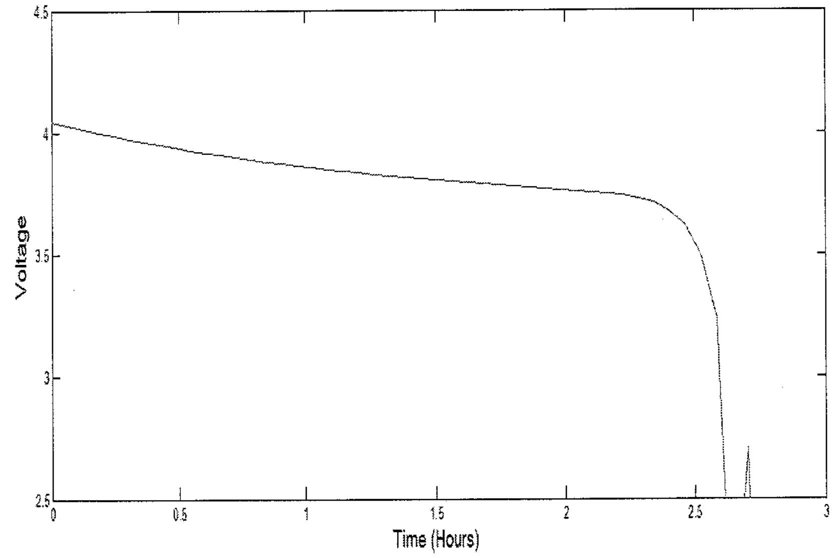


Figure 4.18: Discharge profile of Li-ion battery 0.6A and SOC initial 0.89

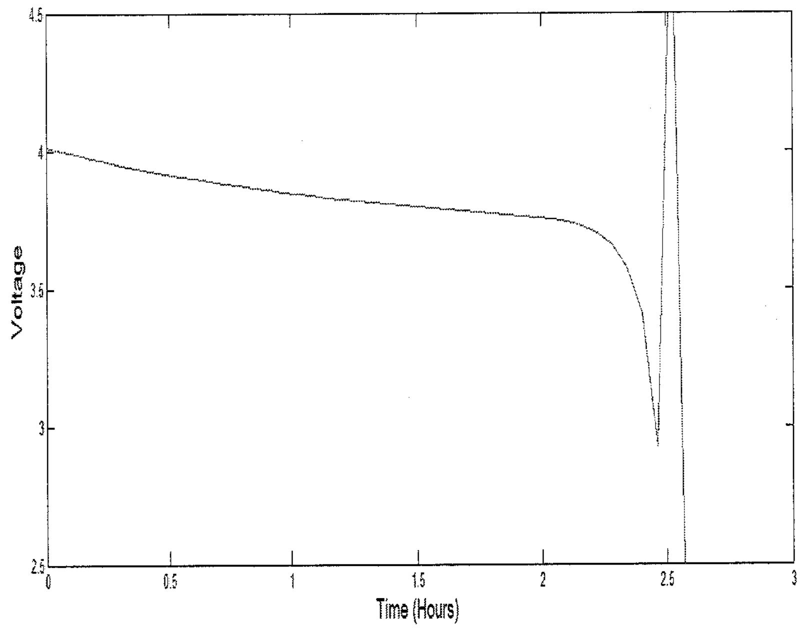


Figure 4.19: Discharge profile of Li-ion battery for 0.6A and SOC initial 0.84.

Table 4.7: Summary of simulation for different discharge current

SOC Initial	Usable Time for 0.6A	Usable Time for 0.9A
0.84	2.42 hours	1.64 hours
0.89	2.60 hours	1.74 hours

4.8 Hybrid Electical Vechiles

New technologies in the modern world such as HEV will heavily depend on battery packs. It is therefore important to develop models that can conveniently be used to study the behaviour of the battery under the various driving condition for the HEV.

As new contribution the discharge model of the lithium-ion battery is used to study the characteristic of the battery for the electrical scooter. The scooter current or load current was varied between 18A to 20A [51]. It is shown clearly in Figure 4.32, that the Li-ion battery can produce 11.8V, for 3600s for the effective operation of the electrical scooter as the load current varied. After this time period the battery have to charge again for further use.

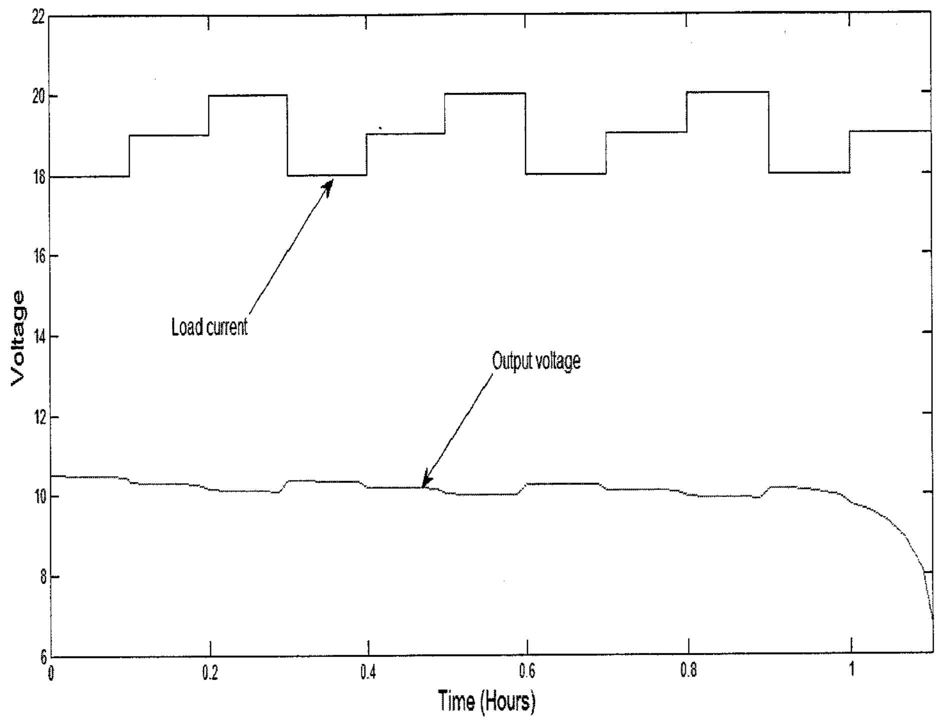


Figure 4.20:Results obtained for Electrical Scooter

4.9 Model Validation

In order to validate the dynamic Lithium-ion battery model results simulated in this work using MATLAB/Simulinik, comparision was made with already published and available results. This will also be helpful to examine the accuracy of the model development and the results simulated therein.

Figure 4.21 shows the simulation results of the presend model, for the condition of 140mAh and the battery was discharged at for a discharge current of 0.77A. The battery was simulated at room temperature 25°C for six different cycle number. It is seen from Figure 4.21 and 4.22, that the results obtained by the simulation of the prsend model are similar with the results given in [27]. The summary of the results is shown in the Table 4.8, for the different cycle number. It is seen from Figure 4.21 that the battery can retain the flat potential for 0.12 hours, for the cycle 1 nu mber and 0.09 hours for the 50^{th} cycle number, which represents the usable time of the battery before the voltage drop below 3.62 The simulation results shows clearly that the battery run time can be prolonged when at lower cycle time compare to higher cycle time. The results also shown that the usable capacity in the battery is reduce when the cycle number is increased.

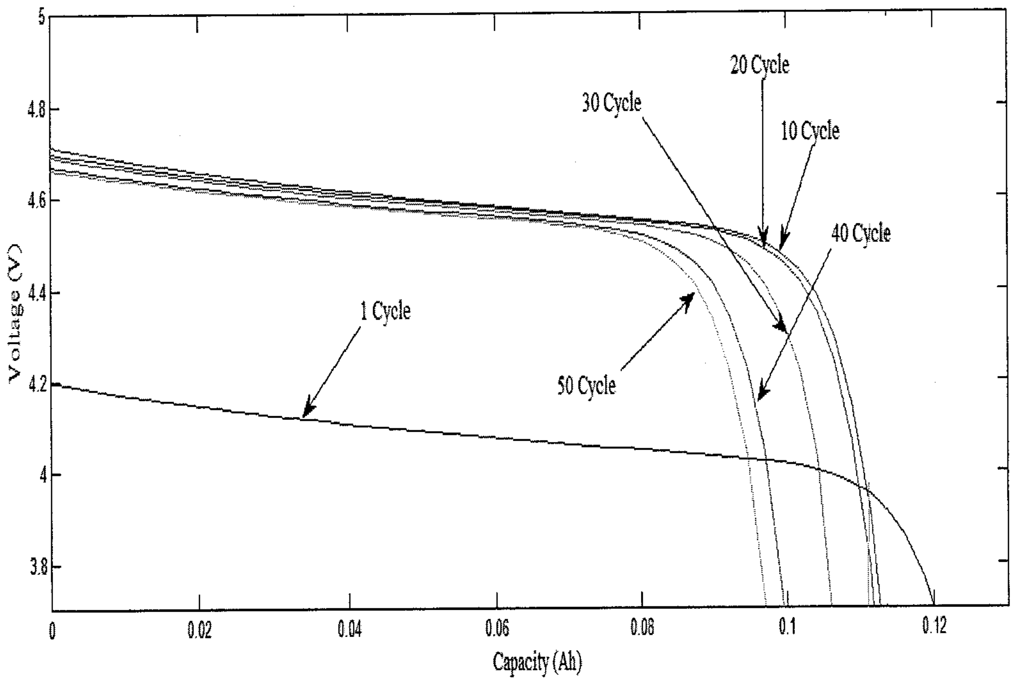


Figure 4.21: Results obtained by present model

Table 4.8: Summary of proposed model and Jongsoon results [24].

Cycle Number	Jongsoon (Remaining capacity mAh)	Proposed model (Remaining capacity mAh)
1	0.120	0.120
10	0.112	0.112
20	0.110	0.110
30	0.100	0.100
40	0.098	0.098
50	0.090	0.090

The presened dynamic lithium-ion model also validated with show experimental results obtained by already published and available results [47] . Figure 4.23 shows the results of the battery output voltage with different cycle number for 25°C and Figure 4.24 shows the results for the 50°C obtained by the presend model for discharge condition ,0.9A and 1.8Ah lithium ion battery. It is clearly seen from the Figure 4.23 and Figure 4.24, that the presend model and results obtained by Ramadass [47] are similar and also can see that, as the capacity fading significantly increases with increment of temperature and cycle number. The summary of the results is shown in the Table 4.9, for the different cycle number. The simulation results clearly shows that the potential flatness in a bit narrowed down when the battery is discharged at 50°C compared with 25°C. Therefor, we can conclude that the suitable temperature to operate the lithium-ion battery is 25°C. Table 4.10 shows the summary results for the different cycle for 50°C.

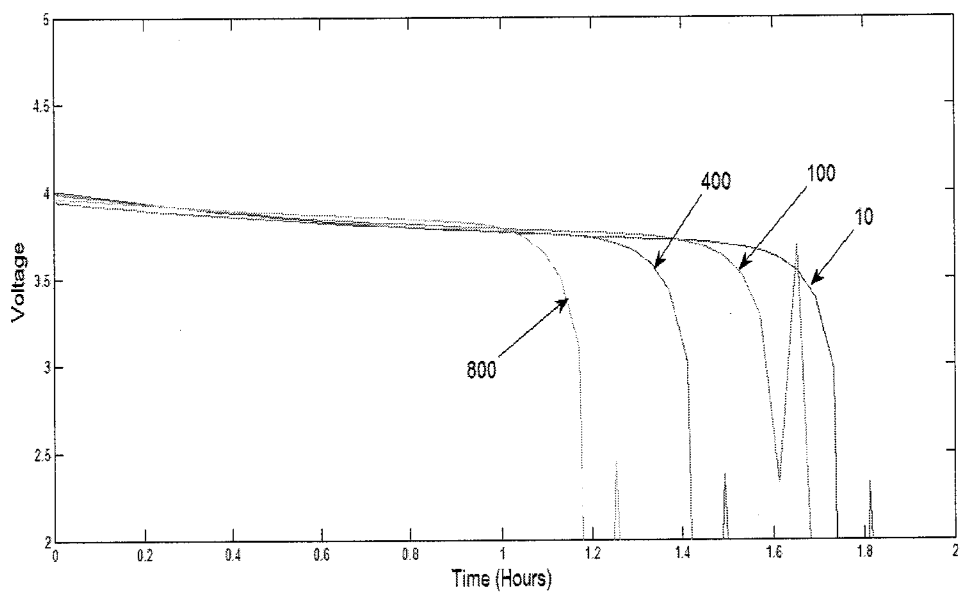


Figure 4.22: Results obtained by present model (25°C)

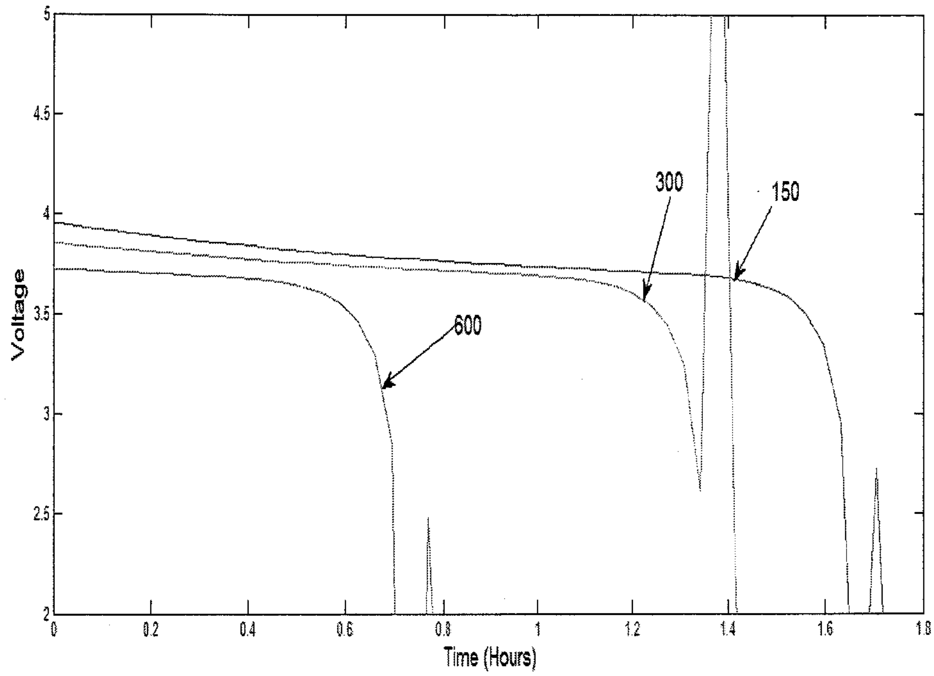


Figure 4.23: Results obtained by present model (50°C)

Table 4.9: Summary of proposed model and Ramadass results 25°C

Cycle Number	Ramadass (Remaining capacity Ah)	Proposed model (Remaining capacity Ah)
10	1.78	1.78
100	1.6	1.6
400	1.5	1.5
800	1.2	1.2

Table 4.10: Summary of proposed model and Ramadass results for 50°C

Cycle Number	Ramadass (Remaining capacity Ah)	Proposed model (Remaining capacity Ah)
150	1.63	1.63
300	1.28	1.28
600	0.7	0.7

4.10 Summary

In these chapter seven case studies, with twenty simulations was carried out to study the characteristics of the lithium-ion battery for various discharging condition. The simulation was carried out for various SOC, two different temperatures, various cycle numbers, various discharge current, storage time and simulation also carried out for the Hybrid Electrical Vehicles (HEV). The results shown very clearly, that when the lithium-ion battery discharged at room temperature, low discharge current and high SOC values the battery usage time will be increases dramatically. There is small capacity will be loss when the battery was stored for long time (few month). The aging loss also increases when the battery cycle time was increase.

CHAPTER 5

CONCLUSIONS, CONTRIBUTIONS AND RECOMMENDATIONS

5.1 Conclusions

Lithium-ion batteries have become inseparable commodity not only in microelectronics field, but also in large scale energy sources in HEV. Nowadays it is rare to find portable electronic devices without lithium-ion batteries being used as a portable power generator. It is well known that they gain pride as the advanced power source technology and are classified under smart power source for the future.

Lithium-ion battery models capture the characteristics of real batteries and therefore can be used to envisage their behavior under various operating conditions. Three battery models are available to analyse the battery characterisitics, which are electrochemical, mathematical and electric circuit-based models. Electric circuit-based models can be useful to represent electrical characteristics of batteries and has good accuracy (95% to 99%) which makes it suitable to be used in this work. Consequently, dynamic model of Li-ion battery was developed in this work using mathworks MATLAB/Simulink. The results were simulated for various values of battery parameters such as capacity, discahrge current, operating temperature, storage time, cycle number and initial capacity. Each parameter was found to have influence on the battery characteristics. The aim is to enhance the battery life without much capacity degradation and the simulation results obtained in this work are summarised here.

It was found that the run time (maximum time upto which the battery usage is sustained at a flat voltage, which is well shown in figures, chapter 4) of the battery and hence the capacity (in Ah) could be increased by lowering the discharge current. Also higher initial capacity resulted in longer operating time.

As for the operating temperature, room temperature (25°C) gave rise to good results in terms of capacity and hence the battery run time. High temperature (50°C) operation resulted in large reduction in capacity. The capacity was found not to change much even after 500 cycles when the battery is operated at ambient temperature and so presumed to be the best operating temperature.

Capacity loss due to storage significantly affects the battery life when the battery is not in use and the storage loss was influenced negatively by the storage time. The battery can be used for how long with good capacity retention depends on how many times it is charged and discharged (cycle number). Room temperature capacity loss of 10% was observed after 100 cycles and it increased to 32% at the end of 800 cycles. The loss in capacity was found to increase when operated at 50°C.

When an investigation was made with regard to the effect of load current on the discharge characteristic of the battery, constant load current yields better results as for the life of the battery than using it with variable load current. When the battery was discharged with variable load current, the battery sustained only for 1.7 hrs which is 55% of the run time when used with constant load current (3.1 hrs). So applying constant load current yields almost double the capacity when compared to applying variabl load current. This factor is really noteworthy to extend the battery life.

It is interesting to note that the run time has a direct relation with the initial State Of Charge (SOC_{initi}). The battery was able to function well for 1.74 hrs run time when the SOC_{initi} was set to 0.89 (This means that the battery charge is 89% before discharge begins). A slight change in SOC_{initi} from 0.89 to 0.84 reduces the time from 1.74 hrs to 1.64hrs.

The simulation results were validated with experimental data and it was found that there is a good agreement between the simulated and experimental results and thus validating the battery model developed in this research work.

5.2 Contributions

Developing a model for Li-ion batteries which can analyse the properties of batteries under various conditions. Paving way to use Li-ion batteries with extended run time with good voltage maintenance by a suitable combination of battery parameters ensuring good cycling stability, large values of specific capacity and a very low capacity fading (like the commercially available materials) between the first cycle and the rest of the cycles to avoid abuse of batteries under abnormal operating conditions.

5.3 Recommendations

This study provides a platform for further work to enhance the battery performance in terms of the following.

1. Study of battery impedance and analysis of impedance whenever operating conditions change and to reveal the effect of impedance and thereby optimizing the values whenever and wherever required through the addition of passive elements.
2. This research work covered the modeling, simulation and analysis for a single cell. However, practical applications require the use of multiple cells as a battery pack. Hence modeling can be modified/extended for the whole battery pack, results can be simulated and compared with real battery pack. The simulation is anticipated to provide room for possible improvement in battery pack.
3. Possible future study will also aim at further developing the battery model for Hybrid Electric Vehicle (HEV) due to the finite nature (CO_2 emission) of fossil fuel. The simulation results may be of use fortechnology development which will be useful in Malaysian cars thereby serving the Nation as well.

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LIST OF PUBLICATIONS AND AWARD

[1] ChelladuraiSinkaram,Vijanth S. Asirvadam,Nursyarizal Bin Mohd Nor, MumtajBegam.; "Battery Characteristics Due to Various discharging current and temperatures. A simulation Approacht," in*IEEE Student International Conference on Research and Development (SCORED), 2012,* Penang, Malaysia, 05-06December 2012.

[2] ChelladuraiSinkaram, Vijanth S. Asirvadam, KausillyaRajakumar, "Modelling Battery Management System Using The Lithium-Ion Battery" in*IEEE Student International Conference on Control System,Computing and Engineering (ICCSCE), 2012,* Penang, Malaysia, 23-26November 2012.

APPENDIX A

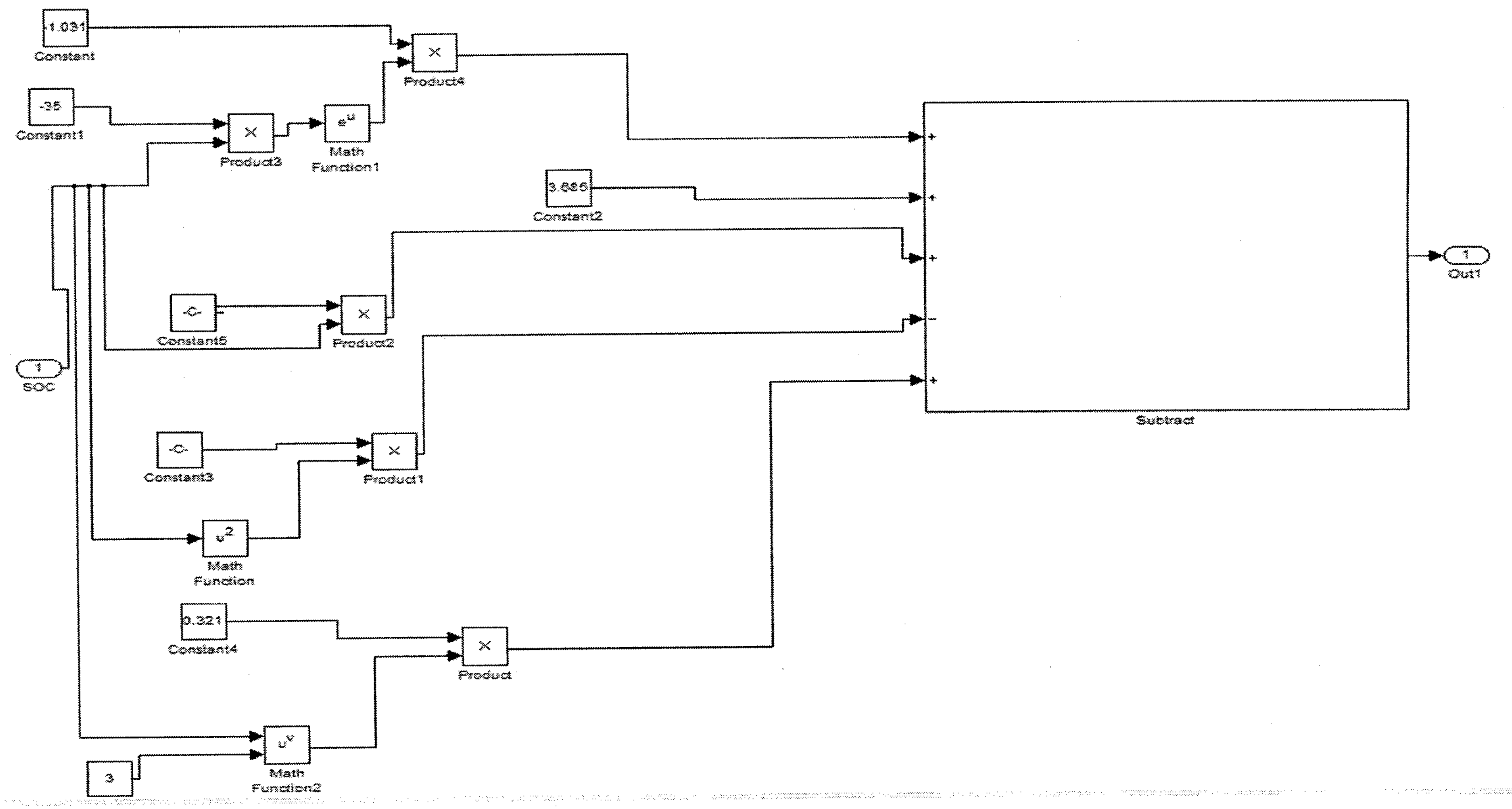

Figure A 1: Model od V_{oc}

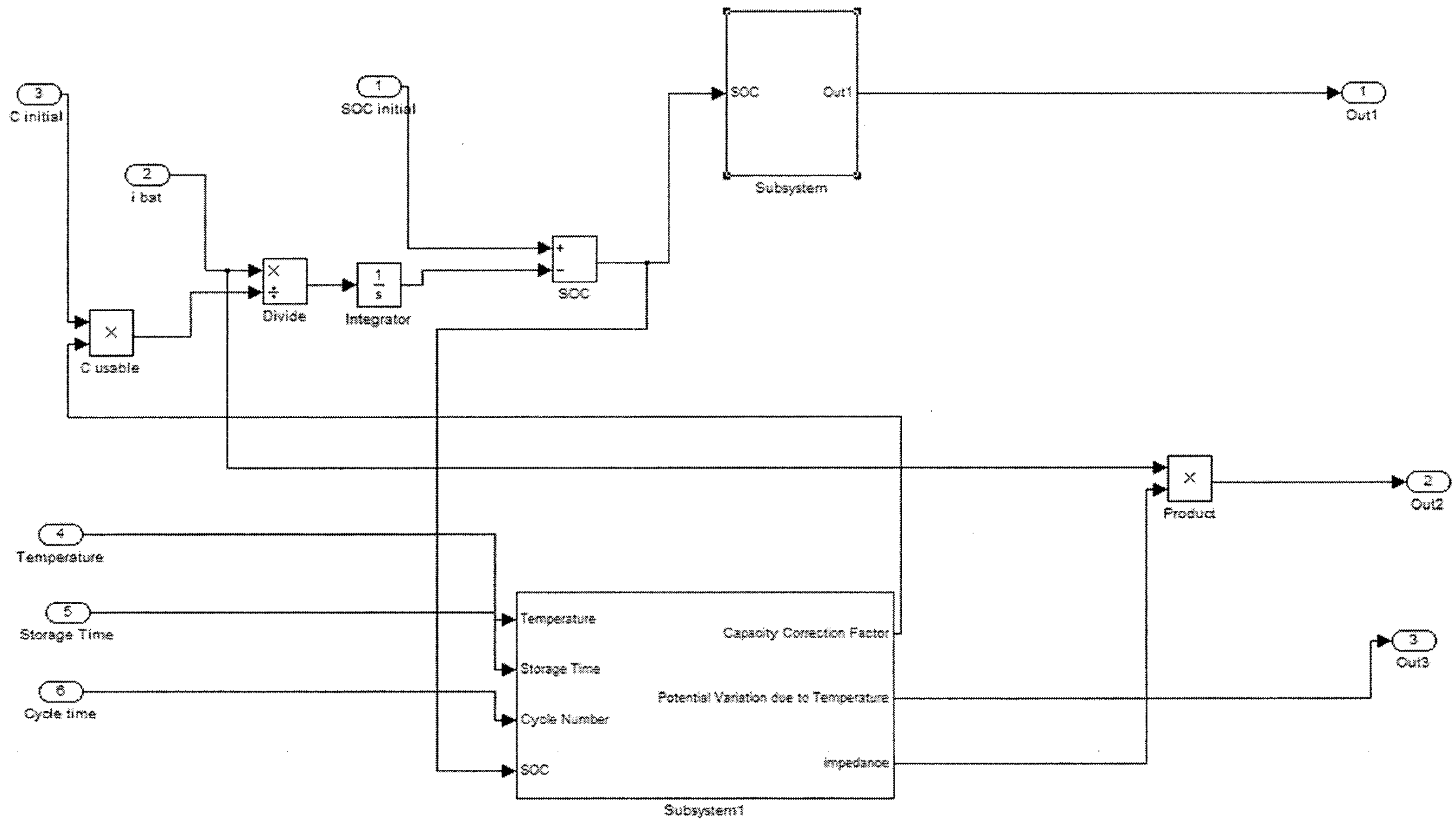

Figure A 2: Model od SOC

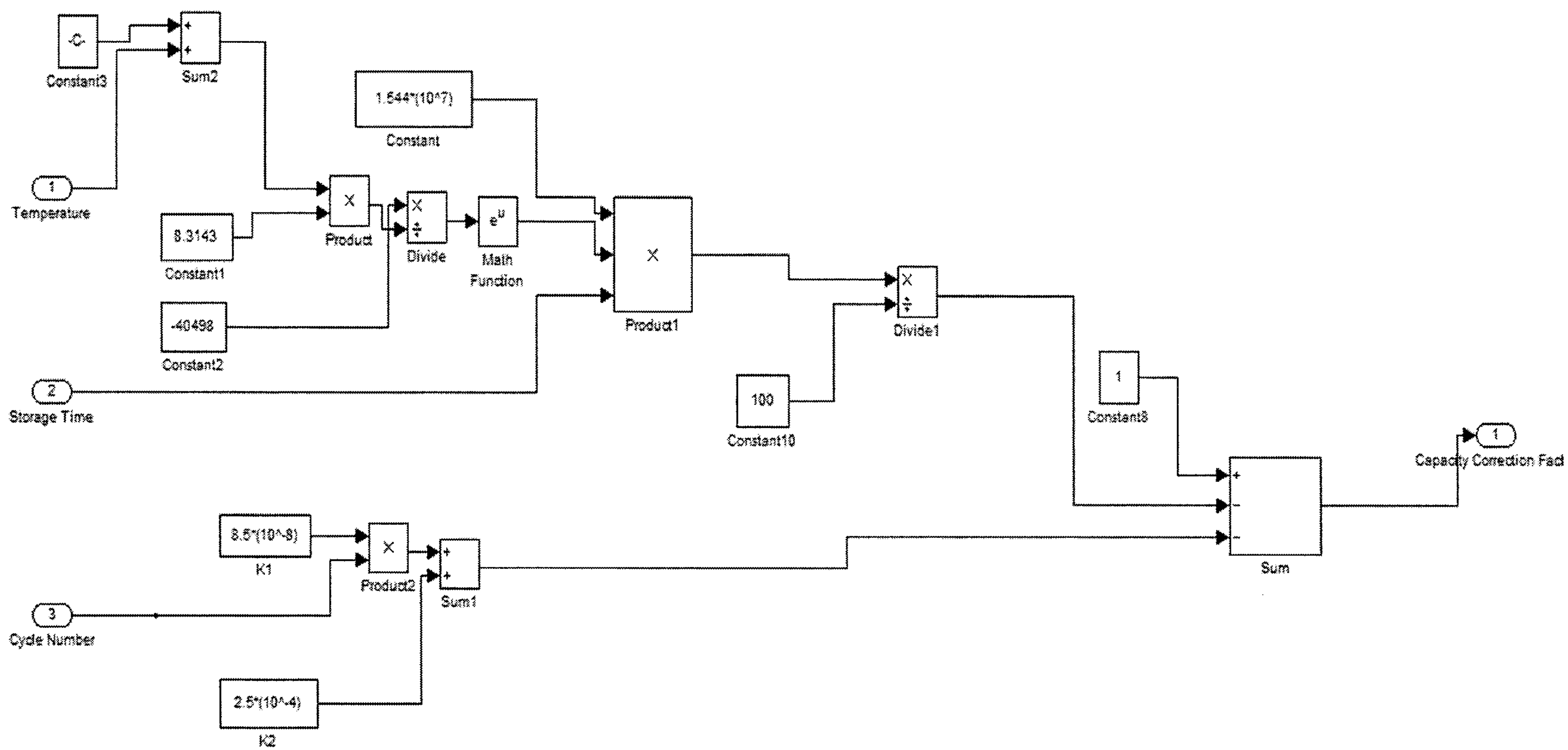

Figure A 3: Model of CCF

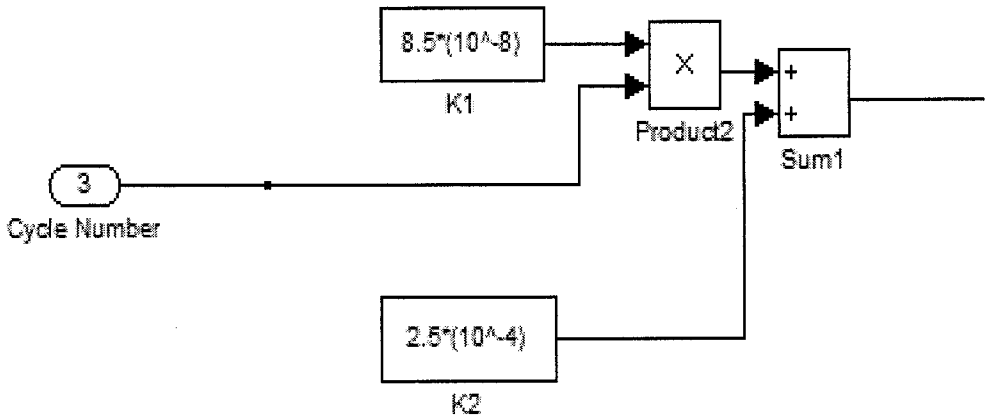

Figure A 4: Model of Cycle resistor

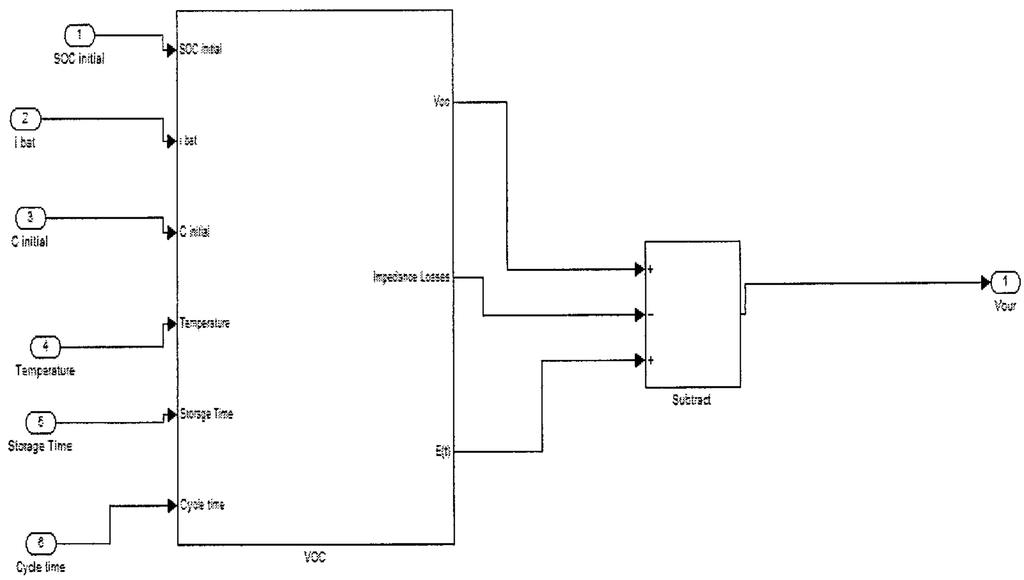

Figure A 5: Model of V_{out}

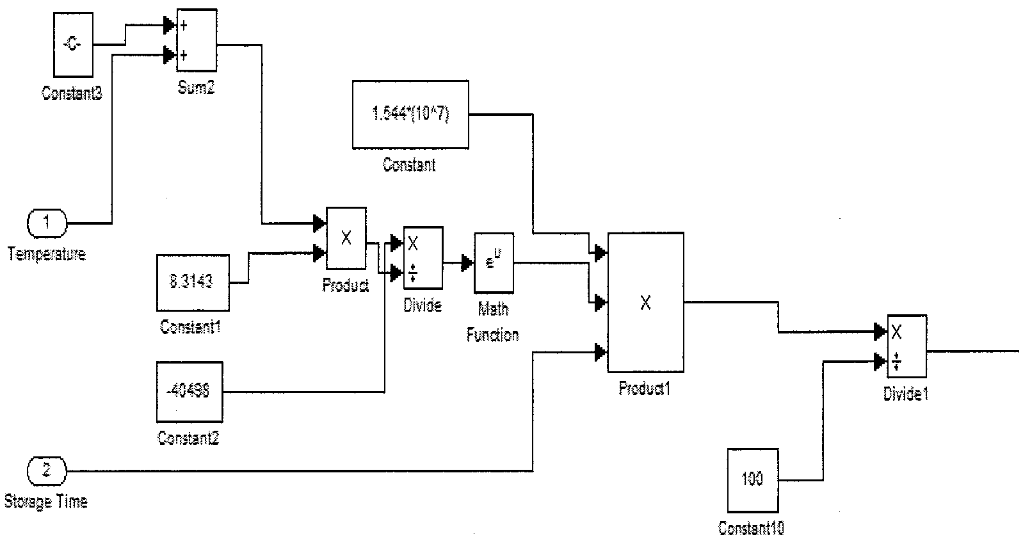

Figure A 6: Model of Storage losses

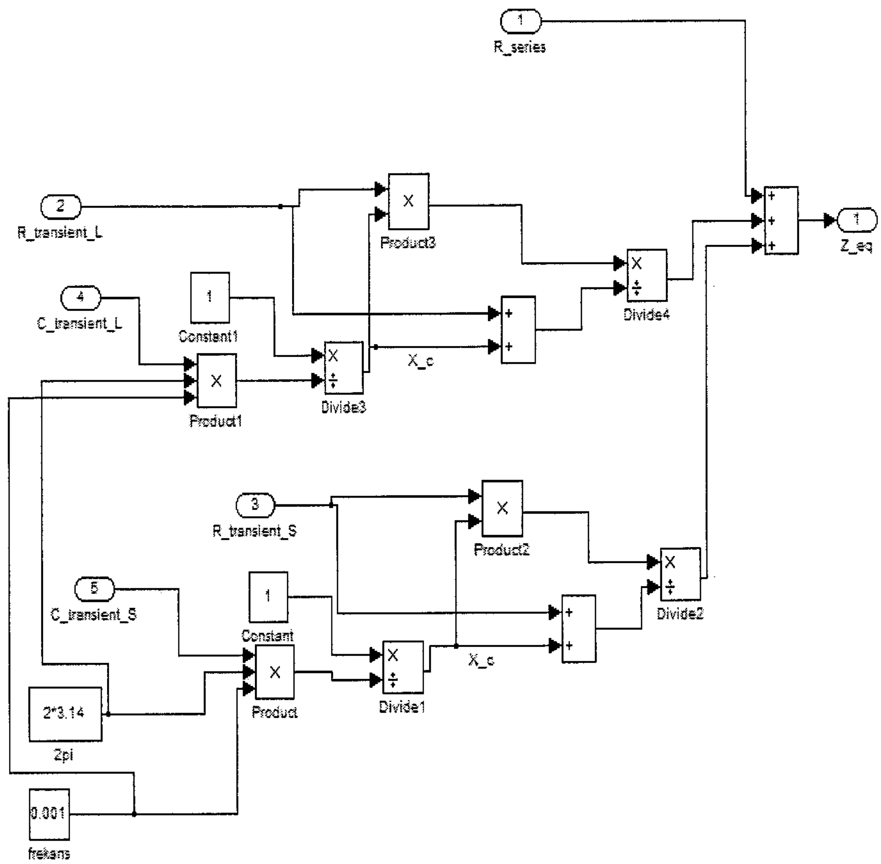

Figure A 7: Model of Impedance

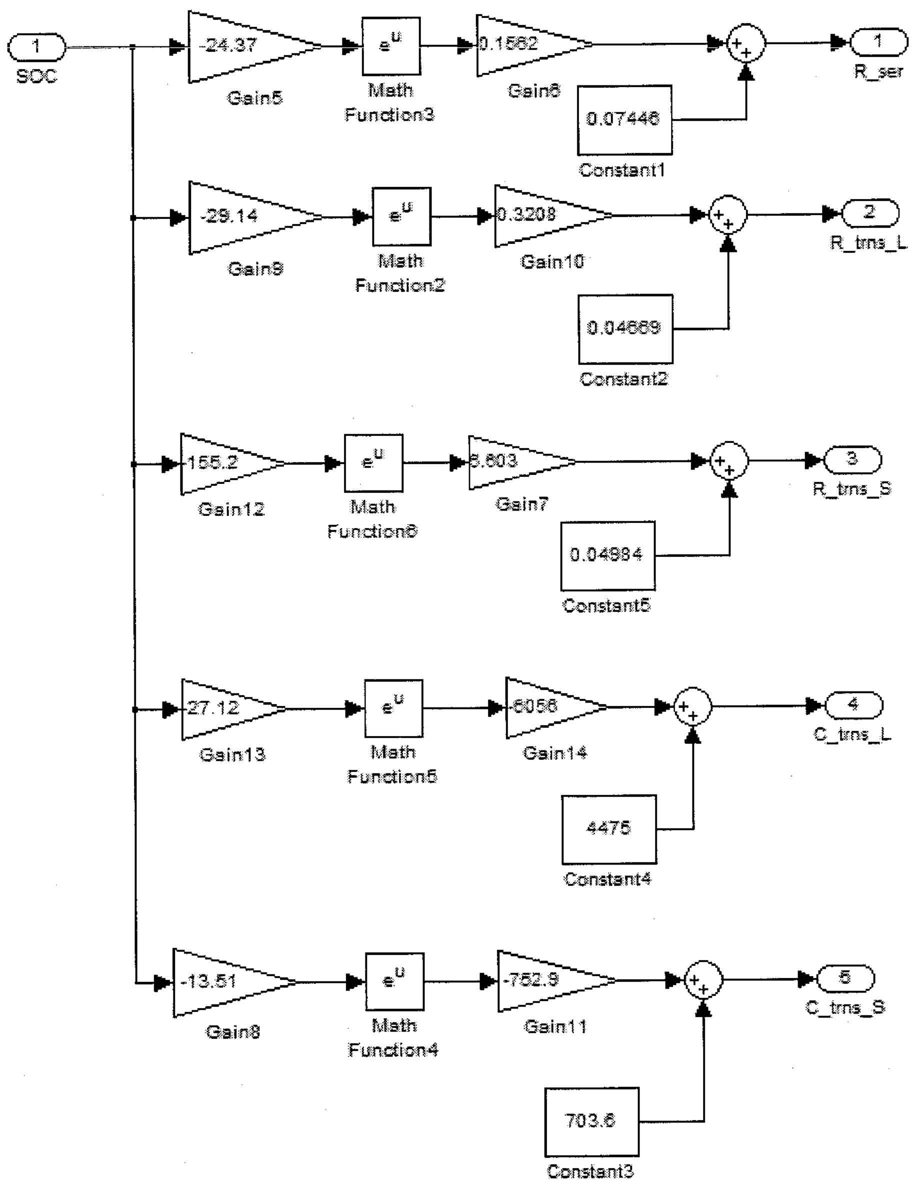

Figure A 8: Model of Transient