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Evaluation of rapid electric battery charging techniques

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EVALUATION OF RAPID ELECTRIC BATTERY CHARGING
TECHNIQUES

By

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Bachelor of Science
University of Nevada, Las Vegas
2005

A thesis submitted in partial fulfillment of
the requirements for the

Master of Science in Engineering
Department of Electrical and Computer Engineering
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Graduate College
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THE GRADUATE COLLEGE

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Ronald Baroody

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Evaluation of Rapid Electric Battery Charging Techniques

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ABSTRACT

Evaluation of Rapid Electric Battery Charging Techniques

by

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Battery powered electric vehicles are gaining popularity worldwide. This trend is driven by several factors including the need to reduce air and noise pollution, and dependence on fossil fuels. The main drawback of today's electric vehicle is its limited range, and the long time duration that is required to charge the electric batteries. This thesis addresses the latter problem.

In recent years, significant progress (through research and development) has been made to accelerate the charging time of the electric vehicle batteries through pulse charging rather than supplying continuous current and/or voltage. Some patented fast charging techniques demonstrated reduced charging times from 8 hours down to 45 minutes, and the current goal is to reduce this to the 10-minute range. This thesis will evaluate the published fast charging techniques in terms of their efficiency, accuracy of state of charge, threat of overcharge and impact of life cycle. The merits of the various battery interrogation techniques will be analyzed through modeling and computer simulation.

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CHAPTER 1

INTRODUCTION

1.1 Battery Definition

The term "battery" is used to denote a device that converts chemical energy into electricity. In general, a battery contains two or more cells connected in series or parallel. In turn, each cell consists of an anode (a negative electrode), a cathode (a positive electrode) and a paste or ionic conductor referred to as an electrolyte. The basic components of an electrochemical cell are shown in Figure 1.1.

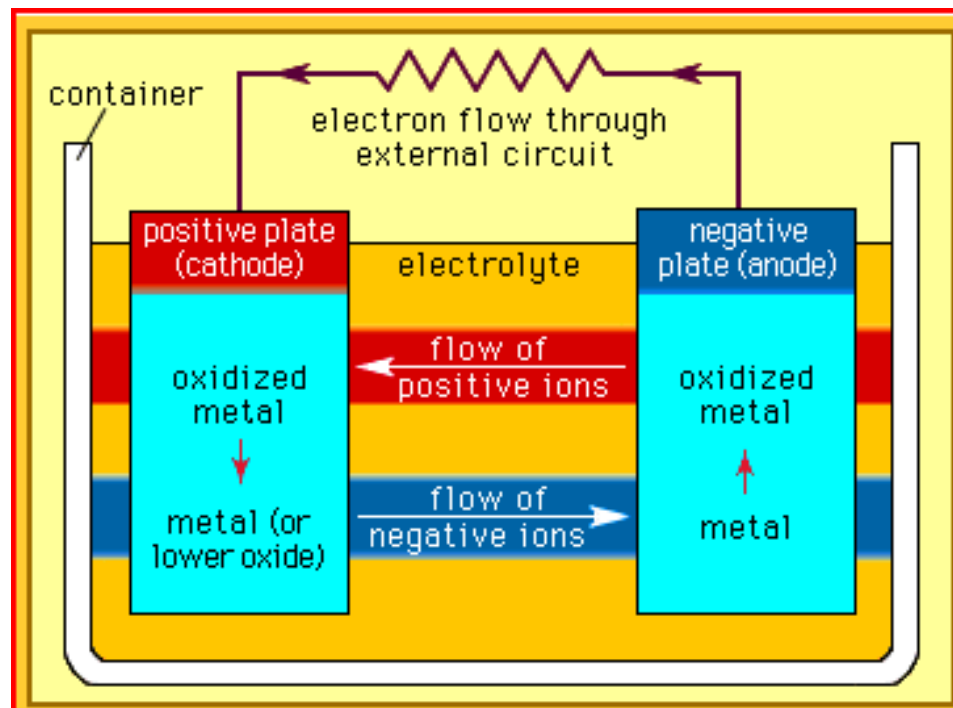


Figure 1.1 Basic components of an electrochemical cell [1].

When a load is connected to the electrodes, a chemical reaction occurs, moving electrons from one electrode to the other thereby generating an electric current. Emerging as early as 1798 with Italian physicist Count Alessandro Volta's first "Voltaic pile"

consisting of a stack of paired copper zinc disks separated from one another by cardboard disks moistened with salt or acid solutions [2], batteries have evolved into different shapes and forms ranging from tiny implantable miniature cells measuring a mere .26-inches long and .09-inches in diameter and lasting up to 15 years of continuous usage [3], to a hefty 1,300 tons 2,000 square meters rechargeable battery capable of unleashing a blistering 40 megawatts of power for up to seven full minutes of operation [4]. Today, batteries have become a common power source for most household and industrial applications, and are now a multi-billion dollar industry.

The common belief that battery development initiated in the late eighteen century was recently challenged by German archeologist Wilhelm König [5]. In 1938, while serving as the director of the National Museum of Iraq, König found a number of artifacts in the museum's collections consisting of tall terracotta jars containing an iron rod housed in a copper cylinder made of a rolled-up copper sheet.

König noticed that at the top of the jars, the iron rod was isolated from the copper by bitumen plugs or asphalt stoppers. Since the copper cylinder was not watertight, filling the jar with liquid would submerge the iron rod in the liquid as well. In 1940, König wrote a paper speculating that the aforementioned artifacts, dating more than two thousand years, now known as "Baghdad batteries", may have been Voltaic cells [5]. König's speculation was supported by the fact that the iron rods discovered inside the earthenware jars showed evidence of acidic corrosion, perhaps having been "submerged in vinegar" [6]. König's claim was in fact proved in 1940 by Willard F. M. Gray of the General Electric High Voltage Laboratory in Pittsfield Massachusetts, who took the time to replicate a Baghdad battery and used a copper sulfite solution, thereby generating

electricity [7]. A cross section of a Baghdad battery, such as the one replicated by Willard F. M. Gray is shown in Figure 1.2

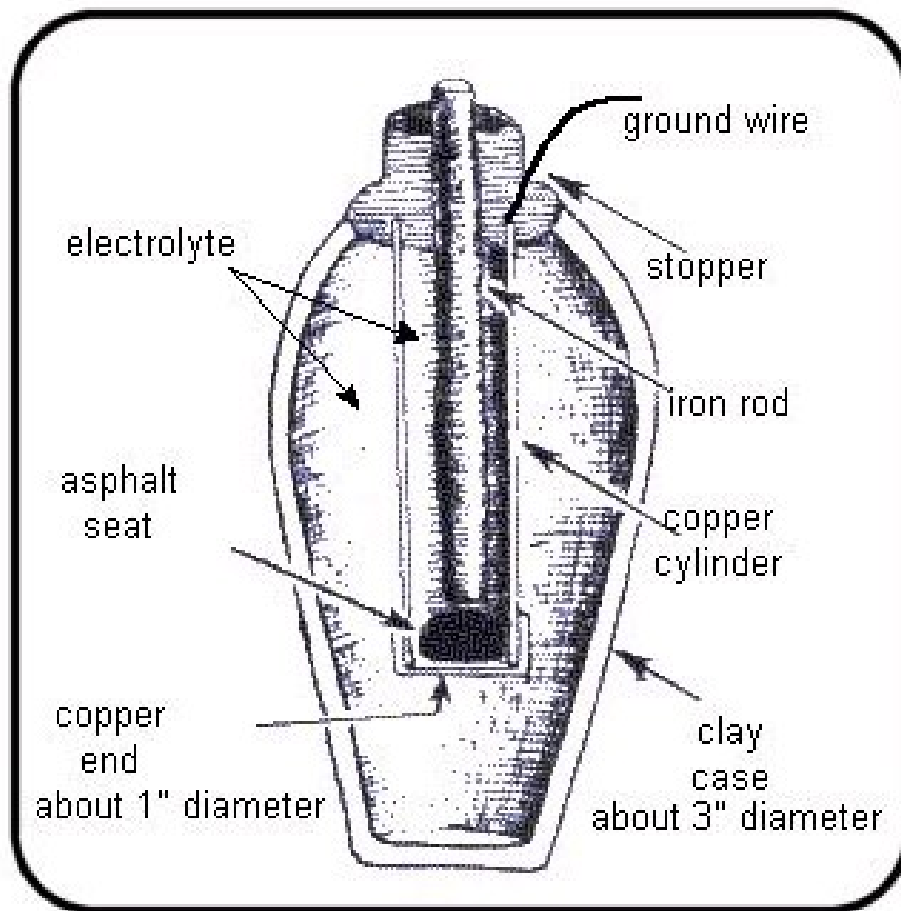


Figure 1.2: Cross Section of a Baghdad Battery [8].

Whether Italian physicist Count Alessandro Volta invented or re-invented the “Voltaic cell” it took until 1836 for his design to be improved by English chemist John F. Daniell [2]. By developing a way to avoid corrosion problems, John F. Daniell effectively enhanced the efficiency of Volta’s batteries.

In 1859 French physicist Gaston Planté invented the lead-acid battery, the pioneer of the rechargeable battery market. The next breakthrough emerged in 1868 when French

chemist Georges Leclanche's created the "wet cell", forerunner of the "dry cell" conceived in 1888 by German's scientist Dr. Carl Glassner. Dry cells became first commercially available in the United States of America in 1896 under the name "Colombia". They were manufactured by National Carbon Company who later became Eveready Battery Company, known today as Energizer. Two years later, in 1898, the "D" size battery was introduced to the world. In 1899, the first nickel-cadmium rechargeable battery was developed by Swedish inventor Waldmar Jugner. At the turn of the century, American inventor Thomas Alva Edison conceived the first alkaline cell [2].

Fifty five years later, in 1955, Eveready commercialized miniature batteries for hearing aids. A year later, in 1956, Eveready expanded their portfolio with the 9-Volt battery, widely used until today. In 1957, watches battery replaced mechanical winding and in 1959 the first commercially viable cylindrical alkaline battery was born. In 1960, advanced silver oxide miniature batteries were created for more efficient use in hearing aids and watches. In 1989, the first "AAAA" battery entered the battery industry followed in 1992 by the first commercially available lithium batteries [2]. From there, the battery industry expanded exponentially to include a wide medley of chemistries of all shape, size and forms. The evolution of the battery timeline is tabulated in Table 1.1

Table 1.1: Battery Evolution Timeline [2].

Year	Event
2,000+ years ago	The Baghdad Battery might have been used for electroplating gold onto silver objects
1798	Voltaic pile built by Italian physicist Count Alessandro Volta
1836	Voltaic pile Efficiency improved by English chemist John F. Daniell
1859	Lead-acid battery developed by French physicist Gaston Planté
1868	Wet cell designed by French chemist Georges Leclanche
1888	Dry cell invented by German scientist Dr. Carl Gassner
1896	A dry cell battery named "Colombia" became the first commercially available battery sold in the U.S.A. by the National Carbon Company which later became the Eveready Battery Company, known today as Energizer
1898	Introduction of the "D" size battery
1899	First nickel-cadmium rechargeable battery invented by Swedish inventor Waldmar Jungner
Early 1900's	First alkaline cell developed by American inventor Thomas Alva Edison
1955	Introduction of miniature batteries for hearing aids
1956	Introduction of the 9-Volt battery
1957	Introduction of the first commercial watch battery
1959	Introduction of the first commercially viable cylindrical alkaline battery.
1960	Introduction of the first silver oxide system miniature battery for use in hearing aids and watches.
1989	Introduction of the first "AAAA" alkaline battery
1992	Introduction of the first commercially available lithium batteries.
2000 to present	Innovations in rechargeable technology introduce products such as nickel-metal hydride rechargeable batteries, titanium high-performance batteries, and 15-minute rechargeable batteries.

1.2 Battery Classification

Batteries are classified as primary or secondary cells. Primary cells, also known as “Voltaic cells”, are any kind of electrochemical cells in which the electrochemical reaction is not reversible. Primary cells cannot be reconstituted into their original state once their chemical energy has been converted into electricity through the battery normal cell operation or discharge process [10]. A common example of a primary cell is the disposable battery. Until the 1970s, primary batteries were predominantly zinc-anode based systems. Exponential performance improvements in terms of energy density, a measure of the amount of energy stored in a given system or region of space per unit volume (known as “Volumetric energy density” and expressed in W.h/m³), or per unit mass (known as “Gravimetric energy density” and expressed in W.h/Kg), was undergone since 1946 as shown in Figure 1.3.

More recently, low-temperature performance and storage capability were greatly improved with the introduction of lithium-anode based systems and specialist couples using anode materials such as cadmium, magnesium and indium-bismuth [11]. Energy densities and corresponding operating temperature range for widely used primary batteries in order of increasing gravimetric energy density are tabulated in Table 1.2.

High energy density is one of many parameters users must rely on in order to select the most appropriate battery system for their specific application. Operating temperature range, shelf life and on-load cell voltage are other crucial parameters that need to be carefully considered as well.

Secondary cells, on the other hand, also known as rechargeable cells, storage cells or accumulators, have the ability to be reconstituted into their original chemical form by

passing an electric current through them in the opposite direction of the normal cell operation. Secondary cells are of primordial importance for this thesis and will be elaborated in Chapter 2

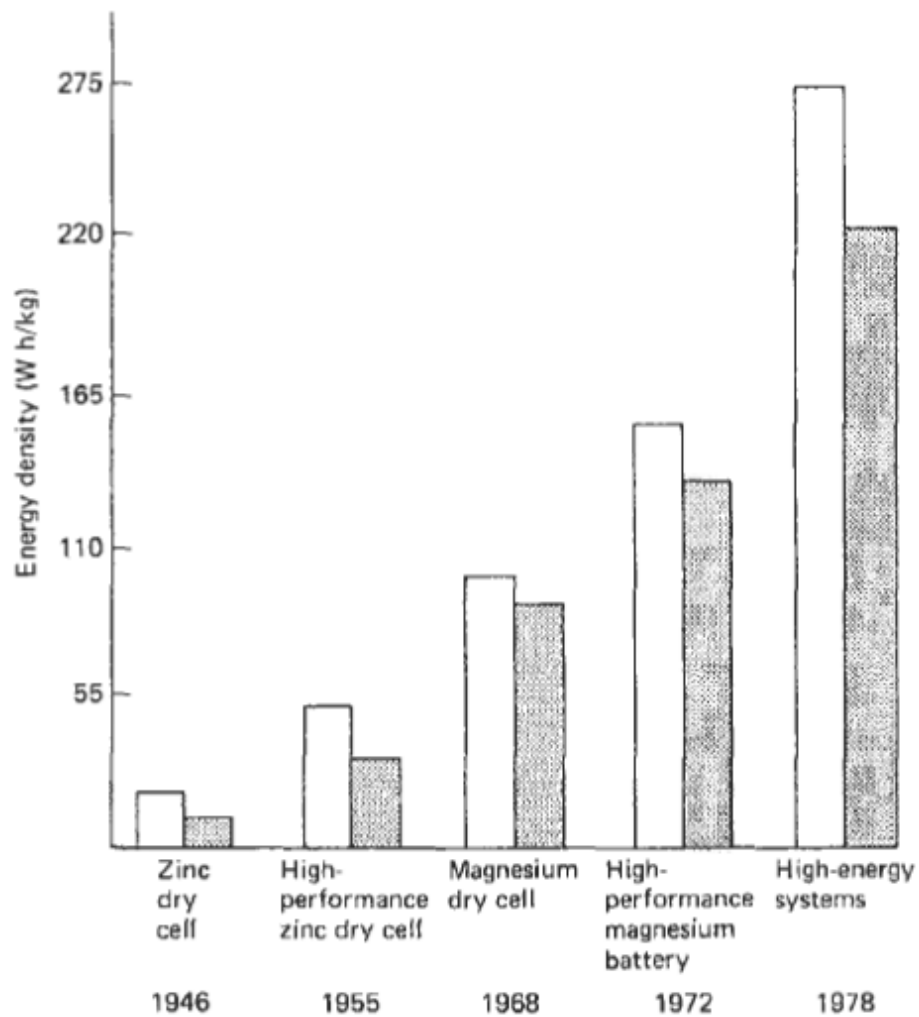


Figure 1.3: Improvement in primary battery performance at 21°C since 1946 [11].

□ Initial; ■ After 2 years storage

Table 1.2: Energy densities and operating temperatures of primary batteries in order of increasing gravimetric energy density [11].

Battery System	Gravimetric Energy Density	Volumetric Energy Density	Operating Temperature (°C)	
	W.h/Kg	W.h/dm ³	From	To
Mercury-cadmium	22	73	-40	70
Carbon-zinc	55-77	120-152	-7	54
Alkaline manganese	66-99	122-268	-30	54
Mercury-cadmium-bismuth	77	201	-20	90
Zinc chloride	88	183	-18	71
Mercury -zinc	99-123	300-500	-20	54
Magnesium-organic electrolyte	133-330	430-610	-54	74
Lithium-sulphur dioxide	260-330	420	-40	60
Lithium-vanadium pentoxide	264	660	-54	60

CHAPTER 2

SECONDARY CELLS

2.1 Common Types of Secondary Cells

Secondary cells batteries are of particular interest to this thesis, specifically lead-acid and lithium-ion (Li-Ion) batteries. Common types of rechargeable batteries are lead-acid, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), lithium-ion (Li-Ion), lithium-ion-polymer and reusable alkaline. The lead-acid battery was the pioneer in the rechargeable battery market. It was invented in 1859 by the French physicist Gaston Planté. Until today, the lead-acid battery remains the most widely used in automobiles, trucks, aircraft, and other vehicles. The cell of a lead-acid battery hosts a negative electrode made of lead, a positive electrode made of lead-dioxide and dilute solution of sulfuric acid. When a load is connected across the main terminals of the battery, the negative lead electrode in each cell dissociates into free electrons and positive lead ions. The electrons travel through the external electric circuit and lead sulfate is formed by combining the positive lead ions with the sulfate ions in the electrolyte [10].

When the electrons re-enter the cell at the positive electrode, they combine with the lead dioxide and the hydrogen ions found in the electrolyte to form water and to release additional lead ions that will in turn combine with the sulfate ions in the electrolyte to form additional lead sulfate. As the sulfuric acid is gradually converted into water and the electrodes are converted into lead sulfate, the lead-acid cell progressively runs down.

Charging the cell by reversing the current flow in its normal operation, the chemical reactions described above are reversed and the cell is restored to its original chemical condition. Today's readily available lead-acid batteries consist of three to six 2-Volts cells

connected in series. Lead-acid batteries are categorized as starting batteries or deep cycle batteries. Starting batteries, like the ones used in automobiles, are designed to deliver quick bursts of energy for a relatively short period of time. They sport a greater plate count and their plates are generally thinner and have somewhat different material composition. Deep cycle batteries on the other hand have less instant energy, but greater long-term energy delivery. Deep cycle batteries have thicker plates and can survive a number of discharge cycles [12].

Wet cell (also known as flooded), gel cell, and absorbed glass mat (AGM) are classified as sub-categories and slightly different versions of the lead-acid battery. The wet cell comes in two flavors: serviceable and maintenance free. The gel cell and the absorbed glass mat batteries are specialty batteries that store charge very well and have the ability not to sulfate or degrade as easily as wet cells. Absorbed glass mat batteries are occasionally referred to as "sealed regulated valve", "dry cell", "non spillable", and "valve regulated lead-acid" batteries. In general, the lead-acid battery system's advantages are low manufacturing costs, relatively high voltage per cell and good capacity life. Its disadvantages on the other hand are that it is relatively heavy, it has poor low-temperature characteristics and it cannot be left in the discharged state for too long without being damaged [11].

Another widely used secondary cell, developed in the 1900's by American inventor Thomas Edison is the alkaline cell, or nickel-iron battery. It operates very similarly to the lead-acid cell except that the negative electrode is made of iron, the positive electrode is made of nickel oxide, and the electrolyte consists of a solution of potassium hydroxide. Producing about 1.15V per cell, rechargeable alkaline batteries are mainly used in heavy

industry applications and have a useful life of about ten years. Caution should be exerted while recharging alkaline batteries due to highly flammable hydrogen gas emissions given off during charging [10].

The nickel-cadmium cell or cadmium battery is an alkaline cell similar to the Edison battery. It also produces about 1.15 V per cell, and its useful lifetime is about two and a half times that of the Edison battery. As the names suggest, the main difference between the nickel-iron battery and the nickel-cadmium battery is the fact that the iron electrode is replaced by a cadmium electrode [10]. The cadmium battery was invented in 1899 by Swedish scientist Waldmar Jungner. It was commercialized in Sweden in 1910 and reached the United States in 1946 [2].

Some advantages of the nickel-cadmium battery include it being mechanically rugged, offering excellent low temperature characteristics (operating/recharging), tolerating deep discharges for long periods, tolerating more charge/discharge cycles than most rechargeable batteries, boasting faster charge/discharge rates than lead-acid batteries with minimal loss of capacity even at high discharge rates. The main disadvantages of the nickel-cadmium battery include extreme toxicity, memory effect, and relatively low energy density and high self-discharge [11].

Similar to the nickel-cadmium cell but offering thirty to forty percent higher capacity, the nickel-metal-hydride cell appeared in the scene in the 1980's. Less prone to memory effects and environmentally friendlier than nickel-cadmium, the nickel-metal-hydride battery suffers however from limited service life, high self-discharge, performance degradation under elevated temperature and relatively low storage lifetime [10].

For their size and weight, lithium-ion batteries pack very high energy density and can hold a charge for much longer than conventional rechargeable lead-acid batteries. And although the electrochemical potential of lithium-based power sources has been known for quite some time, it was not until the 1960's that manufacturers were able to convert its potential to practical cell hardware and demonstrate its benefits. In 1991, lithium-ion batteries started to show up in the rechargeable battery market. Lithium is a lightweight, chemically reactive metallic element with the ability to store large amounts of energy in its atomic bonds [10]. Lithium ions migrate from a negatively charged carbon graphite anode to a positively charged cathode, commonly made of cobalt oxide or lithium-iron-phosphate. Lithium-ion batteries can be recharged hundreds of times but should not be completely discharged before being recharged.

Manufacturers incorporate a small microprocessor into the lithium -ion battery pack in order to manage it and to monitor the cells' temperature and state of charge of the battery [10]. High temperatures will cause lithium-ion batteries to degrade and should be avoided. Lithium-ion batteries only last a few years after manufacture before they degrade and need to be replaced. Lithium-ion-polymer batteries technologically evolved from lithium-ion batteries. The lithium-salt electrolyte, held in an organic solvent in the lithium-ion design, is replaced by a solid polymer composite such as polyethylene-oxide or polyacrylonitrile. Lithium-ion polymer batteries are cheaper to manufacture than lithium-ion batteries and can withstand relatively heavier physical damage [11]. It is only until 1996 that lithium-ion polymer batteries started appearing in consumer electronics. The ranking in terms of on-load voltage of some of the most commonly used secondary battery systems is tabulated in Table 2.1.

Table 2.1: On-load voltage (V) of some of the most commonly used secondary battery systems [11].

Battery System	From (V)	To (V)
Silver-Cadmium	0.81	1.10
Silver-Hydrogen	1.00	1.10
Nickel-Cadmium	1.00	1.25
Nickel-Hydrogen	1.20	1.30
Silver-Zinc	1.30	1.55
Nickel-Zinc	1.50	1.65
Lead-acid	1.50	2.00

Table 2.2: Gravimetric energy density(W.H/Kg) of some of the most commonly used secondary battery systems [11].

Battery System	Gravimetric Energy Density (W.h/Kg)
Lead-acid	20
Nickel-Cadmium	35
Silver-Cadmium	53
Nickel-Zinc	56
Nickel-Hydrogen	62
Silver-Hydrogen	95
Silver-Zinc	113
Zinc-Chlorine	130
Zinc-Air	150
Sodium-Sulphur	240
Lithium-Chlorine	330
Lithium-Silver	370

The ranking in terms of gravimetric energy density of some of the most commonly used secondary battery systems is tabulated in Table 2.2. The gravimetric energy density of some of the most commonly used secondary batteries at a five hour discharge rate is shown in an increasing order in Figure. 2.1. Last but not least, the basic parameters of some of the most common secondary battery systems are tabulated in Table 2.3.

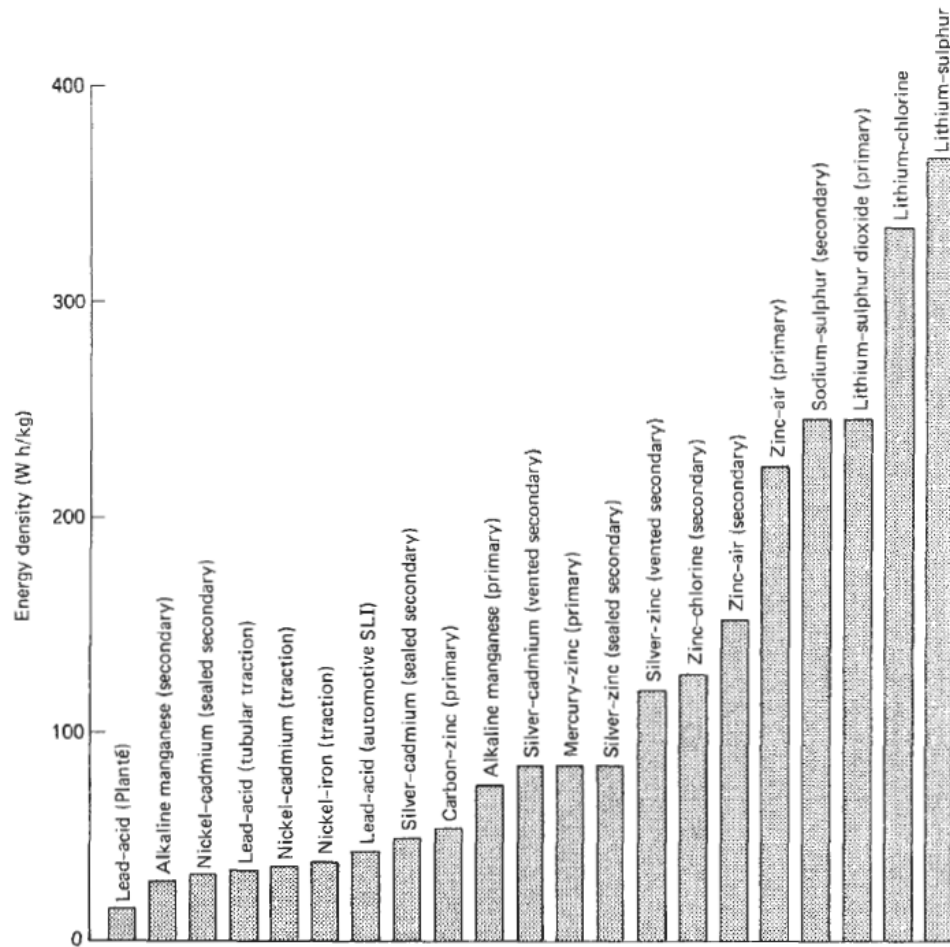


Figure 2.1: Gravimetric energy density of secondary batteries at a 5 hour discharge rate [11].

Table 2.3: Basic parameters of secondary battery systems [11].

	<i>Nickel-cadmium</i>		<i>Lead-acid</i>		<i>Nickel-zinc</i>	<i>Silver-zinc</i>	<i>Silver-cadmium</i>
	<i>Sealed</i>	<i>Vented</i>	<i>Storage</i>	<i>Sealed</i>			
Cathode	nickel hydroxide	nickel hydroxide	lead dioxide	lead dioxide	nickel oxyhydroxide	silver oxide	silver oxide
Anode	cadmium	cadmium	lead-antimony	lead-calcium	zinc	zinc	cadmium
Electrolyte	potassium hydroxide	potassium hydroxide	sulphuric acid	sulphuric acid	potassium hydroxide	potassium hydroxide	potassium hydroxide
Open-circuit voltage (V)	1.35	1.35	2.10	2.10	1.71	1.86	1.40
Energy density (W h/kg)	26–37	26–44	15–26	22–33	33–77	55–220	24–120
Energy density (W h/dm ³)	61–85	61–91	31–122	49–83	67–134	80–610	37–250
Max. discharge rate	15C	50C	20C	20C	10C	50C	10C
Average discharge voltage (V)	1.20 (1 h rate)	1.22 (1 h rate)	1.80 (1 h rate)	1.90 (2 h rate)	1.60 (1 h rate)	1.50 (1 h rate)	1.10 (1 h rate)
Normal operating temperature (°C)	–40 to +60	–51 to +60	–54 to +54	–51 to +71	–48 to +71	–48 to +71	–48 to +71
Normal storage temperature (°C)	–51 to +71	–51 to +74	0 to 21	0 to 21	–48 to +38	–48 to +38	–48 to +38
Charging method	constant current	const. current const. voltage	taper current const. voltage	taper current	const. current const. voltage	const. current const. voltage	const. current const. voltage
Charge and retention (50% cap. 27°C)	60 days	1 year	90 days	1.5 years	1 year	1 year	2 years
Cycle life	100–1500	100–3000	10–600	100–150	100–200	10–200	100–500
Initial cost	high	high	low	low	high	high	high

2.2 Reversible Charge/Discharge Property of Secondary Cells

Almost all rechargeable batteries operate under the same electrochemical principle: as a cell is being discharged, a transfer of ions from one electrode to the other through the electrolyte is fueled by the consumption of ions by one electrode and the generation of ions by the other. On the other hand, when the cell is charged, the process is reversed and the ions travel in the opposite direction. It is important to note that the overall performance of the battery largely depends on the way the electrochemical process is carried out.

2.3 Battery Charge/Discharge Performance Factors

The performance of a rechargeable battery can be heavily affected by the rate and uniformity by which the ions move from one electrode to the other. This is because the chemical reactions that occur at the electrodes are not instant and are limited by the ion concentration on the electrodes respective surfaces. In turn, the concentration of ions around the electrodes respective surfaces is dependent on the aptitude of the ions to travel through the electrolyte and separator. The formation of dendrites, “outgrowths of material from the electrodes”, occurs when the ion concentration across the surface of an electrode is uneven leading to a non-uniform chemical reaction rate [9]. Dendrites can eventually outgrow themselves from one electrode to the other, shorting out the battery.

The metallic structure of the electrode can also drastically hinder the performance of a rechargeable battery. The finer the grain structure, the lower the internal resistance and the bigger the surface area. However, under extensive low current conditions, slower chemical reactions lead to formation of metallic crystals. These crystals reduce the surface area of the electrodes and therefore reduce the performance of the battery by

lowering its capacity and increasing its internal resistance which in turn will result in a lower battery voltage during a fixed discharge current. Furthermore, when the internal resistance of a battery increases, the charging process efficiency drops as unnecessary heat generation arise [9].

CHAPTER 3

BATTERY CHARGING TECHNIQUES

3.1 Introduction

Battery charging techniques can be divided into three categories: conventional charging techniques, pulse charging techniques and state of the art charging techniques. Each category and its corresponding subcategories will be discussed separately.

3.2 Conventional Charging Techniques

3.2.1 Constant Current Trickle (CCT) Charging Technique

Conventional charging starts with the constant current trickle charge technique where a battery is submitted to a very low constant current until it is fully charged. Constant current trickle chargers are relatively simple and inexpensive to design. They are not considered as technologically advanced chargers and they rely completely on the user to start and terminate the charge [9]. Some constant current trickle chargers are specific to certain rechargeable battery types. Others have the capability of adapting to different rechargeable battery types by allowing the user to modify the charging profile. Feedback based on crucial battery parameters is non-existent. Therefore, they run the risks of damaging the battery due to overcharge and potential dendrite outgrowth.

3.2.2 Fast Constant Current (FCC) Charging Technique

The next step up is the fast constant current charge technique where a battery receives a large current until it is fully charged. This concept can reduce the battery charging time from ten hours under constant current trickle charge to three hours in fast constant current charge. However, additional charge control and monitoring circuitry must be embedded into the charger in order to terminate the charge once the battery is full and in order to

monitor the battery temperature while it is being charged. While dramatically reducing the charge time, the fast constant current charging technique does not take into account the internal electrochemical process of the battery being charged resulting in significant negative long-term effects [9]. Dendrites growth, large metallic crystal formation and increased internal resistance caused by the large constant charging current lead to reduced battery capacity and shortened life cycle.

3.2.3 Constant Current Constant Voltage (CCCV) Charging Technique

A slight improved fast constant current charge technique is known as the constant current constant voltage charging technique where a battery receives a constant current until it reaches a predetermined voltage value at which point the charging voltage is held constant until the charging current drops to a near zero value. The constant current constant voltage charging technique produces the same negative long-term effects as of the fast constant current charging technique but to a lesser degree [9].

In short, conventional charging techniques are simple, low cost solutions, aimed at recharging secondary batteries without taking into account eventual long term negative effects such as battery capacity reduction and shortened life span.

3.3 Pulse Charging (PC) Technique

It was not until the 1970's that the pulse charging concept entered the commercial rechargeable battery market [9]. The pulse charging concept derived from taking into account the fact that an extended constant current charge leads to an ion concentration gradient build up on the ion-generating electrode due to the mass transport limitations within the battery. And as previously mentioned, this leads to dendrites outgrowth, metallic crystal formation and an increase in the internal resistance of the battery which

in turn leads to heat generation, poor battery charge efficiency, poorer battery capacity and shorter battery lifespan.

However, by periodically interrupting the charge for a relatively short period of time, ions are able to diffuse and distribute more evenly throughout the battery, minimizing the negative effects mentioned above. The original pulse charging technique relied on supplying a charging pulse current for about a full second followed by a resting period in the order of milliseconds. This charge/rest period was carried on repeatedly until the battery was fully charged. In the late 1970's, the pulse charging technique evolved into a four step charge/rest/discharge/rest period. The introduced discharge impulse was very short in duration and had two and a half times the magnitude of the charging pulse. The newly introduced discharging impulse accounted for even faster ion redistribution throughout the battery which improved the battery charging efficiency and the overall battery performance.

3.4 State of The Art Charging Technique

State of the art battery charging emerged in the early 1990's. It got more and more involved in taking into account the electrochemical properties of rechargeable batteries in order to offer better charging algorithms to charge the batteries faster, more efficiently while still paying extra attention to maximize the battery's capacity and the battery's lifespan. For instance, Podrazhansky [9] discovered that applying multiple shorter discharging pulses with much greater amplitude benefited all secondary battery types.

CHAPTER 4

FAST CHARGING TECHNIQUES EVALUATION

4.1 Introduction

This chapter thoroughly evaluates patented fast charging techniques and apparatus ranging from 1971 to 2002. The evaluation is carried out in order to determine how contemporary chargers make use of today's available knowledge as it relates to efficiently charging secondary batteries. Several criteria leading to a safe and accountable charge are to be probed.

4.2 Control Circuitry for Termination of Rapid Battery Charging

In 1971, inventor Indar K. Sethi patented a method and apparatus for recharging any type of secondary battery irrespectively of its internal impedance [13]. Sethi's hand drawn circuit shown in Figure 4.1 is claimed to rapidly recharge any and all types of secondary batteries irrespectively of their internal impedance via a Pulse Charging Technique consisting of a controlled charging current pulse followed by a discharging pulse that occurs in function of the battery's terminal voltage. A careful circuit analysis seconds that the technique used to generate the pulse charges is contingent on the frequency of the input voltage of the circuit. Moreover, the pulse discharging is dependent on the battery's terminal voltage and is forced to increase with the battery's terminal voltage. Sethi designed a smart apparatus fully capable of rapidly recharging secondary batteries. However, his design bears a heavy set of drawbacks.

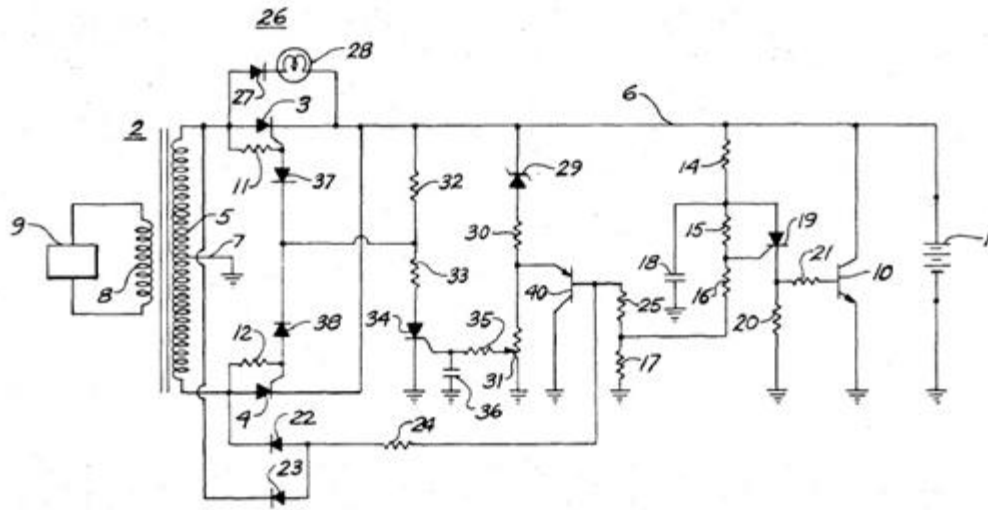


Figure 4.1: Control Circuitry for Termination of Rapid Battery Charging [13].

First and foremost, the pulse charging/discharging originating from Sethi's patented circuit occurs due to layout of its components. Therefore, while inheriting some of the benefits of pulse charging, Sethi's fast charging algorithm is still not specific to the internal chemistry of the battery being recharged. The only feedback received from the battery being recharged is limited to the voltage across its terminals. Moreover, Sethi's circuit relies on user intervention for manually setting the charging current magnitude based on battery characteristics supplied by the battery's manufacturer. Therefore, the end-user operating on Sethi's circuit must possess a good working knowledge of the apparatus and of rechargeable batteries in general. This makes the entire process of recharging a specific battery user dependent and error prone. Furthermore, Sethi's circuit does not account for possible battery overheating or gas generation which could potentially damage the battery and/or hurt the end-user. Last but not least, Sethi's design

does not calculate or disclose the state of charge of the battery being recharged at any point in time.

4.3 Method and Apparatus for Rapid Battery Charging

In 1979, inventor Per-Edward Samsioe, unsatisfied with the long charging period recommended by battery manufacturers of secondary batteries, claims that a secondary battery can be charged to eighty percent (80%) of its capacity by a constant current in less than an hour as long as the charging current can be interrupted if the battery experiences high temperature or gas development [14]. Moreover, Samsioe adds that all contemporary charging methods, except for the constant current charging method, rely heavily on battery parameters and are therefore not sufficiently safe. For the reasons mentioned above, Samsioe patented a method and apparatus that can rapidly charge a secondary battery without depending on its parameters. Samsioe's hand drawn patented charging circuit is shown in Figure 4.2

Samsioe's claim which states that a secondary battery can be charged to eighty percent (80%) of its capacity by a constant current in less than an hour as long as the charging current can be interrupted if the battery experiences a high temperature or gas development is supported by the fact that the charge acceptance (willingness of a battery to accept and retain charge) of a secondary battery is much higher when the battery gets closer to being depleted. An empty battery has the ability to accept and retain much more charge than a battery that is closer to being fully charged. Therefore, Samsioe's patented charging circuitry begins its cycle by discharging the battery that needs to be recharged through a resistor before actually recharging it.

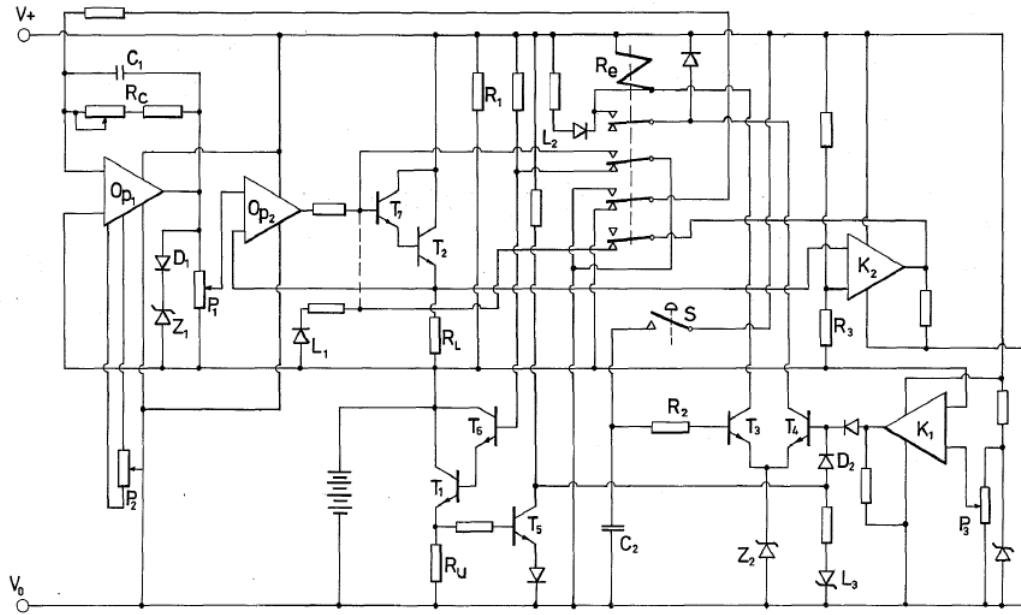


Figure 4.2: Samsioe's patented charging apparatus [14].

The aforementioned discharging behavior could be to some extent looked upon as inefficient and wasteful. The benefits of discharging the battery before recharging can be accounted for via pulse charging without an actual need to heavily discharge the battery that is there in the first place to be recharged. Further, Samsioe's invention relies heavily on manual setting of a variety of potentiometers to vary the charging curves and to adapt the apparatus to a wide variety of secondary batteries. The invention is therefore heavily dependent on an educated end user and can be error prone. Moreover, the entire circuit schematic has to be redesigned for every battery that needs to be recharged. Since Samsioe won't be around to assist with the calculations, we can only hope that the end user has a strong knowledge of the apparatus itself and of rechargeable batteries in general. Last but not least, while Samsioe mentions that the charging current needs to be interrupted if the battery being recharged experiences a high temperature or gas

development, his patented charging circuit does not exhibit a current interrupting mechanism that interacts with safety sensors, such as temperature and gas sensors.

4.4 Method and Apparatus for Rapidly Charging and Reconditioning a Battery

In 1999, inventors Pittman et al. patented a charging method and apparatus designed to quickly and efficiently charge secondary batteries while simultaneously reconditioning them [15]. Unsatisfied with prior art battery chargers associated with long charging times, inefficient charging, and steady decrease in charge acceptance and in life cycles, Pittman et al. built a quick and efficient charger based on the pulse charging technique. Pittman et al. charging circuit is shown in Figure 4.3.

Observing that constant current chargers can easily damage a secondary battery by overestimating the constant charge current which can eventually completely destroy a functional battery, and that pulse chargers that try to deliver bursts of energy to rechargeable batteries through pulses usually operate at a high charging voltage which gets the job done quicker at the expense of gradually destroying the battery through heat generation and electrolyte evaporation, Pittman et al. decided to go with a pulse charging algorithm containing a periodic combination of charging pulses, discharging pulses and recovery periods in order to greatly improve some limiting factors of charge acceptance of secondary batteries. The discharge/charge/stabilize periodic waveform is shown in Figure 4.4.

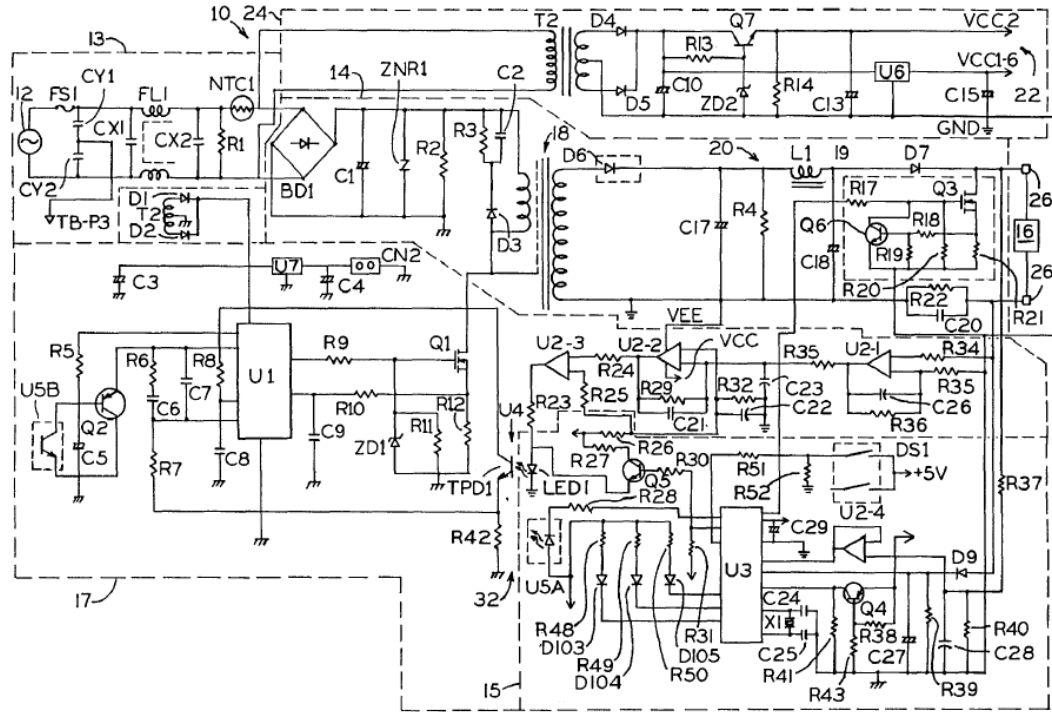


Figure 4.3: Pittman et al.'s patented charging circuit [15].

Pittman et al. were successful at designing an advanced state of the art microprocessor driven charging algorithm minimizing long term negative effects associated with conventional charging techniques.

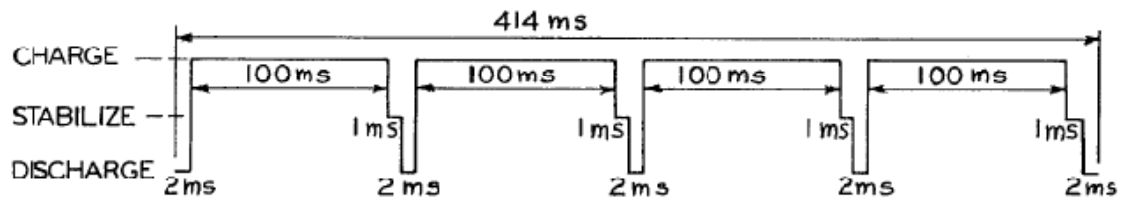


Figure 4.4: Discharge/charge/stabilize periodic waveform used to charge secondary [15].

The charging sequence insists on applying a discharge pulse immediately before the charging pulse in order to minimize the internal impedance of the rechargeable battery and therefore efficiently utilize a lower recharge voltage leading to lower energy wasted in heat and better charge acceptance.

Different charging “profiles” are applied to different battery chemistries in order to optimally recharge them. However, the charging profiles are based on timing data experimentally determined which might not do justice to batteries with different capacities. Furthermore, the fact that the discharge/charge/rest sequence is predetermined affirms that the charging algorithm is not constantly polling the rechargeable battery on hand to optimize the charging based on its internal chemistry. State of charge determination and temperature monitoring of the battery being recharged are referred to as “features” in this patent. In reality these parameters should be constantly polled to provide crucial feedback to the microcontroller in order for it to adjust and modify the charging waveform on the fly.

4.5 Rapid Charging of a Battery by Applying Alternating Pulsed Large Current without a High Temperature

In 2000, inventor James Chin-Ming Chen driven by the belief that there is a need for “simple” and “practical” rapid battery charging that that does not rely on high precision and expensive measuring circuitry so that rapid battery charging can be achieved on a daily basis at a low cost, conceived a charging method to satisfy that need [16]. Chen’s charging method is a simple application of a pulse charging technique to achieve a fast battery charge while avoiding battery overheating and potential overcharge. Chen’s charge current diagram is shown in Figure 4.5. It is important to note that Chen’s

charging method however, is to be applied on nickel-cadmium and nickel-metal-hydride secondary batteries exclusively.

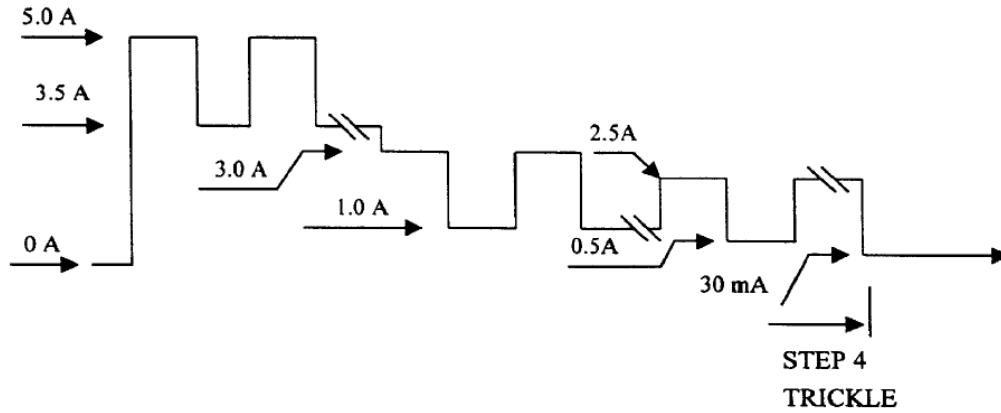


Figure 4.5: Chen's charge current diagram [16]

No apparatus has been developed along with Chen's patent to demonstrate how to carry out the charging concept properly. Moreover, while the disclosed patented charging technique is indeed simple and practical it does not do much to minimize several eventual negative effects such as dendrites growth, large metallic crystal formation, increased internal resistance and reduced battery lifetime. Moreover, Chen's charging technique is not universal and does not account for all battery types. Another associated concern with Chen's charging method is the end-user's safety. Temperature, over current and gas detection sensors are not mentioned in the design. No feedback is reported by these sensors to a central processing unit to interrupt the charge should an anomaly be detected.

4.6 Battery State of Charge Detector With Rapid Charging Capability and Method

In 2000, Ding et al. driven by the belief that there is a need for an "efficient and rapid" battery charger that should "facilitate optimum performance from a rechargeable battery"

patented an advanced electronic design that polls a rechargeable battery at regular intervals to determine its state of charge [17]. Several factors account for the calculated estimation of the state of charge, namely the battery's temperature, pressure, internal impedance and corresponding phase angle. Once the state of charge is calculated then the battery gets recharged according to a preset pulse charging pattern, consisting of positive pulses, negative pulses, or a combination of both, recorded on a lookup table specifically for the contemporary determined state of charge value. The block diagram of Ding et al.'s patented invention is shown in Figure 4.6.

While the Ding et al.'s patented invention follows a correct logic, the implementation of a corresponding apparatus can be quite daunting. For example, and in order for the charger to be universal, an exhaustive list of secondary batteries of all types, sizes and ratings need to be pretested in a lab to determine an accurate and ever increasing look-up table. it is important to notice that different lookup tables per rechargeable battery need to be established at different operating conditions, such as different room temperatures and different room pressures which will exponentially increase the total number of lookup tables to be predetermined in the first place.

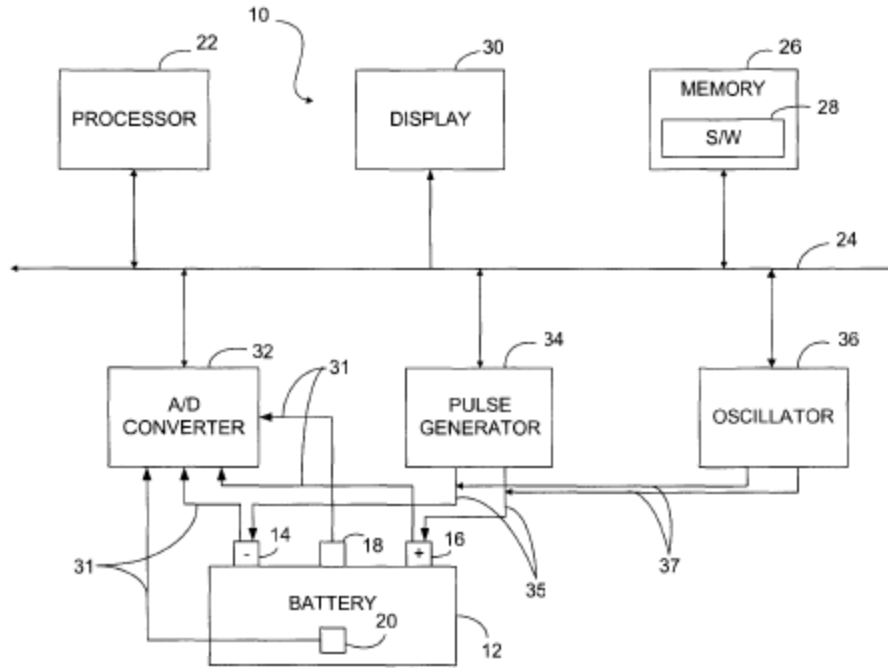


Figure 4.6: Block diagram of Ding et al.'s patented invention [17].

Moreover, in order to determine the battery's internal impedance and electrochemical overvoltage, Ding et al. refer to employing approximation techniques that might not be accurate. Electrochemical Impedance Spectroscopy (EIS) in general, a method aimed at measuring the internal impedance of a device by sending an alternating current and measuring its response at different frequencies relies on three different variables, namely temperature, state of charge and DC-current which are not elaborated in this paper.

Ding et al.'s patented invention seems easier said than done. While the logic that the invention relies on is theoretically solid, concretizing such an invention is no easy task, and by no means did Ding et al. pin down all the problems that will arise from concretizing such a charger.

4.7 Rapid Battery Charging Method and Apparatus

In 2002, Vladimir Petrovic, fueled by the belief that there is a specific need for rapid battery chargers that can quickly recharge lead-acid batteries without reducing their service life patented an invention capable of recharging lead-acid batteries in under two hours [18]. A block diagram of Vladimir Petrovic's invention is shown in Figure 4.7.

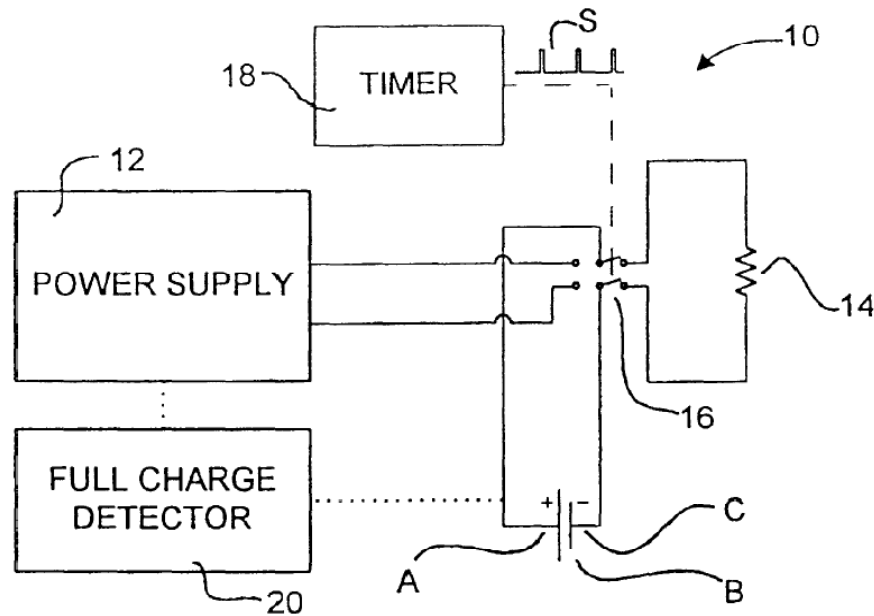


Figure 4.7: Block diagram of Vladimir Petrovic's patented invention [18].

The disclosed charging method is a special case of pulse charging techniques. A periodic charge/rest/discharge/rest charging waveform is applied for two hours until the battery (hopefully) reaches its full charge. Vladimir Petrovic clearly states that his invention relies on the described specific charging waveform because he found that this charging cycle has “unexpectedly beneficial effects in that, in comparison to standard

charging cycles, it reduces the time taken to bring a battery to full charge and increases the total charge that can be delivered to the battery.”

The benefits of pulse charging techniques were common knowledge in 2002. While functional, Vladimir Petrovic’s patented design seemed passé before it was even conceived. The fact that the end-user has to perform manual calculations and manually adjust different potentiometers instead of relying on precise microcontrollers makes the entire design error prone and user dependent. Furthermore, the entire idea of discharging a battery through a power resistor until it reaches a reference voltage before recharging it sounds inefficient and wasteful. Moreover, Vladimir Petrovic failed to mention that different batteries would need different power resistor combinations in order to maintain a constant safe discharge value since no temperature, gas generation or over-current sensors are part of his patented design.

CHAPTER 5

SECONDARY BATTERY MODELING TECHNIQUES

5.1 Electrical Battery Model for Use in Dynamic Electric Vehicle Simulations

Kroeze et al.'s paper focuses on developing an electrical battery model for use in dynamic electric vehicle simulations [19]. The main requirements of the battery model are its capability to simulate at any given time the actual state of charge, I-V characteristics and dynamic behavior of a lead-acid, lithium-ion or nickel-metal-hydride battery. Kroeze et al.'s proposed battery model is shown in Figure 5.1

Researching readily available electrochemical, mathematical and electrical models of lead-acid, lithium-ion and nickel-metal-hydride batteries, Kroeze et al. decided to leave behind electrochemical models due to their lack of parameters and mathematical models due to their inaccuracy and lack of relation between model parameters and I-V characteristics. Therefore, Kroeze et al. opted for a combination of well known electrical models, mainly the Thevenin model and the Runtime-based electrical model in order to take advantage of their respective positive attributes. This combination resulted in a model capable of predicting the state of charge, terminal voltage and power losses of lead-acid, lithium-ion and nickel-metal-hydride batteries.

Nevertheless, in order to simulate a specific rechargeable battery, one must first collect a large set of data using an apparatus consisting of data loggers, an electronic load, a power supply, special computer capture software and other equipment. The data collected undergoes a time consuming analysis that calculates and interpolates values that are finally tabulated for future use.

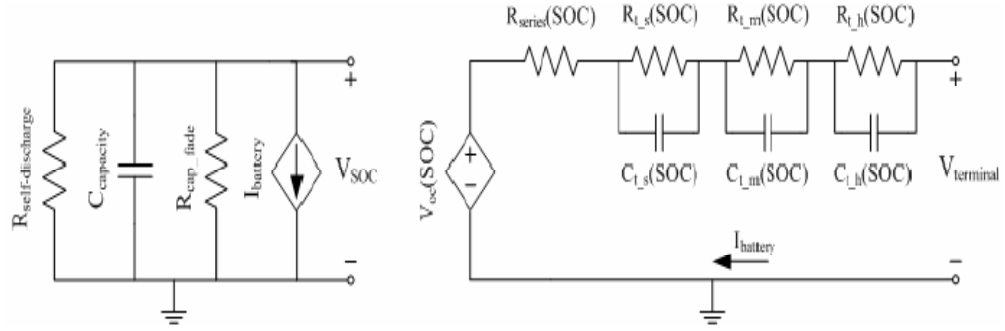


Figure 5.1: Proposed electrical battery model [19].

The aforementioned look-up table is then used by a modeling program to determine open circuit voltages at specific states of charge of the battery being simulated. Kroeze et al. managed to conceive a battery model that successfully simulates a lead-acid, lithium-ion or nickel-metal-hydrate battery within their needs. Nevertheless, the model still lacks accounting for variations in ambient temperature, the battery's self-discharge and its cycling degradation which could substantially alter the final result.

5.2 An Enhanced Dynamic Battery Model of Lead-acid Batteries using Manufacturers' Data

Medora et al.'s paper covers an enhanced dynamic battery model of lead-acid battery, namely the Yuasa DM55-12, 12V, 57-Ah, using the manufacturer's data sheet parameters and some selected handbook curves [20]. The model is then used in conjunction with a Pulse Width Modulator (PWM) model and a DC motor model to simulate a transportation system and to analyze the effect of adding ultra-capacitors to minimize the battery's current peak requirements. Medora et al.'s dynamic battery model with charge/discharge characteristics is shown in Figure 5.2. Medora et al.'s main objective is to derive a "not too complex" battery model capable of simulating a Yuasa

DM55-12, 12V, 57-Ah lead-acid battery's terminal voltage and internal resistance in function of the battery's state of charge and internal capacity at any given time. In order to successfully develop their model, Medora et al. relied on the Yuasa DM55-12, 12V, 57-Ah lead-acid battery's manufacturer data sheet along with a combination of "algebraic equations" that define the battery's capacity as a function of discharge current, the discharge voltage and the battery's internal resistance as a function of state of charge and finally variable multipliers for adjusting model parameters at increasing discharge current.

While Medora et al. might have been able to maneuver a quite specific lead-acid battery model to meet their simulation needs they avoided to deal with real constraints such as battery aging and battery temperature effects that could substantially alter the battery's model behavior during simulation. Moreover, by avoiding to detail the process of embedding the manufacturer's data into the simulation model as well as properly deriving the algebraic equations to come up with a correct model, Medora et al. do not give the audience a chance to build upon their work to come out with their own specific simulation models.

Last but not least, the mandatory use of Analog Behavioral Modeling (ABM) techniques to simulate the rechargeable battery which results in relatively shorter simulation times and less accurate results does not offer the audience a choice of selecting accuracy versus speed.

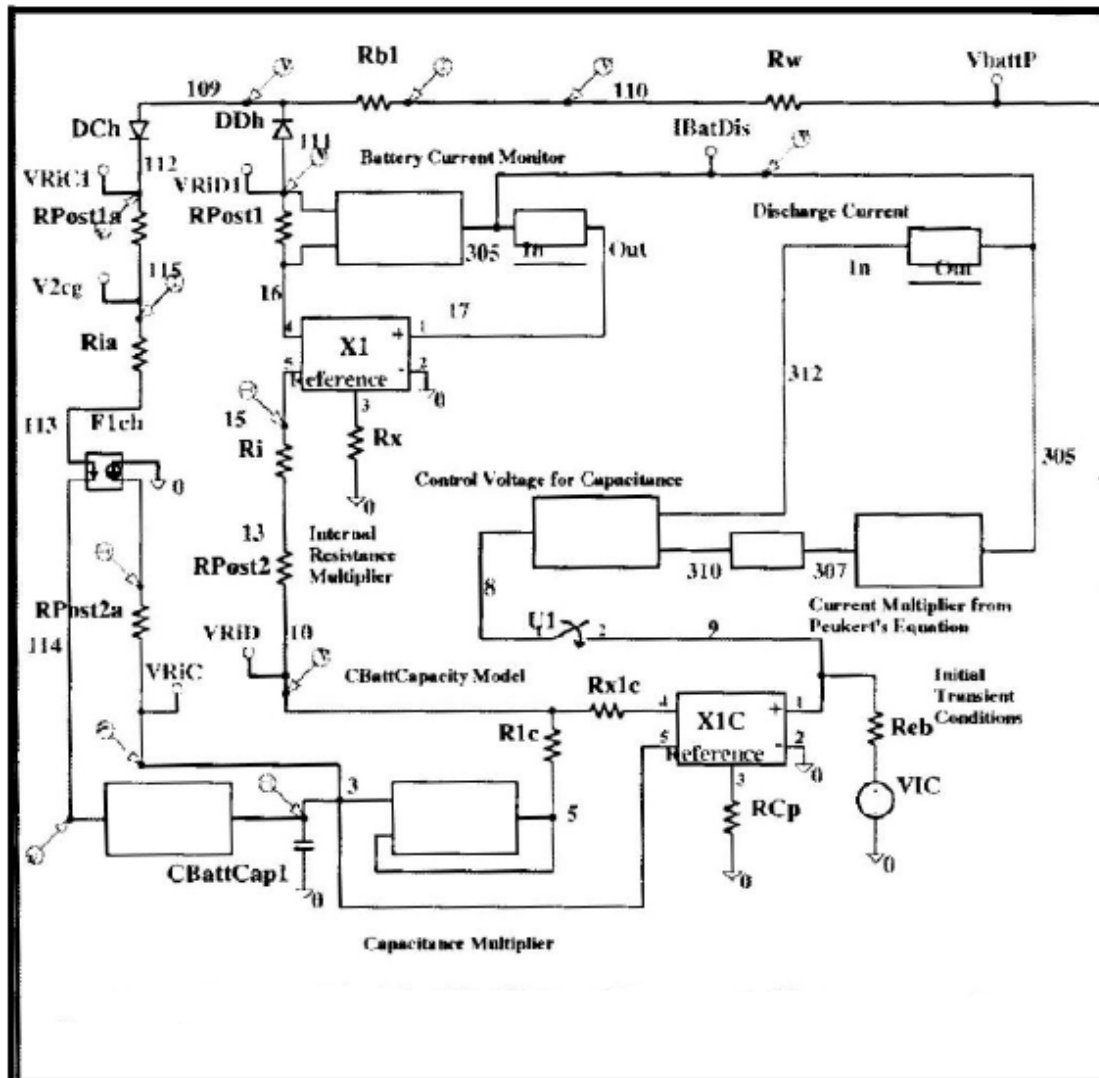


Figure 5.2: Medora et al.’s battery model with charge/discharge characteristics [20].

5.3 Design of Interface Circuits with Electrical Battery Models

Kim et al.'s paper presents three different types of lead--acid battery models, namely the ideal battery model, the linear battery model and the Thevenin battery model shown in Figure 5.3, to be simulated in conjunction with converters and motors models [21]. Kim et al realize that in order to obtain valid simulation results, they need to account for the battery's internal characteristics. The first battery model discussed is the ideal model, represented by a single ideal voltage source. While very simple, this model does not

account for the internal characteristics of a lead-acid battery. The second battery model discussed is the linear model, represented by a single ideal voltage source in series with an “internal” resistance. The voltage of the ideal source and the internal resistance are then represented mathematically as a function of the state of discharge and numerical constants to be determined by experiments. The third battery model discussed is the Thevenin model, represented by a single ideal voltage source, an “internal” resistance and an overvoltage compensator. The latter is, in turn, represented by a parallel combination of a resistance and a capacitor.

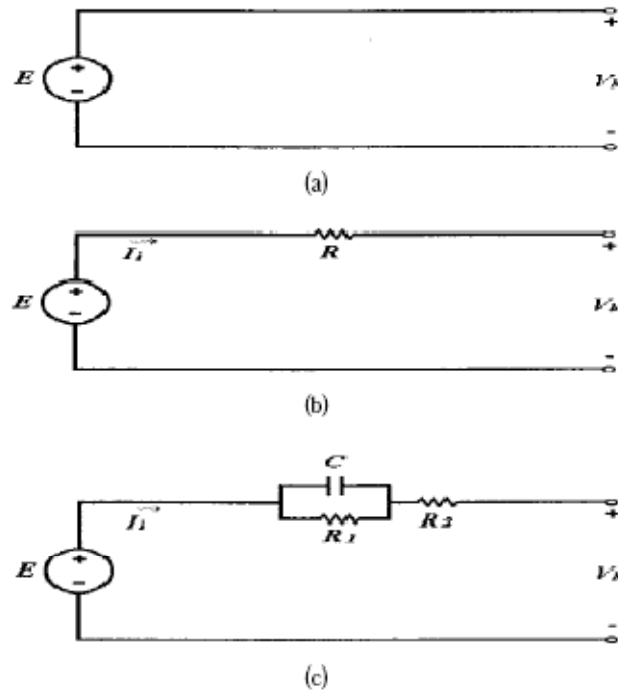


Figure 5.3: Kim et al.'s electrical battery models. (a) Ideal model. (b) Linear model. (c) [21].

A system consisting of batteries, inverters and loads is then analyzed using mathematical analysis and computer simulations for each battery model. The simulated

results confirm that using a Thevenin model of the lead-acid battery (that accounts for the battery's internal characteristics) will provide the most accurate results while designing a condenser filter. However, using the less complicated linear model will still generate acceptable results. It is no secret that accounting for a battery's internal characteristics during simulation will provide results closer to reality. The models presented however account for so little of a real lead-acid battery's internal characteristics that they should only be used in certain specific situations such as the one used in Kim et al.'s paper's scenario.

5.4 A Battery Model Including Hysteresis for State-Of-Charge Estimation in Ni-Mh Battery

Xuyun et al.'s paper presents a powerful nickel-metal-hydride battery model suitable for various simulation-based designs [22]. The model accounts for the hysteresis phenomenon that directly affects the state of charge determination of the battery in question. Xuyun et al.'s equivalent circuit model for the Ni-MH battery is shown in Figure 5.4. Electrochemical Impedance Spectroscopy (EIS) is first used to determine the impedance spectra of a nickel-metal-hydride battery. A basic equivalent circuit of the nickel-metal-hydride battery is then determined.

Open circuit values of an nickel-metal-hydride battery were then measured under different States of charge for a charging battery and then for a discharging battery. An updated equivalent circuit model based on the electrochemical impedance spectroscopy results and the hysteresis measured results is then presented. Calling on external references, state space equations for the specific nickel-metal-hydride model are then derived and the Kalman Filter method is applied to better estimate the state of charge.

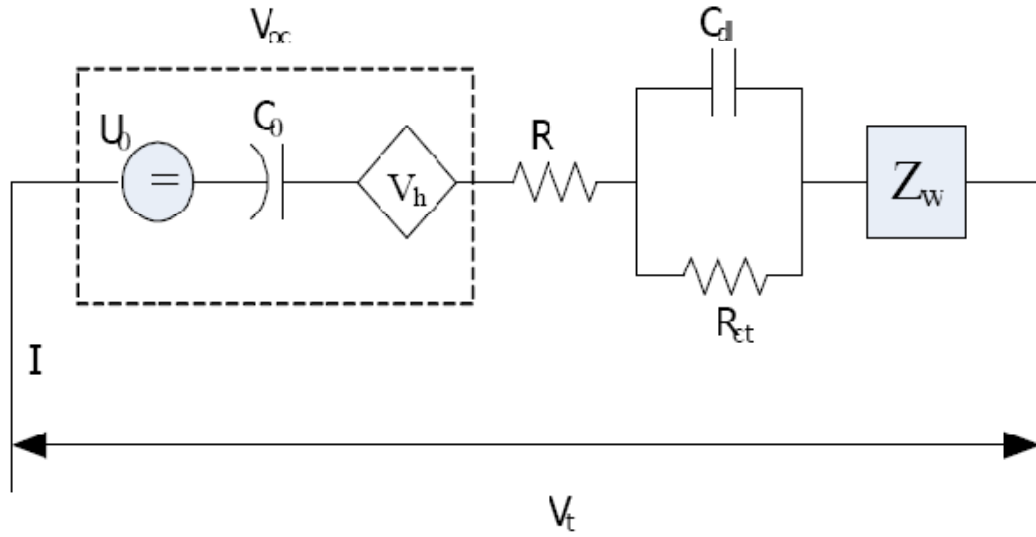


Figure 5.4: Xuyun et al.'s equivalent circuit model for the Ni-MH battery [22].

Last but not least, the model's simulated results are compared to an evaluation model and are shown to come very close to each other. It is important to note that the nickel-metal-hydride model derived herein is based on a large number of assumptions. First and foremost, electrochemical impedance spectroscopy relies on three different variables, namely temperature, state of charge and DC-current. Xuyun et al.'s results used to derive the first equivalent circuit of the model are based on one specific scenario where the temperature is constant and no dc-current is applied. Therefore, two out of the three variables necessary to yield to accurate results while using electrochemical impedance spectroscopy have been ignored. Furthermore, the hysteresis phenomenon data used to derive the second equivalent circuit of the model are based on one specific nickel-metal-hydride battery constituted of five single cells in series. Next, Xuyun et al. clearly specify that an inductive element for the equivalent circuit has been omitted since "nickel-metal-hydride batteries are less used at so high frequency". Further investigation of an omitted

“non-linear resistor” is also needed. While a functional nickel-metal-hydride battery model is presented in this paper, it can only be used in very specific situations to estimate the state of charge under specific conditions limited by the assumptions made to develop the model. In particular, effects of temperature, aging and charging/discharging methods used are not accounted for.

CHAPTER 6

CONCLUSION AND FUTURE DIRECTIONS

6.1 As it Relates to Fast Charging Techniques

Several fast charging techniques were reviewed in this paper, the most advanced and efficient one being the state of the art charging technique. Nevertheless, less advantageous charging techniques are still being widely used on a daily basis due to their easy implementation and low design cost. These less advantageous charging techniques burn more power per charge and shorten the service life of the battery being charged. They are in a way detrimental to the battery being recharged.

If they must coexist, less advantageous inexpensive charging techniques and corresponding chargers should at least be mandated to improve their energy conversion mechanism in terms of efficiency, defined as the ratio of output power over input power. Most electronic appliance wall chargers for instance, are quite inefficient and consume power while in standby. There is a need for a unified standard to enforce such chargers to reduce to a bare minimum their consumption of standby power and to maintain higher conversion efficiencies. Moreover, a large amount of today's battery chargers still discharge rechargeable batteries to a predetermined value before recharging them. The discharge is usually carried out through power resistors that convert all of the energy to wasted heat. Therefore, there is a need for a highly efficient storage mechanism that could potentially store the aforementioned wasted energy for better future use.

Contemporary state of the art battery charging and corresponding chargers however are not perfect either. There is a lot of room for improvement. Today's most advanced chargers still find it challenging to automatically detect the battery's internal chemistry in

order to optimize the charging. With a little more consideration from battery manufacturers or battery distributors, a small scannable tag strategically placed on the rechargeable battery itself could potentially address this issue and provide ample information to the battery charger in order to smartly and efficiently optimize the charge.

Further, we hope to see in the near future a medley of inexpensive yet accurate and low power sensors and microcontrollers embedded into the battery itself. These sensors would provide at any given time the critical internal characteristic of the battery being recharged, such as temperature, gas generation and electrochemical state. All of the data and information collected from the battery would be immediately transferred wirelessly or through a standard exchange protocol to the charger. The latter's central processing unit (CPU) will in turn use the fetched data from the various sensors to calculate on the fly internal parameters of the battery such as state of charge and Depth of Charge and adjust accordingly the charging waveform to deliver the fastest, safest and most efficient charge.

6.2 As It Relates to Battery Modeling for Fast Charging Simulations

Various battery models have been developed to date to mimic the behavior of rechargeable batteries. However, most of these models were conceived to complete specific electric vehicles (EV) and hybrid electric vehicles (HEV) simulations. Therefore, the reviewed models are based on numerous assumptions and do not account for the important effects of temperature, aging, remaining useful life, self discharge and for effects arising from the methods used to charge the battery in the first place, such as memory effect, decreased capacity, increased internal resistance, etc... Therefore, the reviewed models would not be of much help for the scope of this thesis.

The MathWorks, Inc., a leading global provider of software for technical computing and model-based design, creator of the famous Matlab and Simulink suites, recently introduced through their SimPower Systems add-on, a rechargeable battery model capable of simulating the charge and discharge of several different types of popular secondary battery chemistries, namely lead-acid, lithium-Ion, nickel-cadmium and nickel-metal-hydride. The block model and its equivalent block diagram circuit are shown in Figure 6.1. In its simplest form, the battery model is represented by a controlled voltage source that represents the rechargeable battery's open circuit voltage in series with a resistor that represents the internal resistance of the rechargeable battery.

The latter's current feedback, whether under charge or discharge mode of operation, undergoes integration over time, to account for extracted capacity, low pass filtering, to account for low frequency current dynamics and Laplace transform to account for exponential zone dynamics. The aforementioned calculated data then dictates the value of the controlled voltage source.

The parameterized respective discharge functions of the different rechargeable battery chemistries are tabulated in Table 6.1. Moreover, the parameterized respective charge functions of the different rechargeable battery chemistries are tabulated in Table 6.2. Finally a brief description of each parameter is tabulated in Table 6.3.

While being one of the most advanced rechargeable battery model to date, SimPower Systems' model exhibits some serious drawbacks. For one, the model doesn't account for memory effects, self-discharge effects, aging effects and previous charge/discharge history in order to derive remaining useful life. Moreover, the internal resistance of the battery is considered constant during the charge and the discharge cycles and doesn't vary

with the amplitude of the current. Furthermore, the capacity of the battery doesn't change with the amplitude of current. However, in 1897 German scientist W. Peukert presented a law stating that the capacity of a lead-acid battery varied with the rate at which the battery was being discharged.

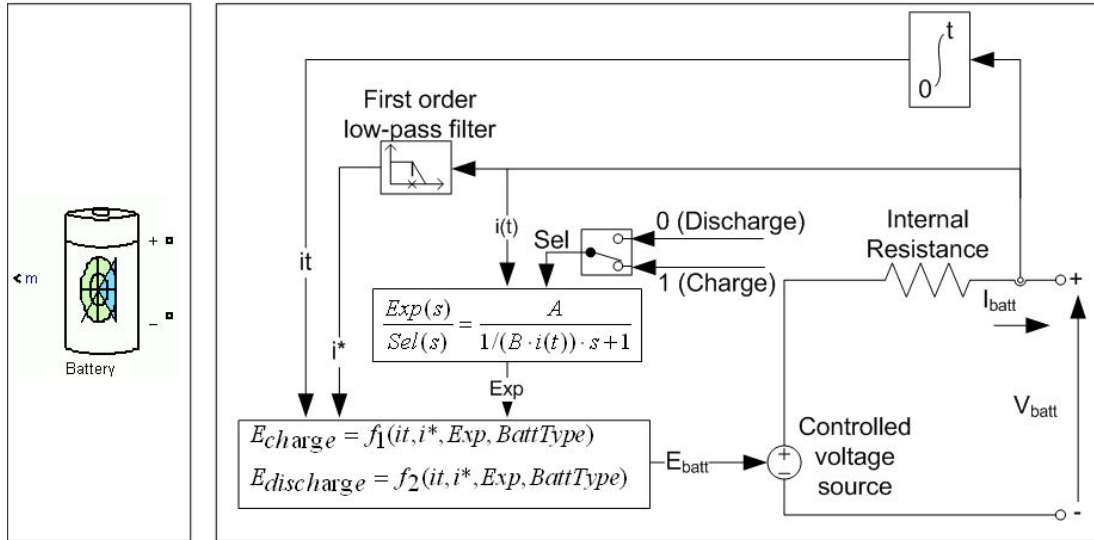


Figure 6.1: SimPower Systems' library battery block (Left) and equivalent circuit (Right).

[23]

Peukert demonstrated that as the rate of discharge increased, the battery's available capacity decreased. Therefore the battery model does not account for the Peukert effect. Last but not least, the presented model doesn't take into account the battery's internal cells temperature.

Table 6.1: Parameterized respective discharge functions of different rechargeable battery chemistries [23].

CHEMISTRY	DISCHARGE MODEL ($i^* > 0$)
Lead-acid	$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right)$
Lithium-ion	$f_1(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$
Nickel-cadmium	$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right)$
Nickel-metal-hydride	$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right)$

Table 6.2: Parameterized respective charge functions of different rechargeable battery chemistries [23].

CHEMISTRY	CHARGE MODEL ($i^* < 0$)
Lead-acid	$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right)$
Lithium-ion	$f_2(it, i^*, i) = E_0 - K \cdot \frac{Q}{it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$
Nickel-cadmium	$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{ it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right)$
Nickel-metal-hydride	$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{ it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right)$

Table 6.3: Brief description of the functions' parameters [23].

PARAMETER	DESCRIPTION	UNITS
E_{Batt}	Nonlinear Voltage	Volts (V)
E_0	Constant Voltage	Volts (V)
Exp(s)	Exponential Zone Dynamics	Volts (V)
SeI(s)	Represents the Battery Mode of Operation (1 for charge, 0 for discharge)	N/A
K	Polarization Constant or Polarization Resistance	Ampere per hour(Ah^{-1}) or Ohms (Ω)
i^*	Low Frequency Current Dynamics	Amps (A)
i	Battery Current	Amps (A)
it	Extracted Capacity	Ampere Hour (Ah)
Q	Maximum Battery Capacity	Ampere Hour (Ah)
A	Exponential Voltage	Volts (V)
B	Exponential Capacity	Per Ampere Hour (Ah) ⁻¹

Not taking temperature into account can be quite dangerous, especially as it relates to fast charging techniques. As frequently emphasized in this thesis, the process of fast charging relies on running a large current into the battery to reduce charge time. Depending on the method of delivery, a high current can engender a high temperature increase. If not dissipated properly, the heat generated could permanently damage the rechargeable battery. Understanding heating effects in batteries is of primordial importance in order to account for it. There are four main types of heating effects that

occur within a battery. The first one is referred to as “Ohmic heating effects” due to Joule heating effects related to operating current and the electrical internal resistance and external contacts resistance of the battery itself.

The Ohmic heating value expressed in calories can be determined by using the following equation: $J = \frac{I_{Total}^2 \times R_{Total} \times seconds}{4.1833}$ where I_{Total}^2 represents the squared value of the current flowing through or from the battery, R_{Total} represents the combined resistance of the battery’s internal impedance and the battery’s contact terminals, and seconds is the duration in seconds. Note that the Ohmic heating value “J” is expressed in calories (Cal).

The second heating effect is known as the “chemical heating effect” due to the heat generated or absorbed by the chemical reaction. Lead-acid batteries engender an exothermic reaction during discharge. However while charging at low current, Lead-acid batteries tend to absorb heat through their endothermic reaction. The “chemical heating effect” is identified with the content change of the reaction, denoted by “ ΔH ” which is given by the following equation: $\Delta H = \frac{-nF}{4.1833} \left[E - T \left(\frac{dE}{dT} \right)_p \right] = \frac{-3600C}{4.1833} \left[E - T \left(\frac{dE}{dT} \right)_p \right]$ where ΔH is the heat change accompanying the cell reaction, n is the number of equivalents of chemical reaction, F is one Faraday or 96,500 Coulombs, E is the electromotive force the cell, T is the temperature in Kelvin, $\left(\frac{dE}{dT} \right)_p$ is the temperature coefficient of the electromotive force at constant pressure and C is the capacity of the battery in Ampere-Hours. The content change of the reaction ΔH , is expressed in Calories (Cal).

The third heating effect encompasses to localized heating effects due to the tracking of current along the low-conductivity paths on the top of the battery. Finally the fourth

heating effect represents the chemical heating effect due to the dissociation of water to hydrogen and oxygen towards the end of the charge. This type of effect applies only to certain batteries, such as Lead-acid batteries, and occurs to an appreciable extent only when batteries are getting overcharged.

With a better understanding of heating effects associated with recharging or discharging a secondary battery an educated user can tackle battery modeling and simulation differently. For instance, a simulation of a lead-acid battery discharging at different rates through a random load is performed. For simulation purposes, the model is assumed to be a lead-acid battery with the respective parameters tabulated in Table 6.4. The simulated discharge curves of the aforementioned model for different discharging rates namely, 50 (A), 100 (A), 150 (A), 200 (A), 400 (A) and 800 (A) are shown in Figure 6.2. More importantly the simulation over a sixty seconds period of the battery being discharged through a random load is shown in Figure 6.3 which is divided into three scope captures. The first scope capture shows the state of charge in yellow of the lead-acid battery decreasing over time from 100% to about 84%.

The second scope capture represents the lead-acid battery's voltage in blue decreasing over time from about 12.5 (V) to about 8.5 (V). Last but not least, the third scope capture depicts the lead-acid battery's discharging current in magenta over time ranging from about 50 (A) up to 690 (A). With the aforementioned data readily available from the simulation software, the Ohmic heating "J" and the content change of the reaction, " ΔH " can be calculated.

Table 6.4: Simulated lead-acid battery model parameters

PARAMETER DESCRIPTION	VALUE	UNITS
Nominal Voltage	12	Volts (V)
Rated Capacity	30	Ampere Hour (Ah)
Initial State of Charge (SOC)	100	Percentage (%)
Maximum Capacity	31.25	Ampere Hour (Ah)
Fully Charged Voltage	13.0658	Volts (V)
Nominal Discharge Current	6	Amps (A)
Internal Resistance	0.004	Ohms (Ω)
Capacity at Nominal Voltage	9.3083	Ampere Hour (Ah)
Exponential Zone Voltage	12.2171	Volts (V)
Exponential Zone Capacity	0.1	Ampere Hour (Ah)

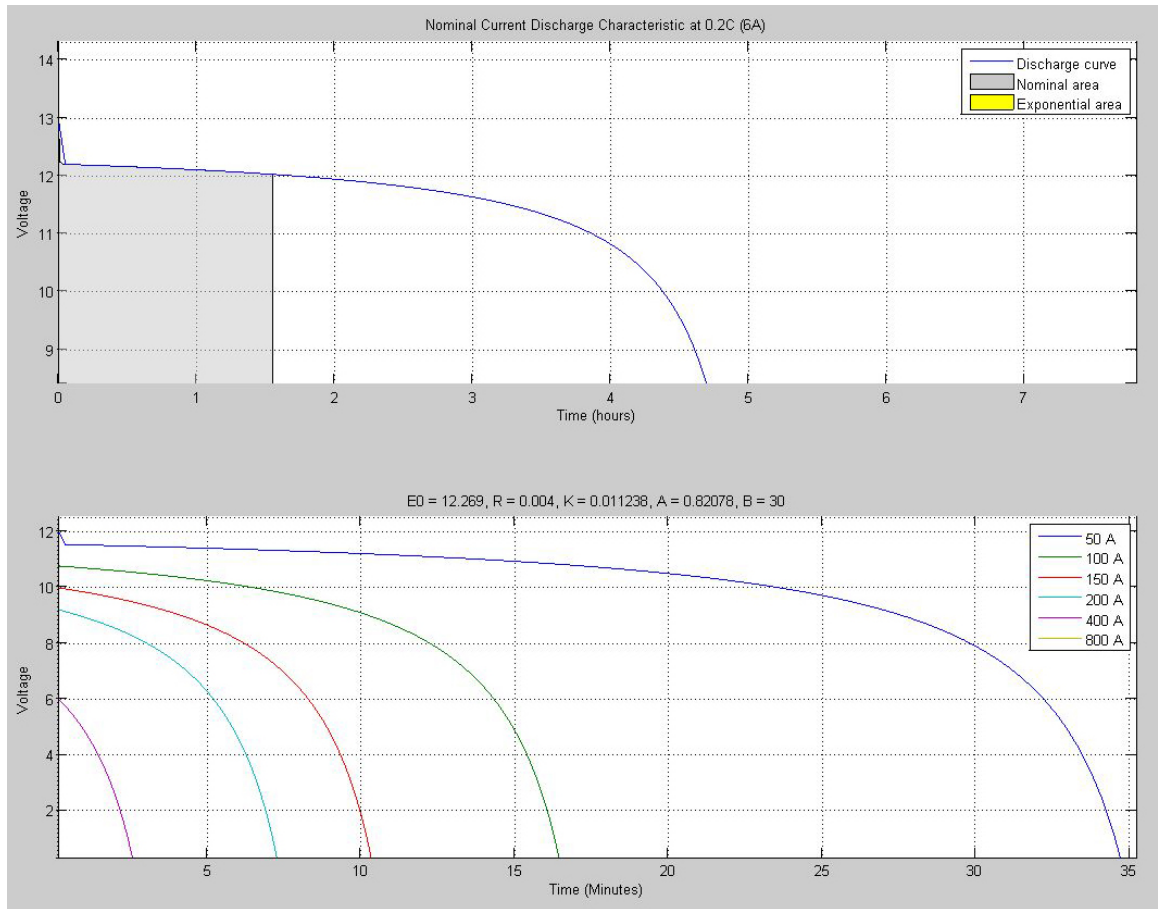


Figure 6.2: Simulated discharge curves of the modeled Lead-acid Battery at different discharge rates.

In order to calculate the Ohmic heating " J " versus time, raw data was exported to excel. The data was then manipulated and resulted in Figure 6.4 that displays the Ohmic heating versus time. Similarly, the chemical heating effect " ΔH " versus time is illustrated in Figure 6.5. Finally the combined heating effects " $J+\Delta H$ " versus time is displayed in Figure 6.6.

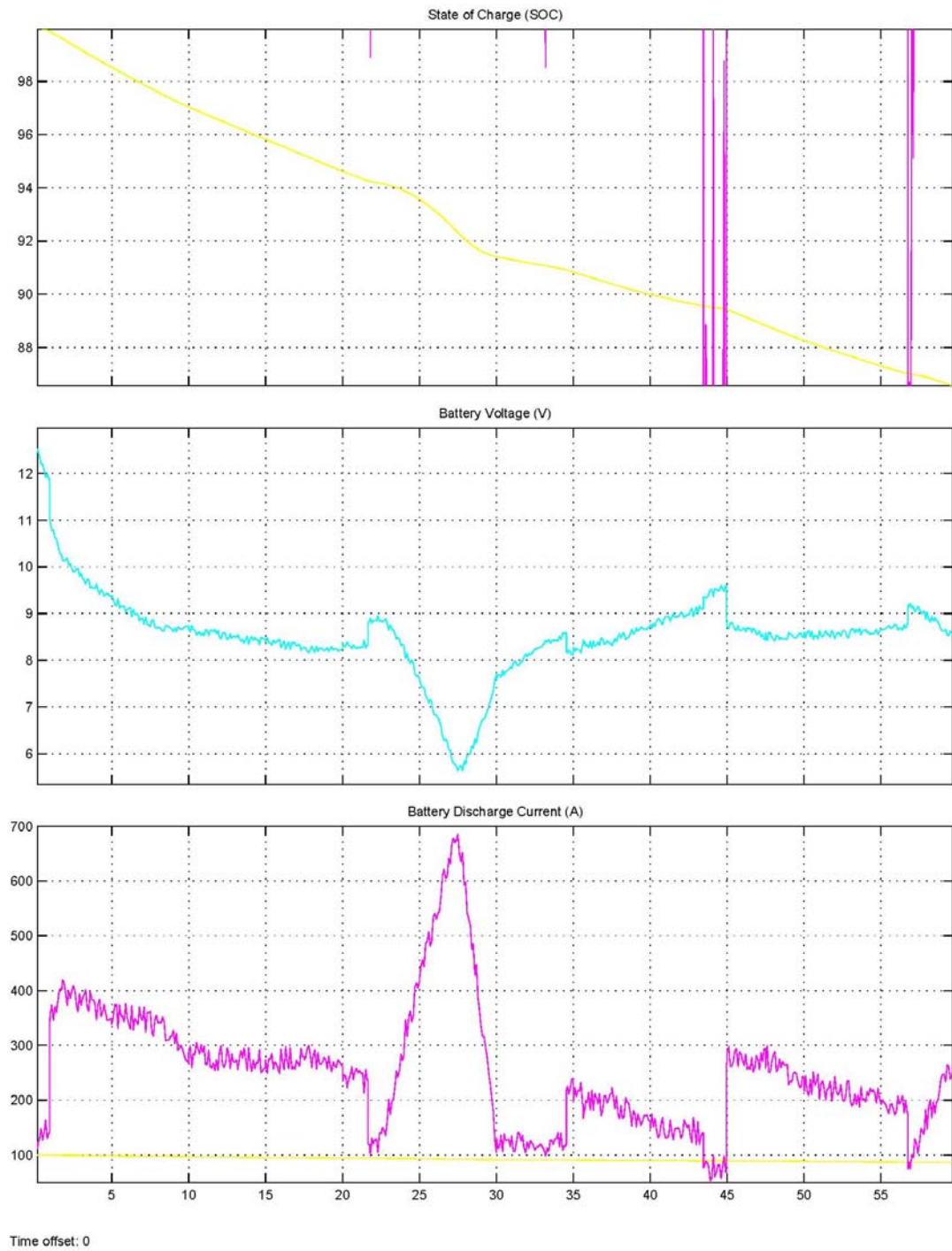


Figure 6.3: Simulation results of the lead-acid battery being discharged.

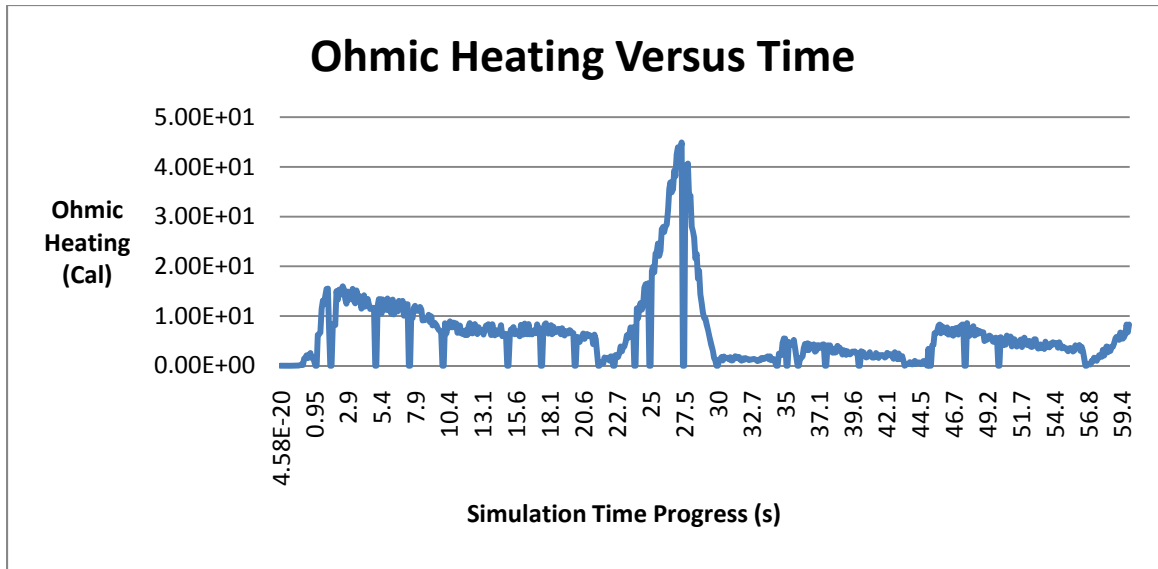


Figure 6.4: Ohmic heating versus time.

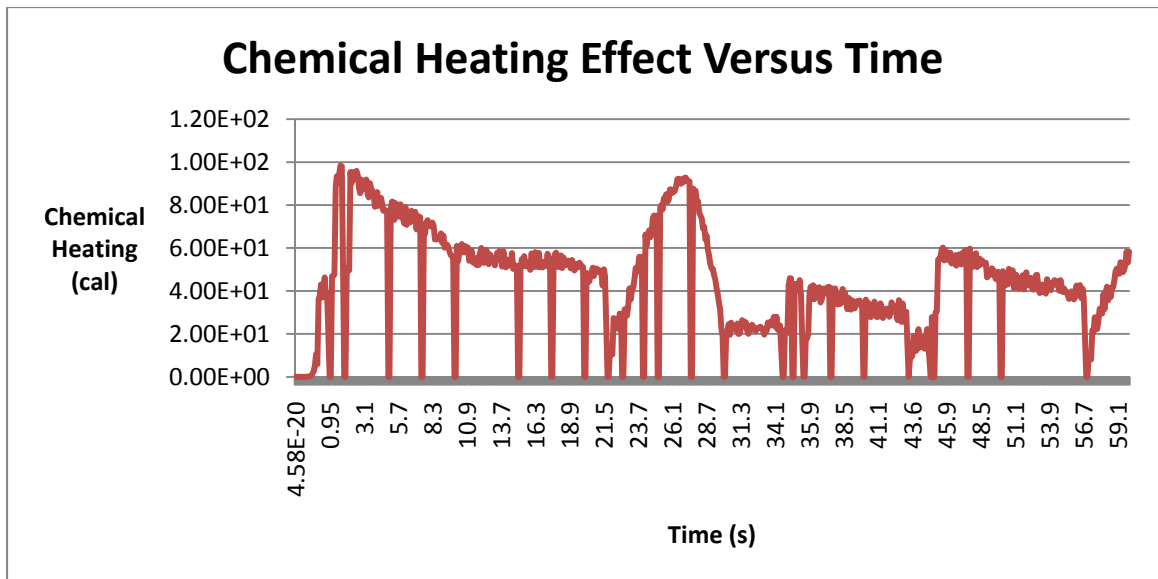


Figure 6.5: Chemical heating effect versus time.

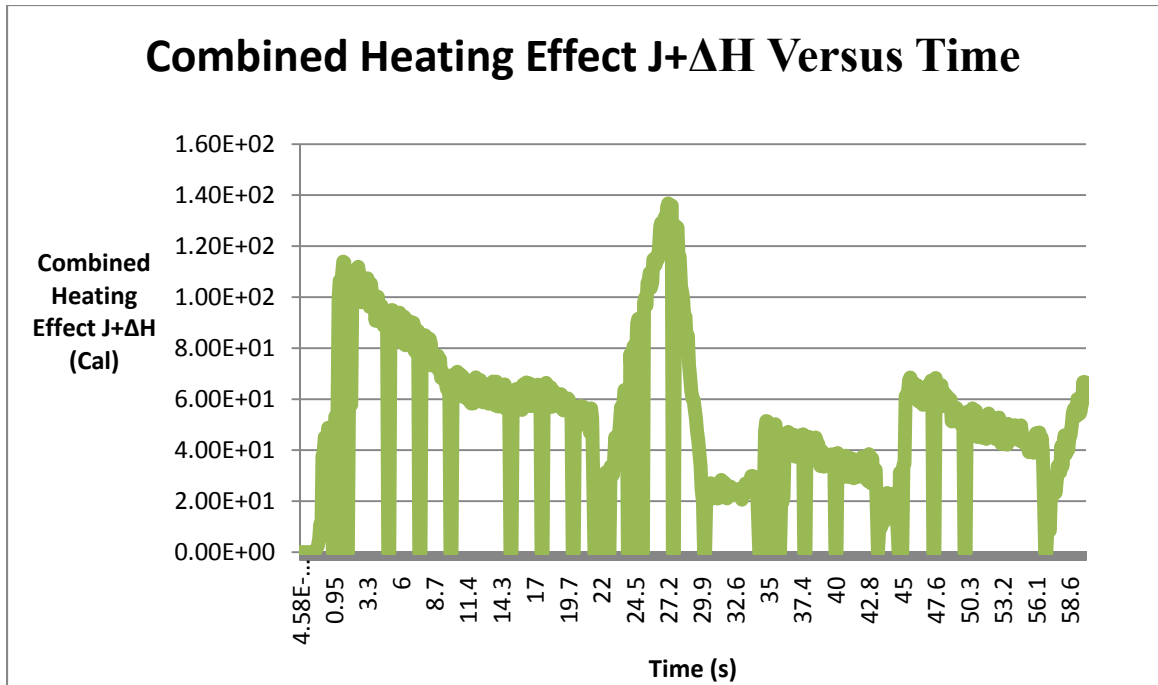


Figure 6.6: Combined heating effect versus time.

Judging by the magnitude of the discharge current of the simulated battery model we can only expect a dangerously high combined heating effect. In fact, the numbers second our expectations since the Ohmic heating was equal to 4,437.5 calories/minute (equivalent to 309.65 Watts), The chemical heating effect was equal to 30,223.05 calories/minute (equivalent to 2,108.96 Watts) and the combined heating effect was equal to 34,660.5 calories/minute (equivalent to 2,418.61 Watts). Consequently, these simulated numbers would actually mean that the model under test would have been damaged by heat generation.

Therefore, as previously mentioned, better understanding of heating effects associated with recharging or discharging a secondary batteries will allow educated users to tackle battery modeling and simulation differently. In fact future work will include developing a model that goes hand in hand with the rechargeable battery model that will account for, at

the minimum, the combined heating effects aforementioned. The developed model will alert the user when heating effects could start to become problematic and will automatically deem the simulation inaccurate.

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