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Fast Charging Technique For Lithium-Ion Cell

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FAST CHARGING TECHNIQUE FOR LITHIUM-ION CELL

By

Shabaz Khan
Bachelor of Science in Electrical and Electronic Engineering, Khulna University of Engineering and Technology, 2015

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Grand Forks, North Dakota

December
2019

This thesis, submitted by Shabaz Khan in partial fulfillment of the requirements for the Degree of Master of Science in Energy Systems Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dean of the School of Graduate Studies

11/26/19

Date

PERMISSION

Title	Fast Charging Technique for Lithium-Ion Cell
Department	Energy Systems Engineering
Degree	Master of Science

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Shabaz Khan

November 25, 2019

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To almighty ALLAH, my Parents, my Brother and my Advisor,

The one Divine, The others Divinely Appointed.

You left fingerprints of grace on my life,

You shan’t be forgotten.

ABSTRACT

Climate change is a big concern among the people. Day by day people are trying to increase the use of the sustainable energy in every sector of their life. Like other sectors, transportation sector manufacturers are beginning to shifting from fossil fuels based models to electric models. Manufacturers are trying to introduce electrified models from bicycles to cars. For energy storage, these electrified models are highly dependent on the battery. Lithium-ion cells have a high energy density, no memory effect, long cycle life and low self discharge quality, and are therefor highly used from portable electronics to electric vehicles everywhere. A main concern with a rechargeable battery is that it needs to recharge in regular intervals. This charging procedure is time consuming and can have a great impact on the total capacity of the battery, cycle life, and charging efficiency (or energy efficiency). A gasoline-base vehicle takes 3-5 minutes to fill the gas tank, but, an electric vehicle may need up to 10-12 hours (depend on the battery pack capacity) to be fully charged. For that, electric vehicles can become unreliable under emergency conditions and a deterent to regular users. As a result, charging technology has become a major concern among the manufacturers of electric vehicles. Using fast charging techniques can create unwanted side effects, like, thermal runaway, capacity fade, lithium platting and other electrochemical changes. In this thesis we developed an optimal fast charging technique for lithium-ion cells, which will be able to charge the cell faster compared with present industrial charging methods and maintain the long cycle life without significant decay of the capcity. We used 18650 lithium-ion cells for testing. During testing continuous cycling test was stopped when the capacity degraded by 20% of it's original capacity. We compared our proposed fast charging technique with an available industrial charging technique. Due to differences in the charging times, when our proposed fast charging technique goes through more than 1600 cycles, the industrial charging technique had completed only 660 cycles. For comparision purposes, we chose 600 cycles as the common comparision point. We had found that our proposed technique took an average 63.7 minutes to charge 100% of the cell after 600th cycle. At the same time, the industrial charging technique took an average of 150 minutes to charge 100% of the cell. From this comparision it was clear the our proposed method is 135% faster than the available industrial charging technique. Capacity degradation was 10.5% for the fast charging technique and 6.6% for the industrial charging. As a result, we can say our proposed fast charging technique is faster and capabale of maintaining the capacity degradation rate within reasonable limits.

CHAPTER ONE: INTRODUCTION

United States Energy Information Administration (EIA) anticipated that the world energy consumption would grow by 56% between 2010 to 2040 [1]. This high demand for energy highly depends on fossil fuels. EIA projected that, till 2040, fossil fuels would continue to fulfill this demand by nearly 80%. Energy economy depends on fossil fuels, but this dependency is creating a lot of issues in our environment. Our climate is changing very fast. The changing rate of climate is faster than any other time of civilization history. Climate doesn’t change in a day. A long term dysfunction in the environment system creates this climate change, with long term fossil fuels burning being the primary catalyst. It is now universally known that gaseous emissions from the burning fossil fuels are not only polluting the air but also creating global warming. Among six different greenhouse gases, three gases, carbon dioxide, methane, and nitrous oxide, are the primary concern [2]. From these three, two come from burning fossil fuels. The main danger lies in carbon dioxide [2]. Today’s environment contains 42 percent more carbon dioxide than it did in the industrial era [3]. In the United States, energy-related carbon dioxide emissions will reach 5019 million metric tons in 2050. If the use of fossil fuels continues, it will increase the carbon dioxide in the environment, and at the same time, the resource of fuels will decrease quickly.

For this reason, renewable energy is gaining popularity among the people. People are trying to use all clean energy sources to fulfill their energy demand. Wind, solar and tidal power are some valuable renewable energy resources. We can see that by 2050, 35% of energy demand will be obtained by wind energy [4]. People are also trying to increase the use of solar and other clean sources as much as possible. The main issue with clean energy is that it is irregular and this characteristic raises the importance of energy storage media to supply power when the demand is peak and necessary. This necessity increases the value of the electrochemical system. The battery is such an electrochemical system that can efficiently store energy and deliver when needed. Recently rechargeable batteries are the main point of attraction for the portable system, e.g., the transportation sector. If we look at carbon dioxide emission sources in the United States, we can see a large portion of carbon dioxide produced from transportation sources, primary from burning fossil fuels [3]. Power plants are another major source of carbon dioxide emission. For that, nowadays, not only the portable, but also stationary applications such as stand-alone power plants and transportation sectors are becoming depended on these rechargeable batteries. As mentioned before, the transportation sector is the main culprit for carbon dioxide emission; as a result, over the last few years, new electric and hybrid vehicles have gained immense popularity among people.

As a result, the demand for rechargeable batteries has become very high. Lithium batteries have high power and energy density, broad operating temperature range, long cycle life, no memory effect, and low self-discharge rate [5]. For all of these peculiar characteristics, the lithium-ion battery has become one of the most promising energy sources for electric vehicles, hybrid electric vehicles, portable electronics, and energy storage systems. As the lithium-ion battery is a rechargeable battery, it is essential to charge many times during high use. Sometimes this charging procedure remains for a long time. Time is a valuable commodity, and it's imperative to reduce charging time to match the pace of everyday work. For this, fast charging technology becomes essential in the field of lithium-ion battery charging technology. In the sector of portable devices like smartphones, and laptops, some fast charging techniques have been introduced, but in the area of electric vehicles, electric bikes, and electric scooter fast charging technology is still being developed. This is critical as when the time comparisons come between refueling the gasoline-powered cars and electric power vehicles, is still an unsolved issue. For that, it is vital to introduce new fast charging technologies to increase the market of electric vehicles. For the promising market, fast charging technology has recieved high attention from both manufacturers and academia.

From the characteristic of the lithium-ion battery, there is an inverse relation between fast charging and life span [6]. During fast charging, charging current remains high, and the temperature of the cell becomes steep, terminal voltage increases rapidly, and sometimes electrochemical reaction decreases the active surface area of electrodes. These changes have a significant impact on battery health and result in fast aging. *The main purpose of this thesis is developing a fast charging technique. This fast-charging technique will help to charge the lithium-ion cell faster than the present industrial charging technique. Besides that, it will maintain the longer cycle life.*

Figure 1 shows the structure of this thesis. From these five chapters, people will understand why the fast charging technique is essential and how it can help in the future. In Chapter 2, the fundamentals of lithium-ion battery charging have been described. As our thesis has focused on capacity degradation during cycling, a brief outlook of lithium-ion battery aging is included in this section. In Chapter 3, different available charging protocols are described. In this thesis, we developed a fast charging technology that will charge the lithium-ion battery faster. It is very significant to know the other available charging techniques to help understand the difference between our proposed technology and other available methods. In Chapter 4, we discuss our proposed fast charging technique, the most used industrial charging technique, explain the experimental setup and compare the result with available industrial charging techniques. In Chapter 5, the conclusion is given based on the overall discussion. Future targets and research opportunities are included here. From Figure 1, we can see the structure of this thesis.

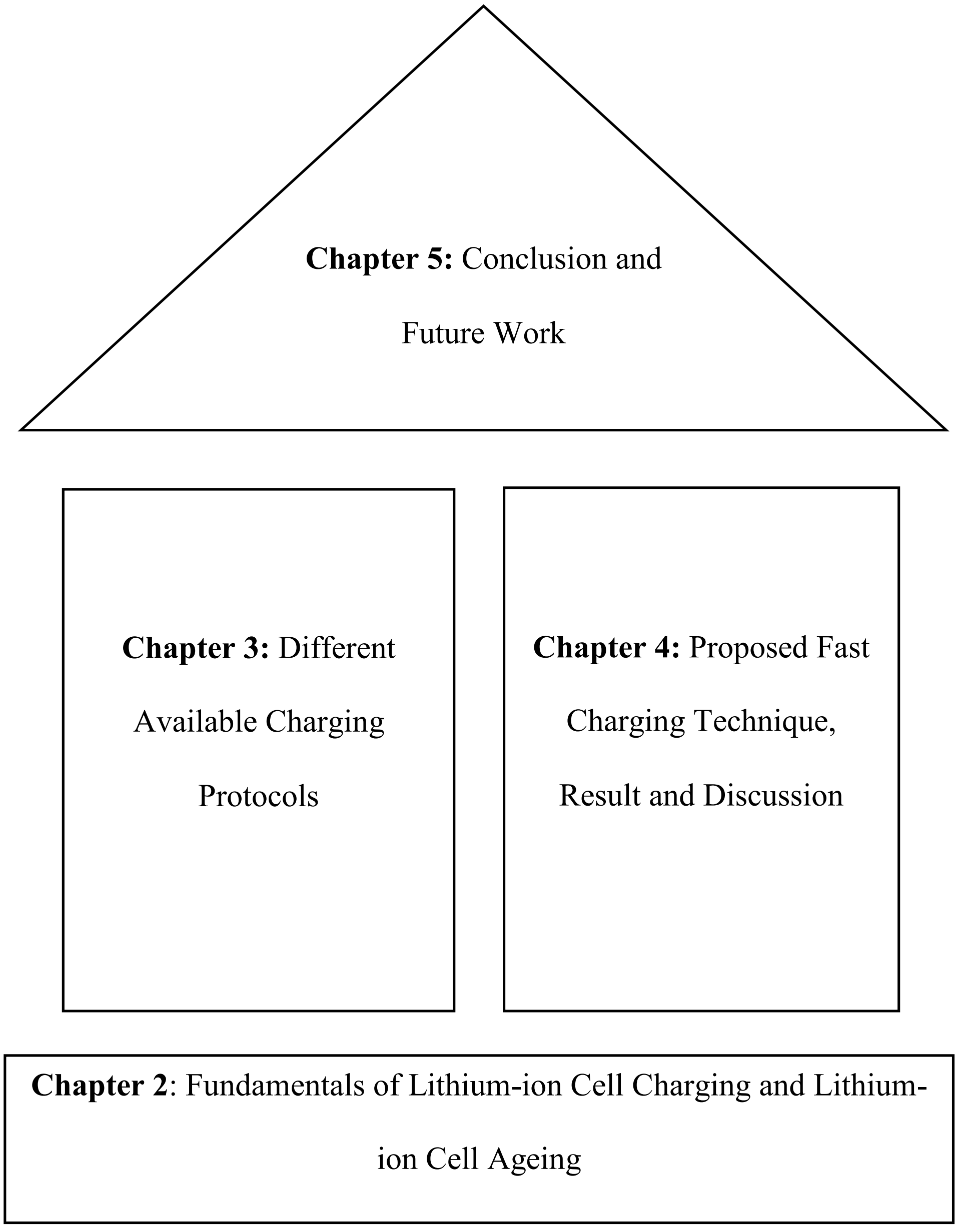

Figure 1: Structure of optimal fast charging technique thesis

CHAPTER TWO: FUNDAMENTALS OF LITHIUM-ION CELL CHARGING AND LITHIUM-ION CELL AGEING

2.1. What is the Battery?

A battery is a device be made up of one or more electrochemical cells with external connections provided to electrical power devices [7]. Electrochemical cells are a system that can generate electrical energy from chemical reactions. When a battery is used as a power supply, the positive terminal is known as a cathode and the negative terminal known as an anode [8].

2.2. History of Battery

The Parthian battery, consists of a clay jar and vinegar solution. An iron rod is inserted into this solution surrounded by a copper cylinder, and is believed to be the first invented battery in history. People conceived the idea 2000 years ago during the Parthian empire [9]. Figure 2, shows the Parthian battery [9]. Some scientists still do not believe the Parthian battery is a source of power. In 1660, Otto Von Guerike was able to prove electricity in nature [9]. In 1744, the Leydan Jar invented by Ewald Georg Von Kleist, was able to provide electric shock [9]. In 1780, Luigi Galvani introduced a new idea and called it animal electricity [9]. Alessandro Volta invented the first pure battery and it was known as Voltaic pile [10]. The voltaic pile was better than the Leyden Jar, but it was not free from error. In 1836, chemistry Professor John Fredric Danell introduced a way to solve the hydrogen bubble problem of the voltaic pile and called it the Daniell cell. It was able to provide 1.1 volts [9]. In 1837, Golding Bird invented an upgrade version of Daniel's battery, and the next year, in 1838, John Dancer introduced the porous pot version of a Daniel cell. The Gravity cell was developed in 1860 by Frenchman Callaud, and it was stronger than any other cell. Because of its excellent quality, it became trendy among the American and British Telegraph Society. French physicist Gaston Plante in 1859, developed the first lead-acid battery. After a few years, in 1868 and 1888, the wet cell and dry cell was invented. The first nickel- cadmium rechargeable battery was invented by Swedish inventor waldmar Jugner in 1899. In the early 1900's Thomas Alva Edison invented the first alkaline cell [11]. For the small size, low atomic weight, and excellent electrochemical potential, lithium got excellent attention from the battery researcher, and it became an ideal component for battery technology [12]. In 1912, G. N. Lewis started to experiment with the lithium-ion battery, but commercial lithium-ion batteries did not become available until 1970 [13], [14].

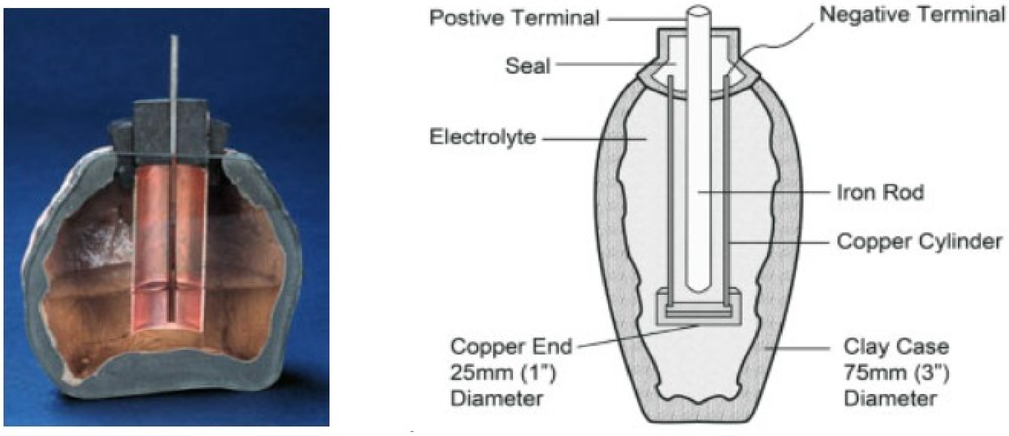

Figure 2: Parthian Battery [9]

Three significant up-gradation marked the 1980s. In 1980 an American chemist, John B. Goodenough, invented the $LiCoO_2$ cathode (positive lead), and a Moroccan research scientist, Rachid Yazami, revealed the graphite anode (negative lead) with the solid electrolyte. In 1981, Japanese chemists Tokio Yamabe and Shizukuni Yata invented a novel nano-carbonacious-PAS (polyacene) [15], bringing into being a material that was beneficial for the anode in the conventional liquid electrolyte [16], [17]. This invention helped to create the first lithium-ion battery prototype that was commercialized by Sony in 1991 [17].

Table 1: Battery Invention Timeline [6], [11]

Year	Event
2,000+ years ago	Parthian Battery First introduced among the people
1798	Italian physicist Count Alessandro Volta invented Voltaic pile
1836	Voltaic pile Efficiency upgraded by English chemist John F. Daniell

1859	Lead-acid battery invented by French physicist Gaston Plante
1868	Wet cell developed by French chemist Georges Leclanche
1888	German scientist Dr. Carl Gassner discovered dry cell
1899	First nickel-cadmium rechargeable battery discovered by Swedish inventor Waldmar Jugner
Early 1900's	American inventor Thomas Alva Edison first developed alkaline cell
1955	Introduction of miniature batteries for hearing aids
1956	Introduction of the 9-Volt battery
1957	Starter of the first commercial watch battery
1959	Starter of the first commercially viable cylindrical alkaline battery.
1989	Introduction of the first “AAAA” alkaline battery
1992	Lithium ion battery commercialized the first time
2000 to present	Upgradation of rechargeable technology introduce products like nickel-metal hydride rechargeable batteries, titanium high-performance batteries, and other batteries.

2.3. Types of Battery

Currently there are different types of batteries in the market. A lot of new up-gradation is being introduced in the field of the cell. All of these batteries can be classified into two forms. They are

1. Primary Batteries
2. Secondary batteries

2.3.1. Primary Battery

The primary battery is known as a non-rechargeable battery. For the non-reversible cell chemistry, the manufacturer suggests not to charge the primary battery. Primary batteries are used where the portable device has low current drain capability. It has a high energy density, but also a high current drain system and does not sustain a long time. Available primary batteries and their characteristics give in Table 2.

2.3.2. Secondary Battery

The secondary battery is known as a rechargeable battery. Its active material gives the capability to recharge the battery. Rechargeable batteries allow the maximum use of portable applications. Available secondary batteries and their characteristics give in Table 3.

Table 2: Primary batteries and their characteristics [18]–[20]

Chemistry	Nominal voltage	Specific Energy (MJ/kg)	Elaboration
Zamboni pile	0.8		Very long life, Shallow current
Silver-oxide (silver–zinc)	1.5	0.47	Very expensive.
Zinc–air	1.1	1.59	Used mostly in hearing aids
Alkaline (zinc–manganese dioxide)	1.15	0.4–0.59	Good for high- and low-drain uses.
Nickel oxyhydroxide			Good for high drain uses.
Zinc–carbon	1.2	0.13	Inexpensive.

Lithium (lithium manganese dioxide) $LiMnO_2$		0.83–1.01	Used only in high-drain devices.
Lithium (lithium–iron disulfide) $LiFeS_2$	1.5	1.07	Expensive

Table 3: Secondary batteries and their characteristics [18]–[20]

Chemistry	Nominal voltage	Specific Energy (MJ/kg)	Elaboration
$LiFePO_4$	3.3	360	Lithium-Iron-Phosphate chemistry
Lead-acid	2.1	140	Higher discharge rates create a considerable loss of capacity. Environmental hazard due to lead.
NiZn	1.6	360	Moderately inexpensive, High drain device suitable Low self-discharge rate
NiCd	1.2	140	Inexpensive, Moderate rate of self-discharge, Moderate energy density
NiMH	1.2	360	Inexpensive
AgZn	1.5	460	Extremely expensive due to silver, Very high energy density, Very high drain capable
Lithium-ion	3.6	460	Various Lithium Chemistries, Very Expensive, Very high energy density

2.4. Why Lithium-Ion Cell?

The Lithium-ion cell is currently one of the most popular rechargeable cells among the people. Over the last few years, it has been able to achieve high popularity among the portable electronic devices and transportation sectors. Its chemistry has an excellent load characteristic and high voltage level. For that, it has become the first choice for different battery sectors. The lithium-ion battery needs less maintenance. Compared to other secondary batteries, it has fewer memory effects and a low discharge rate. The lithium-ion battery doesn’t need to charge for a long time to prolong its life. For its high longevity, the buyer also doesn’t need to spend money to frequently change the battery. This quality is significant for transportation applications. Transportation sectors are highly depended on lithium-ion batteries. Still, for winning the competition against gasoline cars, all electric vehicles need a suitable battery management system for safety and fast charging techniques for saving time.

2.4.1. Principle of Lithium-ion Cell

A rechargeable lithium-ion cell is made up of two electrodes (anode and cathode), electrolyte, separator, and two current collectors (positive and negative). Lithium-ion cells can’t be used directly after the assembly. A lithium-ion cell remains discharged at the very beginning. For this discharge state, the lithium-ion remain tied with the cathode. In this state, it can’t produce any electricity. It needs to be charged before its first use. When it plugs in for a charge, a negatively charged electron starts to separate from the cathode. It is known as oxidization. During the charging time, the same number of positively charged lithium-ions dissolve into the electrolyte solution and try to keep the charge balance in the cathode [21]. This journey continues until they reach the anode. After reaching the anode, the lithium-ions remain in the anode.

During discharge, lithium-ions leave anode and travel to the cathode via the electrolyte. At the same time, electrons which remained in the anode, travel through the external electrical wire. We use this outer wire for our work. Following this procedure charging and discharging continues. Based on different cell chemistry and different charging techniques, this charging and discharging can take a long time and in same cases the cell capacity isn't sustainable for a long time. From Figure 3, we can see the charging and discharging mechanism of the lithium-ion battery [22].

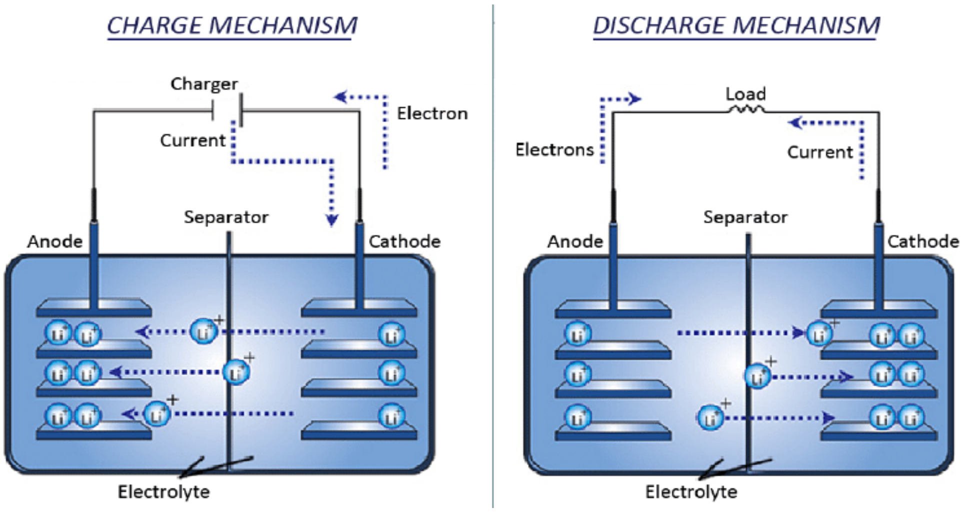

Figure 3 : Charging and Discharging mechanism of Lithium-ion cell [22]

2.4.2. Negative Electrode

Different kinds of material can be used for the negative electrode. Among them, comparing the cost and availability, graphite is the most popular negative electrode. The negative electrode highly faces the dendrite problem. Graphite has fewer dendrite problems compared to others. It also has a suitable working voltage, which makes it more appropriate for lithium-ion cells. Lithium titanium dioxide as a negative electrode has recieved great attraction from the manufacturer and academia over last few years. It has high thermal stability. In the electric vehicles industry, thermal stability is essential. At the same time, it has a fast-charging capability, which makes it more popular in the transportation industry. Valuable negative electrode materials and their characteristics are provided in Table 4.

Table 4: Negative electrode materials [23]

Materials	**Graphite (LiC_6)**	**LTO ($Li_4Ti_5O_{12}$)**	**Si ($LiSi_{22}$)**
Mass capacity (mAh/g)	372	175	4200
Volumic capacity (mAh/cm^3)	837	613	9786
Voltage range (V)	[1.5 – 0.01]	[2.0 – 1.0]	[1.2 – 0.01]
Volume change (%)	10%	0.20%	270%
Cost	Medium	High	Low
Advantages	Long cycle life	Good cycling and efficiency	High capacity
Inconvenient	Relatively low energy density	High voltage, low capacity (low energy density)	Volume expansion

2.4.3. Positive Electrode

There are different kinds of positive electrodes. Lithium cobalt oxide is a famous positive electrode material, and this is also the first material used as a positive electrode. The source of lithium cobalt oxide is minimal. For the limitation of this material, it is very costly. This cost also increases the price of the cells. Besides, it has inferior stability at high temperatures, and this material is very toxic [24]. For solving this issue, the researcher [24] tried to develop some other materials that can be used as a positive electrode. Lithium nickel manganese cobalt oxide helped at some point in solving this problem. These cells are manufactured with a cathode with one-third nickel, one-third manganese, and one-third cobalt, but the ratio can vary according to the manufacturer's "secret" formulas [21]. It has excellent thermal tolerance, is less costly and has a high specific capacity [24]. Another available positive electrode is lithium iron phosphate. Lithium iron phosphate cells are the same as lithium cobalt oxide cells. The anode and electrolyte materials are similar. The main difference is that the lithium cobalt dioxide cathode is replaced with the more constant lithium iron phosphate. Generally, in the fully charged cell, lithium-ions leave the cathode. Lithium-ion phosphate has excellent thermal stability which is very important for safety. Its characteristics make it the right choice for electric vehicles and portable power tools. It can discharge and charge many times. Nevertheless, Lithium-ion phosphate has a lower energy density than a lithium cobalt oxide cell and a higher self-discharge rate [24]. Valuable positive electrode materials and their characteristics provide in Table 5.

Table 5: Positive electrode materials [23]

Materials	**NCA**	**NMC**	**LFP**	**LMO**	**LCO**
Mass capacity (mAh/g)	279	280	170	148	274
Volumic capacity (mAh/cm^3)	1284	1333	589	596	1362
Voltage range	[3.0 – 4.25]	[2.6 – 4.3]	[2.0 - 4.0]	[3.5 – 4.3]	[3.6 – 4.85]
Cost	Medium	Medium	Low	Low	High

Advantages	High capacity and voltage	High voltage, moderate safety	Excellent safety, the abundance of Fe, low toxicity	The plenty of Mn, high voltage, moderate safety,	Performance
Inconvenient	Safety, Limitation of Ni and Co	Limitation of Ni and Co	Low voltage and capacity, Low energy density	Limited cycled life, Low capacity	Safety, Limitation of Co, Low capacity

2.4.4. Electrolyte

There are various types of electrolytes, such as liquid electrolyte, solid electrolyte, and gel electrolyte. Usually, the secondary cells use liquid electrolytes for their ion travel media. Lithium-ions can’t move from one electrode to another one directly. Electrolytes play a vital role in this case. Liquid electrolyte however present two significant issues, which are less conductivity and also robust inflammability. For solid electrolytes, the lithium salts are united into a polymer material and, after several engineering steps, a film obtained. This film can also be used directly as a separator. Solid electrolytes have less conductivity at room temperature. Sometimes it required high heat for the battery to be active. The very first solid electrolytes were introduced for negative electrode cells. Nowadays, they are used for lithium-ion cells. The gel electrolytes are obtained by dissolving a solid membrane in a solvent [24]. Compared to solid electrolytes, gel electrolytes provide enhanced contact with the electrodes and enough conductivity at room temperature. Yet, the contact resistance of the cells remains higher [24].

2.4.5. Separator and Collector

The separator is an integral part of the cell. It is a mono or multilayer polyethylene and polypropylene sheet which helps to isolate both electrodes. Some qualities are essential for a suitable separator. First of all, it needs to have good strength to separate the contact between two electrodes. Next, it is necessary to have good ionic conductivity and less electronic conductivity. Again chemical neutrality is vital for it. It needs to be neutral during any reaction. The current collector is responsible for transferring the electrons from the active material of the electrode to the external circuit. Aluminum is a good candidate for this, very light and a good electrical conductor. Copper is also an excellent electrical conductor. Hence the choice frequently comes across: aluminum collector for the positive electrode and copper for the negative electrode [24].

2.5. Fundamental of Lithium-ion cell Aging

The demand for lithium-ion cells is constantly increasing. With the increase in the production of mobile devices and electric vehicles, the interest in lithium-ion cell development also increased. The main barrier to this development is the aging and capacity degradation mechanism of the lithium-ion cell. Identifying aging and capacity degradation mechanisms is very complicated. Different kinds of environmental parameters and the utilization of cells have a significant impact on cell aging and capacity degradation. As lithium-ion cell is manufactured from various types of components, we give a brief overview of how each element is playing a role in battery capacity degradation.

2.5.1. Negative Electrode

Graphite, carbon, titanate, and silicon are some relevant active materials for the negative electrode. Among these graphite is a more common material for it [25]. During electrolyte reaction with graphite, a solid passive layer forms on the anode. During the first charge, this solid layer forms on anode naturally. This solid layer is known as the Solid Electrolyte Interface (SEI) [26]. SEI formation highly depends on active materials, electrolyte, solvent, conducting salt, additives in electrolyte and procedure of layer formation. It forms at the very beginning of any cycle and creates a barrier between electrolyte and electrodes. It plays a vital role in the anode. It tries to save anode from any possible deterioration and helps reduce the reduction of electrolyte [27]. SEI is a solid layer, but it becomes unstable when any battery operates above the electrochemical operation range. It is permeable for lithium-ion but not for other electrolyte components [28]. When any solvent interacts with graphite, it will decay the graphite electrode. During this time, a gas is formed from the reaction. This gas breaks the SEI layer and expands the area of this layer. This expansion of the SEI layer increases the impedance and decreases the active anode surface for the reaction. This behavior of anode reduces the capacity of the lithium-ion cell.

Besides SEI formation, Lithium platting also takes place on the anode. From the charging procedure we know, lithium-ions travel from cathode to anode and store quickly in the anode material. During overcharging or for high charging rate, low temperature and other conditions induce a high anode polarization. As a result, anode potential reaches the threshold level of lithium plating, and lithium-ion plating starts on the anode [29] for this electro plating. Metal lithium is deposited into the electrolyte. It can easily consume active lithium and can provide a barrier for active lithium to create contact with the anode. The passage of this platting becomes the reason for capacity fade, and sometimes the area becomes so big that it creates internal short circuits. From Figure 4, we can see the SEI formation and lithium plating [25].

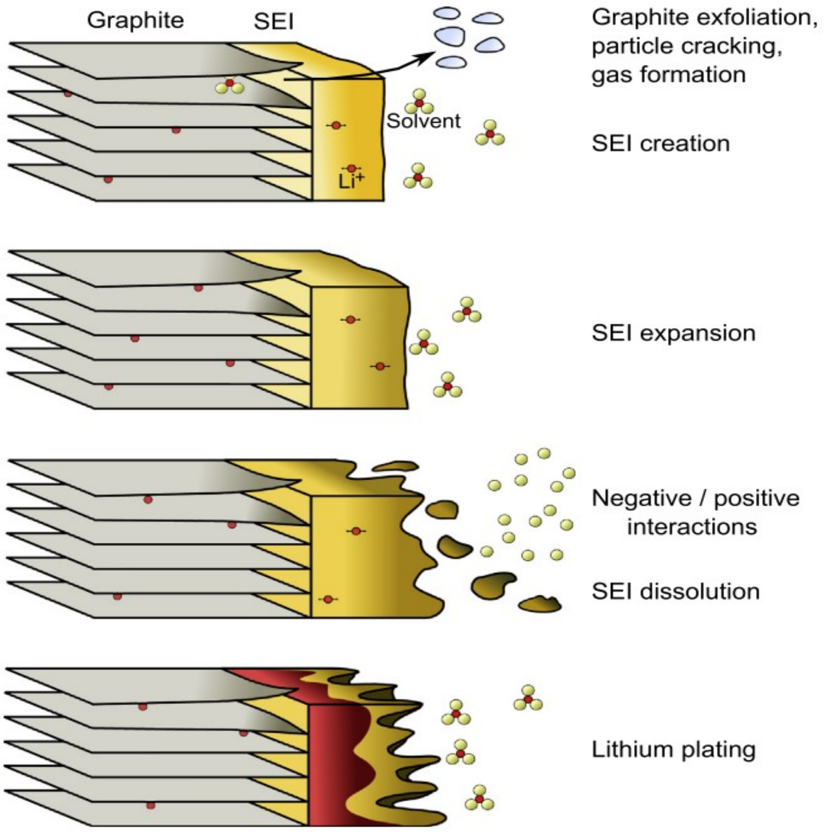

Figure 4: SEI formation and lithium platting [25]

2.5.2. Positive Electrode

Based on different observation of several cell utilizations, it was found that positive electrodes have less significant changes compared to negative electrode [30]. Over time, the active material of the cathode electrode does experience some alteration. SEI layer forms on the electrode, but for the high voltage of cathode, it’s become hard to detect. Overall some critical changes can occur in the positive electrode, and they are [25]:

- The decay of active mass
- Degradation of electrolyte
- Formation of SEI

All of the changes play a vital role in capacity degradation.

2.5.3. Electrolyte

The electrolyte has involvement in both positive and negative electrode reaction. SEI formation for both electrodes happens in the presence of an electrolyte. During the charging and discharging cycle, a large amount of conductive salt is decomposed. The changes in resistance are highly depend on the concentration of conductive salt [24]. Electrolyte oxidation at the positive electrode and reduction at the negative electrode both have opposite behavior with cycleable lithium-ion consumption. When the reaction takes place in the electrolyte, gaseous product releases in the electrolyte. When this occurs electrolytes can’t play a proper role in maintaining the capacity, and capacity starts to decrease.

2.5.4. Separator

The separator is another essential component of lithium-ion cells. Electrochemically, the separator remains inactive during cycling. As it stays inside the cell, during electrolyte decomposition, over time, the pores of separator start to clog. For that, the electrode active surface area starts to reduce, and at the same time, the resistance of the cell begins to increase. High current cycling rate create a high impact on current collector foils. For cycling, active materials begin to decay [24]. As a result, improper current distribution, lithium-ion plating takes place. Besides, over stress deforms the cell, and the connection between electronics and separator become weak. Overall, the capacity of the cell degrades.

2.5.5. Calendar Aging and Cycle Aging

Two important terms in cell aging are calendar aging and cycle aging. Aging of the lithium-ion cell during non-operating conditions is known as calendar aging and during the operating condition, aging is known as cycle aging [25]. In both operating and non-operating conditions reduction and oxidation between electrolytes and electrodes continue. Calendar aging is slow but is highly dependent on the temperature, state of charge (SOC), and time. Cycle aging depends on charging and discharging current, cycle depth, cut-off voltage, the current through output. In both cases capacity degradation remains to continue [24]. Possible reasons and capacity degradation mechanisms have given in Figure 5 [31].

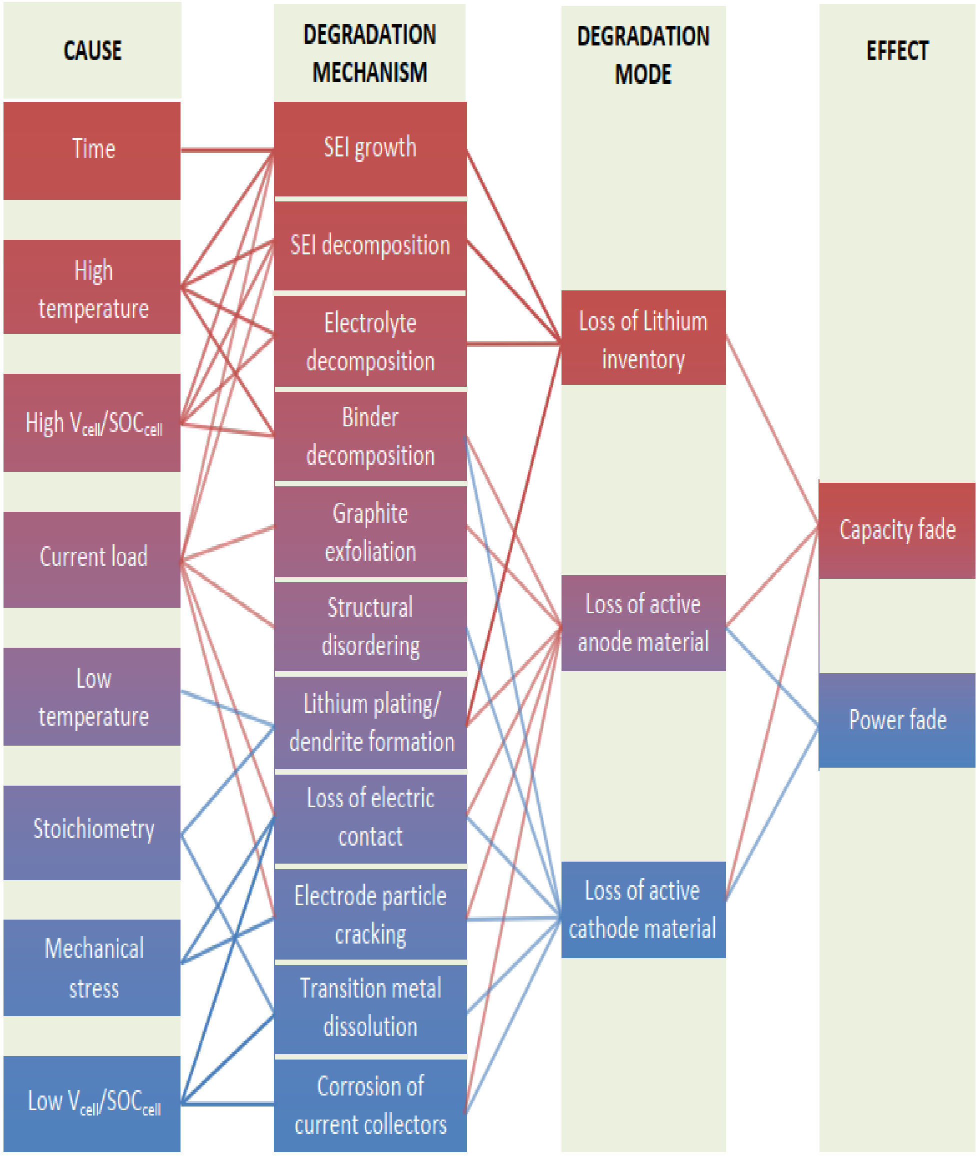

Figure 5: Possible capacity degradation mechanism [31]

CHAPTER THREE: DIFFERENT AVAILABLE CHARGING PROTOCOLS

Different charging techniques have been developed for the betterment of rechargeable lithium-ion cells. Charging techniques of lithium-ion cells have a direct relationship with its long-time run. All of these charging techniques can be separated into two essential groups. They are simple charging techniques and optimized charging techniques. Simple constant current charging and simple constant voltage charging are the two charging systems of the simple charging procedure. These charging techniques are old, and these techniques have a significant impact on cell health. For improving the charging technology different optimized charging techniques have been developed. Optimized charging techniques be can differentiated into three important categories: waveform-based charging methods, model-based charging methods, and AC charging methods. In this chapter, available charging techniques are briefly discussed.

3.1. Simple Charging Methods

3.1.1. Constant Current Charging

The constant current charging method is a process where you need to maintain the constant current during the whole charging sequence. It highly depends on the proper estimation of the state of charge (SOC) [32]. This charging process is straightforward. During this charging process, it is very easy to understand the charging current from the charging time and capacity [32]. This technique is highly depending on SOC, and as a result, sometimes the cell becomes overcharged, and sometimes it remains undercharged. This behavior can create a significant impact on the life of the cell. It can degrade the lithium-ion cell capacity faster. During this constant current charging process, the constant current remains between 0.2C to 1C [33]. With the increase of state of charge, the current limit decays inversely. If the current does not change with the increasing of state of charge, then the active materials of the electrode start to react and degrade the capacity. Sometimes this charging technique use trickle charging which helps the cell to maintain its full charge.

3.1.2. Constant Voltage Charging

The constant voltage charging method is another simple charging method where, during the entire charging sequence, a constant voltage is applied. During the constant voltage charging, the cell terminal voltage starts to increase, but at the same time, charging current starts to decrease. There are pre-set values for charging current when it stops charging. The advantage of this charging process is that it prevents overcharging. This charging technique can provide an extended service life for the cell. At the initial charging stage, SOC remains low, but the current level remains high which creates a significant impact on lithium-ion cell health [32].

3.2. Optimized Charging Methods

3.2.1. Constant Current-Constant Voltage Charging

After understanding the benefits and disadvantages of simple constant current and constant voltage charging methods, researchers explored other advanced charging techniques combining those both at these methods. Combing the potential benefits from constant-current and constant voltage techniques they introduced a new charging technique called constant current-constant voltage (CC-CV) method. During CC-CV charging, a constant current is applied to charge the cell until the cell voltage rises to a pre-set maximum charging voltage; then the charging voltage is held constant at the pre-set voltage and the charging process will stop when the charging current reaches the lower current level [34]. In Figure 6 we can see changes in the CC-CV graph [34]. This charging method is independent of the cell model, and as a result it has become prevalent charging method. Another up-gradation comes in this method when trickle charge (TC) and end of

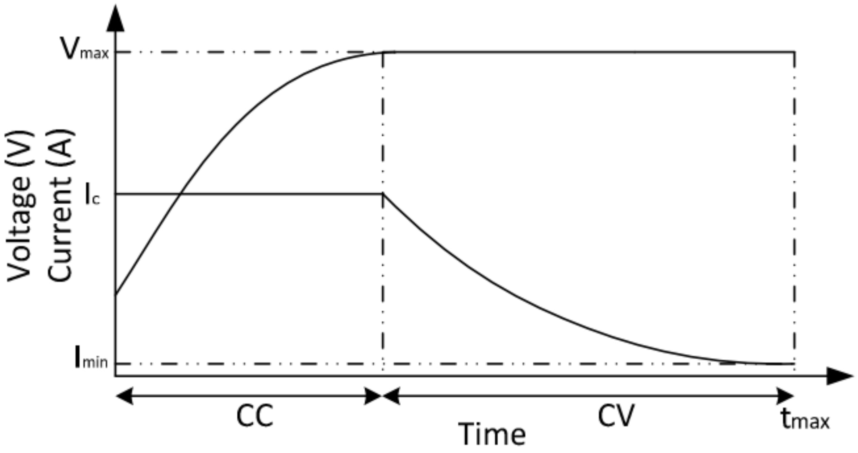

Figure 6: CC-CV charging technique [34]

charge (EOC) are added with the CC-CV charging technique. This is called the TC-CC-CV charging method [35]. The new two steps only work for some exceptional cases.

When the cell deeply discharges then the trickle charge mode is activated, and when the charging current crosses a lower cut-off limit, then the EOC mode is activated. Usually, this process increases the cycling time. From Figure 7, we can see this charging algorithm [34]. This charging algorithm has three critical stages. At the very beginning, it checks the safety condition and measures the temperature and open-circuit voltage. If the open-circuit voltage remains less than the pre-set cut-off voltage, then the trickle charge mode is on at that time. If the voltage passes the cut-off voltage mode, during that time, the CC current mode is started. It remains to continue until it reaches the pre-set maximum voltage (V_{max}). When it touches the V_{max}, it switches to CV mode. Sometimes, this mode continues until it reaches a pre-set maximum charging time or minimum cut-off current level. This method is advanced but not free from side effects. Sometimes, noticeable voltage changes can be seen during charging. Besides, it takes a long time to charge. Because of these drawbacks, some other notable improvements have been introduced in this method. Pre-accelerated charging method, double loop CC-CV method, Fuzzy- Logic CC-CV method, Grey-predict charging process and Phase-locked loop charging techniques are some improved procedures in the field of CC-CV charging procedure.

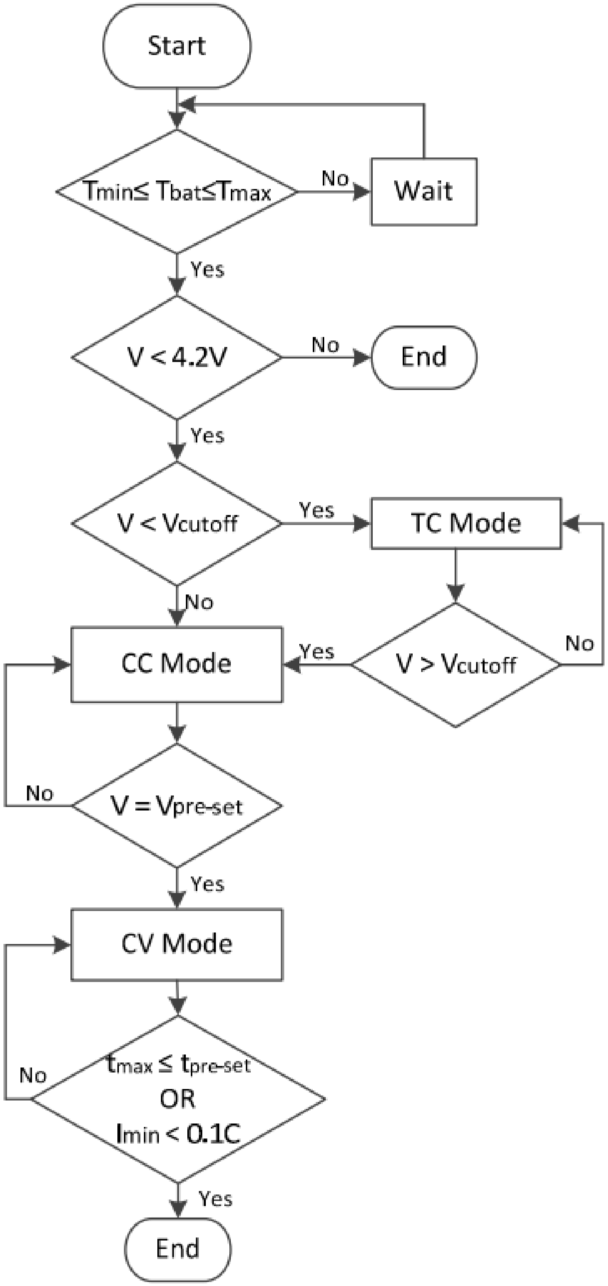

Figure 7: CC-CV charging algorithm [34]

3.2.2. Multistage Constant Current Charging (MSCC)

During CC-CV charging, the CV phase takes a long time to reach its desired pre-set value. To overcome this difficulty and to maintain the health quality of the cell, some different charging techniques are introduced. Multi-stage constant current charging (MSCC) is such a technique. For fast charging, it is essential to increase the current level, but high current can increase the terminal voltage. In MSCC, this difficulty can be overcome, and high charging current can be applied during charging. MSCC has multiple charging current stages. At the very beginning, the pre-set current is used for charging. This charging current continues until a pre-set voltage level is reached. Then the charging current level changes and this change between current and voltage remains for four to five stages [34]. The charging method starts with very high current and this current level decreases with every stage. Figure 8 and 11, shows the MSCC charging graph and algorithm [34]. If these changes take place when the voltage reaches the upper cut-off voltage limit, then this condition is known as shifting condition based on upper cut-off voltage. And, if this change takes place base on state of charge, then that is known as shifting condition based on the state of charge [32]. In Figures 9 and 10, the shifting condition base charging graph is given [32]. During MSCC, it is vital to find the optimal charging current pattern. Different techniques are use to find the optimal pattern. Fuzzy control base charging, the Taguchi method, and the Ant Colony System are the most used process for finding the optimal charging pattern [32].

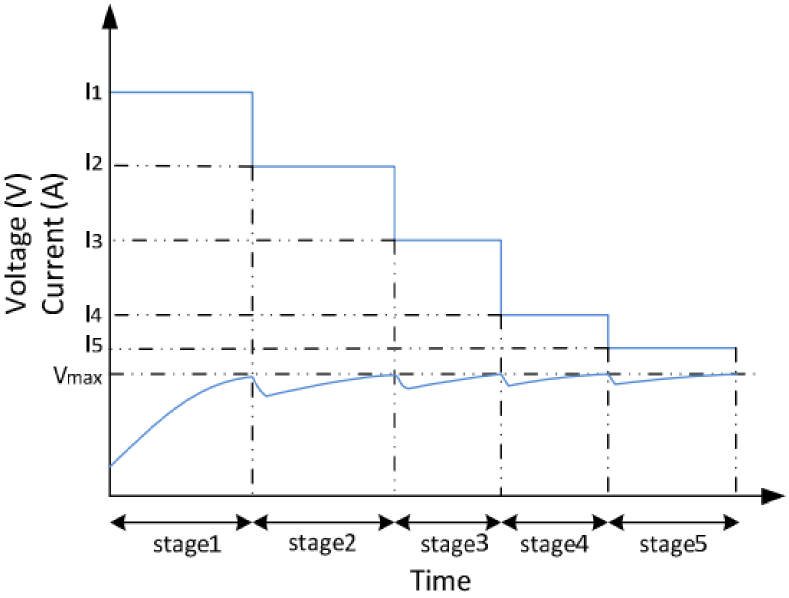

Figure 8: MSCC charging technique [34]

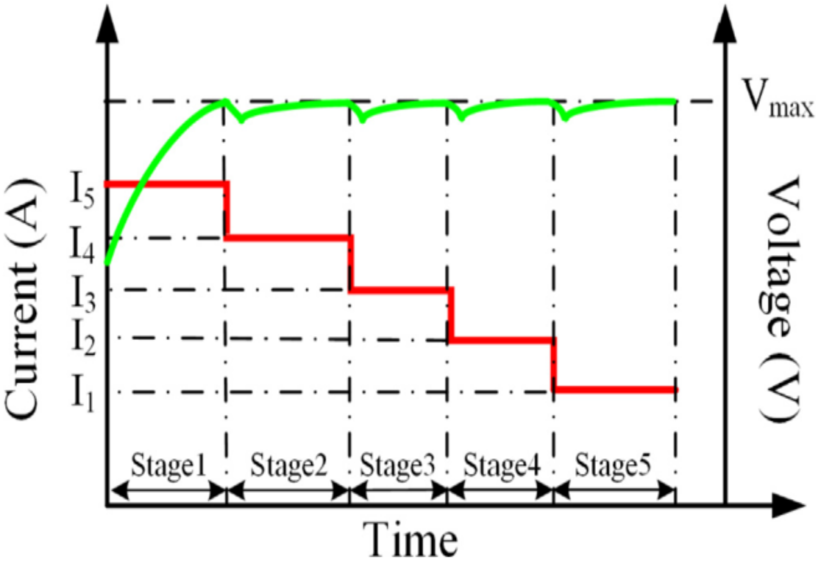

Figure 9: MSCC charging with shifting condition based on upper cut-off voltage [32]

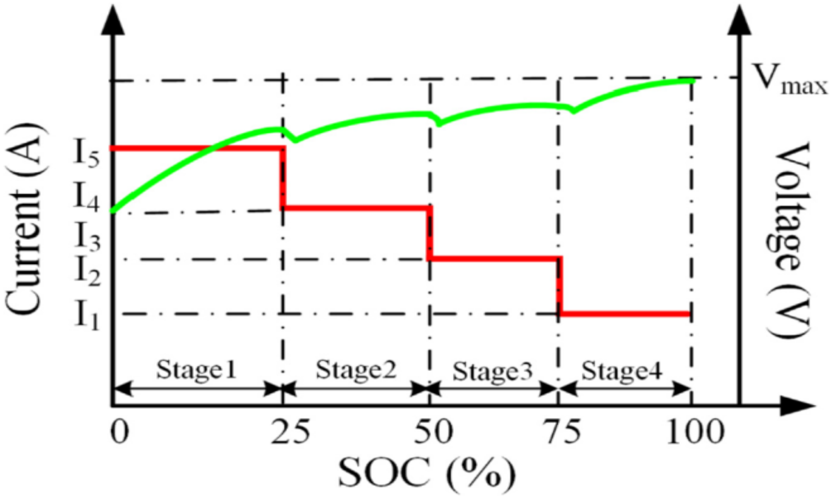

Figure 10: MSCC charging with shifting condition based on a limit of SOC interval [32]

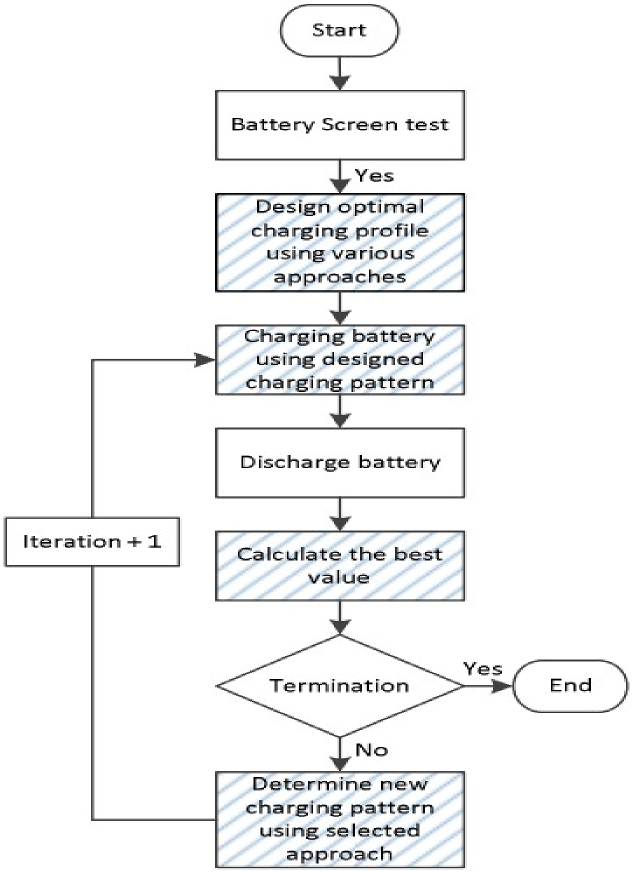

Figure 11: MSCC charging algorithm [34]

3.2.2.1. Fuzzy Control Base Charging

The fuzzy control base charging technique provides a good quality of faster charging with excellent efficiency and lower temperature rise. The fuzzy logic controller has four vital parts: fuzzifier, fuzzy rule base, fuzzy inference engine, and defuzzifier [36]. The fuzzifier provides the membership function to convert the real system value into fuzzy linguistic sets. Fuzzy rule base works according to the professional experience and the system control operating method. Transformation of the fuzzy rule base into fuzzy linguistic output is performed by the fuzzy inference engine. The Defuzzifier helps to convert the fuzzy linguistic sets into actual values. Fuzzy control base charging is free from sudden shut-off. It has fewer temperature increments and the cycle life remains higher for this technique [36].

3.2.2.2. Taguchi method

The Taguchi technique can provide a systematic and efficient approach for charging [37]. The Taguchi process has four important steps. They are problem formation, experiment/data collection, parameter analysis, prediction/confirmation [37]. In the first stage, it tries to classify the variables which connect with the product into noise, control, input signal, and output response factors. Here signal to noise ratio plays a vital role. The Taguchi method helps to determine the optimal combination in a series of experiments. In the second step, the experiment is done in the hardware or the simulation method. The orthogonal array developed in the previous step is used here for experimenting. The parameter analysis step helps to determine the optimum setting of the control factors. In the final prediction/ confirmation step, the performance of the system under the baseline and optimum setting of the parameter are predicted. Sometimes the whole system needs to be repeated to obtain the proper value [37].

3.2.2.3. Ant Colony System (ACS)

Inspired by real ant colony characteristics, the ant colony system was developed for finding the proper charging pattern. Positive feedback, distributed compulsion, and the use of a constructive greedy heuristic are three important characteristics of the ant colony system [38]. Positive feedback confirms the rapid search of global solutions. Distributed computation helps to avoid premature, convergence and the use of practical greedy heuristic helps to find the right way faster. ACS algorithm has five crucial steps. They are initialization phase, ant dispatching phase, fitness evaluation phase, trail intensity updating phase and convergence determination phase [38]. During the initialization step, all ants locate on arbitrarily generated opening nodes, and initial values for trail intensity set on boundaries. In the next phase, based on the estimation, ants like to choose the shorter distance point where the maximum pheromone will be present. This process continues until all the ants finish the tour. In third stage, after completing the tour, the capability of every ant will be measured. Any restrictions associated with the optimization problem can unite into the objective function as disadvantage functions. These capability values are then used to fill in the pheromone strength of edges between each stage. In the trail intensity updating phase, two important factors play a vital role in trail intensity of every individual edge. Pheromone intensity in edges decrease with time if no other ant leaves their pheromone there. For that overall pheromone updating place an important characteristic in this movement. This total system will end if the movement reaches the maximum number or the same tour is choosen by the maximum number of ants. This overall process is known as ant colony system. The ACS algorithm is provided in figure 12.

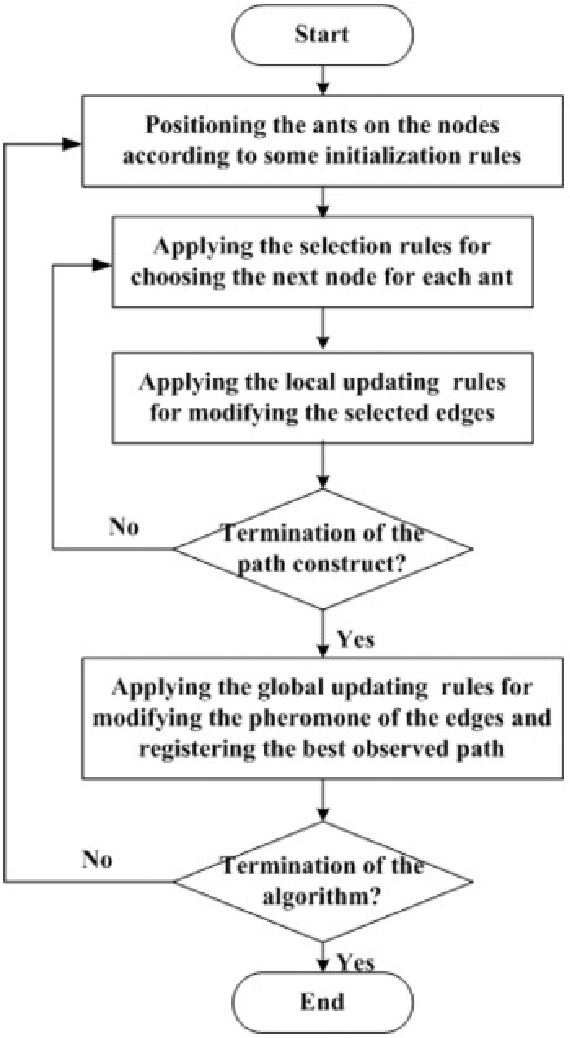

Figure 12: ACS charging algorithm [38]

Particle swarm optimization (PSO) and Integer linear programming [37] are two important techniques which know for finding the proper optimum charging process. They also have a significant contribution to the field of MSCC.

3.2.3. Pulse Charging

For both simple charging and multistage constant current charging, it was common that both were using constant current or constant voltage for their charging phase. But for pulse charging, researchers follow a different pathway. Discontinuous constant current and constant voltage apply for pulse charging. Pulse charging has a good quality of accepting high charging current during charging [32]. As pulse charging has less polarization voltage effect, it can accept high current multiple times. During pulse charging a short time resting period is applied which helps to achieve less polarization voltage effect and at the same time, maintain the ion concentration in the battery. This process is helpful to increase the charging efficiency of the battery. There are two important pulse charging techniques. They are current pulse charging and voltage pulse charging. The current pulse charging has three important sequences. They are Constant current-Constant frequency pulse charging (CCCF-PC), Constant current-Variable frequency pulse charging (CCVF-PC), Variable current- constant frequency pulse charging (VCCF- PC) [32]. During these charging techniques a resting time is provided between two maximum charging currents. As it has the capability of taking high charging current, it takes less time for charging compared to others. Voltage pulse charging can be separated into two parts: duty-varied voltage pulse and variable frequency voltage pulse. Duty varied voltage pulse charging has three significant modes, and they are full charge detect mode, sense mode, and charge mode. The variable-frequency voltage pulse charging technique can find the optimal charging frequency [32], [34]. Overall, the pulse charging technique is good for time-saving. However, it has some strong restrictions on maintaining the charging process, as the high charging current can create a thick solid electrolyte interface (SEI). If this thickness becomes large, then it can increase the internal voltage and can create some irreversible damage inside the cell.

3.2.4. Boost Charging

For the high demand for decreasing charging time, boost charging was introduced. This charging technique can charge one-third of a full discharge battery in 5 minutes [39]. It provided a new way to think about charging methods. It also has some limitations. It is decreasing the charging time, but it is also reducing the capacity of the cell. If a simple method is going 300 cycles, the boost charge is going 100-150 cycles. For that, it becomes a severe concern for the users.

3.3. Model-Based Charging Methods

Equivalent circuit temperature model: Temperature plays a vital role in battery performance. During charging, the battery temperature rises very fast. If the temperature crosses the maximum limit, then it can affect the cathode materials and can degrade the capacity of the cell. Therefore, it is essential to maintain the temperature during charging. The equivalent circuit temperature model is a model where the optimum current charging pattern is selected in such a way that it will follow the temperature limit [40].

Equivalent circuit power loss model: Keeping the minimum power loss in mind the equivalent circuit model design can sometimes be used for finding the optimal charging pattern. Charging time, temperature, charging current, and voltage limit are controlled in a way that will minimize the power loss of the battery [41].

3.3.1. Electrical-thermal aging model

This circuit system is capable of identifying the thermal aging of the cell. This model can maintain safe and fast charging. The charging sequence supports every parameter following the effect of electrical, thermal aging. It is complex to design [42].

3.3.2. Electro-chemical model-based charging

During charging, internal reactions take place inside the cell. Temperature changes, power loss, thermal aging, etc. happen for this internal electrochemical reaction. When finding a specific charging pattern for lithium-ion cells, these parameters are always kept in mind, however, it is rare to see the chemical reactions that are happening, how the internal potential changes and how the concentration of lithium-ion is changing. The electrochemical model-based charging tries to charge the cell faster and maintain the internal chemical reaction in the limit, which has less effect on the electrode [43].

3.3.3. AC charging method

The AC charging technique is new in the charging technique market. This charging technique is essentially a sinusoidal ripple current technique. It is not like a pulse charging procedure. During AC charging, sinusoidal ripple current is superimposed with a direct charging current [44].

CHAPTER FOUR: PROPOSED FAST CHARGING TECHNIQUE, RESULT AND DISCUSSION

The objective of this thesis is to develop a fast-charging technique that will help to decrease the charging time of the cell without increasing the lithium-ion cell capacity degradation. Following the target, we had developed a fast charging technique. In this chapter, we explain the experimental setup, proposed fast charging algorithm, industrial charging algorithm, what we used for comparison charging time, capacity degradation, and result of the outputs. Here we discuss the output result and provide a clear idea of why our proposed technique is better than available industrial charging. As our target was minimizing the time compared to available present industrial charging, we only compared with that technique.

4.1. Experimental setup

4.1.1. Lithium-ion cell

Since the lithium-ion cell is the preferred for electric vehicles, we have chosen a lithium-ion cell for testing. O’Cell new energy-technology Co. ltd supplied this cell. All safety parameters that the provider recommended were followed. The nominal voltage and charge cut-off voltages for this cell are respectively 3.2V and 3.65V. During charging and discharging the usage temperature ranges between 0°C to 45°C and -20°C to 60°C. The nominal capacity of this cell is 3300 mAh. Its standard charge and discharge rate is 1C. A 1C rate means the cell can charge or discharge entirely in 1 hour. The manufacturer suggested that this cell can perform in max charge current at a 2C rate. We tried to maintain our maximum current rate between 1C and 2C. The discharge cut-off voltage is 2V. For safety reasons, we followed all the suggested parameters for designed our algorithm base on all of the manufacturer's specified parameters. Table 6, list key cell specifications.

Figure 13: Lithium-ion cell

Table 6: Cell Specifications

Parameters	**Value**
Weight	80.0g ± 2.0 g
Dimension	Length: 65.5 ± 0.3 mm; Diameter: 26.2 ± 0.2 mm
Nominal Capacity	3300 mAh
Standard Charge	1C (3.3A)
Nominal Voltage	3.2 V
Standard Discharge	1C (3.3A)

Max Charge Current	2C (6.6A)
Charge Cut-off Voltage	3.65V
Discharge Cut-off Voltage	2.0V
Max Discharge Current	3C (9.9A)
Temperature Ranges	Charging: 0℃ ~45℃; Discharging: - 20℃ ~ 60℃

4.1.2. Cell testing system

The Battery Testing System 9000 (BTS-9) is a well-known lithium-ion cell testing system. It is manufactured by Neware technology ltd. And is highly used for cycle life tests and charge and discharge testing. This system has eight-channels and according to the international standard design, individually all channel of the system have a constant-current source and a hardware constant-voltage source which make the system stable and reliable. Proper heat dissipation system helps to ensure 24-hour full load condition operation. Modular design and a well designed holder selection make it convenient to use. Each channel of this testing system is capable of operating the individual programs. For testing of our proposed algorithm, we have used all eight-channels. We created two groups for two different algorithm testing, and we have selected four similar kinds of the cell for the same algorithm testing. We started testing the cells all at the same time. Since the cell chemistry is the same for all cells, these tests are a reliable way to assess the capacity changes during charging. The testing system [45] is shown in Figure 15 and 17 and how the cells have been set up for charging is shown in Figure 16.

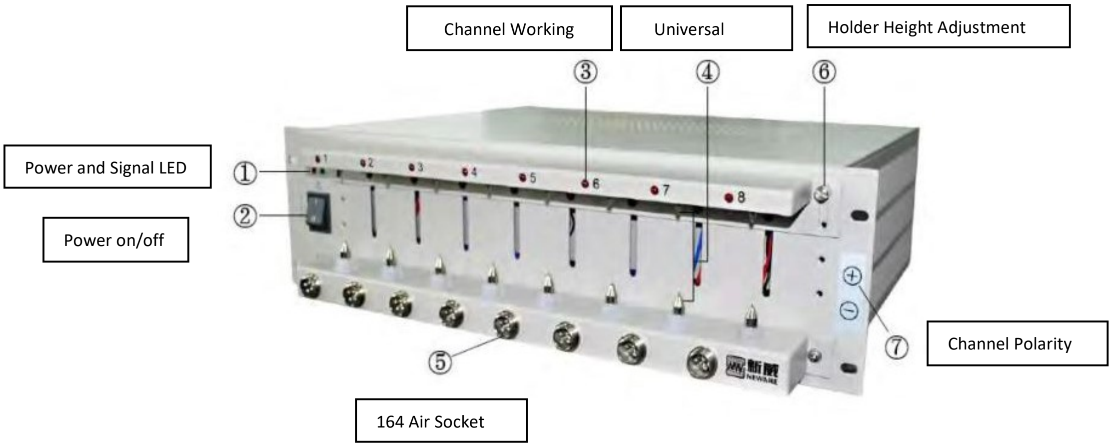

Figure 14: Front Panel [45]

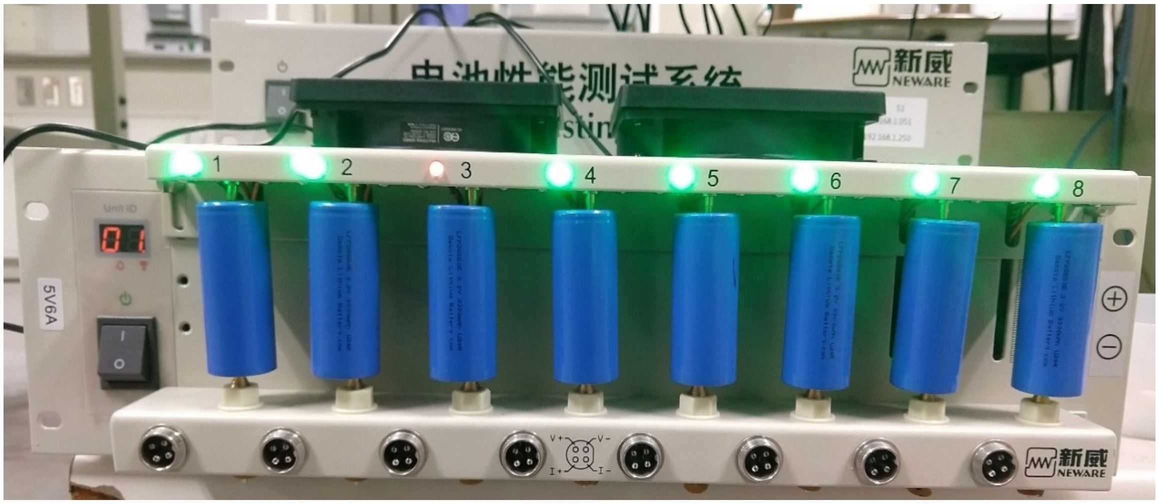

Figure 15: Battery set up for testing

Figure 16: Rear Panel [45]

4.1.3. Proposed algorithm

At the beginning of the test, the eight cells for testing were separated into two groups (4 cells for each group)—one group for industrial charging and another group for our proposed fast charging method. The same type of cells were used for testing of both methods. Among all other methods, we had selected the industrial charging technique because at the present time most small electric vehicle industries are using this technique for charging their battery. For industrial charging, a 0.5C (1650mA) rate had selected for charging and discharging. Before starting each charging and discharging cycle, 2 minutes was provided for rest, and after every cycle, 1-minute rest had given to the cells.

Our proposed fast charging technique has five different steps. During the fast charging technique, 0.5C (1650mA) current was used for reaching 2.5 voltage level in constant current-1 (CC-1) step. A lower current was used, initially, since the high current can significantly decrease the capacity when used for the initial charge. When the voltage had reached at 2.5V, the constant current-2 (CC-2) step started. For CC-2, 5500mA was provided until the voltage reached 3.55V. From the battery specification, we know that the maximum charging current is 2C (6600mA). It is not suitable for any cell to use its maximum cut-off charging current limit for a long time, therefore we used a maximum current below the maximum limit. When CC-2 touched 3.55V, then a 20-second rest was given. This rest period was provided for maintaining cell stability. For constant current-3 step (CC-3), 3965mA current used until the voltage reached the cut-off voltage 3.65V. At stage five, constant voltage (CV), 3.65 remained until the current reached at 33mA. Before starting the discharging, we had given two minutes' rest. Figure 17 depicts the fast charging technique used for this work.

For the industrial charging technique, we used the same time interval. During the fast charging technique we had used 5500mA for discharging and set the lower 2V for lower cut-off voltage. Based on the cell lower cut-off voltage, we fixed the cut-off point as the testing machine has the maximum 2C current limit for charging and discharging. Setting the limit to 2V will decrease the chance of internal damage and will help to maintain the long-time cell life. Before starting the next cycle, we had given 1 minute for rest.

Figure 18 shows the algorithm used for the industrial testing. For both methods continued the full cycle 200 times. After every 200 cycles, data was saved and analyized to identify any possible damage inside the cells and testing machine. After investigation, we started our testing again. The tests were repeated for a total of 1600 cycles for the fast charging technique. Due to the slower cycle time, only 657 cycles were completed on the same time period. The long term testing helped average out cycle-to-cycle variations.

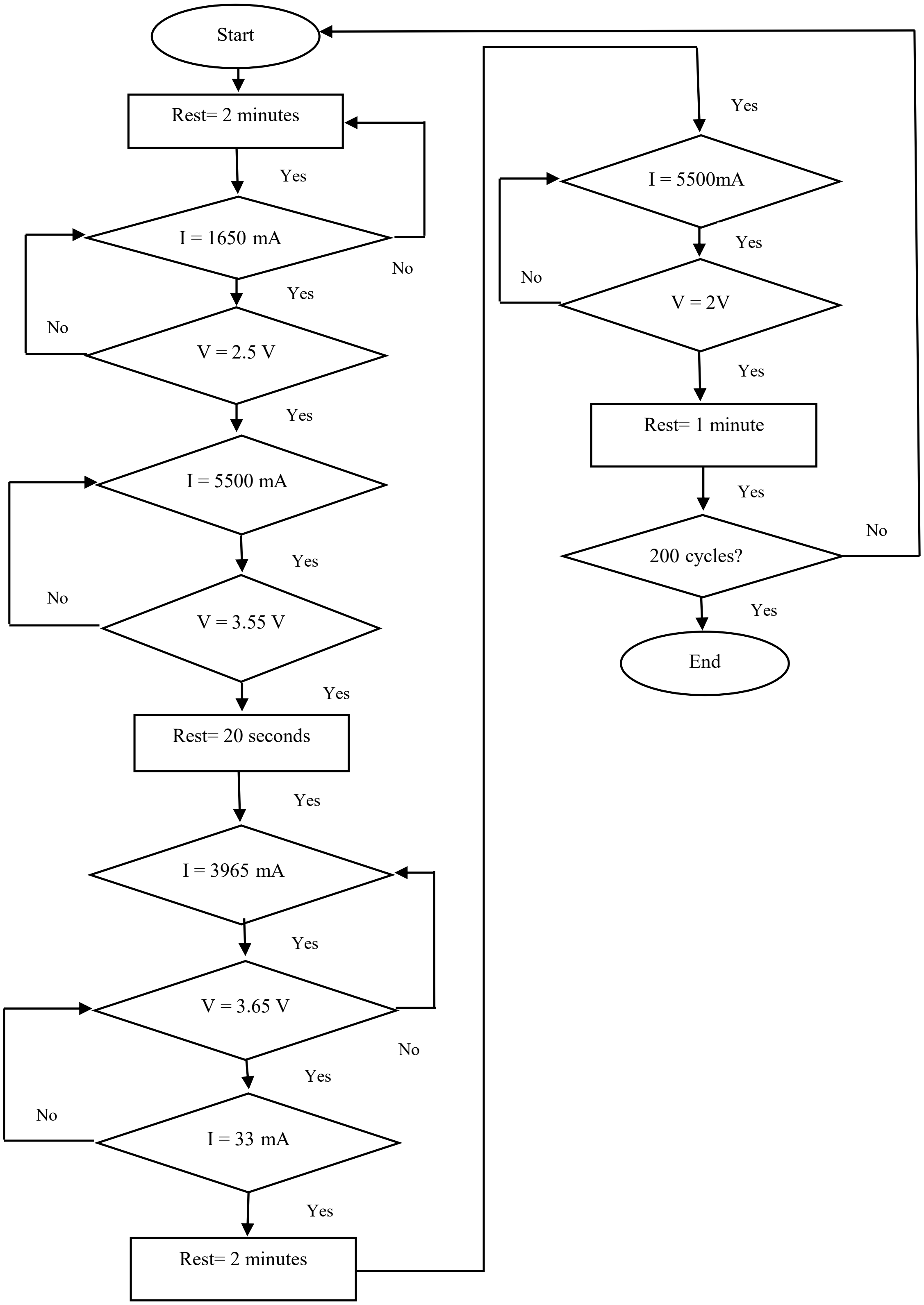

Figure 17: Proposed fast charging algorithm

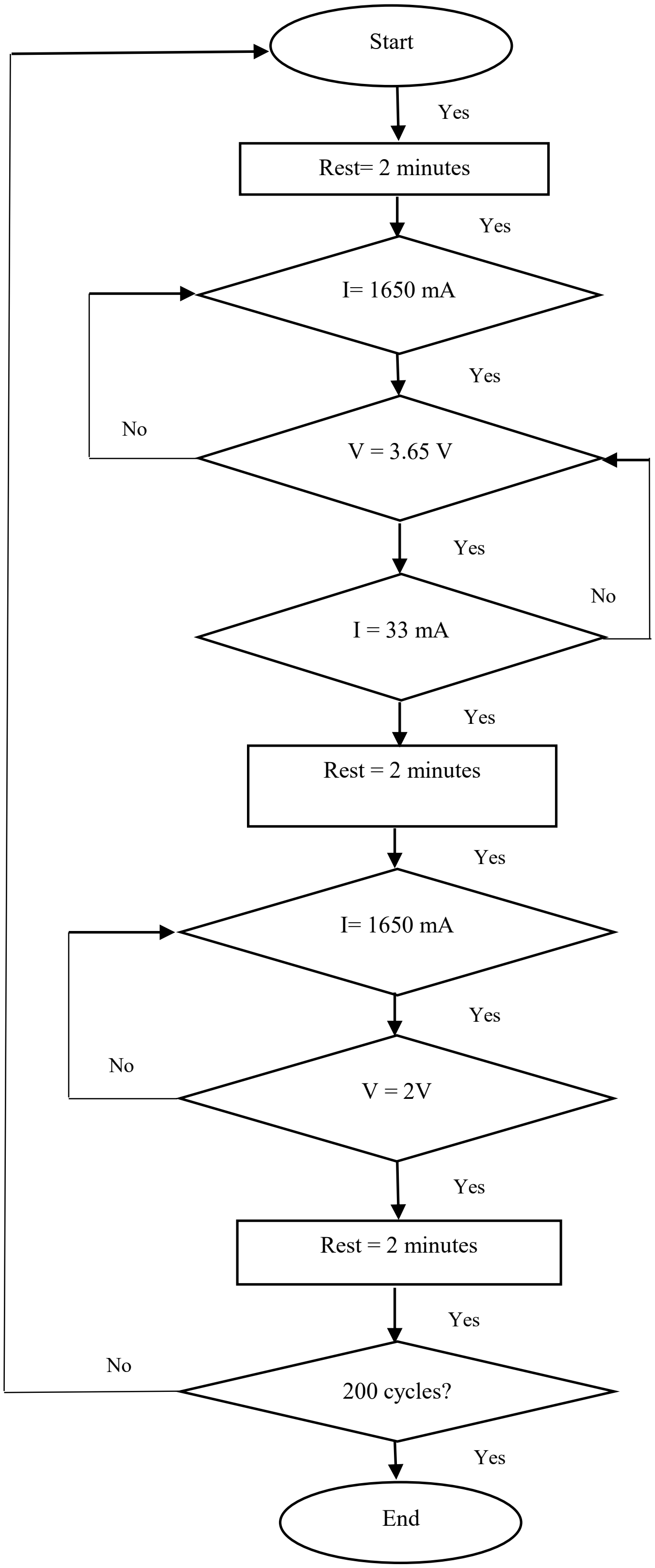

Figure 18: Industrial charging algorithm

4.2. Result and Discussion

Both charging algorithms were started at the same time. For the electric vehicle market and from lithium-ion cell characteristics, it can see that up to 20% capacity degradation is considered acceptable for maximum use. For some cases, the cell is still used until 25-30% capacity degradation, but this depends on its method and specific electric vehicle quality. Cell capacity can degrade for different reasons, but as our focus on finding the minimum charging time and maximum cycle life, we only tried to compare the cycling capacity degradation and charging time capability. First, we determined how many cycles each individual cell can run until 20% capacity degradation is reached. Then we averaged over 1600 cycles to find the maximum capacity degradation. During the fast charging technique, cell one had undergone 1508 cycles, cell two had 1679 cycles, cell three had 1496 cycles, and cell four had 1541 cycles before the 20% degradation limit was reached. All the cell chemistry is the same, however the number of cycles until 20% degradation varied. As this work didn’t focus on inside material behavior, the potential differences are not discussed here. Here our focus is on cycling aging. As number of cycles to 20% degradation are different, we took the capacity degradation for average 1600 cycles for our overall comparison. We saw that 1600 cycles was a good test duration. For these cycles, we determined how the capacity is changing and how much time it is taking for every step, the overall time for any single cycle, and the average time for charging and discharging. During fast charging for cell one the starting full discharge capacity was 3368 mAh, after 1600 cycles it was 2653 mAh, for cell two it was 3446 mAh, after 1600 cycles it was 2824 mAh. For cell three it was 3398 and 2604 mAh, and for cell four, it was 3401 and 2683 mAh. The average capacity for degradation was 20.9% with a standard deviation of 2.2%. The capacity difference between the 1st and 1600th cycles was 712 mAh and standard deviation was 70.6 mAh. The results are summarized in Table 7.

Table 7: Capacity changes for fast charging technique

Cell No	1st Cycle (mAh)	1600th Cycle (mAh)	Difference (mAh)	Capacity remaining (%)
1	3368	2653	715	78.8
2	3446	2824	622	82.0
3	3398	2604	794	76.6
4	3401	2683	718	78.9
Average			712	79.1
Capacity Degradation (%)=				20.9
Standard Deviation			70.6	2.2

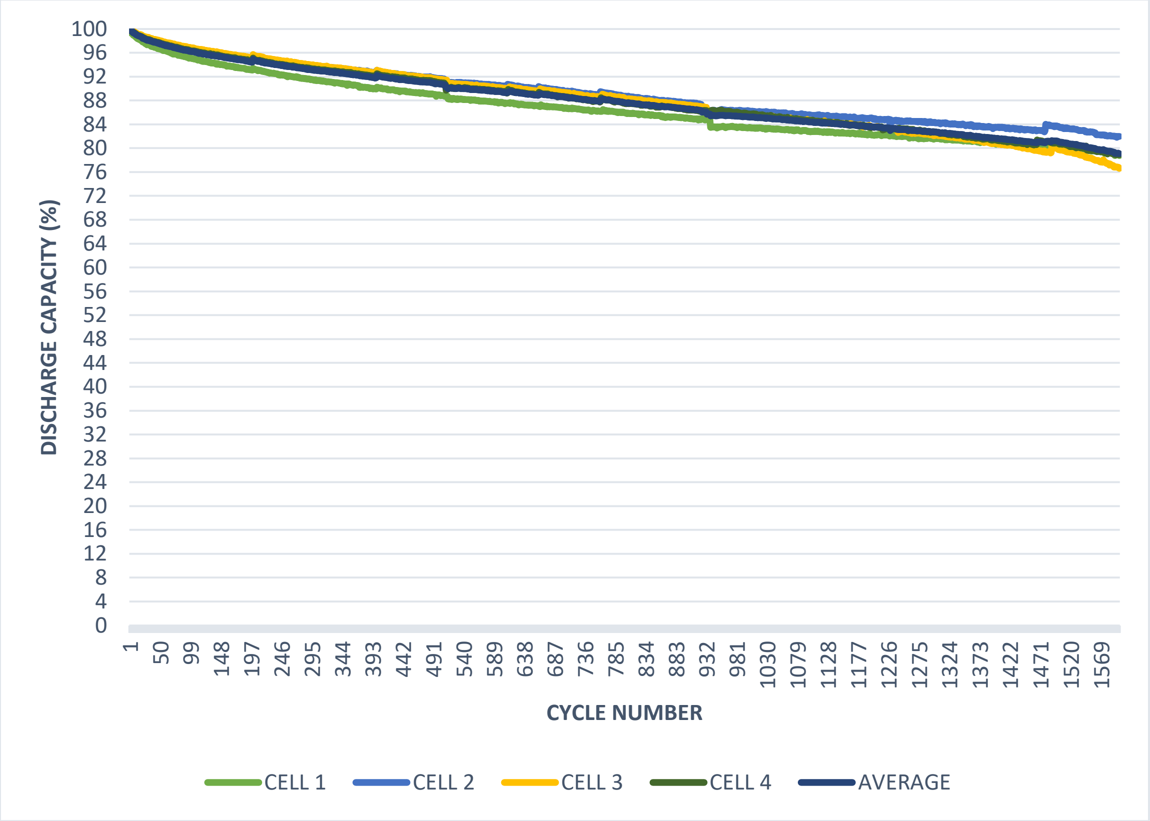

Figure 19: Behavior of discharge capacity with cycle number for fast charging technique

From Table 7, we can see the capacity degradation from the first to the 1600 cycle. From Figure 20, we can see the change in the discharge capacity for each cell and their average capacity degradation. From this table and figure, we can see that the capacity degradation rate for every cycle is 0.01%. For the batter understanding, we looked at how the cell's capacity degrades after the 1st, 500th, 1000th, and 1600th cycles. We also found how much average charge was achieved from each individual step and how much average time had taken to reach the charging level for four cells. Data is summarized in Table 8. Discharging time is summarized in Table 9.

During Fast charging the first stage took an average of 1 second, and this stage the cell charged near to 0.01% - 0.02%. From the second stage, we can see the variation in charging time as a function of cycle number. Initially, except cell one, others took an average 25 minutes to reach an average 66% charge, while cell one took 17 minutes to arrive at 46% charge. After 20 second resting period except for the first cell, the other three cells took an average 12 minutes to reach near 90% charge. This time first cell took 20 minutes to reach 87% charge. If we see the average overall time, then we can see 37.4 minutes was required to reach near 89.1% charge when the capacity is 100% . The last 10.9% charge took an average of 40.7 minutes while the average time for 100% discharge was 37.1 minutes when the capacity is 100%. From the data we can see after 500 cycles, 9.1% capacity degrade. This time for charging 87.7% after 500 cycles is taking 33.8 minutes. This is less than the initial stage but the capacity is also less than the beginning. At 500 cycles the last 12.3% charging is accomplished in 31.8 minutes. After 500 cycles the discharging time was 33.7 minutes. After 1000 cycles, the capacity had been degraded near to an average of 14.7% from the beginning. After 1000 cycles, 86.8% charging time was near to 31.8 minutes' average, and discharging time averaged 31.7 minutes. After 1600 cycles, 20% degradation was noted. Charging time was 29.7 minutes for an average of 85.2% charging and discharging time for 100% was 29.4 minutes. From our testing, we found that until 20% degradation, our proposed technique took 33.2 minutes for charging to 87.2% capacity before starting constant voltage state. It took an average of 68.4 minutes for 100% charging. From stage two data we can see 53.7% charge can achived by 18 minutes with the high constant current (CC 2) rate. The fourth charging stage carried less constant current (CC 3) than the previous step but was still able to manage 33.5% charge to reach a 87.2% charge in 14.9 minutes. The constant voltage (CV) stage took the maximum time to reach the 100% charge. This stage took an average of 35.5 minutes. This last 12.8% of charge took more charging time than the first 87.2% of charging. From the overall results, we can assume that in 30 minutes, this charging technique can charge the cell near to 80-85%. The average discharge time was 33 minutes. Here we showed 100% discharge . The capacity degradation cycle was 0.01% which is suitable for long term use. Data from each individual cell that was tested is given in the appendix A.

Table 8: Average charging time and charging level for Fast Charging Technique

		1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
		Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC 1	Mean	0.01%	0.02	0.01%	0.02	0.02%	0.02	0.02%	0.02
	SD	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0
CC 2	Mean	61.6%	22.9	58.4%	19.8	53.6%	17.1	41.1%	12.2
	SD	10.4%	4.0	9.7%	3.7	12.7%	4.4	15.4%	4.8

Rest	Mean	61.6%	0.3	58.4%	0.3	53.6%	0.3	41.1%	0.3
	SD	10.4%	0.0	9.7%	0.0	12.7%	0.0	15.4%	0.0
CC 3	Mean	89.1%	14.2	87.7%	13.7	86.8%	14.5	85.2%	17.2
	SD	1.6%	4.5	1.5%	3.6	2.2%	4.5	2.3%	6.2
CV	Mean	100.0%	40.7	100.0%	31.8	100.0%	33.6	100.0%	35.0
	SD	0.0%	2.9	0.0%	1.3	0.0%	5.1	0.0%	3.9
Total	Mean		78.05		65.57		65.50		64.60
	SD		11.38		8.48		13.92		14.89

Table 9: Average discharging time and discharging level for Fast Charging Technique

		1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
		Charge %	Time (m)	Charge %	Time (m)	Charge %	Time (m)	Charge %	Time (m)
Discharge	Mean	3402	37.1	3091	33.7	2902	31.7	2692	29.4
	SD	32.4	0.4	68.9	0.7	69.3	0.8	93.9	1.0
Capacity Remaining	Mean	100.0%		90.9%		85.3%		79.1%	
	SD	0.0%		1.3%		1.3%		2.2%	

Testing of the industrial charging method was started at the same time as the fast charging technique. During testing we found that our proposed fast charging algorithm is three times faster than present industrial charging. As a result, when the fast charging method had undergone more than 1600 cycles, the Industrial charging had only achieved an average of 657 cycles. During Industrial charging for cell one starting at full discharge, the capacity was 3437 mAh. And after 600 cycles, it was 3193 mAh; for cell two, it was 3432 mAh and after 600 cycles it was 3232 mAh. For cell three it was 3486 and 3258 mAh, cell four was 3429 and 3190 mAh. The average capacity decrease for four cells from 1st to 600th cycles was 227 mAh and standard deviation was 19.8 mAh, or a reduction of 6.6% of overall capacity and standard deviation 0.6%. Capacity changes for the industrial charging technique is provided in Table 10.

Table 10: Capacity changes for industrial charging technique

Cell No	**1st Cycle (mAh)**	**600th Cycle (mAh)**	**Difference (mAh)**	**Capacity remaining (%)**
1	3437	3193	244	92.9
2	3432	3232	200	94.2
3	3486	3258	228	93.5
4	3429	3190	239	93.0
Average			227	93.4
Capacity Degradation (%)=				6.6
Standard Deviation			19.8	0.6

From Table 10, we can see a capacity degradation of approximately 6.6% from the first to 600 cycles. From Figure 21, we can see the capacity degradation for each single cell and their average capacity degradation. From Table 10 and Figure 21 we can see that the capacity degradation rate for every cycle is 0.01%. Data is also presented for the capacity of the cells after the 1st, 300th, and 600th cycles, and how much average charge was added during each individual charging step and the average time required to reach that charging level. Data is summarized in Table 11. Discharging time is summarized in Table 12.

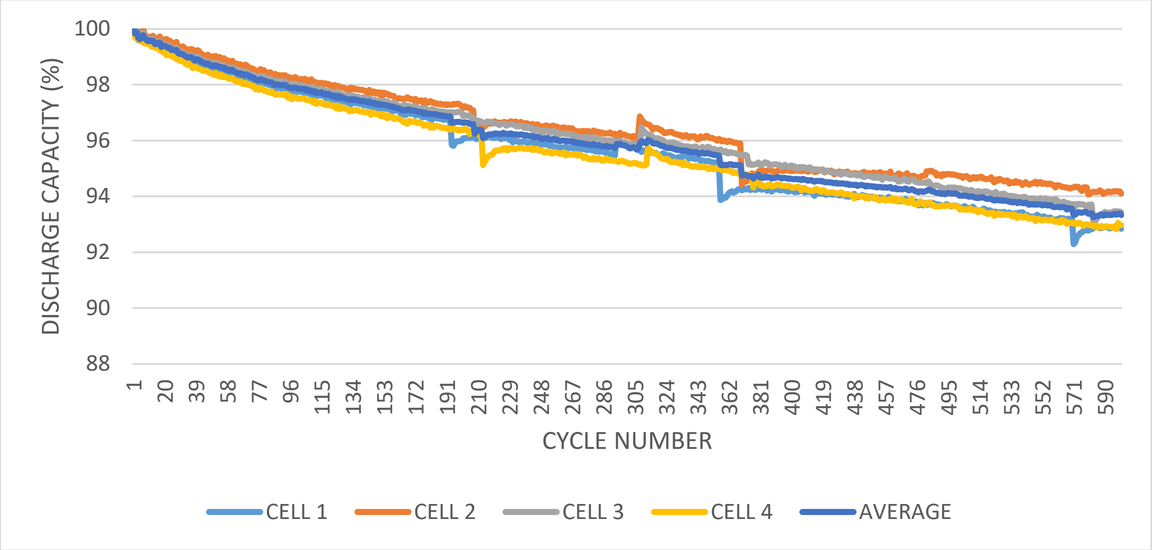

Figure 20: Behavior of discharge capacity with cycle number for industrial charging technique

For industrial charging, there are only two steps: constant-current and constant-voltage charging stage. During the 1st cycle capacity remained at 100% and for 100% charge it took 167 minutes. The constant current stage resulted in 93.7% charge in 116 minutes and last 6.3% charge took an additional 51 minutes. After 300 cycles, the capacity degraded 4.2%, and constant charging time was 112 minutes for 93.3% charge and last 6.7% charge took 43 minutes. An average of 120 minutes was needed discharge the cell after 300 cycles. After 600 cycles the capacity had decreased by on average of 6.2%. The charging time also decreased but was still more than 150 minutes to full charge. An average of 93.4% charge took place during the constant current phase for a charging time of 113 minutes. The remaining 6.6% charging took place during the constant voltage charging stage, and nearly 45 minutes to charge the last 6.6% of the cell. With the change of capacity, charging time and discharging time are also decreasing. It indicates that time is decreasing not for the technique, but due to the degradation of the capacity. Data from each individual cell that was tested is given in Appendix B.

The automatic algorithm processing capability of BTS-9 test system helped us to test different algorithms before determing the fast charging technique. Real-time battery testing requires a long time to test the cells. Therefore, some researchers test the cell in a simulation system to save time and money. However, real-time testing such as that used for this work provides more accurate information for any test. As our analysis used real-time testing the data is reliable. We tested our cells for a long time (up to 1600 cycles for fast charging and 600 cycles for industrial charging), however, our testing is not free from error. During long time testing, the testing machine sometimes stops due to internal disturbances. Sometimes it took, up to a few days to resolve the issue and restart the test. If cells “rest” without any use for a long time, they can gain some capacity level, creating an anomaly in real-time measurements. During our testing, we tried to avoid these errors. Still, in Figure 20 and 21, in the graphs show some interruption points as noted by the periodic rises in capacity. The interruption of the machine creates these data anomalies, but does not impact the overall accuracy or comparability of the results.

Table 11: Average charging time and charging level for Industrial Charging Technique

		1st Cycle		**300th Cycle**		**600th Cycle**	
		Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC	Mean	93.7%	116.2	93.3%	112.2	93.3%	109.3
	SD	0.4%	3.3	0.2%	1.1	0.4%	1.5
CV	Mean	100.0%	50.7	100.0%	42.8	100.0%	40.5
	SD	0.0%	3.1	0.0%	3.3	0.0%	2.8
Total	Mean		166.9		155		149.8
	SD		6.3		4.4		4.2

Table 12: Average discharging time and discharging level for Industrial Charging Technique

		1st Cycle		**300th Cycle**		**600th Cycle**	
		Capacity	Time	Capacity	Time	Capacity	Time
Discharge	Mean	3447.5	125.5	3302.6	120.2	3218.6	117.2
	SD	27.6	1.0	32.6	1.2	32.9	1.2
Capacity Remaining	Mean	100.0%		95.8%		93.4%	
	SD	0.0%		0.3%		0.5%	

For better comparison we compared the 1st to 600th cycle capacity difference and degradation for fast charging technique to the industrial charging technique. Table 13 shows the individual cell values for the fast charging technique. Similar values for the industrial charging technique were given in Table 10. Table 14, presents a 1st to 600th cycles comparison of the two charging techniques. From these results, it is seen that the fast charging technique is charging the cells 2.3 times faster (86.1 minutes less time) than the industrial charging method. This is the primary advantage at this technique. We show the capacity degradation for till 600 cycles for the two technique in Figure 22, allowing us to compare the capacity degradation that occurred over the 600 cycles. During the fast charging technique, we can see after 600 cycles, the overall capacity degradation is 10.5% as compared to 6.6% for an industrial charging technique. The standard deviation is 1.2% for fast charging capacity degradation and 0.6% for industrial charging capacity degradation. Figure 23, shows the cell to cell capacity difference comparison. This small difference in capacity loss is may be considered a small penalty when considering the significant savings in charging time. It should also be noted that during fast charging we can see capacity degrades more rapid for the 1st 500 cycles than the subsequent 500 cycles.

Table 13: Capacity changes for fast charging technique (Till 600th cycles)

Cell No	1st Cycle (mAh)	600th Cycle (mAh)	Difference (mAh)	Capacity remaining (%)
1	3368	2951	416	87.6
2	3446	3117	328	90.5
3	3398	3062	332	90.2
4	3401	3047	355	89.5
Average			358	89.5
Capacity Degradation (%)=				10.5
Standard Deviation			39.5	1.2

Table 14: Comparison between Fast Charging Technique and Industrial Charging Technique until 600th cycle

Charging Method	Fast Charging		Industrial Charging	
	Mean	STD Dev	Mean	STD Dev
1st Cycle (mAh)	3403	32.1	3446	27
600th Cycle (mAh)	3045	69.5	3218	32.7
Capacity Loss (mAh)	358	39.5	227	19.8
Capacity remaing (%)	89.5	1.2	93.3	0.6
Capacity Degradation (%)	10.5	1.2	6.6	0.6
Total charging time for 600th cycle (min)	63.7	2	149.8	2.8

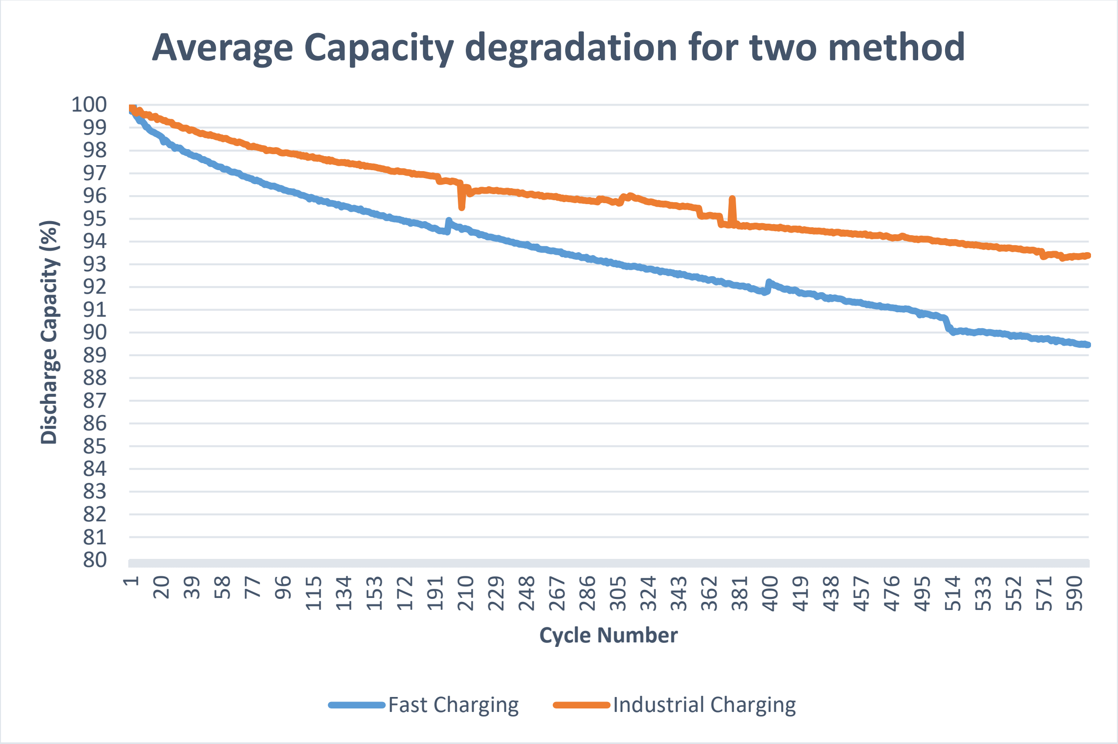

Figure 21: Comparison of average capacity degradation for 4 batteries for both methods

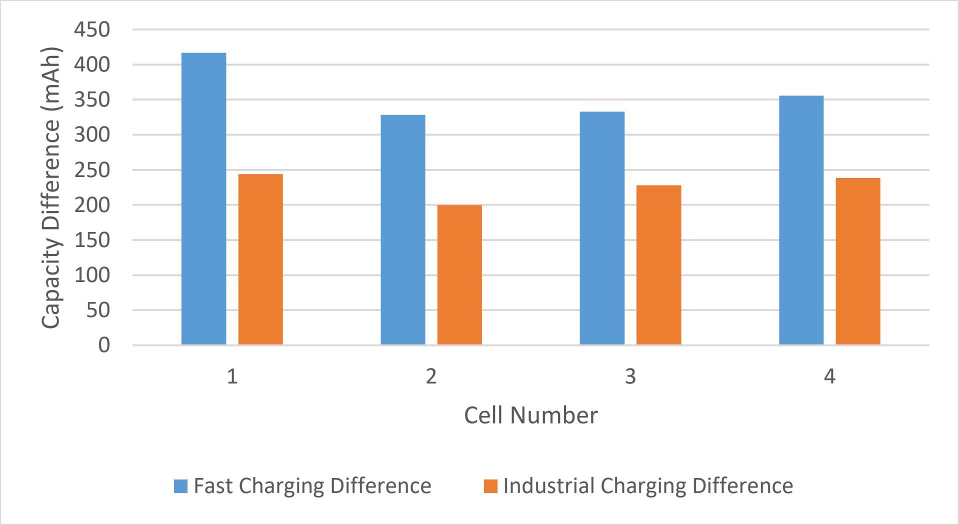

Figure 22: Cell to cell capacity difference comparison

CHAPTER FIVE: CONCLUSION AND FUTURE WORK

This thesis aims to develop a fast charging technique for lithium-ion cell. This fast charging technique will be able to charge the cell quicker and maintain a long-time cycling capability without affecting the cell capacity. Based on the target, we developed a fast charging algorithm and applied it to a 18650 lithium-ion cell. As our cell has standard specifications like most of the available lithium-ion cells for that, this technique is translatable to other available lithium-ion cells. For testing, we followed safety parameters and cell specifications to provide a relevant result for manufacturers. We used a Neware battery testing system, which has an excellent reputation in the lithium-ion cell testing field. In this thesis, we only focus on cycling aging. Temperature changes, pressure changes and internal cell chemistry changes are some important issues for the cell capacity degradation but were not observed during these tests. Our main goal was to decrease the charging time without decrease cycling life. Our results show that we were able to charge the battery approximately three times faster than present industrial charging while maintaining the cycle life near the industrial charging.

Our thesis results provide a lot of possibilities where researchers can work in the future. Our results came from testing of single-cells and represent a four cells average, however, the battery pack is different from single cells. It is possible incorporate advanced charging techniques into the large battery pack using a battey management system. A battery management system (BMS) is essential for any electric vehicle to maintain the battery pack. This BMS has a direct connection with charging methods. During our testing, the capacity didn’t degrade at the same rate for every cell. An improper charge management negatively impacting single-cells can destroy the battery pack. BMS can help provide equal distribution of charge among the cells. Advanced BMS can help to operate the battery pack more easier. Other future research can explore, the impact of temperature changes, state of charge, state of health, pressure changes and internal material changes. Improvement in cell performance can change the future market of electric vehicles.

REFERENCES

[1] EIA, “EIA projects world energy consumption will increase 56% by 2040 - Today in Energy - U.S. Energy Information Administration (EIA),” *Today in Energy*, 2013. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=12251. [Accessed: 09-Sep-2019].

[2] “What are greenhouse gases? - David Suzuki Foundation.” [Online]. Available: https://davidsuzuki.org/what-you-can-do/greenhouse-gases/. [Accessed: 09-Sep-2019].

[3] “EIA projects U.S. energy-related CO2 emissions will remain near current level through 2050 - Today in Energy - U.S. Energy Information Administration (EIA).” [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=38773. [Accessed: 09-Sep-2019].

[4] Department of Energy, “Wind Vision | Department of Energy,” 2015.

[5] J. B. Goodenough and K. S. Park, “The Li-ion rechargeable battery: A perspective,” *Journal of the American Chemical Society*, vol. 135, no. 4. pp. 1167–1176, 30-Jan-2013.

[6] R. Baroody, “Evaluation of rapid electric battery charging techniques,” 2009.

[7] T. R. (Thomas R. Crompton, “Battery reference book,” *Choice Rev. Online*, vol. 28, no. 03, pp. 28-1573-28–1573, 1990.

[8] M. Randall, “Electrolytic Cells,” *Am. J. Phys.*, vol. 7, no. 5, pp. 292–314, 1939.

[9] Battery Univerisity, “Information on the Invention of the Battery - Battery University,” 2016. [Online]. Available: https://batteryuniversity.com/learn/article/when_was_the_battery_invented. [Accessed: 10-Sep-2019].

[10] F. Decker, "'Volta and the "Pile,"'" *Electrochemistry Encyclopedia*. p. Case Western Reserve University, 2005.

[11] "Battery History | Dry and Wet Cell Battery History | Energizer." [Online]. Available: https://www.energizer.com/about-batteries/battery-history. [Accessed: 11-Sep-2019].

[12] M. Winter, B. Barnett, and K. Xu, "Before Li Ion Batteries," *Chemical Reviews*, vol. 118, no. 23. American Chemical Society, pp. 11433–11456, 12-Dec-2018.

[13] B. Scrosati, "History of lithium batteries," *Journal of Solid State Electrochemistry*, vol. 15, no. 7–8. pp. 1623–1630, Jul-2011.

[14] C. A. Vincent, "Lithium batteries: A 50-year perspective, 1959-2009," *Solid State Ionics*, vol. 134, no. 1–2, pp. 159–167, Oct. 2000.

[15] T. Yamabe, K. Tanaka, K. Ohzeki, and S. Yata, "Electronic structure of polyacenacene. A one-dimensional graphite," *Solid State Commun.*, vol. 44, no. 6, pp. 823–825, 1982.

[16] S. Yata, K. Tanaka, and T. Yamabe, "Polyacene (PAS) Bάtteries," *MRS Proc.*, vol. 496, p. 15, Feb. 1997.

[17] O. Haas, K. Mu, and O. Haas, "ChemInform Abstract : Electrochemically Active Polymers for Rechargeable Batteries Electrochemically Active Polymers for Rechargeable Batteries," no. MARCH 1997, 2015.

[18] Power Japan Plus, "PowerJapanPlus official," *powerjapanplus.com*, 2014. [Online]. Available: http://powerjapanplus.com/media/media/2.php. [Accessed: 11-Sep-2019].

[19] ProLogium Corporation, "ProLogium Corporation," *www.prologium.com.tw*, 2017. [Online]. Available: http://www.prologium.com.tw/TechnologyClass01.aspx. [Accessed: 11-Sep-2019].

[20] "CeraLink Capacitors - Ceramic Capacitors - Product Catalog - Products - Home - TDK Electronics - TDK Europe," *https://en.tdk-electronics.tdk.com/tdk-en/1054426/products/product-catalog/ceramic-capacitors/ceralink-capacitors*. [Online]. Available: https://www.tdk-electronics.tdk.com/en/ceracharge. [Accessed: 11-Sep-2019].

[21] G. W. Anand Bhatt, "Lithium-ion batteries - Curious," *Australian Academy of Science*. [Online]. Available: https://www.science.org.au/curious/technology-future/lithium-ion-

batteries. [Accessed: 12-Sep-2019].

[22] N. Omar *et al.*, “Rechargeable energy storage systems for plug-in hybrid electric vehicles-assessment of electrical characteristics,” *Energies*, vol. 5, no. 8, pp. 2952–2988, 2012.

[23] N. Nitta, F. Wu, J. T. Lee, and G. Yushin, “Li-ion battery materials: Present and future,” *Materials Today*, vol. 18, no. 5. Elsevier B.V., pp. 252–264, 01-Jun-2015.

[24] M. H. Noh, “Fast-charging of Lithium-ion batteries with ohmic-drop compensation method Mohd Hilmi Noh To cite this version : HAL Id : tel-01718584 Charge rapide de batteries Lithium-ion basée sur la compensation de chute- Fast-charging of Lithium-ion batteries with,” 2018.

[25] A. Barré, B. Deguilhem, S. Grolleau, M. Gérard, F. Suard, and D. Riu, “A review on lithium-ion battery ageing mechanisms and estimations for automotive applications,” *J. Power Sources*, vol. 241, pp. 680–689, 2013.

[26] I. Warshawsky, “The Electrochemical Behavior of Alkali and Alkaline Earth Metals in Nonaqueous Battery Systems—The Solid Electrolyte Interphase Model,” *J. Electrochem. Soc.*, vol. 127, no. 6, p. 1324, 1980.

[27] H. Buqa, A. Würsig, J. Vetter, M. E. Spahr, F. Krumeich, and P. Novák, “SEI film formation on highly crystalline graphitic materials in lithium-ion batteries,” in *Journal of Power Sources*, 2006, vol. 153, no. 2, pp. 385–390.

[28] M. Gauthier *et al.*, “Electrode-Electrolyte Interface in Li-Ion Batteries: Current Understanding and New Insights,” *J. Phys. Chem. Lett.*, vol. 6, no. 22, pp. 4653–4672, 2015.

[29] Q. Liu *et al.*, “Understanding undesirable anode lithium plating issues in lithium-ion batteries,” *RSC Adv.*, vol. 6, no. 91, pp. 88683–88700, 2016.

[30] S. Bourlot, P. Blanchard, and S. Robert, “Investigation of aging mechanisms of high power Li-ion cells used for hybrid electric vehicles,” *J. Power Sources*, vol. 196, no. 16, pp. 6841–6846, Aug. 2011.

[31] R. H. Peng *et al.*, “Switching-based charger with continuously built-in resistor detector (CBIRD) and analog multiplication-division unit (AMDU) for fast charging in Li-Ion

battery," *Eur. Solid-State Circuits Conf.*, pp. 157–160, 2013.

[32] Q. Lin, J. Wang, R. Xiong, W. Shen, and H. He, "Towards a smarter battery management system: A critical review on optimal charging methods of lithium ion batteries," *Energy*, vol. 183, pp. 220–234, 2019.

[33] R. Xiong, J. Tian, W. Shen, and F. Sun, "A Novel Fractional Order Model for State of Charge Estimation in Lithium Ion Batteries," *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 4130–4139, 2019.

[34] W. Shen, T. T. Vo, and A. Kapoor, "Charging algorithms of lithium-ion batteries: An overview," *Proc. 2012 7th IEEE Conf. Ind. Electron. Appl. ICIEA 2012*, no. November 2017, pp. 1567–1572, 2012.

[35] E. Ayoub and N. Karami, "Review on the charging techniques of a Li-Ion battery," 2015, pp. 50–55.

[36] H. Asadi, S. H. Aghay Kaboli, A. Mohammadi, and M. Oladazimi, "<title>Fuzzy-control-based five-step Li-ion battery charger by using AC impedance technique</title>," *Fourth Int. Conf. Mach. Vis. (ICMV 2011) Mach. Vision, Image Process. Pattern Anal.*, vol. 8349, no. December, pp. 834939-834939–6, 2012.

[37] Y. H. Liu and Y. F. Luo, "Search for an optimal rapid-charging pattern for li-ion batteries using the Taguchi approach," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3963–3971, 2010.

[38] Y. H. Liu, J. H. Teng, and Y. C. Lin, "Search for an optimal rapid charging pattern for lithium-ion batteries using ant colony system algorithm," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1328–1336, 2005.

[39] P. H. L. Notten, J. H. G. O. H. Veld, and J. R. G. Van Beek, "Boostcharging Li-ion batteries: A challenging new charging concept," *J. Power Sources*, vol. 145, no. 1, pp. 89–94, Jul. 2005.

[40] M. Ye, H. Gong, R. Xiong, and H. Mu, "Research on the Battery Charging Strategy with Charging and Temperature Rising Control Awareness," *IEEE Access*, vol. 6, pp. 64193–64201, 2018.

[41] E. Inoa and J. Wang, “PHEV charging strategies for maximized energy saving,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 2978–2986, 2011.

[42] H. E. Perez, X. Hu, S. Dey, and S. J. Moura, “Optimal Charging of Li-Ion Batteries with Coupled Electro-Thermal-Aging Dynamics,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 7761–7770, Sep. 2017.

[43] C. Zou, X. Hu, Z. Wei, T. Wik, and B. Egardt, “Electrochemical Estimation and Control for Lithium-Ion Battery Health-Aware Fast Charging,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6635–6645, 2018.

[44] L. R. Chen and C. H. Wu, “Sinusoidal ripple current charging system with PLL function,” *IEEE Int. Symp. Ind. Electron.*, pp. 1836–1841, 2014.

[45] “Battery Testing System,” p. 2001.

Appendix A

Individual cell test data for fast charging technique

Table 15: Charging time and charging level for fast charging technique (cell one)

	1st Cycle		500th Cycle		1000th Cycle		1600th Cycle	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC 1	0.01%	0.02	0.02%	0.02	0.02%	0.0	0.02%	0.0
CC 2	46.1%	17	43.9%	14.3	35.5%	10.9	19.6%	5.7
REST	46.1%	0.3	43.9%	0.3	35.5%	0.3	19.6%	0.3
CC 3	87.1%	20.9	85.8%	19	85.1%	21.1	84%	25.9
CV	100.0%	43.1	100.0%	30.9	100.0%	29.8	100.0%	29.7
Total		81.3		64.5		62.1		61.6

Table 16: Discharging time and capacity level for fast charging technique (cell one)

	1st Cycle		500th Cycle		1000th Cycle		1600th Cycle	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3368	36.7	2995	32.7	2807	30.7	2657	29
Capacity Remaining	100.0%		88.94%		83.35%		78.91%	

Table 17: Charging time and charging level for fast charging technique (cell two)

	1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC 1	0.01%	0.02	0.01%	0.02	0.02%	0.0	0.02%	0.0
CC 2	67.5%	25.4	63.4%	21.9	64.3%	20.9	55.4%	17.1
REST	67.5%	0.3	63.4%	0.3	64.3%	0.3	55.4%	0.3
CC 3	90.7%	12.1	89.1%	12.3	89.3%	11.3	88.6%	11.2
CV	100.0%	38.1	100.0%	31.7	100.0%	30.8	100.0%	34.5
Total		75.9		66.2		63.3		63.1

Table 18: Discharging time and capacity level for fast charging technique (cell two)

	1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3446	37.6	3159	34.5	2974	32.5	2824	30.8
Capacity Remaining	100.0%		91.7%		86.3%		82%	

Table 19: Charging time and charging level for fast charging technique (cell three)

	1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC 1	0.01%	0.02	0.01%	0.02	0.02%	0.0	0.02%	0.0
CC 2	67.7%	25.1	63.2%	21.5	60.1%	19.1	41.8%	11.9
REST	67.7%	0.3	63.2%	0.3	60.1%	0.3	41.8%	0.3
CC 3	90%	11.4	88.8%	12.1	88.0%	12.3	83.4%	16.4
CV	100.0%	38.2	100.0%	31	100.0%	32.8	100.0%	37.2
Total		75		64.9		64.5		65.8

Table 20: Discharging time and capacity level for fast charging technique (cell three)

	1st Cycle		**500th Cycle**		**1000th Cycle**		**1600th Cycle**	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3395	37.1	3113	33.9	2909	31.8	2604	28.4
Capacity Remaining	100.0%		91.7%		85.7%		76.7%	

Table 21: Charging time and charging level for fast charging technique (cell four)

	1st Cycle		500th Cycle		1000th Cycle		1600th Cycle	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC 1	0.01%	0.02	0.01%	0.02	0.02%	0.0	0.02%	0.0
CC 2	65.2%	24.2	63.2%	21.4	54.7%	17.4	47.6%	13.9
REST	65.2%	0.3	63.2%	0.3	54.7%	0.3	47.6%	0.3
CC 3	88.8%	12.2	87.3%	11.3	84.7%	13.3	85.1%	15.2
CV	100.0%	43.2	100.0%	33.6	100.%	41.0	100.0%	38.4
Total		79.9		66.6		72		67.8

Table 22: Discharging time and capacity level for fast charging technique (cell four)

	1st Cycle		500th Cycle		1000th Cycle		1600th Cycle	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3397	37.1	3096	33.8	2917	31.9	2683	29.3
Capacity Remaining	100.0%		91.1%		85.9%		79.0%	

Appendix B

Individual cell test data for Industrial charging technique

Table 23: Charging time and charging level for industrial charging technique (cell one)

	1st Cycle		300th Cycle		600th Cycle	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC	93.6%	111.6	93.2%	111.9	92.8%	108.0
CV	100.0%	50.6	100.0%	42.0	100.0%	40.8
Total		162.2		153.9		148.8

Table 24: Discharging time and capacity level for industrial charging technique (cell one)

	1st Cycle		300th Cycle		600th Cycle	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3438	125.1	3297	120.0	3194	116.3
Capacity Remaining	100.0%		95.9%		92.9%	

Table 25: Charging time and charging level for industrial charging technique (cell two)

	1st Cycle		300th Cycle		600th Cycle	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC	93.2%	116.6	93.1%	111.8	93.1%	109.6
CV	100.0%	54.8	100.0%	46.6	100.0%	44.2
Total		171.4		158.4		153.8

Table 26: Discharging time and capacity level for industrial charging technique (cell two)

	1st Cycle		300th Cycle		600th Cycle	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3436	125.1	3302	120.2	3232	117.7
Capacity Remaining	100.0%		96.1%		94.1%	

Table 27: Charging time and charging level for industrial charging technique (cell three)

	1st Cycle		**300th Cycle**		**600th Cycle**	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC	93.9%	119.3	93.4%	113.7	93.9%	111.3
CV	100.0%	50.1	100.0%	44.0	100.0%	37.9
Total		169.4		157.7		149.2

Table 28: Discharging time and capacity level for industrial charging technique (cell three)

	1st Cycle		**300th Cycle**		**600th Cycle**	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3488	127.0	3345	121.8	3258	118.6
Capacity Remaining	100.0%		95.9%		93.4%	

Table 29: Charging time and charging level for industrial charging technique (cell four)

	1st Cycle		**300th Cycle**		**600th Cycle**	
	Charge %	Time (min)	Charge %	Time (min)	Charge %	Time (min)
CC	93.9%	117.2	93.5%	111.2	93.4%	108.4
CV	100.0%	47.4	100.0%	38.7	100.0%	39.0
Total		164.6		149.9		147.4

Table 30: Discharging time and capacity level for industrial charging technique (cell four)

	1st Cycle		**300th Cycle**		**600th Cycle**	
	Capacity	Time (min)	Capacity	Time (min)	Capacity	Time (min)
Discharge	3427	124.8	3266	118.9	3189	116.1
Capacity Remaining	100.0%		95.3%		93.1%	