Samir Zagorčić, BSc

# Characterisation of Li-Ion batteries

**MASTER THESIS**

In Partial Fulfillment of the Requirements for the Degree of

Master of Science (M.Sc.)

**Graz University of Technology**

Supervisor : Ass.Prof. Dipl.-Ing. Dr.techn. Bernd Eichberger

Institute of Electronic (IFE)

Supervisor : Dipl.-Ing. Friedrich Luhn

Dialog Semiconductor

Graz, November 2014

# Declaration

I declare that I have authored this thesis independently, that I have not used other then the declared source/resource, and that I have explicitly marked all material which has been quoted either literally or by content from the used source.

Datum

Signature

Dialog Semiconductor

*The power to be ...*

# Abstract

Today a lot of mobile devices are used all over the world. "Mobile" indicates a usage of a transportable power supply to drive the devices. This power supply is provided from batteries, where several types are available on the market. Dependent of the used chemistry, the capacity differs. Also the behavior under specific conditions (load , temperature,...) is different. In addition the user of this devices should be able to get an information about how long the battery can be used until the divise is shutting down.

There are some ways to get the information about the battery status, but in most cases the accuracy is not sufficient. To increase the accuracy, mobile devices are using a so called "Fuel Gauge" (FG) which consists of a special circuitry for measureing the current and voltage of the batteries. In addition some calculation software is necessary to generate the information, which is then visible for the customer (mostly used in combination with a colored battery symbol on the display).

Measuring only the voltage and current of the battery leads to deviations. Other parametes, like temperature, aging, etc. are not taken into account during battery charge and discharge. After some time the user can no longer rely on the information about the battery status. Therefore, it is necessary to carry out corrections of the displayed values in order to achieve a better accuracy.

For these corrections a lookup table is necessary, which is created from several measurements and calculations. Components for this lookup table are the OCV (Open Circuit Voltage) table and the empty/flat table. The OCV table contains data from battery capacity at different temperatures without any load. The flat/empty table contains the information about the battery in lower voltage area with certain load conditions. This area is dependent on the chemistry of the used battery, so it is necessary to characterize the used batteries under several conditions to find out the data for the lookup table.

With all these informations the FG can be readjusted (calibrated) if necessary or if special calibration conditions are reached. The calibration of FG with these tables is usually performed when the battery is connected to the mobile device for the first time.

The aim of this work is to create a proper setup for the characterization of the batteries where discharge is performed with different ($C_{rate}$) and different temperatures are used. The second part of this thesis is writing a program to collect a large number of recorded data, processing them and create the lookup table. For processing this data, Python programming language and Gnuplot for graphical check of the results will be used. The last step is to create a new firmware for the charger chip that incorporates the new lookup tables.

With a defined setup and a program that performs data processing, it should be possible to characterize any battery. This should lead to the relization of an overall accuracy within a +/- 1 % deviation of the FG related to the actual capacity of the battery.

# Acknowledgement

I am using this opportunity to express my gratitude to everyone who supported me throughout the course of this Master Thesis. I would like to thank my supervisor, Ass.Prof. Dipl.-Ing. Dr.techn. Bernd Eichberger at the technical University of Graz, for all his guidance.

I express my warm thanks to Dpl.-Ing. Friedrich Luhn for his support and guidance at Dialog Semiconductor. I couldn't wish for a better or friendlier supervisor. I wish also to thank all my colleagues at Dialog Semiconductor who always shared their precious time and answered all my questions. I'm really glad to be part of so nice team.

Special thanks are due to my friends and colleagues, who made my life and study time in Graz more interesting and supported me over the years.

Last but not the least important, I owe more than thanks to my family members which includes my parents Slađan and Suada and brother Azer, for encouragement throughout my life. Without their support, it would impossible for me to finish my college and graduate.

# Thesis Structure

The first part of the thesis describes the discovery and development of batteries throughout history, their use and application. This section also gives an overview about the chemical elements which are used in the production of batteries. In additon, the basic classification of the batteries on primary and secondary batteries is shown.

The second part contains informations especially about the Lithium-Ion battery with its chemical and electrical properties. This section discusses the development of lithium batteries, their classification and usage as well as the limitations and precautions when using lithium-ion batteries.

The third part describes the process and developing the setup (including an reference setup) for the battery characterisation.This also contains the processing of data and some facts about processing where it is necessary to pay attention to avoid bad accuracy. A graphical evaluation of the data which are obtained during battery discharge should give a short check compared to the calculated values. Also the behaviour of single batteries during the test and the (different) behaviour of the same batteries at different temperatures is visible in this section. In addition the procedure for creating the tables and the new firmware for the chip is shown.

The last part of this thesis gives an impression how to use the obtained tables, the calculation of the FG errors related to the reference setup and discussion about the results.

# Acronyms

**V** Volt

**A** Ampere

**e** Electron

$\mathbf{Na^+}$ Natrium

**FG** Fuel Gauge

**°C** Celsius

**I** Current

$\mathbf{I_{load}}$ load current (discharge current)

$\mathbf{V_{terminate}}$ Terminate voltage of application

**T** Temperature

$\mathbf{B_n}$ Battery Number

**LUT** LookUp Table

**FCC** Full Charge Capacity

**C** Coulomb

**C-rate** Charger Rate

$\mathbf{Q_n}$ Nominal Capacity

**Q** Capacity

**SOC** State Of Charge

**CCV** Close Circuit Voltage

**Ah** Ampere hour

**mio** Million

**OCV** Open Circuit Voltage

**CH** Channel

**PC** Personal Computer

**USB** Universal Serial Bus

**OHP** Over Heat Protection

**OCV** Over Current Protection

**OVP** Over Voltage Protection

**RS-485** Serial communication interface

**DUT** Device Under Test

**CV** Constant Voltage

**CC** Constant Current

**EV** Electrical Vehicles

**NMC** Lithium manganese cobalt oxide

**LMO** Lithium manganese oxide

**LCO** Lithium cobalt oxide

**$\mathbf{LiClO_4}$** Lithium perchlorate

**$\mathbf{LiAsF_6}$** Lithium hexafluoroarsenate

**$\mathbf{LiBF_4}$** Lithium tetrafluoroborate

**$\mathbf{LiPF_6}$** Lithium hexafluorophosphate

**DMC** Dimethyl carbonate

**DMS** Dimethoxyethane

$\gamma$-**BL** gamma-Butyrolactone

**PC** Propylene Carbonate

**EC** Ethylene Carbonate

**US$** United States dollar

**NiMh** nickel–metal hydride

**$Li-FeS_2$** Lithium Iron Disulphide

**m** Meter

**min** Minute

**s** Second

**kg** Kilogram

**l** Liter

**Wh** Watt hour

**W** Watt

**Li-Ion** Lithium Ion

**NiCd** nickel – cadmium

**$NH_4Cl$** Ammonium chloride

**$H_2O$** Water

**$MnO_2$** Manganese oxide

**$SO_4$** Sulfate

**Cu(S)** Copper sulfide

**Cu** Copper

**O** Oxide

**Zn(s)** Zinc sulfide

**Zn** Zinc

**UPS** Uninterruptible Power Supply

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Batteries

## 1.1 Battery Developments

One of the most important discoveries in last four hundred years is electricity. The discoveries in this scientific field are much more older but man was not taught its use. The oldest form of getting electricity is the use of static electricity. For first time the word battery was used by Benjamin Franklin in 1749. He used this word to describe his device with connected capacitors. The battery represents specific way of "storing" energy in chemical form, then converting it into electrical energy. This battery is known as a primary cell. Secondary batteries have the possibility of "regeneration", so recharging is possible. They are able to transform electricity into chemical energy. Technically, a battery is made of several galvanic elements. Each battery contains three basic elements: anode, cathode and electrolyte. The anode is the negative electrode and its purpose is to oxidize and release electrons, while the cathode makes reduction in the process of electron accepting. To separate the anode and cathode an electrolyte is used which is a good conductor of protons, but a poor conductor of electrons. In 1936 archaeologists found an interesting bottle, about 2000 years old, near Baghdad. It was made of clay with the copper cylinder placed in the middle. The container was fastened with asphalt on the top. A copper cylinder was placed inside the oxidized metal tube not touching the bottom of cylinder, the top was only one centimeter outside the vessel. The entire compound filled with a liquid as "electrolyte" indicates the usage as a battery. In scientific experiments and provings, scientists made carved replica of that bottle and filled it with wine solution. The measured voltage in the battery was up to 2 V. This device is called Baghdad battery.

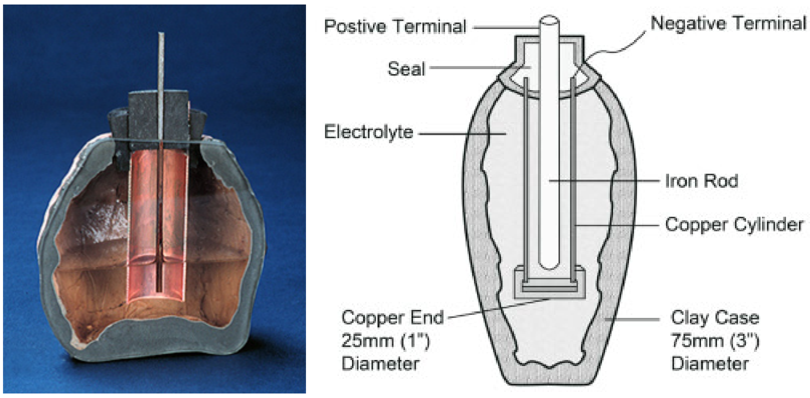


Figure 1.1: Baghdad battery [1].

Officialy, the development of batteries started in 1800 s when Alessandro Volta constructed the so-called Voltaelectric pillar . Volta's electric pillar represents the dry cell element. This was the first type of primary batteries that could be used in practical applications. Voltas pole (voltaic pole) is a battery consisting of alternating piles made of copper and zinc. As an electrolyte between the plates he used a cardboard. Volta experimented with different materials, but copper and zinc gave the best results. The invention was very important for the field of electrochemistry and electricity.

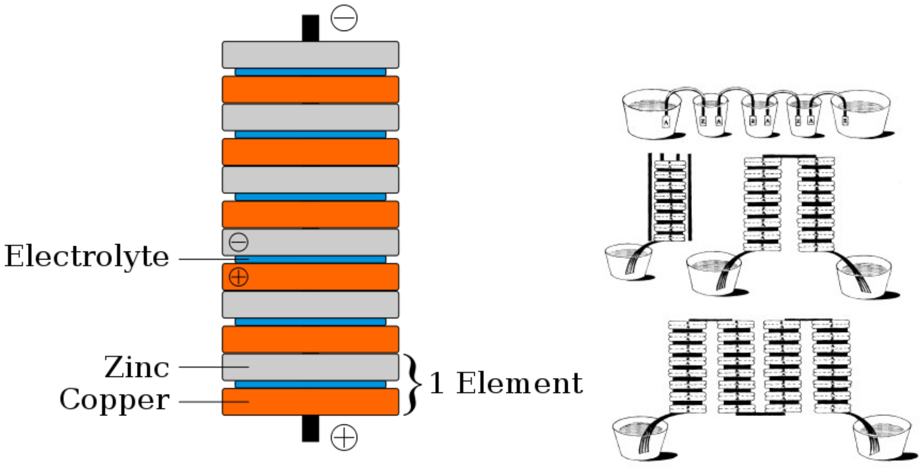


Figure 1.2: Voltaic pile [2].

The first primary cell for mass production was designed by William Cruickshank in 1802. This was the improved version of Volta's battery.

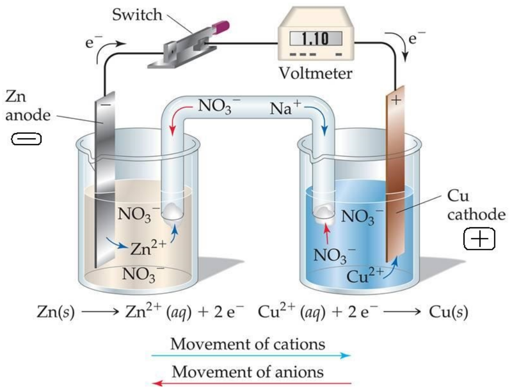


Figure 1.3: Daniell cell battery [3].

John Federico Daniell also carried out experiments similar to Volta. Unlike Volta, Daniells took anode and cathode and immersed them in separate containers with different electrolyte solution (solution of copper sulfate and sulfuric acid solution). This has enabled the improvement of used batteries so far. This battery gave more energy and lasted longer than the Volta pillar. The voltage in this experiment was 1.1 V

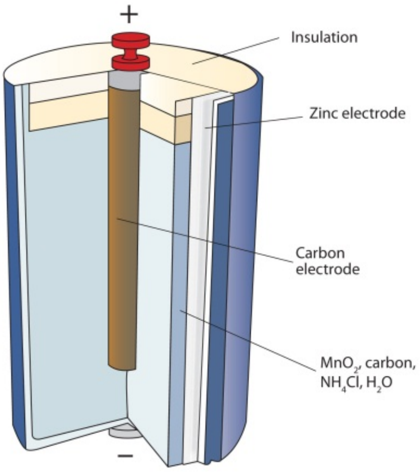


Figure 1.4: Leclanché battery [4].

Georges Leclanché patented a new type of cells in 1866. Its voltage was 1.5 V. Anode and cathode were made of graphit which were dipped in an electrolyte of ammonium chloride. Later, this electrolyte was replaced with a moist electrolyte paste (gel) in order to obtain so-called dry batteries.

These cells were primary cells and could not be recharged. In 1859 french physicist Gaston Plante invented the first battery with storage functionality (secondary cell). This cell was initially placed in a wooden or glass containers and contained two lead ballots that were separated by a rubber band and wrapped into a spiral. This was the first battery where charge and discharge was possible. These batteries were often used in trains, they were bulky and heavy. In 1881 Camille Faure used the lead net inside the battery and created an accumulator, which is still used in automobile industry. In 1899 swedish scientist, Waldemar Jungner built the first alkaline battery whose electrodes were made of nickel-cadmium (NiCd). In 1910 he started production of these batteries in Sweden and in America in 1946. The batteries were very solid, they produced elecricity much better but they were expensive.

NiMH battery exploration was started at the beginning of the 1970s. They have a longer lifetime than NiCd batteries and they are more environmentally friendly. Yet in 1920 s they started experiments with lithium batteries and finally in 1970, the first lithium ion battery was sold. At the beginning of the 1980 s, chemist John B. Goodenough gathered a team that produced a Li-Ion battery. It was more stable than ordinary lithium batteries. The first Li-Ion battery was sold in 1991.

## 1.2 Battery definitions

**Cell**

It is a basic electrochemical unit. Purpose of it is creating electric energy derived from chemical energy. Basically, it consists of two electrodes immersed in electrolyte.

**Battery**

It represents a combination of two or more cells connected in series or parallel order to get the optimal capacity or voltage for a specific load.

**Nominal Voltage**

The nominal voltage is the one that is generally used as typical value for the operating voltage of the battery.

**OCV**

open cicuit voltage represents the voltage of the battery without load. OCV of fully charged batteries may be higher than the nominal voltage

**CCV**

close circuit voltage represents the battery voltage while the battery is loaded.

**Cut-off Voltage**

The minimum allowed voltage. It is the voltage that generally defines the "empty" state of the battery [1].

**Capacity**

It is the amount of energy that can be stored in the battery. Nominal capacity is the one that is guaranteed by the manufacturer for new batteries. Battery capacity is presented in (m)Ah. A battery that has a capacity of 2000 mAh, can be discharged in one hour if the nominal current of discharge is 2 A for tis time. This is equvalent to the discharge rate of "1C", or

e. g. if the nominal current of discharge is 1 A in two hours (=0.5C) and so on. This relationship is also valid for the charging process of the battery.

**Energy Density**

It is the volumetric energy storage density of a battery, expressed in watt-hours per liter (Wh/l)

**Power Density**

It is the volumetric power density of a battery, expressed in Watts per litre (W/l)

**Rated Capacity**

It represents the capacity of a battery, expressed in Ampere-hours (Ah), which is the total charge expressed in Ah that can be obtained from a fully charged battery under specified discharge conditions. These conditions are specified by the manufacturer.

**Specific energy or gravimetric energy density**

It defines the battery capacity in weight (Wh/kg). A battery can have a high specific energy but poor specific power (load capability), as is the case with alkaline batteries. Alternatively, a battery may have a low specific energy but it can deliver high specific power. This is possible with a supercapacitor. Specific energy is synonymous for the battery capacity and runtime[1].

**Specific power**

Specific power or gravimetric power density indicates the loading capability, or the amount of current the battery can provide. Batteries for power tools have high specific power but reduced specific energy (capacity).[1].

**Load**

A load draws energy from the battery. Internal battery resistance and depleting state-of-charge cause the voltage to drop.[1].

### State of Charge ($\mathbf{SOC_{\%}}$)

An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated out of several parameters.[9]

$$SOC = \frac{Q(t)}{Q_n} \tag{1.1}$$

### FCC

Full Charge Capacity represents the max. battery capacity

### $\mathbf{C_{rate}}$ (Charger rate)

Charles-Augustin de Coulomb claimed that a battery, that receives a charge current of one ampere (1 A) passes one coulomb (1 C)in charge every second. The C-rate is a measure of the rate at which a battery is charged/discharged relative to its maximum capacity.

$$C_{rate} = \frac{I}{FCC} \tag{1.2}$$

A 1000 mAh battery that is discharged at 1 C rate should, under ideal conditions, provide a current of 1000 mA for one hour. The same battery discharging at 0.5 C would provide 500 mA for two hours, and at 2 C, the 1000 mAh battery would deliver 2000 mA for 30 minutes in ideal case. In reality only new batteries are close to this values.

### Internal resistance

The resistance within the battery is generally different for charging and discharging[9]. The internal resistance is also dependet on the SOC.

## 1.3 Battery classification according to the shape and size

Nowadays, it is possible to find batteries in different shapes and sizes. They can be applied in mobile devices, communication devices, watches, cars and so on.

Figure 1.5: Battery shapes and sizes

According to their basic function batteries are divided into primary cells, those which have no possibility of renewing the "chemical storage" (not rechargeable) and secondary batteries, which have the possibility of recharging or returning electricity into chemical energy

Example of battery shapes and sizes:

1. The most common sizes of cylindrical batteries are:
    (a) AAA - 10.5 x 44.5 mm
    (b) AA - 14.5 x 50.5 mm
    (c) C - 26.2 x 50 mm
    (d) D - 34.2 x 1.97 mm
2. Non-cylindrical batteries:
    (a) 4.5 Volt - H: 67, L: 62 mm W22
    (b) 9 Volt - H: 48.5, L: 26.5, W: 17.5 mm
    (c) Lantern - H: 115, L: 68.2, W: 68.2 mm
    (d) Button Cell
    (e) Prismatic Cell
    (f) Pouch Cell

## 1.4 Primary batteries vs. Secondary batteries

Even nowadays as the development of the secondary battery has a growing priority, primary batteries are still widely used. For example if charging is not possible or it is difficult to achieve optimal charge, primary batteries have a significant role. Their energy storage capability is much higher than the secondary battery, they are less harmful to the environment, they can be stored for a very long time and there are no major storage problems because their self-discharge is very small. They are used in applications where power consumption is low, such as in children's toys, clocks, pacemaker's battery. They also play a very important role in the military industry and equipment intended for rescue at sea, in a forest fire, etc. Until the 1970s, primary batteries had a zinc anode. Their function was based on the Leclanché battery (carbon-zinc). This was the cheapest and the most common used battery. In this period new compounds began to dominate such as zinc-mercury oxide, alkaline manganese dioxide, and zinc-silver oxide. Alkaline batteries provide much more energy with increased load. Their disadvantage is that they are more expensive and release toxic gases during discharge. Lithium iron disulphide represents an upcoming, new generation of primary batteries. $Li{-}FeS_2$ can provide voltage of 1.5 V, they have much higher capacity and lower internal resistance. Another advantage of these batteries is their use at low temperatures, low emissions of toxic substances and gases and a very small self-discharge. Their disadvantage is the price and transport problems caused from additional safety requirements. Primary batteries have one of the highest energy density. Even secondary batteries are very good in everyday use and their development is still going on, an ordinary primary alkaline battery can deliver up to 50 % more energy than a lithium-ion battery of the same size.

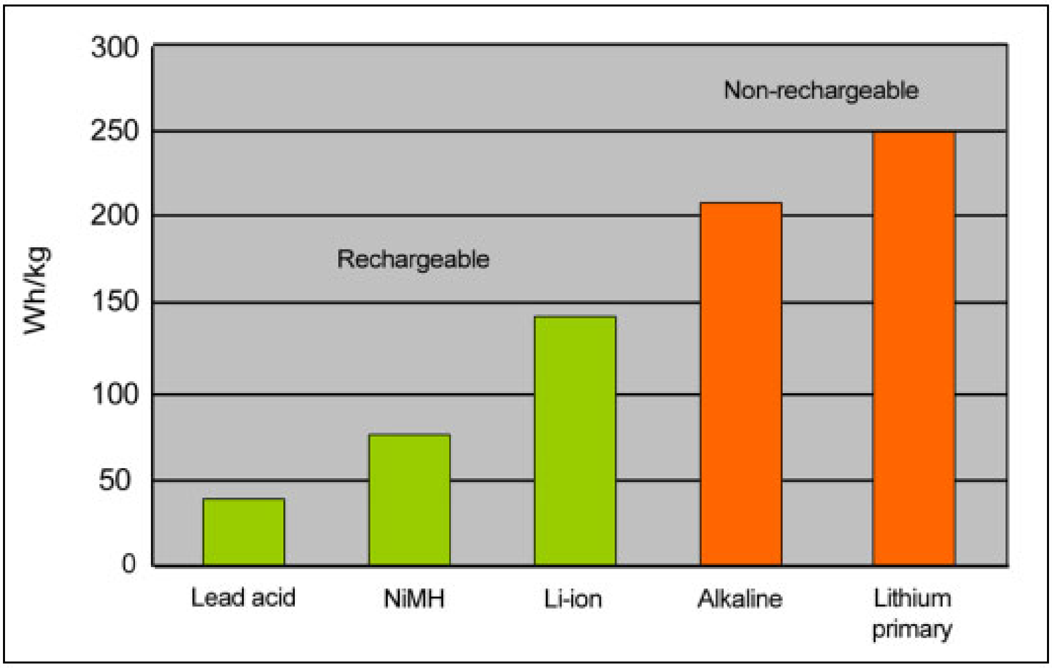


Figure 1.6: Specific energy comparison of secondary and primary batteries [1].

Figure 1.6 shows the gravimetric densities of several primary and secondary batteries. Gravimetric energy density "controls" the weight of the battery required for a given output energy. Secondary batteries are typically validated at 1 C discharge. Primary batteries have a much lower rate of discharge.

All manufacturers of primary batteries are publishing the specific energy in batteries specifications [1]. Primary batteries have a very large internal resistance and a very small self discharge compared to secondary batteries.

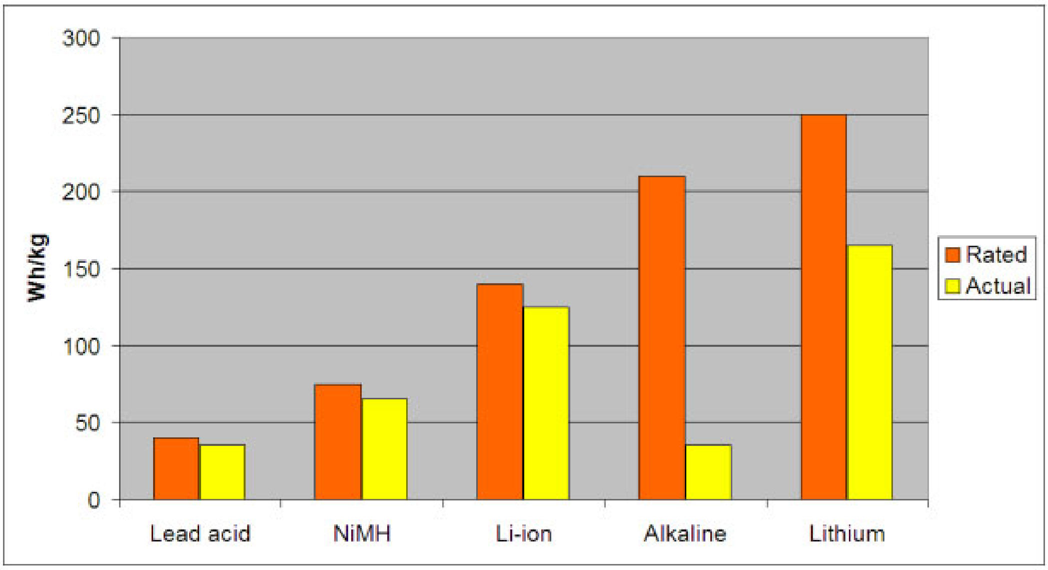


Figure 1.7: Energy comparison under high load.[1]

Figure 1.7 represents the performance of primary and secondary batteries in applications such as a digital camera. Actual Wh / kg, that a battery delivers during discharge at 1 C, and the related one Wh / kg is defined by manufacturer during battery discharge at very low current.

The reason for lack of performances of primary batteries is a high internal resistance that causes a large voltage drop during high current discharge. The choice of batteries depends on the applications in which batteries are used. There is no battery system that fits all applications and delivers maximum performance. It is necessary to determine which battery specifications are required for a particular application. There are three basic applications that use the primary batteries:

- Miniature equipment
- Mobile devices with low current consumption (e.g remote control unit)
- Standby/backup support (e. g. battery back up clocks, etc)

A high number of requirements influences the decision for choosing a specific battery. For selection of the "right" battery, it should be choosen that one, which fulfills the important features or needs, e. g .:

- Maximum voltage after charging
- Normal voltage during discharge (voltage stability on load)
- End-voltage: lowest allowed voltage for the battery during discharge
- Capacity [mAh]
- Type of discharge: continuous, intermittent, pulsed
- Storage
- life cycle
- Environmental conditions in storage and in service
- Physical restrictions such as dimensions and weight
- other special requirements

During the last ten years, e. g. armies and emergency teams have switched to rechargeable batteries. Improvements in battery technology, better charge methods and more readily available power sources made it possible. The most important reason, however, is cost, where primary cells are less expensive. But rechargeable batteries are able to provide power when a supply with fresh batteries is not possible. The batteries can be charged through solar power, windmills and hand-crank generators. Another advantage of secondary batteries is their low internal resistance. This allows high current on demand, an attribute that is essential for digital devices and instruments (e. g. high inrush currents). Rechargeable batteries have their limitations. Beside lower energy density, secondary batteries have a defined shelf life and lose the capacity with increasing number of charging cycles. While a primary battery has a shelf life of 10 years, lithium-based batteries can be stored for 2-3 years. Storage under cool conditions at a 40 % charge level increases the shelf life.

Nickel-based batteries are usable for 5 years (and longer) but require priming to regain the performance after long storage. Another disadvantage of rechargeable batteries is the high self-discharge. E. g. Nickel-based batteries exhibit a 10-20 % self-discharge per month, 5-10 % for lithium and lead-based batteries. The self-discharge increases at higher temperatures. For this reason, secondary batteries are not an effective media for long-term energy storage; primary batteries are better suited.

## 1.5 Comparison of Secondary Batteries

### 1.5.1 Lead Acid

Lead-Acid is one of the oldest rechargeable battery systems. They are rugged, forgiving if abused and economical in price, have a low specific energy and limited cycle life. Lead acid is used for wheelchairs, golf cars, personnel carriers, emergency lighting and uninterruptible power supply (UPS).

### 1.5.2 Nickel-Cadmium (NiCd)

Is used where long service life, high discharge current, extreme temperatures and economical price are of importance. Due to environmental concerns (cadmium is poisonous), NiCd is being replaced by other chemistries, like NiMH. Main applications are power tools, two-way radios, aircraft and UPS.

1. Advantages of NiCd batteries:
    (a) Quick and easy charging, even after long storage
    (b) They can have over 1500 charge/discharge cycles
    (c) Long storage time in any state of charge
    (d) Easy storage and transport
    (e) Good characteristics at low temperatures
    (f) Available in various shapes and designs
2. Disadvantages:
    (a) Relatively small capacity compared to newer batteries
    (b) Memory effect and they should be periodically charged-discharged for ensuring a long service life

   (c) Containing hazardous metals
   (d) They have a relatively large self discharge and require charging after storage

### 1.5.3 Nickel-Metal-Hydride (NiMH)

A practical replacement for NiCd; has higher specific energy with less toxic metals. NiMH is used for medical instruments, hybrid cars and industrial applications. NiMH is also available in several shapes for consumer use.

1. Advantages:
   (a) 40-50 % higher capacity than NiCd batteries and there is the potential for even better performance
   (b) Easy storage and transport
   (c) recycling potential
2. Disadvantages:
   (a) In case of deep discharge, especially due to large current the life span of the battery is shortened
   (b) Compared to Nickel-based batteries (good in quick charge),not all NiMH can be charged fast. The temperature rises up caused by a charge current that is too high, or when overcharging battery.
   (c) They have about 50 % higher self discharge than NiCd batteries. New improvements have reduced the problem, but the capacity is unfortunately also reduced
   (d) Increased sensitivity to temperature and for shelf storage they should be kept in a cold place at 40 % charge
   (e) Around 20 % more expensive compared to NiCd batteries, especially those that are designed for high current

### 1.5.4 Lithium-ion (Li ion)

Most promising battery systems up to now it is used for portable consumer products as well as electric powertrains for vehicles; more expensive than nickel- and lead acid systems and needs protection circuit for safety. The lithium-ion family is divided into three major battery types, so named by their cathode oxides, which are cobalt, manganese and phosphate.

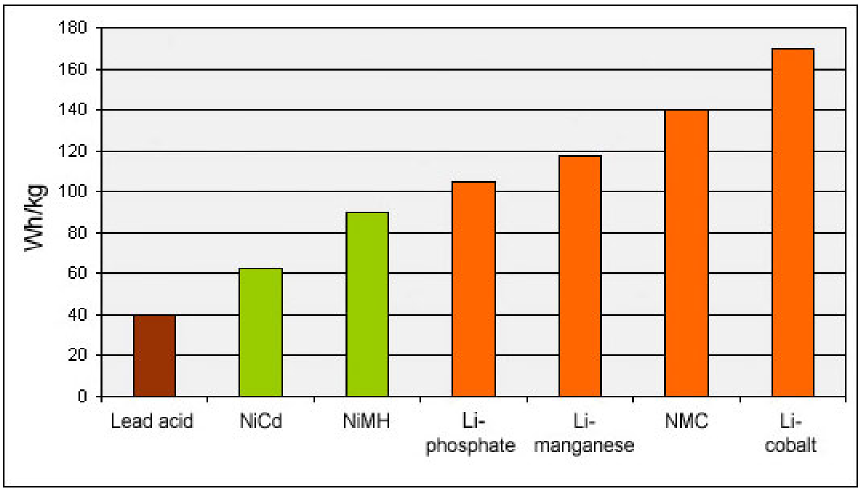


Figure 1.8: Typical energy densities of lead, nickel- and lithium-based batteries[1].

## 1.6 Global Battery Market

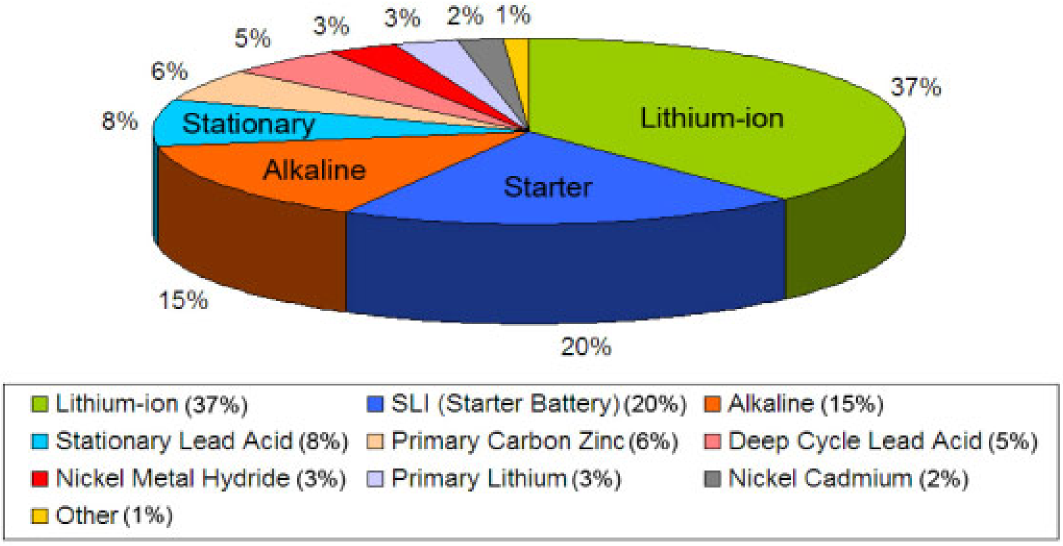


Figure 1.9: Revenue contributions by different battery chemistries [1].

Figure 1.9 shows an overview of battery types, Frost & Sullivan. Primary batteries made up 23.6 % of the global market. Frost & Sullivan predict a 7.4 % decline of the primary battery in revenue distribution by 2015. Rechargeable batteries account for 76.4 % of the global market, a number that is expected to increase to 82.6 % in 2015.

# Chapter 2

# Lithium-Ion Batteries

Devices as a cameras, laptop computers, mobile phones and other electronic consumer products need lightweight rechargable batteries of high energy and power. These requirements have led to faster development of lithium batteries. Non-rechargeable lithium batteries are commercially available since 1970s. Attempts to develop rechargeable lithium batteries followed in the 1980s but the endeavor failed because of instabilities in the metallic lithium used as anode material. A large number of lithium batteries in 1991 was withdrawn from the market and returned for recycling. Same year, Sony patented the first commercial lithium-ion battery and put it on the market. Lithium-ion batteries are the most advanced secondary sources of electricity currently available on the market. Their advantage compared to other batteries is reflected in higher operating voltage (nominal voltage) of about 3.6 V, higher energy density, low weight, etc..

Lithium-Ion commercial cells are different from other secondary cells by following characteristics:

- The high operating voltage value of about 3.6 V, which is three times higher compared to NiCd and NiMH cells
- Low weight and high energy density
- The possibility of fast charging. Within an hour it is possible to safely charge the battery up to 80-90 %
- Fast discharge
- Lithium-ion self-discharges about 5 % in the first 24 hours and then loses 1 % to 2 % per month [1]
- Long service life
- Do not contain heavy metals (pollution)
- prevalence and demand

## 2.1 Distribution and demand of Lithium

- Main source: salt liquors and minerals
- Main Producer: Chile, Argentina, China, Bolivia, USA
- According to the polls in 1980 there were around 15-30 million tons lithium available from many sources
- The need for lithium according to the statistic data in 2008 was 28000t/year. Data from 2013 show a quantity of 35-40000 t/year.
- 0.2-0.3 kg Lithium/kWh of Battery capacity
- Market value of lithium constantly varies and current price is about 7US $/kg.[10]

## 2.2 The structure and principle of operation of a Lithium-Ion Cell

As already mentioned, one battery cell consists of two electrodes, separator and electrolytes. The use of lithium metal as the anode, or negative electrode of the secondary cell, is not safe. High number of charge/discharge cycles increases the reactivity of lithium electrodes with organic liquid electrolytes. In these cells, a carbon electrode is implemented for the anode instead of the metal lithium. In this way the active lithium is always present in ionic form. Metallic lithium is highly reactive with moisture, oxygen and nitrogen, which makes it difficult to handle. The use of intercalating[1] compounds for the anode and cathode is important for the assembly/production of the battery in normal environment. Among the most important metal oxides that are used as an electrode for lithium-ion batteries there are oxides of:

- titanium
- vanadium
- manganese
- iron
- cobalt
- nickel

---

[1] In chemistry, intercalation is the reversible inclusion or insertion of a molecule (or ion) into compounds with layered structures. Examples are found in graphite intercalation compounds.

There are many options of salts and solvents that may be used as a solid electrolyte. Their choice is very wide:

- propylene carbonate (PC)
- ethylene carbonate (EC)
- dimethyl carbonate (DMC)
- $\gamma$-butirolakton ($\gamma$-BL)
- dimethoxyethane (DME).

Important is also the selection of electrolyte salts which are commonly used: $LiPF_6$, $LiBF_4$, $LiAsF_6$, $LiClO_4$[11]. All these electrolytes have certain advantages and disadvantages. Good electrolytes provide high dissociation of positive and negative ions for increasing conductivity. Electrochemical stability of the electrolytes has high importance, because when the electrolyte is more stable, the energy density is increasing.

Figure 2.1 and 2.2 represents the battery charge and discharge cycle. The working principle of Li-Ion batteries is similar to the principles of work of other secondary batteries. During battery discharge, the battery delivers electrical energy that is stored in the form of chemical energy. During discharge there is an electrochemical reduction-oxidation reaction. Through the chaotic movement of electrons from the negative to the positive electrode through the external electrical circuit, the reaction is possible.

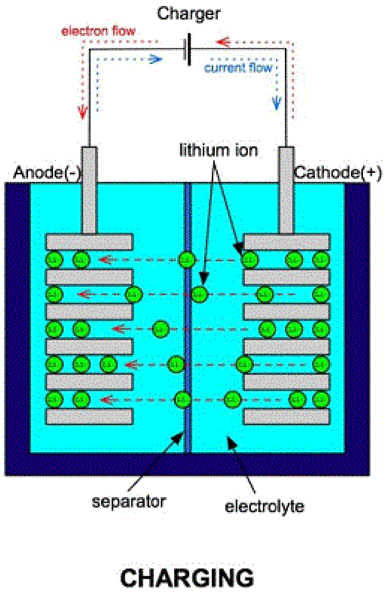


Figure 2.1: Li-Ion cell Charge cycle [5].

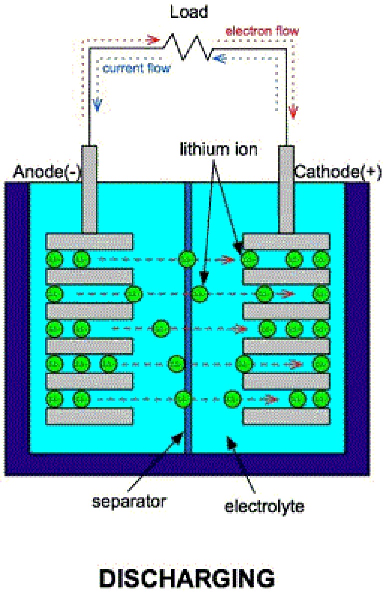


Figure 2.2: Li-Ion cell Discharge cycle [5].

A similar process occurs when charging the battery. The only difference is that the electrons begin to move in the opposite direction. This movement is ensured by the merger of an external source of electricity (e.g. charger). When charging, Li-Ion battery electric energy is converted into chemical and remains stored in the battery. By definition, the anode represents the oxidation reaction and the cathode represents reducing reaction. Oxidation reaction releases electrons used in the reduction reaction. During battery discharge, electrons move from the anode to the cathode, negative and positive ions are dissolved in the electrolyte and move in the opposite direction of the electrons. The charging process takes place in the same way, only with a change in the direction of movement of electrons, positive and negative ions. The movement of ions in one cell can be represented by the chemical equation:

$$Li_xH' + H'' \leftrightarrow Li_{x-y}H' + Li_yH''[11] \tag{2.1}$$

In this case, the H' and H" are referring to the negative or positive electrode. During the discharge lithium ions are released from the structure of the negative electrode with simultaneous oxidation of H' electrode they are inserted into the structure of the positive electrode H" which is reduced. H' and H" are compounds that can receive and release lithium ions so that their structure remains unchanged.[11]

## 2.3 Classification of Li-Ion battery (anode)

### 2.3.1 Lithium Metall

Batteries with these electrodes show a very high density. Their biggest problem is the safety. Today, more and more scientists are working on the development of this type of electrode where polymer electrolyte is used as a new separator. [10]

### 2.3.2 Graphite

Graphite shows significantly better safety compared to the lithium metal. Today, graphite is used as a standard material for the anode. The theoretical capacity is about 372 mAh/kg.[10]

## 2.4 Classification of Li-Ion battery (cathode)

As previously stated, Li-Ion batteriy consists of two electrodes, separator and electrolyte. The negative electrode, or anode, made of pure carbon and the cathode, or positive electrode, made of metal-oxide. The following section contains a classiffication of Li-Ion batteries by type of cathodes and some of the most important compounds, their advantages and disadvantages.

### 2.4.1 LiCoO2 (LCO) Lithium Cobalt Oxide

LCO is one of the first materials that are used to create the cathode of a Li-Ion battery, despite high price and low capacity in comparison with other substances. Today it is used as a standard material for making electrodes. The disadvantage of this material is that its capacity decreases a lot during the lifecycle of the battery. The biggest advantage of these batteries is the high specific energy and density [6]. The LCO are used for thin battery technologies. We can find $LiCoO_2$ batteries mostly in application as a mobile phones, cameras and laptop devices. The safety circuit of the cobalt-based battery is typically limited to a charge and discharge rate of about 1 C. $LiCoO_2$ battery provide very low discharge currents (load about 0.8 C). A high load would overheat the pack.

### 2.4.2 LiMn2O4 (LMO) Lithium manganese oxide

Mangan dioxid $MnO_2$ is used as a material for batteries since 1996. Although crystallized in various forms it is historically known as $\gamma-MnO_2$ used in primary cells of 1.5V (Leclanché cells and alkaline cells). Three dimensional spinel structure of $LiMn_2O_4$ substance allows higher ions flow and lowers the internal resistance. Very low internal resistance of the cell provides very high current charging and discharging of the battery, 20-30 A. However, the battery ages. One of the factors that significantly affect the reduced capacities are electrochemical reactions that occur at higher voltages than allowed[6]. Capacity of LMO is 120 mAh/g[10]. $LiMn_2O_4$ have less capacity, one third than the same battery made of $LiCoO_2$ but still produce 50 % more energy than batteries based on nickel.

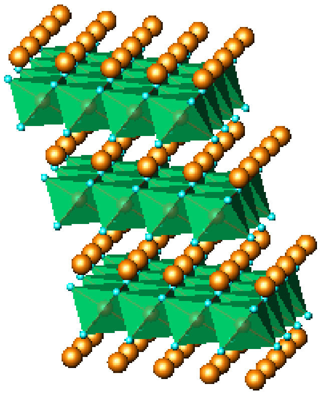


Figure 2.3: Three-dimensional spinel structure[6].

### 2.4.3 (LiNiMnCoO2) Lithium Nickel Manganese Cobalt Oxide

The combination of nickel-manganese-cobalt (NMC) can be tailored to high specific energy or high specific power, but not both. Nickel is known for its high specific energy but low stability; manganese has the benefit of forming a spinel structure to achieve very low internal resistance but the specific energy is lower[1]. Capacity: 130-160 mAh/g [10]

### 2.4.4 (LiNiCoAlO2) Lithium Nickel Cobalt Aluminum Oxide

These batteries are very poorly represented in the market due to their high price and volatility. If these disadventages are not taken into account, these batteries have importance in the car industry due to high specific energy and power densities and long life cycle. Capacity: 160 mAh/g.[10]

## 2.5 Comparison table of Li-Ion batteries

| **Specifications** | **Li-cobalt LiCoO2 (LCO)** | **Li-Manganes LiMn2O4 (LMO)** | **Li-phosphate LiFePO4 (LFP)** | **NMC LiNiMnCoO2** |
|---|---|---|---|---|
| **Voltage** | 3.60V | 3.80V | 3.30V | 3.60/3.70V |
| **Charge limit** | 4.20V | 4.20V | 4.20V | 3.60V |
| **Cycle life** | 500 - 1000 | 500 - 1000 | 1000 - 2000 | 1000 - 2000 |
| **Operating temperature** | Average | Average | Good | Good |
| **Specific energy** | 150–190Wh/kg | 100–135Wh/kg | 90–120Wh/kg | 140-180Wh/kg |
| **Loading (Crate)** | 1C | 10C, 40C pulse | 35C continuous | 10C |
| **Safety** | Average. Requires protection circuit and cell balancing of multi cell pack. Requirements for small formats with 1 or 2 cells can be relaxed | | Very safe, needs cell balancing and V protection. | Safer than Li-cobalt. Needs cell balancing and protection. |
| **Thermal runaway** | 50°C (302°F) | 250°C (482°F) | 270°C (518°F) | 210°C (410°F) |
| **Cost** | Raw material high | Moli Energy, NEC, Hitachi, Samsung | High | High |
| **In use since** | 1994 | 1996 | 1999 | 2003 |
| **Researchers, manufacturers** | Sony, Sanyo, GS Yuasa, LG Chem Samsung Hitachi, Toshiba | Sony, Sanyo, GS Yuasa, LG Chem Samsung Hitachi, Toshiba | A123, Valence, GS Yuasa, BYD, JCI/Saft, Lishen | Sony, Sanyo, LG Chem, GS Yuasa, Hitachi Samsung |
| **Notes** | Very high specific energy, limited power; cell phones, laptops | High power, good to high specific energy; power tools, medical, EVs | High power, average, specific energy, safest lithium-based battery | Very high specific energy, high power; tools, medical, EVs |

Table 2.1: Characteristics of the four most commonly used lithium-ion batteries[1].

## 2.6 Charging of Li-Ion Battery

Very important for charging or discharging Li-Ion batteries is the protection circuit. With this circuit, the batteries are prevented from "overcherging" or charging with too high currents. Also a deep discharge is not possible. Without protection circuit, the recommended voltage and current limits during charge or dishcarge must no be exceeded. E. g. w/o protection circuit, in case that the upper voltage limit is exceeded, it could lead to damage of the battery or even complete destruction. When discharge of the battery is too excessive, the battery enters to the so-called "sleep mode" and can not be recharged with conventional chargers, the battery is considered unusable or being thrown away. To prevent high currents or too high voltages at the full state of the battery, chargers of Li-Ion batteries have a precisely defined cut-off voltages at the end of charge with very low tolerance of about +/- 50 mV (e. g. for the 4.2 V battery cells). For defined charging, one carging cycle consists of a constant current - constant voltage procedure (CC-CV). At first stage of battery charging constant charge current is used. This is approximately in the range of 0.8 C or 1 C. During this CC-stage, the battery voltage raises from some low value close to the maximum. When it comes close to the upper limit of battery voltage, charging current decreases to keep the voltage constant. When the current value reaches a defined range (in this case obout 3 %) of the value that the current had in CC mode, charging stops. The Figure 3.11 shows a graphical representation of transition from CC to CV mode during battery charging.

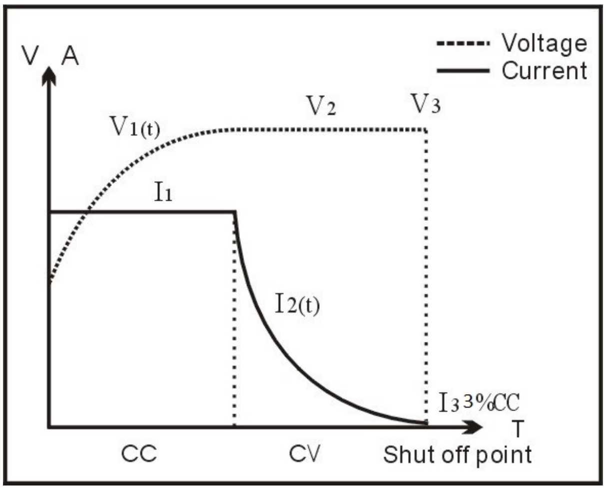


Figure 2.4: Li-Ion Battery charge on CCCV mode.

# Chapter 3

# Battery characterization

## 3.1 Fuel Gauge

The FG monitors the battery state of charge and shows it on the display of a device as a percentage value. The Fuel Gauge monitors the current that charges and discharges the battery and according to that it shows the actual/remaining capacity of the battery. The SOC of a battery represents a relationship between current battery capacity and maximum battery capacity. Only the new battery shows actual 100 % of battery capacity that a manufacturer guarantees. But this not includes the discharging conditions (temperature and load) as well as battery ageing. All these conditions decrease the FCC - the full charge capacity.

Fuel gauge of course has the possibility of "learning" new FCC by calculating the new FCC and store it in memory. This happens during battery discharge to a defined minimum and afterwards recharging again to the maximum battery capacity. Based on this, the battery fuel gauge gives the information of the SOC. It should be taken into account that the fuel gauge does not provide information about the battery capacity. For example it is possible to have SOC = 100 % new battery that is possible to use under certain conditions (load and temperature) for 10 hours. After a while, under these same conditions (load and temperature), 100 % SOC of that battery is possible to use for 7 hours. Modern fuel gauge for smart phones and laptops use coulomb counting and voltage comparison. The complexity lies in managing these variables when the battery is in use.

Measuring state-of-charge by voltage is simple but it can be inaccurate. When disturbing the battery with a charge or discharge, the open circuit voltage no longer represents the true SoC reading and the battery will require a few hours of rest before the measurement. SOC battery characteristics could be inaccurate and give users a wrong information about the status of the battery. For the purpose of improving and precision of operation fuel gauge a kind of calibration is necessary.

## 3.2 Battery characterization flow

The aim of this work is to create a proper setup for the characterization of the batteries where discharge is performed with different ($C_{rate}$) at different temperatures. Calibrating the fuel gauge will be made by means of lookup tables that consist of the OCV-tables and empty/flat tables. OCV-Tables will include OCV and SOC of a battery at different temperatures. OCV-Tables can be accessed when the battery is not under a load. Based on the data of battery voltage and temperature, the FG SOC value will be updated to the actual SOC. Empty/flat tables contain the information about SOC, in particular $C_{rate}$ and voltage at a certain temperature. These tables are used when the battery voltage reaches a certain point. It usually takes two values for calibration: Flat battery voltage and empty battery voltage. Empty battery voltage is usually at 3.4 V while the flat battery voltage is at 3.1 V. The value of empty and flat battery voltage depends on the battery. Figure 3.1 shows Open Circuit Voltage discharge curve at 10 temperatures, voltage drop from 4.2 to 2.75 V and SOC from FULL to FLAT.

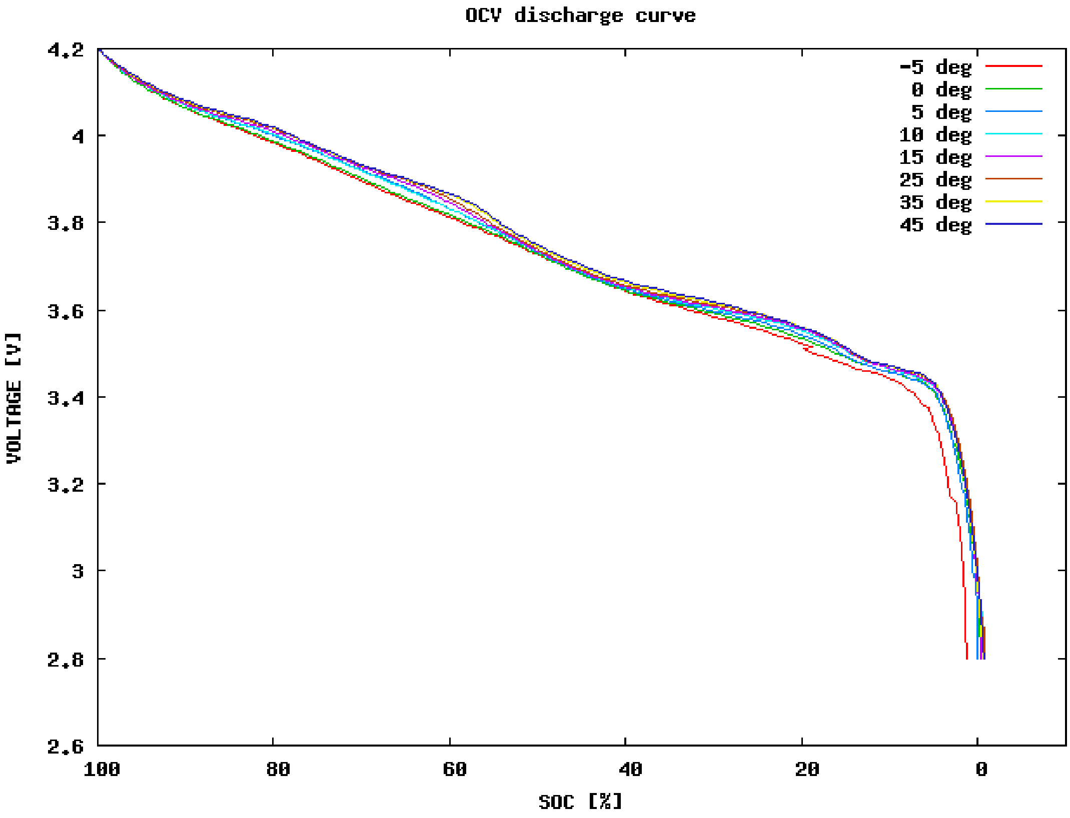


Figure 3.1: OCV discharge cureve.

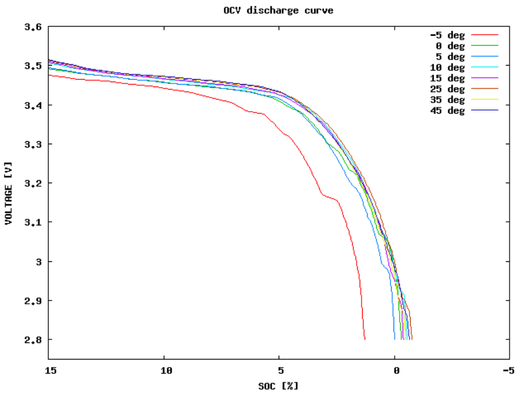


Figure 3.2: OCV Discharge curve; 3.5 V to 2.75 V.

As seen from Figure 3.2, ΔSOC/ΔV between 4.2 V 3.4 V is much higher as the ΔSOC/ΔV between 3.4 V 2.75 V. In this area, where the change of SOC is very low compared to the change of voltage, it is possible to have higher accuracy during the FG calibration. Characterization of the battery will be effected at 10 different temperatures: -25, -10, -5, 0, 5, 10, 15, 25, 35 and 45 °C. Batteries will be charged and discharged at all temperatures above under equal conditions. The battery charge will be done at room temperature (25 °C) at every test. There will be determination of maximum capacity of the battery (FCC), which will be used in further calculations. After the data collection of the SOC voltages for different $C_{\mathrm{rate}}$ for all 10 batteries at 10 different temperatures data will be processed and turned into one lookup table. Data processing and classification and certain calculations will be done by using Python program language.

## 3.3 Setup overview

As discussed in the chapter above, the aim of this Master thesis is the characterization of Li-ion batteries for mobile devices. During characterization it is necessary to charge and discharge the batteries at different temperatures, save the data of battery voltage at different loads, also without load (OCV), and calculate SOC for each voltage measurement. The chosen setup consists of the following components:

1. Oven ESPEC su241: fulfills all test requirements (e.g. communication protocol, temperature range...)

2. Kikusui PFX2011 (5 x 2 Channels) is one of the best available charge/discharge battery systems on the market. It is very stable and an accurate current source with high accuracy of the voltage sensing.

3. 10 x 4.2 V Samsung Li-Ion 18650 cell with protection circuit and 10 x 4.2 V Samsung Li-Ion 18650 cell without protection circuit. The characteristics of those batteries fulfill requirements of our charger chip application. These batteries have an EOC voltage @ 4.2V like most of the used batteries in mobile applications. In addition, these batteries are used in many applications as standard cell for years. So this battery is well known an can be used as reference. Relatively low cost of these batteries and availability in the market are additional advantages.

4. Data processing will be done by using the Python programming language

(e.g. Python 2.6.6). The python language is an open source language, standard and easy to handle.

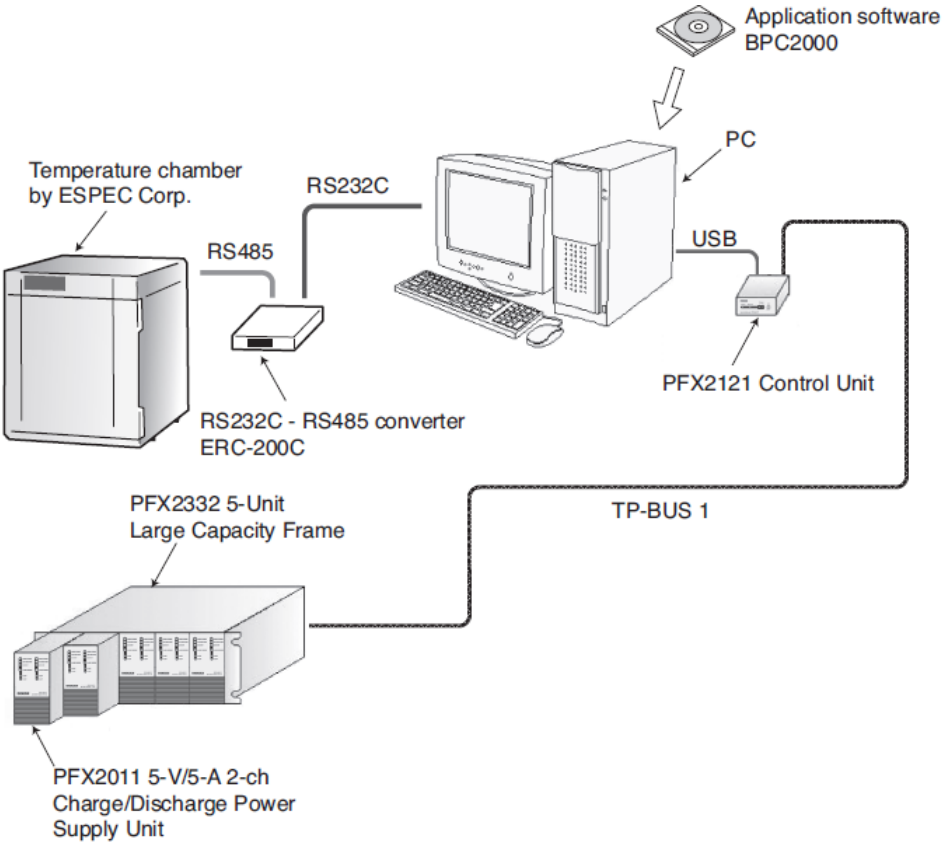


Figure 3.3: Battery Characterization Setup.[7]

### 3.3.1 Lithium-ion Rechargeable Cell Model: ICR18650-22P

Nominal battery specifications of CR18650-22P are given in the Table 3.3.1.

| **Item** | **Specification** |
|---|---|
| Typical Capacity | 2150mAh (0.2C, 2.75V discharge) |
| Minimum Capacity | 2050mAh (0.2C, 2.75V discharge) |
| Charging Voltage | 4.2V±0.05 V |
| Nominal Voltage | 3.62V (1C discharge) |
| Charging Method | CC-CV<br>(constant voltage with limited current) |
| Charging Current | Standard charge: 1075mA<br>Rapid charge : 2150mA |
| Charging Time | Standard charge : 3hours<br>Rapid charge : 2.5hours |
| Max. Charge | Current 2150mA |
| Max. Discharge Current | 10A (Continuous discharge) |
| Discharge Cut-off Voltage | 2.75V |
| Cell Weight | 44.5g max |
| Operating Temperature | Charge : -10 to 50°C<br>Discharge: -20 to 70°C |

Table 3.1: ICR18650-22P Cell - Nominal Specifications[8].

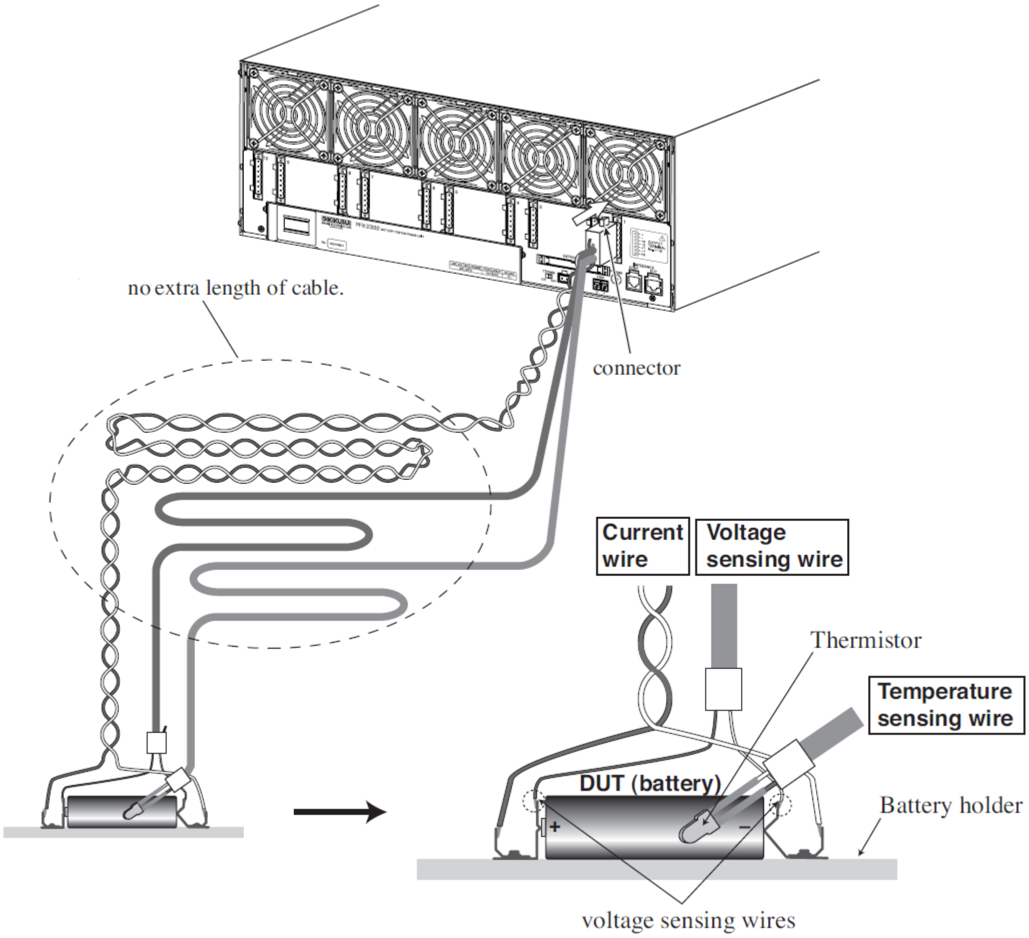


Figure 3.4: Battery connection during characterization[7].

For higher accuracy of the measurements connection between battery and the measurement system, the connection to the device under test should be as short as possible to avoid voltage drops along the cables during the test. Charge and discharge current is applied via Kikusui directly on the + and - pole of the battery. On the same point are the voltage sensing wires connected. The temperature sensor is fixed to the battery body.

### 3.3.2 Temperature chamber

Figure 3.5: Temperature chamber.

For the temperature simulation the temperature chamber ESPEC su241 with a temperature range from -40 °C to +150 °C is used. The communication with the chamber is established via RS -485.

### 3.3.3 Charge/Discharge battery test system

Figure 3.6: KIKUSUI PFX2000 Series - battery test unit[7]

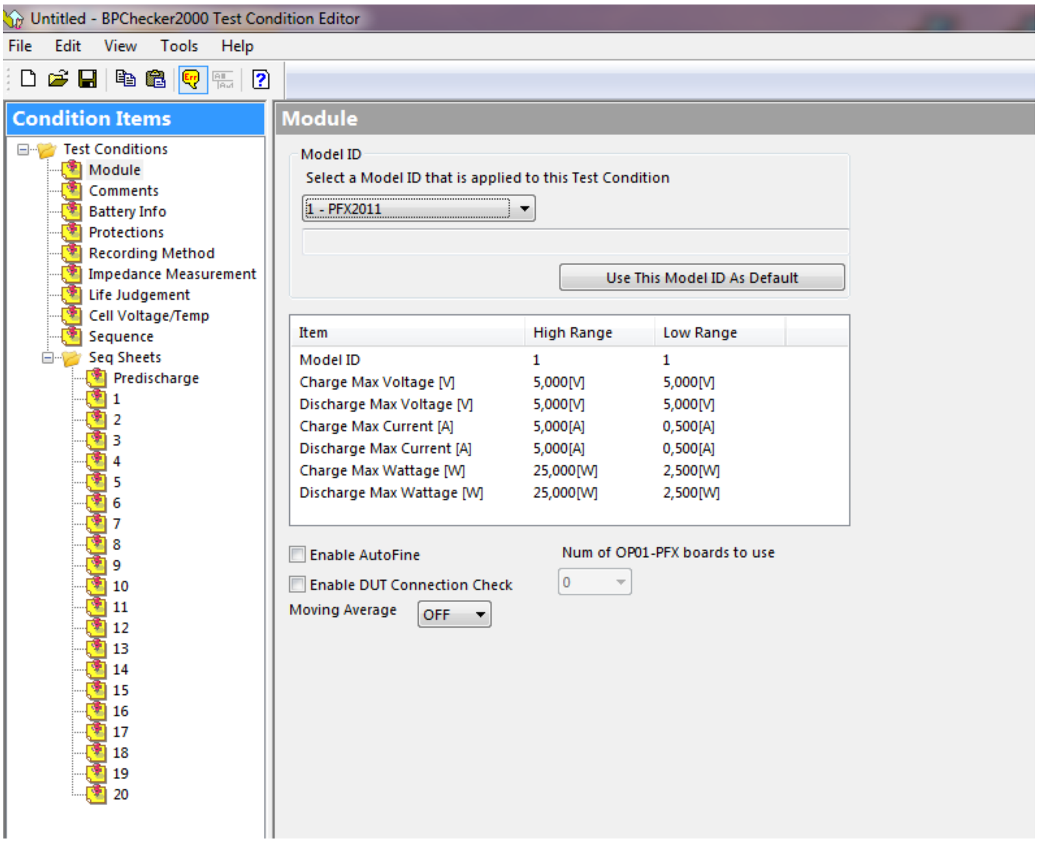
The battery charge/discharge test system is capable to meet various needs of the user by allowing the user to select the required units from different types, group units by functionality and combine the required number of those units. The product adopts a unit structure that houses charging/discharging power supply units (PFX2011) inside a unit frame (PFX2332). Each unit has two channels, each channel is completely independent of one another and can be controlled under different test and timing conditions. In addition, a rich set of protection features (OVP, UVP, OHP, etc.) is supported to prevent the device under test from being destroyed by a system malfunction or operation mistake. The USB is used to connect PC and the control unit. The TP-BUS (Kikusui internal BUS system) is used to connect each unit. All units can be controlled from BPChecker2000 software, which is part of Kikusui. BPChecker2000 is a dedicated application software for the PFX2000 series charge/discharge battery test system controller. BPChecker2000 enables to set the conditions of the battery charge/discharge characterisation test, execute the test and analyze the test results on a PC. To control the temperature chamber with BPChecker2000 it is necessary to have an RS232 to RS485 converter.

Kikusui features:

- CC, Pulse and CC-CV charge mode
- CC, PULSE and CP pulse discharging mode
- Temperature measurement function
- Synchronized operation with thermostatic chamber
- Expandable on a unit-by-unit basis
- Versatile charge/discharge cut off conditions
- High precision measurements (Adopts the 24-bit A/D converter for measuring voltage and current)
- Two independent channels on a single unit

### 3.3.4 BPChecker2000 software

There are the necessary options for configuring the test conditions, for charging and discharging the battery, temperature control as well as the number of cycles in the B2kCond editor. Figure 3.7 shows the main options panel B2kCond editor of application.



Model ID

Select a Model ID that is applied to this Test Condition: 1 - PFX2011

| Item | High Range | Low Range |
|---|---|---|
| Model ID | 1 | 1 |
| Charge Max Voltage [V] | 5,000[V] | 5,000[V] |
| Discharge Max Voltage [V] | 5,000[V] | 5,000[V] |
| Charge Max Current [A] | 5,000[A] | 0,500[A] |
| Discharge Max Current [A] | 5,000[A] | 0,500[A] |
| Charge Max Wattage [W] | 25,000[W] | 2,500[W] |
| Discharge Max Wattage [W] | 25,000[W] | 2,500[W] |

☐ Enable AutoFine

☐ Enable DUT Connection Check

Moving Average: OFF

Num of OP01-PFX boards to use: 0

Figure 3.7: BPChecker2000 Test Conditions Module.

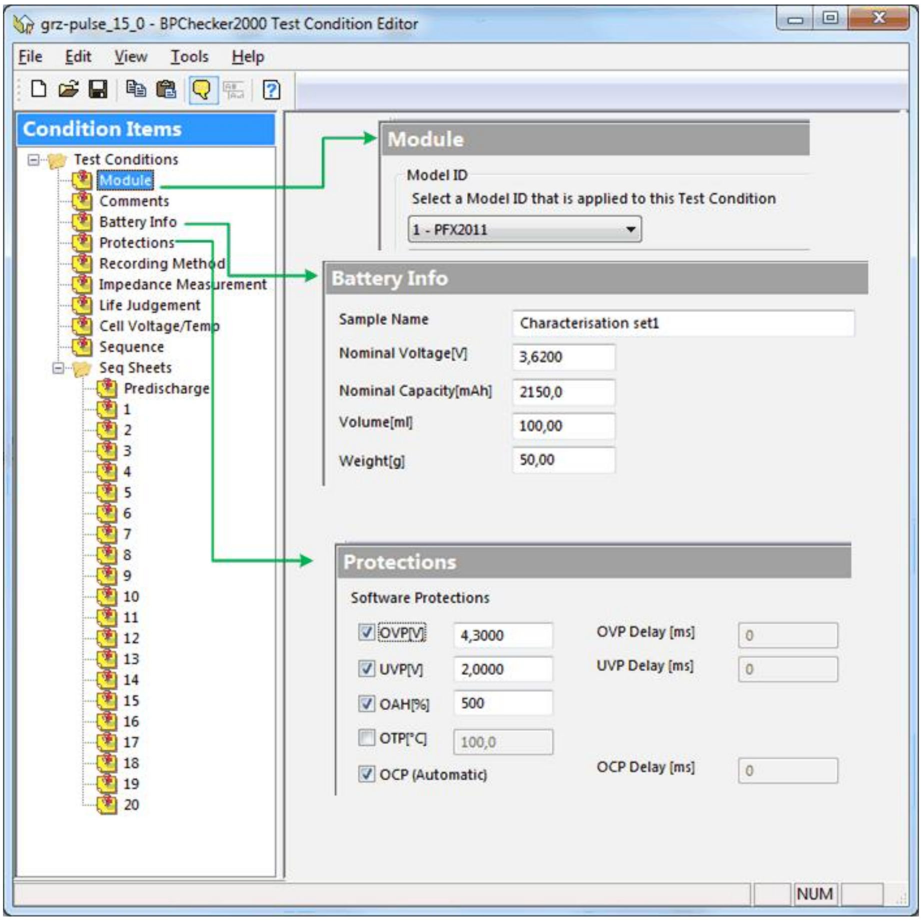
For the battery characterization it is necessary to set some options and test conditions in "Test Condition Editor":

- Module – set the model (Model ID) to use. In this case PFX2011. When this is set, the suitable input range for the current and the voltage setting can be done

- Battery info – as battery info is possible to enter data like nominal voltage, nominal capacity and battery name.
- Protections – OVP, UVP and OHP. If battery exceeds one of those values during testing, an alarm occurs and the test is aborted
- Recording Method – to set recording time. During this test Kikusui is recording the data every second.
- Sequences – sequence defines how to execute the charge/discharge cycles that are specified in sequence sheet 1 to 20. 'Repeat' specifies the number of times a sequence sheet is repeated; 'Loop' specifies the number of times the set of sequence sheet is repeated.
- Seq. Sheet – there are 21 sequence sheets including the predischarge sheet and the sheets 1 to 20. Since each sheet from 1 to 20 consist of a charge condition sheet and discharge condition sheet.

### 3.3.5 Test conditions

The first step sets up a profile for charging and discharging the battery. Figure 3.8 shows the basic settings.



**Module**

Model ID

Select a Model ID that is applied to this Test Condition

1 - PFX2011

**Battery Info**

Sample Name: Characterisation set1
Nominal Voltage[V]: 3,6200
Nominal Capacity[mAh]: 2150,0
Volume[ml]: 100,00
Weight[g]: 50,00

**Protections**

Software Protections

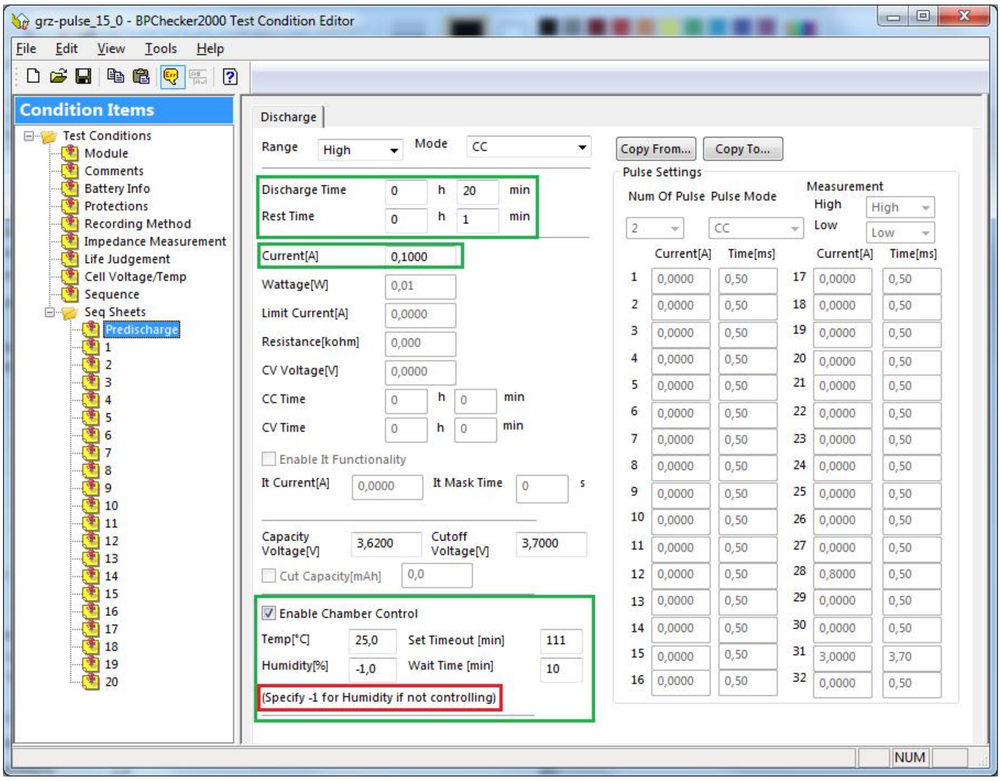
☑ OVP[V] 4,3000 — OVP Delay [ms] 0
☑ UVP[V] 2,0000 — UVP Delay [ms] 0
☑ OAH[%] 500
☐ OTP[°C] 100,0
☑ OCP (Automatic) — OCP Delay [ms] 0

Figure 3.8: BPChecker2000 Test Conditions Editor.

In the module "field", the right system model of Kukisui that is used, must be selected. For this test it is PFX2011. Battery info section is also used for data extracted from the data sheet of the battery that will be tested. So nominal Voltage of 3.62V and nominal capacity of 2150 mAh is used. According to the data sheet it is also necessary to set protection conditions in protection field to avoid overvoltage, undervoltage and overtemperature effects. For the battery, that is used in the test, following protection values are set: OVP 4.3V, UVP 2.0V, OTP 50°C.

### Predischarge

Predischarge is executed when starting the test, or when the sequence sheet is used for the first time. During the test the predischarge sheet can be executed only once. The predischarge section set conditions to predischarge. Predischarge sheet i used to check if the setup is working properly, e. g. if there is some strange behavior of the batteries like very high or very low voltage, high temperature etc. For this functional check, simple battery discharge conditions are set: discharge current is set to 100 mA, the discharge time to 20 minutes and rest time is 3 minutes. In this section, we establish the communication with the temperature chamber and set the temperature at which the test will be performed. Temperature is set at 25°C, because it is only a functional check of the batteries. All other settings (incl. temperatures) are set then on the next sheet, the charge sheet.



Range High Mode CC

Discharge Time 0 h 20 min
Rest Time 0 h 1 min

Current[A] 0,1000
Wattage[W] 0,01
Limit Current[A] 0,0000
Resistance[kohm] 0,000
CV Voltage[V] 0,0000
CC Time 0 h 0 min
CV Time 0 h 0 min
☐ Enable It Functionality
It Current[A] 0,0000 It Mask Time 0 s

Capacity Voltage[V] 3,6200 Cutoff Voltage[V] 3,7000
☐ Cut Capacity[mAh] 0,0

☑ Enable Chamber Control
Temp[°C] 25,0 Set Timeout [min] 111
Humidity[%] -1,0 Wait Time [min] 10
(Specify -1 for Humidity if not controlling)

Pulse Settings
Num Of Pulse 2 Pulse Mode CC
Measurement High High
Low Low

|  | Current[A] | Time[ms] |  | Current[A] | Time[ms] |
|---|---|---|---|---|---|
| 1 | 0,0000 | 0,50 | 17 | 0,0000 | 0,50 |
| 2 | 0,0000 | 0,50 | 18 | 0,0000 | 0,50 |
| 3 | 0,0000 | 0,50 | 19 | 0,0000 | 0,50 |
| 4 | 0,0000 | 0,50 | 20 | 0,0000 | 0,50 |
| 5 | 0,0000 | 0,50 | 21 | 0,0000 | 0,50 |
| 6 | 0,0000 | 0,50 | 22 | 0,0000 | 0,50 |
| 7 | 0,0000 | 0,50 | 23 | 0,0000 | 0,50 |
| 8 | 0,0000 | 0,50 | 24 | 0,0000 | 0,50 |
| 9 | 0,0000 | 0,50 | 25 | 0,0000 | 0,50 |
| 10 | 0,0000 | 0,50 | 26 | 0,0000 | 0,50 |
| 11 | 0,0000 | 0,50 | 27 | 0,0000 | 0,50 |
| 12 | 0,0000 | 0,50 | 28 | 0,8000 | 0,50 |
| 13 | 0,0000 | 0,50 | 29 | 0,0000 | 0,50 |
| 14 | 0,0000 | 0,50 | 30 | 0,0000 | 0,50 |
| 15 | 0,0000 | 0,50 | 31 | 3,0000 | 3,70 |
| 16 | 0,0000 | 0,50 | 32 | 0,0000 | 0,50 |

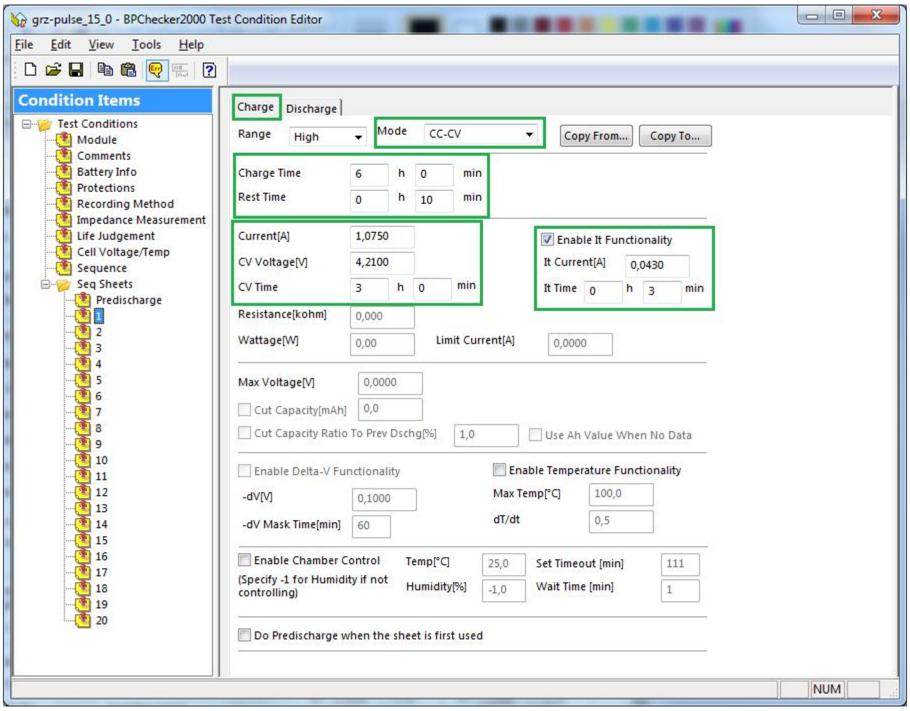
Figure 3.9: Predischarge conditions.

Considering there is not the option for humidity, in a humidity box we enter

"-1". With this, the humidity option is disabled.

### Charge conditions

Charging the battery will always be done at a temperature of 25 °C with CC-CV sequence. In the Seq Sheets the charging conditions of batteries are set. As noted in previous sheet the temperature value is determined and enabled. In this sheet it is not necessary to re-define the same conditions because the program has already memorized and keeps the settings. Charging the battery will execute current of 1075 mA which is a 0.5 C rate considering the nominal capacity of 2150 mAh. Charging with this current in CC mode is done until the battery voltage reaches a value of 4.2 V then the system changes from CC to CV mode.



Range: High
Mode: CC-CV
Charge Time: 6 h 0 min
Rest Time: 0 h 10 min
Current[A]: 1,0750
CV Voltage[V]: 4,2100
CV Time: 3 h 0 min
☑ Enable It Functionality
It Current[A]: 0,0430
It Time: 0 h 3 min
Resistance[kohm]: 0,000
Wattage[W]: 0,00
Limit Current[A]: 0,0000
Max Voltage[V]: 0,0000
☐ Cut Capacity[mAh]: 0,0
☐ Cut Capacity Ratio To Prev Dschg[%]: 1,0
☐ Use Ah Value When No Data
☐ Enable Delta-V Functionality
-dV[V]: 0,1000
-dV Mask Time[min]: 60
☐ Enable Temperature Functionality
Max Temp[°C]: 100,0
dT/dt: 0,5
☐ Enable Chamber Control
(Specify -1 for Humidity if not controlling)
Temp[°C]: 25,0
Humidity[%]: -1,0
Set Timeout [min]: 111
Wait Time [min]: 1
☐ Do Predischarge when the sheet is first used

Figure 3.10: Ccharge conditions.

Voltage remains constant and current begins to drop to the current value of 43 mA, which is 4 % of the charging current. After three minutes charging with 43 mA, the battery enters "rest mode". Three minutes of 43 mA charge current are enough to check that the voltage is stable at the end of charge voltage. To relax the battery after charging cycle 10 minutes are enough. Charge Time is set to 6 hours to ensure that the charge sheet will be active for the time that is needed to charge the battery with these charge conditions. This avoids a system time out from Kikusui. As soon as the conditions given in the sheet are achieved the charge cycle stops and the battery goes into rest mode. The battery is charging with 0.5 $C_{rate}$ and it will be charged for 2 hours.

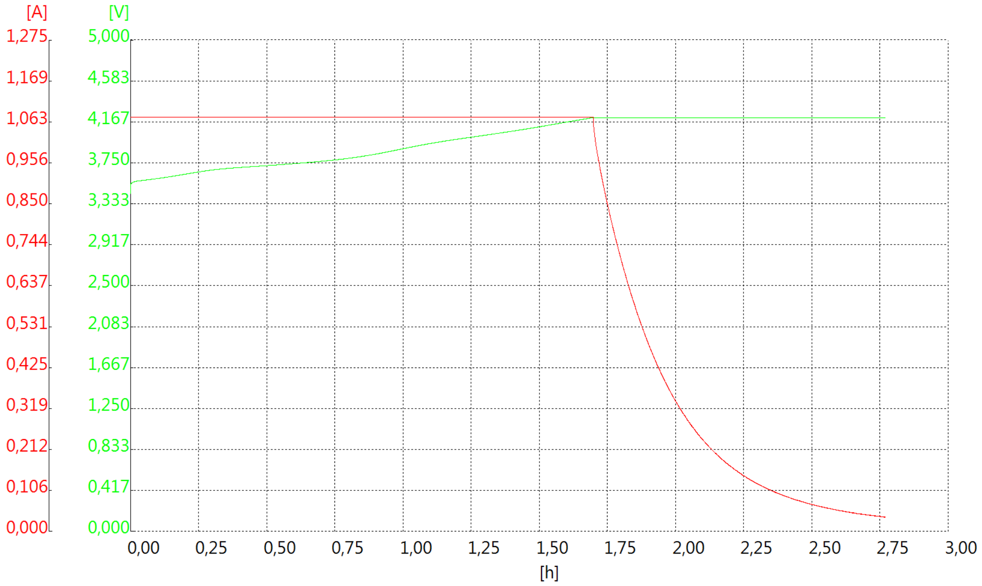


Figure 3.11: Charging battery with CC-CV mode

In the next Seq Sheet - one discharge tab is only used to adjust the temperature for the first battery discharge. All other values are set to zero or are marked as disable. Considering that they all were set to zero and tagged as disable we continue with the procedure set in the discharge tab. After charging, the program activates the first sheet for discharge. The program takes about 60 seconds (Kikusui default settings)to verify the charge/discharge conditions.

### Discharge conditions

Under certain circumstances of charging and discharging battery and during characterization of the battery data on voltage and SOC are not always recorded by Kikusui unit. Kikusui's adds sync when switching from charge to discharge and from discharge to charge or checking the test conditions. During this time OCV is not recorded. Hence the setup of the discharge profile is a bit tricky. For calculating the OCV of the battery a 120s voltage relaxation curve needs to be recorded. To make correct calculation of the SOC during relax time this relaxation curve must not show any gaps!

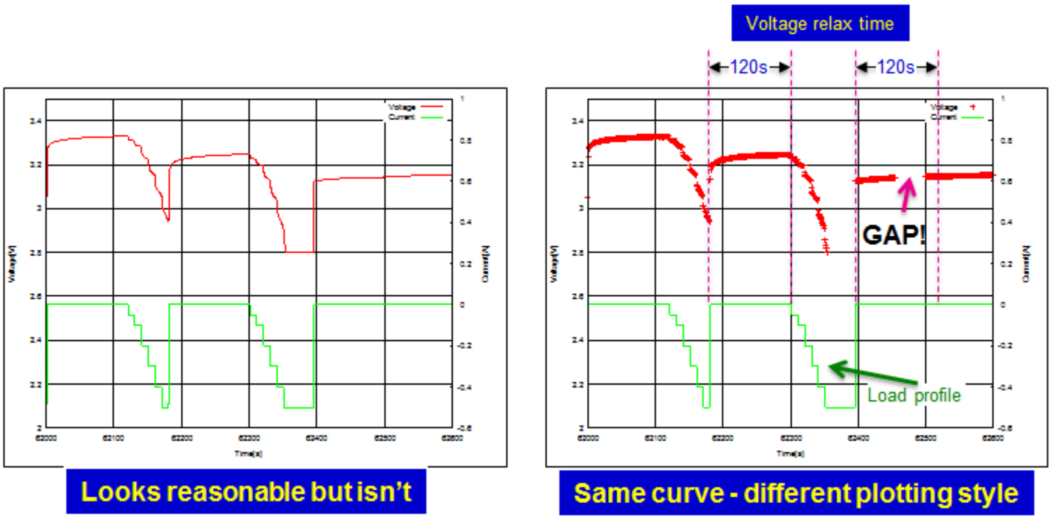
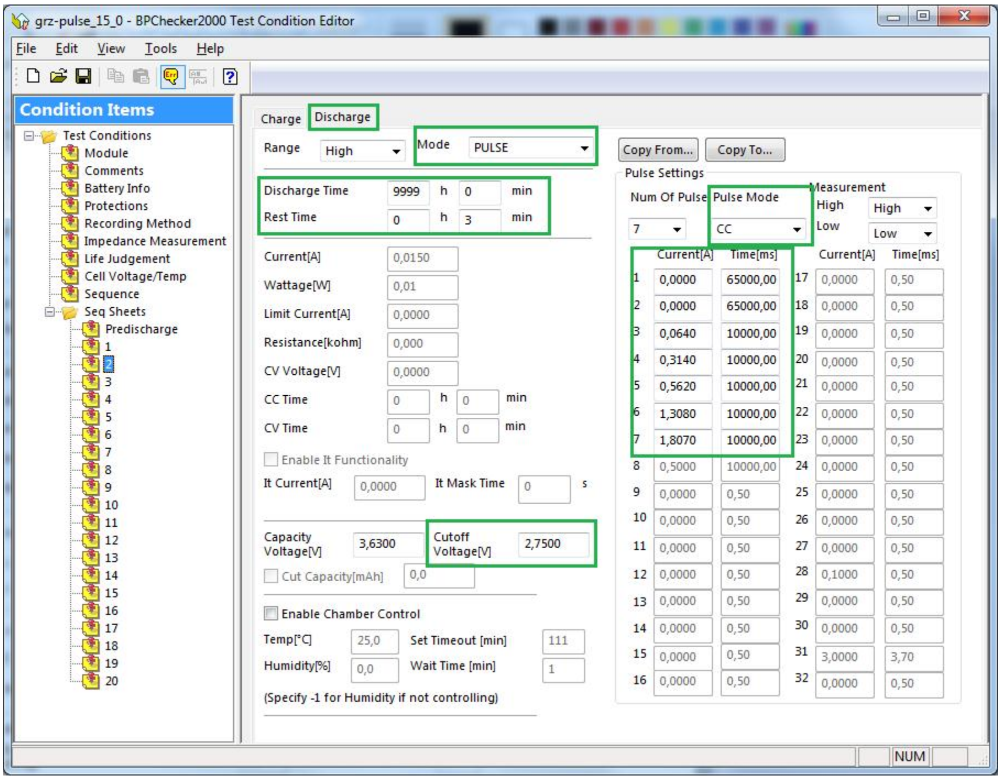


Figure 3.12: KIKUSUI discharge gaps

While plotting the same discharge curve with different plotting style (lines vs. points), it is possible to see the gaps in the voltage curve. These gaps should be avoided. Battery discharging will be executed in pulse mode, which means that it will use five pulses with different amplitude. Pulse mode is set as CC and the individual pulse period to 10 s. After the last pulse there follows a relaxing time of

130 seconds in which the OCV of the battery is measured. The values of the amplitude of these pulses are set to 0.064 A, 0.314 A, 0.562 A, 1.807 A and 1.308 A. The pulse mode is the shortest way to do a discharge of battery with many different currents. Battery discharge from full to flat battery with a low constant current (e.g. 64 mA, 314 mA..) takes a lot of time. Also, the pulse mode with relax curve allows recording of OCV values. The 10s steps are chosen to provide enough long discharge that not stress the battery but provide as much as possible samples of OCV. The Figure 3.13 show discharge setup.



Range: High
Mode: PULSE
Discharge Time: 9999 h 0 min
Rest Time: 0 h 3 min
Current[A]: 0,0150
Wattage[W]: 0,01
Limit Current[A]: 0,0000
Resistance[kohm]: 0,000
CV Voltage[V]: 0,0000
CC Time: 0 h 0 min
CV Time: 0 h 0 min
☐ Enable It Functionality
It Current[A]: 0,0000  It Mask Time: 0 s
Capacity Voltage[V]: 3,6300  Cutoff Voltage[V]: 2,7500
☐ Cut Capacity[mAh]: 0,0
☐ Enable Chamber Control
Temp[°C]: 25,0  Set Timeout [min]: 111
Humidity[%]: 0,0  Wait Time [min]: 1
(Specify -1 for Humidity if not controlling)

Pulse Settings
Num Of Pulse: 7
Pulse Mode: CC
Measurement High: High
Measurement Low: Low

|  | Current[A] | Time[ms] |  | Current[A] | Time[ms] |
|---|---|---|---|---|---|
| 1 | 0,0000 | 65000,00 | 17 | 0,0000 | 0,50 |
| 2 | 0,0000 | 65000,00 | 18 | 0,0000 | 0,50 |
| 3 | 0,0640 | 10000,00 | 19 | 0,0000 | 0,50 |
| 4 | 0,3140 | 10000,00 | 20 | 0,0000 | 0,50 |
| 5 | 0,5620 | 10000,00 | 21 | 0,0000 | 0,50 |
| 6 | 1,3080 | 10000,00 | 22 | 0,0000 | 0,50 |
| 7 | 1,8070 | 10000,00 | 23 | 0,0000 | 0,50 |
| 8 | 0,5000 | 10000,00 | 24 | 0,0000 | 0,50 |
| 9 | 0,0000 | 0,50 | 25 | 0,0000 | 0,50 |
| 10 | 0,0000 | 0,50 | 26 | 0,0000 | 0,50 |
| 11 | 0,0000 | 0,50 | 27 | 0,0000 | 0,50 |
| 12 | 0,0000 | 0,50 | 28 | 0,1000 | 0,50 |
| 13 | 0,0000 | 0,50 | 29 | 0,0000 | 0,50 |
| 14 | 0,0000 | 0,50 | 30 | 0,0000 | 0,50 |
| 15 | 0,0000 | 0,50 | 31 | 3,0000 | 3,70 |
| 16 | 0,0000 | 0,50 | 32 | 0,0000 | 0,50 |

Figure 3.13: Discharge conditions.

To ensure that the settings for the discharge cycle time will not interrupt the test, in an earlier stage the time for discharge time field is set to 9999. When the battery voltage drops to 2.75V which is set as a condition for the cut-off voltage, the complete cycle ends and battery goes into rest mode for 3 minutes. After that the program changes to the next Seg Sheet and continues battery discharging. To ensure that the battery is completely discharged at the voltage of 2.75 V the next discharge sheet will have one pulse less in its settings. The highest current pulse from the previous sheet is omitted. In the last discharge sheet for that temperature, battery is discharged only with a current pulse of 0.064 A. This ensures the battery is fully discharged and that the actual battery voltage corresponds to the measured value with a high accuracy. Figure 3.14 shows a voltage relax curve and a voltage response on the current load. With these discharge conditions the voltage curves are without any gaps.

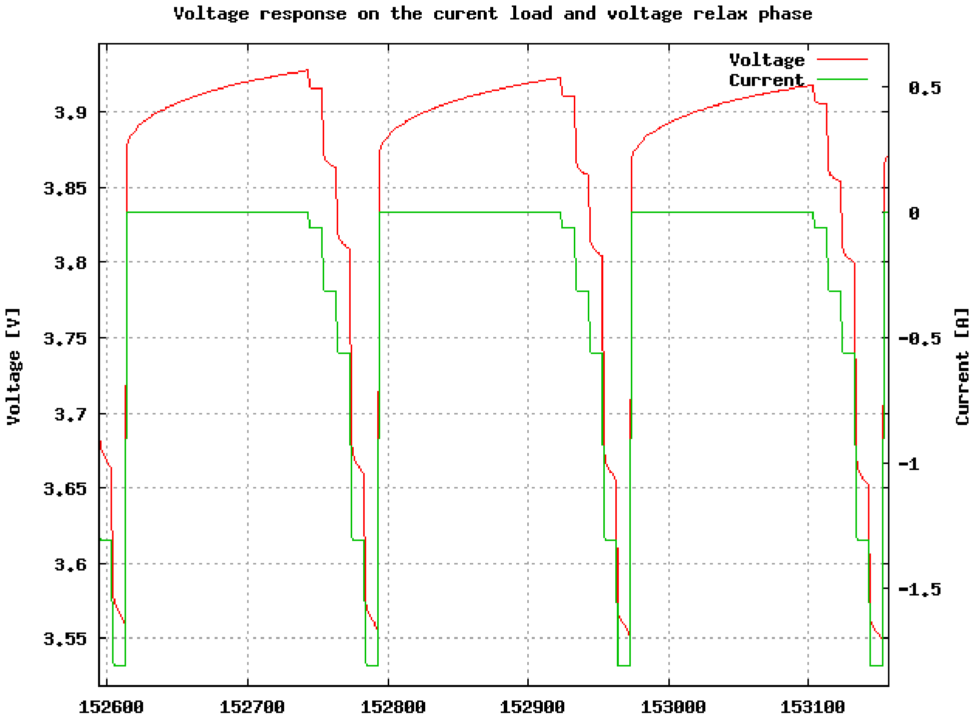
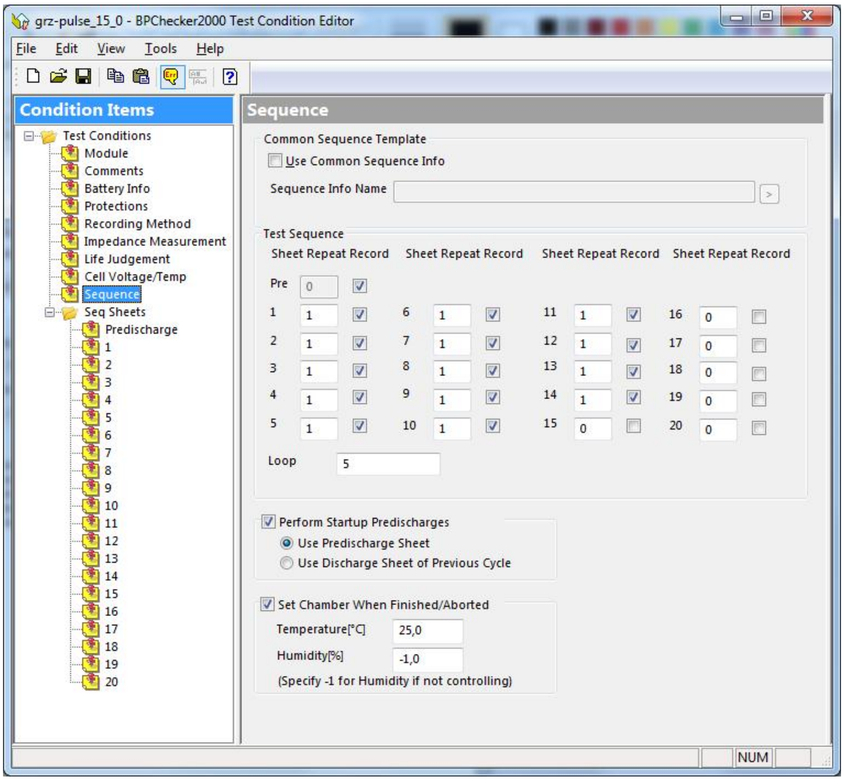


Figure 3.14: Voltage relax curve.

After the battery voltage reached the cutoff voltage of 2.75V, battery will be set to rest for 3 minutes. Afterwards, the battery was completely discharged, starts the charging cycle again with the current of 100 mA for a period of one hour. The temperature is set at 25 °C again. After this it is safe to charge the battery with higher currents. Exactly the same test conditions will be repeated for the other discharge temperatures.

### Sequence

Since BPChecker2000 possess only 20 Seq Sheet is is possible to set the conditions of testing for two different temperatures simultaneously. The Figure 3.15 shows number of sequences and their repetitions.



Common Sequence Template

☐ Use Common Sequence Info

Sequence Info Name

Test Sequence

| Sheet | Repeat | Record | Sheet | Repeat | Record | Sheet | Repeat | Record | Sheet | Repeat | Record |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pre | 0 | ☑ | | | | | | | | | |
| 1 | 1 | ☑ | 6 | 1 | ☑ | 11 | 1 | ☑ | 16 | 0 | ☐ |
| 2 | 1 | ☑ | 7 | 1 | ☑ | 12 | 1 | ☑ | 17 | 0 | ☐ |
| 3 | 1 | ☑ | 8 | 1 | ☑ | 13 | 1 | ☑ | 18 | 0 | ☐ |
| 4 | 1 | ☑ | 9 | 1 | ☑ | 14 | 1 | ☑ | 19 | 0 | ☐ |
| 5 | 1 | ☑ | 10 | 1 | ☑ | 15 | 0 | ☐ | 20 | 0 | ☐ |

Loop 5

☑ Perform Startup Predischarges

● Use Predischarge Sheet

○ Use Discharge Sheet of Previous Cycle

☑ Set Chamber When Finished/Aborted

Temperature[°C] 25,0

Humidity[%] -1,0

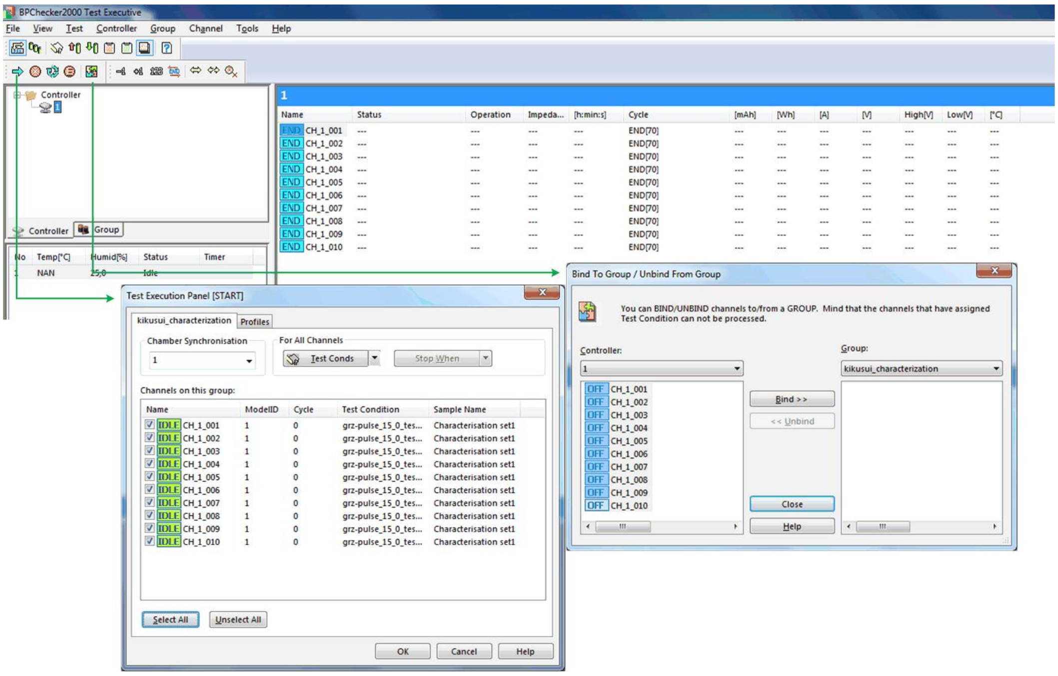
(Specify -1 for Humidity if not controlling)

Figure 3.15: Sequence settings.

In sequence /options/it is possible to choose which of the defined sheet to use during the test, how many times one sheet will be repeated and how many times to repeat the entire test (Loop). It is also possible to set whether the predischarge sheet turned on and at which value will the temperature be set after the completion of the entire test. For characterization of these batteries each test must be repeated five times in order to collect sufficient data and determine the average characteristics of the battery.

### 3.3.6 Test execution

After all test conditions are set and the whole setup is set in a correct way, it is possible to run the test with BPChecker 2000 test condition software. At first it is necessary to put all channels that are used for the test in a group that will have the same test conditions (Bind to group / Unbind from group). Then, in the main program window, there are displayed channels that are ready to run the test. By clicking on the arrow in the top left corner of the program (Figure 3.16), a new window is opened where it is possible to choose test conditions that are pre-defined in BPChecker2000 Test Conditions program. After we have marked all the channels through which we will execute, charging and discharging of battery test can be run.



| Name | Status | Operation | Impeda... | [h:min:s] | Cycle | [mAh] | [Wh] | [A] | [V] | High[V] | Low[V] | [°C] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| END CH_1_001 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_002 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_003 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_004 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_005 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_006 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_007 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_008 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_009 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |
| END CH_1_010 | --- | --- | --- | --- | END[70] | --- | --- | --- | --- | --- | --- | --- |

| No | Temp[°C] | Humid[%] | Status | Timer |
|---|---|---|---|---|
| 1 | NAN | 25,0 | Idle | |

Chamber Synchronisation: 1

Channels on this group:

| Name | ModelID | Cycle | Test Condition | Sample Name |
|---|---|---|---|---|
| ☑ IDLE CH_1_001 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_002 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_003 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_004 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_005 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_006 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_007 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_008 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_009 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |
| ☑ IDLE CH_1_010 | 1 | 0 | grz-pulse_15_0_tes... | Characterisation set1 |

You can BIND/UNBIND channels to/from a GROUP. Mind that the channels that have assigned Test Condition can not be processed.

Controller: 1

Group: kikusui_characterization

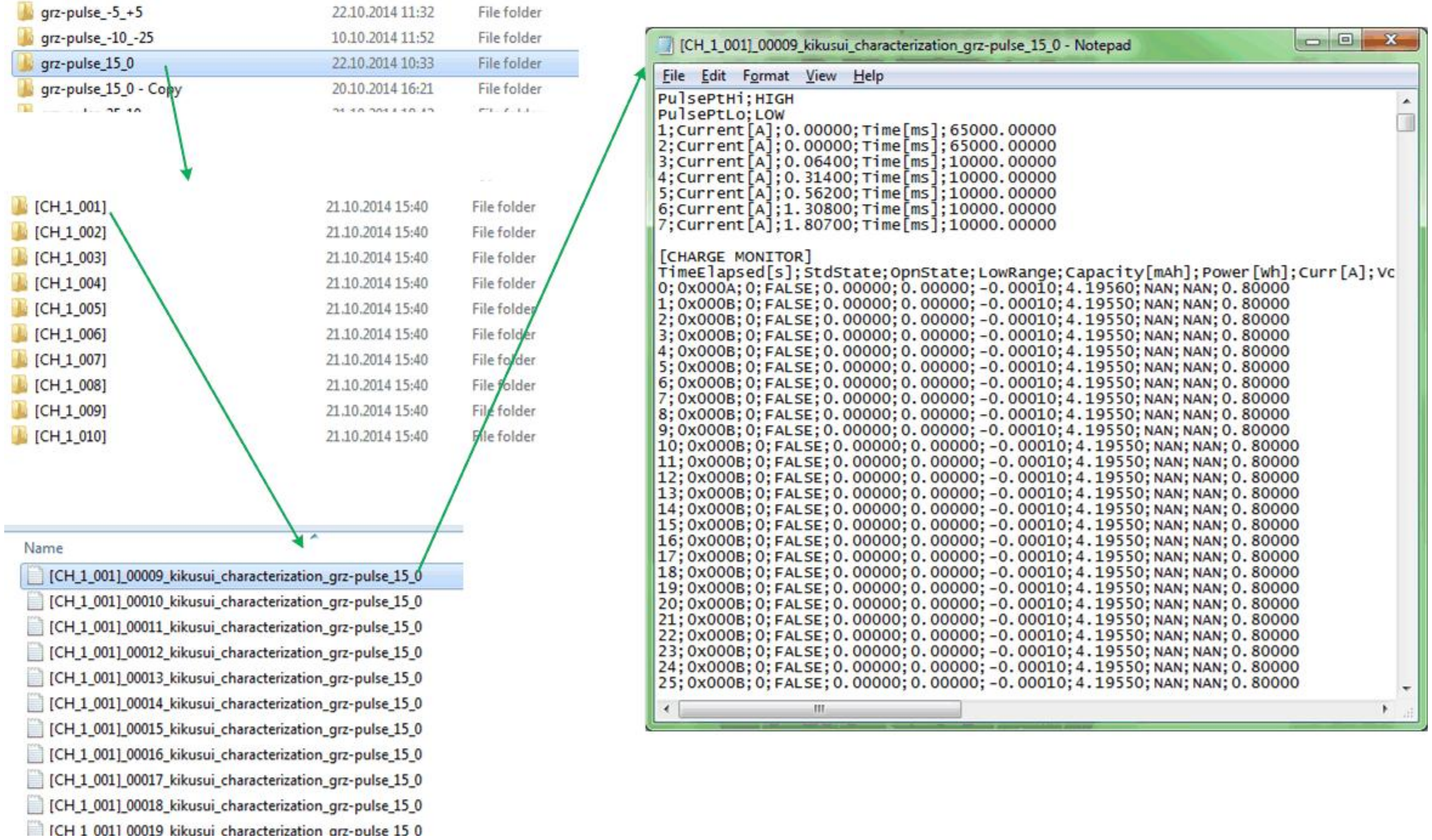
OFF CH_1_001
OFF CH_1_002
OFF CH_1_003
OFF CH_1_004
OFF CH_1_005
OFF CH_1_006
OFF CH_1_007
OFF CH_1_008
OFF CH_1_009
OFF CH_1_010

Figure 3.16: Test Execution Steps.

BPChecker2000 automatically creates a folder for storing all the test data. The folder name is the same as the test conditions. In folder, there are subfolders using names of control unit and regular channel number. In each of those folders there are saved text files for each sheet and each new loop, which contain the following information:

- Test conditions
- Date and Time
- Battery Informations (Nominal Capacity, Nominal Voltage...)
- Sheet No
- Mode (CC, CV, CC-CV, Pulse)
- Battery Voltage [V]
- Charge/Discharge Current [A]
- Timestamp [s]
- Capacity [mAh]

The data (voltage, current, capacity etc.) is saved in these files by sampling every second.



```
grz-pulse_-5_+5          22.10.2014 11:32   File folder
grz-pulse_-10_-25        10.10.2014 11:52   File folder
grz-pulse_15_0           22.10.2014 10:33   File folder
grz-pulse_15_0 - Copy    20.10.2014 16:21   File folder
```

```
[CH_1_001]   21.10.2014 15:40   File folder
[CH_1_002]   21.10.2014 15:40   File folder
[CH_1_003]   21.10.2014 15:40   File folder
[CH_1_004]   21.10.2014 15:40   File folder
[CH_1_005]   21.10.2014 15:40   File folder
[CH_1_006]   21.10.2014 15:40   File folder
[CH_1_007]   21.10.2014 15:40   File folder
[CH_1_008]   21.10.2014 15:40   File folder
[CH_1_009]   21.10.2014 15:40   File folder
[CH_1_010]   21.10.2014 15:40   File folder
```

```
Name
[CH_1_001]_00009_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00010_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00011_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00012_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00013_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00014_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00015_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00016_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00017_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00018_kikusui_characterization_grz-pulse_15_0
[CH_1_001]_00019_kikusui_characterization_grz-pulse_15_0
```

```
PulsePtHi;HIGH
PulsePtLo;LOW
1;Current[A];0.00000;Time[ms];65000.00000
2;Current[A];0.00000;Time[ms];65000.00000
3;Current[A];0.06400;Time[ms];10000.00000
4;Current[A];0.31400;Time[ms];10000.00000
5;Current[A];0.56200;Time[ms];10000.00000
6;Current[A];1.30800;Time[ms];10000.00000
7;Current[A];1.80700;Time[ms];10000.00000

[CHARGE MONITOR]
TimeElapsed[s];StdState;OpnState;LowRange;Capacity[mAh];Power[Wh];Curr[A];Vc
0;0x000A;0;FALSE;0.00000;0.00000;-0.00010;4.19560;NAN;NAN;0.80000
1;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
2;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
3;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
4;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
5;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
6;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
7;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
8;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
9;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
10;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
11;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
12;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
13;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
14;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
15;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
16;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
17;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
18;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
19;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
20;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
21;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
22;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
23;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
24;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
25;0x000B;0;FALSE;0.00000;0.00000;-0.00010;4.19550;NAN;NAN;0.80000
```

Figure 3.17: Kikususi data saving.

# Chapter 4

# Data processing

As described in chapter 3 the stored data is used for creating LookupTables (LUT). When creating OCV tables it is necessary to know the OCV, SOC for the OCV and the temperature at which the test was executed. Also it is necessary to sort the data related to the battery at first and then according to the loop where the measurement was made. After that it is necessary to calculate the average values for temperature for all 10 batteries and five charge/discharge loops. LUT should have the following form for using them in the mobile devices under these conditions:

| OCV Table | Temperature °C | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Voltage | -5 | 0 | 5 | 10 | 15 | 25 | 35 | 45 |
| 4.200 | | | | | | | | |
| 4.150 | | | SOC<br>PERCENTAGES | | | | | |
| ⋮ | | | | | | | | |
| | | | | | | | | |
| ⋮ | | | | | | | | |
| 3.00 | | | | | | | | |

Table 4.1: OCV Table; SOC[%].

| Empty/Flat Table | Temperature [°C] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C rate | -5 | 0 | 5 | 10 | 15 | 25 | 35 | 45 |
| 0 % | | | | | | | | |
| ⋮ | | SOC | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | PRECENTAGES | | | | | | |
| ⋮ | | | | | | | | |
| max % | | | | | | | | |

Table 4.2: Flat/Empty; SOC[%].

## 4.1 OCV - Tables

After the measurement the voltage over time is a mixture of a load profile and relax phases. For the OCV calculation the relaxation phases need to be fitted to the function:

$$OCV(t) = C + \alpha * e^{-\beta t} \tag{4.1}$$

$$\Rightarrow C = OCV(\infty) \tag{4.2}$$

For calculating the OCV a program is written to:

- Identify the relax curve within a battery discharge cycle
- The voltages at 60, 90 and 120 seconds after the relax curve start have to be identified ⇒ $V_{60}$,$V_{90}$, $V_{120}$
- The OCV voltage at this point in time then can be calculated:

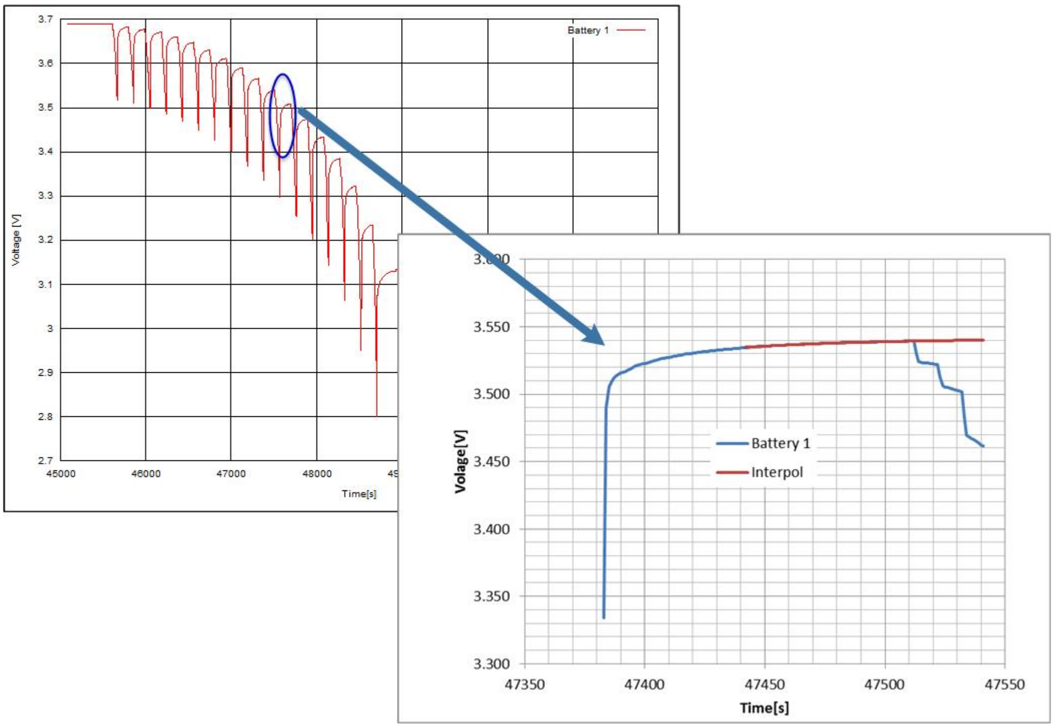


Figure 4.1: Relax cure to calculate OCV.

For solving the equations, the voltage is measured on the three "time points" of the relax curve - after 60 s, 90 s and 120 s. According the equation 4.1, with these three measurements, it is possible to build a system of equations with three variables and calculate all variables.

$$x = \frac{V_{120} - V_{90}}{V_{90} - V_{60}} \tag{4.3}$$

$$OCV = V_{60} - \frac{V_{120} - V_{60}}{x^2 - 1} \tag{4.4}$$

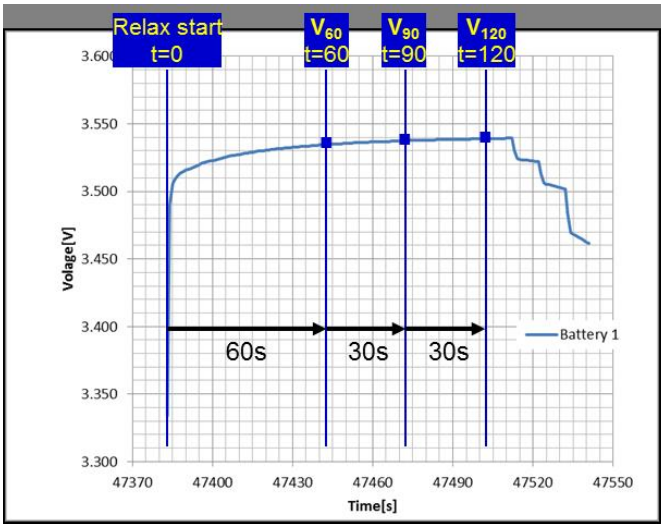


Figure 4.2: Relax cure 60s 90s and 120s OCV.

After releasing the load from the battery, a "regeneration" of the battery voltage is visible. Figure 4.1 shows the relax curve of battery voltage. The SOC during the relaxing phase is constant.

The program is checking for exceptions:

- If $V_{60} \approx V_{90}$ the denominator of 4.3 gets very small or zero and thus x gets very big and inaccurate. These results of extrapolations are invalid and the results need to be ignored (division by zero). For this calculation is OCV is $\gg 4.2\,V$. This is an unreal result and cannot be used.
- If $V_{60} \approx V_{90} \approx V_{120}$ the result would be a flat line and this is also invalid (division by zero).

| Temeperature $T_1$°C | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Battery $B_1$ | | | | | | | | | |
| Cycle $C_1$ | | Cycle $C_2$ | | Cycle $C_3$ | | Cycle $_4$ | | Cycle $C_5$ | |
| OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| Battery $B_2$ | | | | | | | | | |
| Cycle $C_1$ | | Cycle $C_2$ | | Cycle $C_3$ | | Cycle $_4$ | | Cycle $C_5$ | |
| OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] |
| | | | | | | | | | |
| | | | | | | | | | |
| | ⋮ | | ⋮ | | ⋮ | | ⋮ | | |
| | ⋮ | | ⋮ | | ⋮ | | ⋮ | | |
| Battery $B_{10}$ | | | | | | | | | |
| | | | | | | | | | |
| Cycle $C_1$ | | Cycle $C_2$ | | Cycle $C_3$ | | Cycle $_4$ | | Cycle $C_5$ | |
| OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] | OCV [V] | SOC[mAh] |
| | | | | | | | | | |

Table 4.3: Creating OCV tables for the temperature $T_1$

The result is a table of OCV voltages and related SOC's pairs: OCV($B_n$, $C_m$) and SOC($B_n$,$C_m$).

| Battery $B_1$ | |
|---|---|
| Cycle $C_1$ | |
| OCV [V] | SOC[%] |
| $V_{max}$ | 100 |
| ⋮ | ⋮ |
| $V_{terminate}$ | 0 |
| ⋮ | ⋮ |
| $V_{min}$ | -x.xxx |

Table 4.4: SOC Extrapolation Table

When creating a table, at first it is neccesary to do a graphical check of original data stored during the measurements for creating OCV graph vs. SOC. This creates a new table that has in range from $V_{min}$ (2.75V) to $V_{max}$ (4.20V)steps of 5mV . The measured values do not match with scale for the calculation (5mV steps), so adaptions are necessary to match the scale values (interpolation, etc.).

For further investigations, it is necessary to determine the lowest operating voltage of the mobile device. This voltage is called "terminate voltage". Based on the charge for termination voltage and charge for maximum voltage it is possible to determine the FCC (difference between charge for Vterminate and charge for $V_{max}$). It is necessary to calculate the FCC for each cell in every cycle at each temperature. Calculating is done according to the following formula:

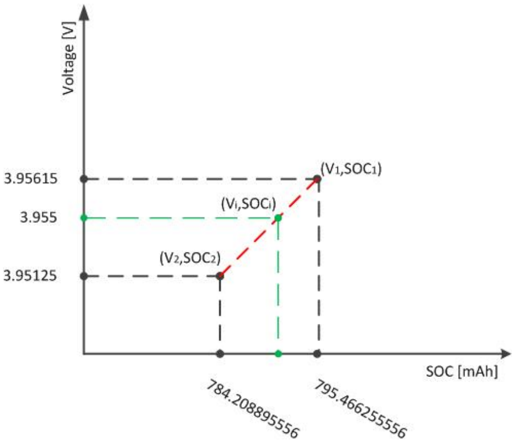


Figure 4.3: Voltage and SOC interpolation.

$$FCC[mAh] = SOC(V_{max})[mAh] - SOC(V_{terminate})[mAh] \tag{4.5}$$

When the SOCs for the desired voltage are determined is necessary to calculate SOC percentage. This calculation is done using next formula:

$$\begin{aligned} &SOC(V_i; B_n, C_m)[\%] = \\ &= 100.0 * \frac{SOC(V_i; B_n, C_m)[mAh] - SOC(V_{terminate}; B_n, C_m)[mAh]}{FCC(B_n, C_m; T = 25°C)[mAh]} \end{aligned} \tag{4.6}$$

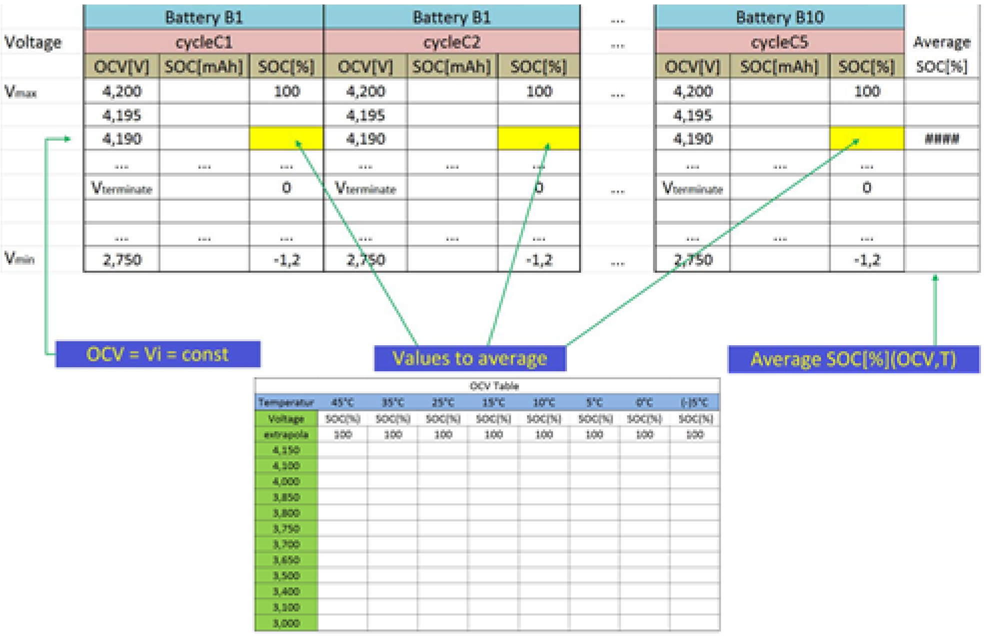
Average values of all FCC at a temperature of 25 °C for all batteries and loops represent the nominal value of the FCC ($FCC_{nominal}$). Considering that all batteries are being charged at the same temperature, $FCC_{nominal}$ will be used in next calculations for all other temperatures.

$$\overline{FCC_{25°C}} = \frac{\sum_{n=1}^{10}\sum_{m=1}^{5} FCC(B_n, C_m; T = 25°C)}{n * m} = FCC_{nominal} \tag{4.7}$$

During the characterization batteries are always charged at a temperature of 25 °C. It is assumed that $FCC_{nominal}$ always be rached during the full charging condition. Calculating the percentage of SOC at temperatures different of 25 °C is carried out according to next formula:

$$SOC(V_i; B_n, C_m)[\%] =$$
$$= 100.0 * (1 - \frac{SOC(V_{max}; B_n, C_m)[mAh] - SOC(V_i; B_n, C_n)[mAh]}{FCC_{nominal}[mAh]} \tag{4.8}$$

The final step of creating the OCV table, will be determined by the average voltage of all batteries in all cycles of individual temperature. Calculated average values are presented in Figure 4.4.



| | Battery B1 | | | Battery B1 | | | ... | Battery B10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Voltage | cycleC1 | | | cycleC2 | | | ... | cycleC5 | | | Average |
| | OCV[V] | SOC[mAh] | SOC[%] | OCV[V] | SOC[mAh] | SOC[%] | | OCV[V] | SOC[mAh] | SOC[%] | SOC[%] |
| $V_{max}$ | 4,200 | | 100 | 4,200 | | 100 | ... | 4,200 | | 100 | |
| | 4,195 | | | 4,195 | | | | 4,195 | | | |
| | 4,190 | | | 4,190 | | | | 4,190 | | | #### |
| | ... | ... | ... | ... | ... | ... | | ... | ... | ... | |
| | $V_{terminate}$ | | 0 | $V_{terminate}$ | | 0 | ... | $V_{terminate}$ | | 0 | |
| | | | | | | | | | | | |
| | ... | ... | ... | ... | ... | ... | | ... | ... | ... | |
| $V_{min}$ | 2,750 | | -1,2 | 2,750 | | -1,2 | ... | 2,750 | | -1,2 | |

OCV Table

| Temperatur | 45°C | 35°C | 25°C | 15°C | 10°C | 5°C | 0°C | (-)5°C |
|---|---|---|---|---|---|---|---|---|
| Voltage | SOC[%] | SOC[%] | SOC[%] | SOC[%] | SOC[%] | SOC[%] | SOC[%] | SOC[%] |
| extrapola | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 4,150 | | | | | | | | |
| 4,100 | | | | | | | | |
| 4,000 | | | | | | | | |
| 3,850 | | | | | | | | |
| 3,800 | | | | | | | | |
| 3,750 | | | | | | | | |
| 3,700 | | | | | | | | |
| 3,650 | | | | | | | | |
| 3,500 | | | | | | | | |
| 3,400 | | | | | | | | |
| 3,100 | | | | | | | | |
| 3,000 | | | | | | | | |

Figure 4.4: Averaging SOC[%](OCV,T).

## 4.2 Empty/Flat Tables

Empty/Flat tables are used to calibrate the remaining battery SOC % at EMPTY and FLAT threshold. The calculation flow is similar to the OCV calculation flow:

- Each temperature is treated separately
- Each cycle of each battery at each temperature is treated separately
- Each cycle of each battery at each temperature has to be separated by battery loads:

$$I_{load} = const \Rightarrow C_{rate} = \frac{I_{load}}{FCC_{nominal}} \approx const \quad (4.9)$$

- Equidistant interpolation over Voltage separately for each cycle of each battery at each temperature at each $C_{rate}$
- Averaging over 10 batteries, 5 cycle at the same temperature

If the FCC's of the individual batteries are only slightly varying the $C_{rates}$ for a $I_{load}$=const load can be assumed to be equal. The selected $C_{rate}$ respectively the loads attached by the Kikusui during the characterization process should be more dense within the realistic current profile of target system and less dense for e.g. exceptionally high currents.

Data separation:

1. The Python program needs to sort the different loads into different data samples
2. Each data sample is taken from the last measurement in the interval $I_{load}(x)$ = const; x = {1,2,3,4,5}. All batteries are charged at the same temperatures and the same conditions. During the characterization there was no deep discharge of the batteries and no ageing effects are represented.

Taking into account these facts it is possible to do further calculations using only $FCC_{nominal}$. $C_{rate}(B_1)$ and $C_{rate}(B_2)$ might not be identical if battery individual $FCC(B_n)$ is used for calculation.

For the correct characterization data, the Voltage/SOC pairs 10 s after the load has been attached are used. Otherwise is possible to have difference SOC for the same voltage and same $C_{rate}$. Figure 4.5 shows example of wrong Voltage/SOC pairs.

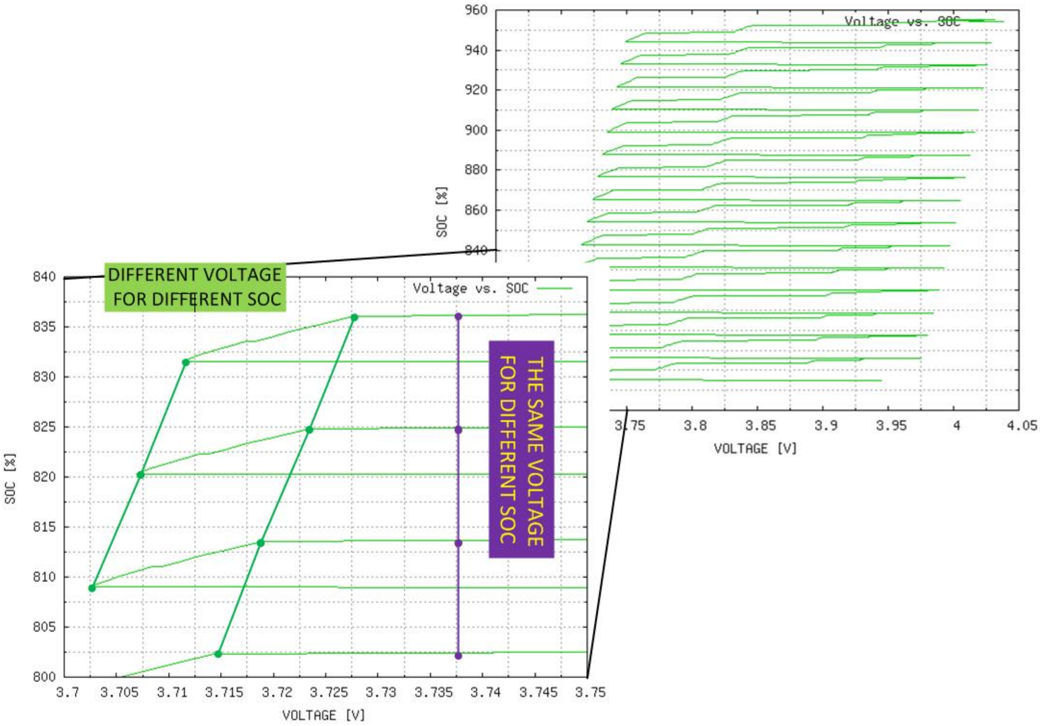
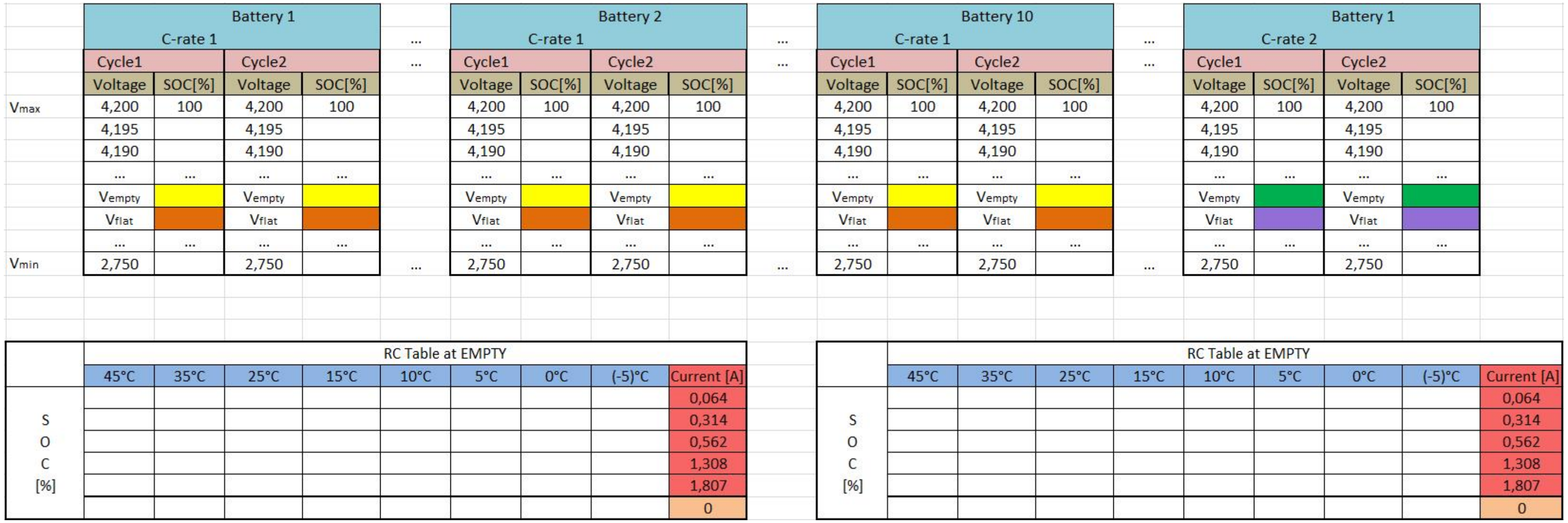


Figure 4.5: 10s Voltage/SOC pair.

3. For each different $I_{load}$ a different table needs to be populated.

During calculation and interpolation the data for each SOC column in table need to be converted to SOC % similar to the OCV calculation. The voltage data equidistant of 5 mV from $V_{max}$ to $V_{min}$. Then SOC % needs be populated by interpolation Voltage/SOC pairs. After all data has been evaluated the $\{SOC(C_{rate}, T, V_{bat}=V_{EMPTY}\}$ table and the $\{SOC(Crate, T, V_{bat}=V_{FLAT}\}$ should be fully populated



| | Battery 1 | | | | | Battery 2 | | | | | Battery 10 | | | | | Battery 1 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C-rate 1 | | | | … | C-rate 1 | | | | … | C-rate 1 | | | | … | C-rate 2 | | | |
| | Cycle1 | | Cycle2 | | … | Cycle1 | | Cycle2 | | … | Cycle1 | | Cycle2 | | … | Cycle1 | | Cycle2 | |
| | Voltage | SOC[%] | Voltage | SOC[%] | | Voltage | SOC[%] | Voltage | SOC[%] | | Voltage | SOC[%] | Voltage | SOC[%] | | Voltage | SOC[%] | Voltage | SOC[%] |
| $V_{max}$ | 4,200 | 100 | 4,200 | 100 | | 4,200 | 100 | 4,200 | 100 | | 4,200 | 100 | 4,200 | 100 | | 4,200 | 100 | 4,200 | 100 |
| | 4,195 | | 4,195 | | | 4,195 | | 4,195 | | | 4,195 | | 4,195 | | | 4,195 | | 4,195 | |
| | 4,190 | | 4,190 | | | 4,190 | | 4,190 | | | 4,190 | | 4,190 | | | 4,190 | | 4,190 | |
| | … | … | … | … | | … | … | … | … | | … | … | … | … | | … | … | … | … |
| | $V_{empty}$ | 🟨 | $V_{empty}$ | 🟨 | | $V_{empty}$ | 🟨 | $V_{empty}$ | 🟨 | | $V_{empty}$ | 🟨 | $V_{empty}$ | 🟨 | | $V_{empty}$ | 🟩 | $V_{empty}$ | 🟩 |
| | $V_{flat}$ | 🟧 | $V_{flat}$ | 🟧 | | $V_{flat}$ | 🟧 | $V_{flat}$ | 🟧 | | $V_{flat}$ | 🟧 | $V_{flat}$ | 🟧 | | $V_{flat}$ | 🟪 | $V_{flat}$ | 🟪 |
| | … | … | … | … | | … | … | … | … | | … | … | … | … | | … | … | … | … |
| $V_{min}$ | 2,750 | | 2,750 | | … | 2,750 | | 2,750 | | … | 2,750 | | 2,750 | | … | 2,750 | | 2,750 | |

| | RC Table at EMPTY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 45°C | 35°C | 25°C | 15°C | 10°C | 5°C | 0°C | (-5)°C | Current [A] |
| | | | | | | | | | 0,064 |
| S | | | | | | | | | 0,314 |
| O | | | | | | | | | 0,562 |
| C | | | | | | | | | 1,308 |
| [%] | | | | | | | | | 1,807 |
| | | | | | | | | | 0 |

| | RC Table at EMPTY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 45°C | 35°C | 25°C | 15°C | 10°C | 5°C | 0°C | (-5)°C | Current [A] |
| | | | | | | | | | 0,064 |
| S | | | | | | | | | 0,314 |
| O | | | | | | | | | 0,562 |
| C | | | | | | | | | 1,308 |
| [%] | | | | | | | | | 1,807 |
| | | | | | | | | | 0 |

Figure 4.6: Filling the Empty/Flat tables.

# Chapter 5

# Characterisation results and discussion

After starting the first profile containing two temperatures, 10 °C and 25 °C, it was estimated that the complete characterization - using the actual measurement parameters - will be completed within six weeks. But at temperatures from 0 °C to 15 °C an increased duration of the test was visible. The reason why the test lasts longer at lower temperatures, is a rapid voltage drop under a higher load. After the load is released the voltage will recover. For higher currents $I_4 = 1.308$ A and $I_5 = 1.807$ A at low temperature very quickly reaches cut-off battery voltage, which is at 2.75 V. Thereafter Kikusui BPChecker2000 changes the Seq. Sheet in its setting and ejects the highest current in the discharge process. In this case, the battery is discharged by minor value current which significantly increases the discharge time.

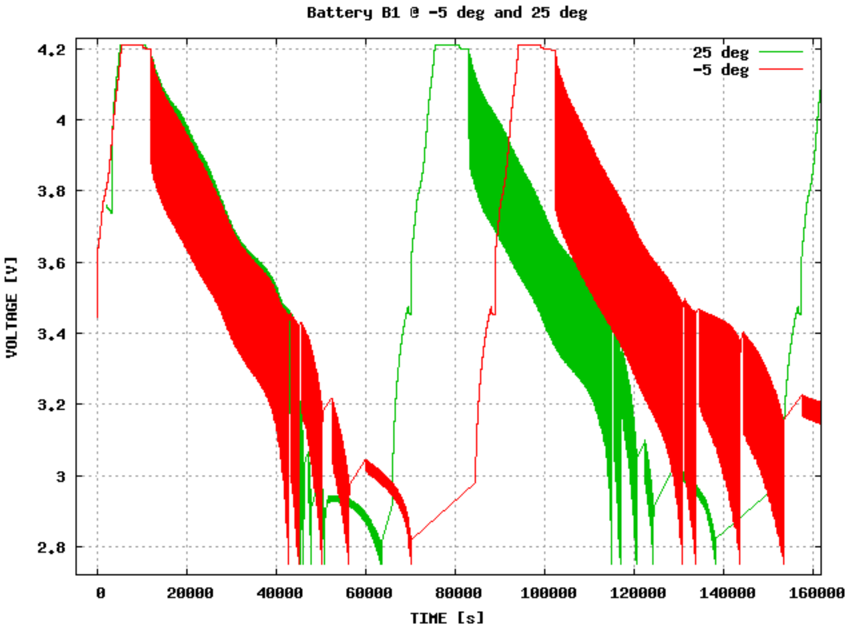


Figure 5.1: Charge/Discharge of Battery $B_1$ at 25°C and -5°C.

As can be seen from the Figure 5.2, characterization of batteries at lower temperatures is much slower. The voltage drop at low temperatures is caused by the change of the internal resistance of the battery which depends on the temperature. The fall of battery temperature increases its internal resistance and that causes a higher voltage drop.

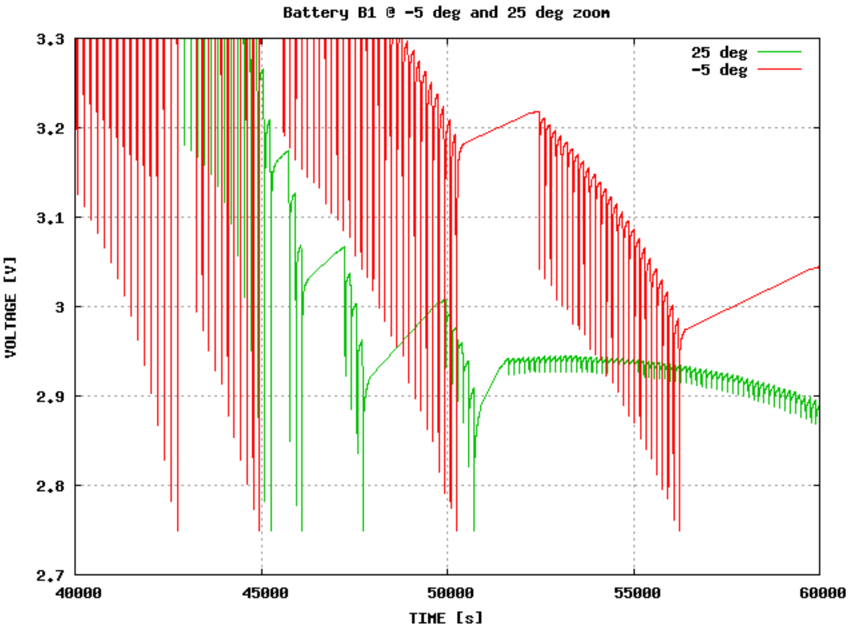


Figure 5.2: Cut-off Voltage over time of Battery $B_1$ at 25°C and -5°C.

Observing complete graphics of Kikusui profile that contains charging and discharging data of battery at the same temperature, it is visible that the discharge time varies from battery to battery. In this case, Kikusui is waiting until the last one of 10 batteries finish the cycle in the Seq Sheet and only then passes on to the next one. In the case of the last completed processed battery discharge all batteries start charging at the same time(Figure 5.3). The reason for the distinct and individual time of discharge of batteries at the same temperature lies in its chemical properties and internal resistance which causes different values of voltage recovery after releasing of load. As more voltage recovers after the battery is released from the loads, the time is longer to reach the cut-off voltage.

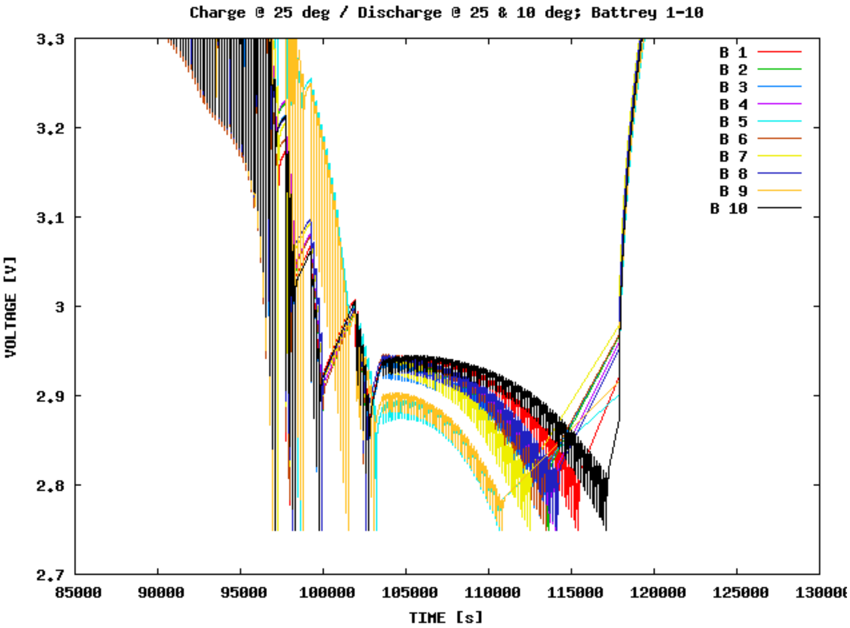


Figure 5.3: Discharge of all 10 batteries at the same temperature

From Figure 5.3 it is visible that batteries have unequal voltage drop during discharge but when charging again, the voltage rises identical for all batteries. During the test it was noted that particular batteries $B_5$ and $B_9$, deviate from the other eight batteries by charge and discharge time. These deviations are also considered in description or characterization of the batteries and we have to take into account all the results that the batteries show and create a table of average values.

Figure 5.4 stage 1 shows charge in constant current mode, stage 2 is constant voltage mode, stage 3 is relax mode and in stage 4 starts the discharge mode. After the battery voltage reaches nominal value the current drops in order to hold voltage value constant. When current reaches value that is set in the Seq Sheet ($I_t$ = 43 mA) battery goes from charge mode to relax stage. After that the program runs discharge sheet and sets the nominal temperature. The time for which the battery is located in the area 3 is about of 10 min relaxation time, the time required for reaching the set temperature and the 60 seconds that takes to check or initial Seq Sheet. During this time a voltage drop of the battery could appear (but only a few mV).

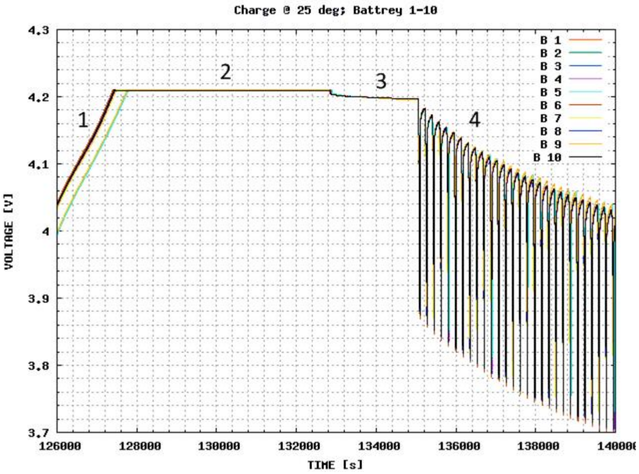


Figure 5.4: Transitions: Charge in CC-CV, relaxing and discharge

## 5.1 $\mathbf{FCC_{nominal}}$ vs. $\mathbf{FCC_{bat}}$

During characterization of the battery there were measurements of FCC value when charging batteries. It is between 4.2 V 2.75 V at a temperature of 25 °C then the average value across all 10 batteries is calculated. This value of FCC is taken as the nominal value. During battery discharge there are calculated FCC values for each battery individually at all temperatures. The table below shows the relationship of the $FCC_{bat}$ values with the $FCC_{nominal}$ value.

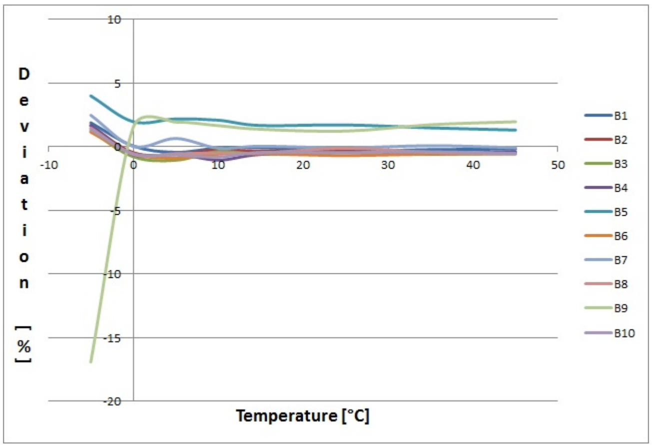


Figure 5.5: Transitions: Charge in CC-CV, relaxing and discharge

As can be seen from this graph battery $B_9$ shows much larger variations than any battery.

| B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | °C |
|---|---|---|---|---|---|---|---|---|---|---|
| FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | FCC [%] | Temp |
| -0.44 | -0.44 | -0.53 | -0.40 | 1.31 | -0.56 | -0.08 | -0.56 | 1.97 | -0.53 | 45.00 |
| -0.52 | -0.52 | -0.59 | -0.55 | 1.48 | -0.58 | 0.08 | -0.43 | 1.73 | -0.39 | 35.00 |
| -0.36 | -0.36 | -0.46 | -0.44 | 1.71 | -0.69 | -0.09 | -0.12 | 1.23 | -0.46 | 25.00 |
| -0.35 | -0.35 | -0.56 | -0.61 | 1.67 | -0.56 | 0.04 | -0.49 | 1.37 | -0.45 | 15.00 |
| -0.25 | -0.25 | -0.37 | -1.05 | 2.09 | -0.58 | -0.11 | -0.49 | 1.66 | -0.81 | 10.00 |
| -0.60 | -0.60 | -1.06 | -0.57 | 2.18 | -0.91 | 0.65 | -0.54 | 1.94 | -0.66 | 5.00 |
| -0.46 | -0.46 | -0.79 | -0.63 | 1.96 | -0.57 | 0.03 | -0.60 | 1.55 | -0.55 | 0.00 |
| 1.64 | 1.64 | 1.23 | 1.70 | 4.00 | 1.15 | 2.48 | 1.47 | -16.91 | 1.36 | -5.00 |
| 1.12 | 1.12 | 0.43 | 1.32 | 5.82 | 0.61 | 3.06 | 3.30 | -19.08 | 1.81 | -10.00 |
| -17.68 | -17.68 | -18.00 | -16.00 | -9.83 | -13.04 | -27.47 | -30.08 | -23.28 | -15.19 | -25.00 |

Table 5.1: Deviation from $FCC_{bat}$ of $FCC_{nominal}$

As can be seen from Table, the battery, gives unreasonable results at very low temperatures, -25 °C. This also coincides with the data sheet of the battery where the lowest recommended discharge temperature states -20 °C. As previously considered the deviations $FCC_{bat}$ are not drastic compared to $FCC_{nominal}$. For all the calculations for empty/flat panels take $FCC_{nominal}$.

## 5.2 Calibration Tables

Table 5.2 shows the calculated values of OCV for temperatures between -5 °C and 45 °C. At temperatures below -5 °C (e.g. -10 °C and -25 °C) the values are not within realistic ranges, so they are not used for calculations. In real applications, the mobile devices are seldom used in this temperature range (selfheating, etc.).

| Temp | 45°C | 35°C | 25°C | 15°C | 10°C | 5°C | 0°C | -5°C |
|---|---|---|---|---|---|---|---|---|
| Voltage | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) |
| extrapola | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 4.150 | 96.70 | 96.73 | 96.94 | 97.12 | 97.14 | 96.98 | 97.36 | 97.38 |
| 4.100 | 92.23 | 92.35 | 92.61 | 93.01 | 93.15 | 93.07 | 93.58 | 93.62 |
| 4.000 | 77.79 | 77.80 | 77.97 | 78.69 | 79.59 | 79.83 | 81.51 | 82.00 |
| 3.850 | 57.98 | 58.24 | 59.47 | 60.33 | 61.94 | 61.68 | 64.02 | 64.65 |
| 3.800 | 54.21 | 54.47 | 55.28 | 55.80 | 56.43 | 56.57 | 57.75 | 58.35 |
| 3.750 | 50.00 | 50.32 | 50.93 | 51.28 | 51.45 | 51.62 | 52.16 | 52.48 |
| 3.700 | 44.70 | 45.16 | 45.95 | 46.35 | 46.45 | 46.67 | 47.01 | 47.04 |
| 3.650 | 36.95 | 37.74 | 38.81 | 39.48 | 39.73 | 40.23 | 40.77 | 40.90 |
| 3.500 | 13.83 | 13.82 | 13.98 | 14.26 | 14.46 | 15.43 | 15.99 | 18.50 |
| 3.400 | 4.05 | 4.02 | 3.91 | 4.15 | 3.97 | 4.54 | 4.71 | 6.88 |
| 3.100 | 0.67 | 0.74 | 0.52 | 0.68 | 0.70 | 1.00 | 0.83 | 2.10 |
| 3.000 | 0.08 | 0.16 | 0.00 | 0.25 | 0.04 | 0.56 | 0.06 | 1.65 |

Table 5.2: OCV Table - calculated values

Increased temperature also increases the voltage of the battery. The table shows that the SOC decreases with increasing temperature. First value of OCV voltage is measured at about 4.14 to 4.18 V. The measured values are not matching the 5mV steps exactly, ao an interpolation was done for all values to create a table in steps of 5 mV. For last the step at 4.2 V an extrapolation was necessary (only 4.18V reached in measurements after first relaxing time)

The tables below show the value of empty/flat table

| 45 °C<br>SOC[%] | 35 °C<br>SOC[%] | 25 °C<br>SOC[%] | 15 °C<br>SOC[%] | 10 °C<br>SOC[%] | 5 °C<br>SOC[%] | 0 °C<br>SOC[%] | -5 °C<br>SOC[%] | 3.4 V<br>C-rate[%] |
|---|---|---|---|---|---|---|---|---|
| 4.05 | 4.02 | 3.91 | 4.15 | 3.97 | 4.54 | 4.71 | 6.88 | 0,00 |
| 4.95 | 5.42 | 4.61 | 5.00 | 4.90 | 7.46 | 6.65 | 11.49 | 3,00 |
| 6.30 | 7.09 | 6.55 | 8.21 | 9.67 | 14.55 | 17.13 | 25.79 | 14,71 |
| 11.89 | 12.26 | 12.03 | 13.98 | 15.37 | 18.85 | 19.96 | 26.91 | 26,33 |
| 22.68 | 23.13 | 24.94 | 27.32 | 35.59 | 40.00 | 42.80 | 51.39 | 61,27 |
| 34.37 | 36.58 | 42.10 | 44.07 | 48.02 | 52.29 | 53.85 | 63.43 | 84,65 |

Table 5.3: Calibration table for EMPTY battery voltage

| 45 °C<br>SOC[%] | 35 °C<br>SOC[%] | 25 °C<br>SOC[%] | 15 °C<br>SOC[%] | 10 °C<br>SOC[%] | 5 °C<br>SOC[%] | 0 °C<br>SOC[%] | -5 °C<br>SOC[%] | 3.1 V<br>C-rate[%] |
|---|---|---|---|---|---|---|---|---|
| 0.67 | 0.74 | 0.52 | 0.68 | 0.70 | 1.00 | 0.83 | 2.10 | 0,00 |
| 1.56 | 2.02 | 0.96 | 1.21 | 1.48 | 3.05 | 1.57 | 8.66 | 3,00 |
| 1.91 | 2.30 | 1.25 | 1.73 | 2.34 | 5.61 | 7.10 | 15.94 | 14,71 |
| 2.15 | 2.63 | 1.75 | 2.54 | 3.31 | 7.23 | 6.70 | 12.68 | 26,33 |
| 3.26 | 3.76 | 3.43 | 5.57 | 7.56 | 13.79 | 14.22 | 21.64 | 61,27 |
| 4.38 | 5.03 | 5.29 | 8.96 | 11.66 | 18.50 | 20.20 | 31.05 | 84,65 |

Table 5.4: Calibration table for FLAT battery voltage

Interpolation was also performed during the creation of these tables to obtain the desired voltage values and their given SOC. When it is about extrapolation for higher voltages it is visible that unrealistic values of SOC are possible. This is due to a sudden drop in voltage after we put some load on a fully charged battery. So in case of a major electricity discharge, we have extrapolation value to 3500 mAh which is impossible for the battery capacity of 2150 mAh. Since it is necessary to determine the average value of the battery capacity for a given discharge voltage and current at a temperature based on 10 batteries it is necessary to set the point at which the voltage values coincide and determine the average value of capacity. It is also considered that the batteries are not damaged in any way during the characterization and during that time the aging process can be ignored. Since all battery are charged at 25 °C with the same charging current, the $FCC_{nominal}$ is used as a starting point. To that point we "move" the FCC of all individual batteries. Graphic sets equal starting point for all the curves. In this case we have different voltage drops but equal capacity starting point of discharge for each battery (Figure 5.6).

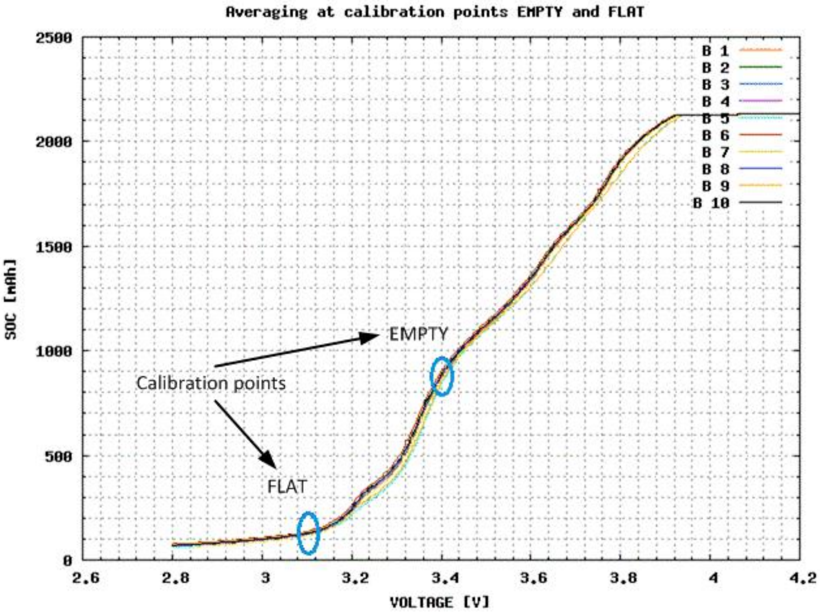


Figure 5.6: Aligning $\text{FCC}_{\text{bat}}$ to the $\text{FCC}_{\text{nominal}}$

To align all discharge curves we use the next formula:

$$SOC_{align}(V_i) = FCC_{nominal} - SOC_{max} + SOC_{Vi} \tag{5.1}$$

After completing the alignment the curve for voltages 3.1 V 3.4 V we calculate SOC as percentage.

$$SOC_{bat}(V_i) = 100 * \frac{FCC_{nominal} - SOC_m ax + SOC_{Vi}}{FCC_{nominal}} \tag{5.2}$$

After that we do the averaging of values:

$$SOC_{aver}(V_i) = 100 * \frac{\sum_{n=1}^{10} \sum_{m=1}^{5} (B_n, C_m, I_{load})}{n * m} \tag{5.3}$$

## 5.3 Comparison of Look Up tables for batteries with and without protection circuit

As is well known, smart Li-ion batteries in almost all applications are used with additional protection circuit in order to prevent any adverse effects and permanent damage of the battery. For comparison and observing the impact of protection on the battery the characterization of the battery is made without protection for several temperature levels. Comparison of the values is shown in the following tables

| 45 °C<br>SOC[%] | 35 °C<br>SOC[%] | 25 °C<br>SOC[%] | 15 °C<br>SOC[%] | 10 °C<br>SOC[%] | 0 °C<br>SOC[%] | 3.4 V<br>C-rate[%] |
|---|---|---|---|---|---|---|
| 4.05 | 4.02 | 3.91 | 4.15 | 3.97 | 4.71 | 0,00 |
| 4.95 | 5.42 | 4.61 | 5.00 | 4.90 | 6.65 | 3,00 |
| 6.30 | 7.09 | 6.55 | 8.21 | 9.67 | 17.13 | 14,71 |
| 11.89 | 12.26 | 12.03 | 13.98 | 15.37 | 19.96 | 26,33 |
| 22.68 | 23.13 | 24.94 | 27.32 | 35.59 | 42.80 | 61,27 |
| 34.37 | 36.58 | 42.10 | 44.07 | 48.02 | 53.85 | 84,65 |

Table 5.5: Calibration table for EMPTY battery voltage, with protection circuit

| 45 °C<br>SOC[%] | 35 °C<br>SOC[%] | 25 °C<br>SOC[%] | 15 °C<br>SOC[%] | 10 °C<br>SOC[%] | 0 °C<br>SOC[%] | 3.4 V<br>C-rate[%] |
|---|---|---|---|---|---|---|
| 3.76 | 3.94 | 4.11 | 4.90 | 4.41 | 6.87 | 0,00 |
| 4.46 | 4.51 | 4.98 | 6.10 | 8.53 | 10.18 | 3,00 |
| 4.92 | 5.20 | 6.14 | 8.88 | 10.77 | 24.51 | 14,71 |
| 5.99 | 6.77 | 8.75 | 12.06 | 13.57 | 20.72 | 26,33 |
| 12.49 | 14.99 | 14.33 | 19.97 | 22.13 | 41.11 | 61,27 |
| 14.82 | 16.39 | 18.28 | 24.09 | 32.80 | 47.91 | 84,65 |

Table 5.6: Calibration table for EMPTY battery voltage, without protection circuit

For a comparison of the calibration values for batteries with and without protection circuit SOC values at 3.4 V are taken. The table shows that the batteries with protection circuit have much larger SOC for the same voltage, temperature and $C_{rate}$ than battery without protection circuit. The reason for this is the additional voltage drop on the protection circuit. With the increase of $C_{\text{rate}}$ the difference between SOC also grows.

| Temperatur | 45°C | 35°C | 25°C | 15°C | 10°C | 0°C |
|---|---|---|---|---|---|---|
| Voltage | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) |
| extrapola | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 4.15 | 96.80 | 96.96 | 97.02 | 97.11 | 97.21 | 97.44 |
| 3.85 | 59.54 | 59.91 | 60.92 | 62.35 | 62.85 | 64.53 |
| 3.80 | 54.95 | 55.45 | 56.27 | 57.55 | 57.60 | 58.61 |
| 3.65 | 38.34 | 39.21 | 39.46 | 40.89 | 41.08 | 41.97 |
| 3.50 | 13.77 | 13.96 | 14.05 | 14.98 | 14.98 | 17.17 |
| 3.40 | 3.76 | 3.94 | 4.11 | 4.90 | 4.41 | 6.87 |
| 3.10 | 0.44 | 0.58 | 0.49 | 1.02 | 0.62 | 0.94 |
| 3.00 | -0.07 | 0.06 | 0.00 | 0.51 | -0.22 | 0.45 |

Table 5.7: OCV table for batteries without protection circuit

| Temperatur | 45°C | 35°C | 25°C | 15°C | 10°C | 0°C |
|---|---|---|---|---|---|---|
| Voltage | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) | SOC(%) |
| extrapola | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 4.15 | 96.70 | 96.73 | 96.94 | 97.12 | 97.14 | 97.36 |
| 3.85 | 57.98 | 58.24 | 59.47 | 60.33 | 61.94 | 64.02 |
| 3.80 | 54.21 | 54.47 | 55.28 | 55.80 | 56.43 | 57.75 |
| 3.65 | 36.95 | 37.74 | 38.81 | 39.48 | 39.73 | 40.77 |
| 3.50 | 13.83 | 13.82 | 13.98 | 14.26 | 14.46 | 15.99 |
| 3.40 | 4.05 | 4.02 | 3.91 | 4.15 | 3.97 | 4.71 |
| 3.10 | 0.67 | 0.74 | 0.52 | 0.68 | 0.70 | 0.83 |
| 3.00 | 0.08 | 0.16 | 0.00 | 0.25 | 0.04 | 0.06 |

Table 5.8: OCV table for batteries with protection circuit

There has been spotted a slight difference of SOC batteries whether with or without protection circuit.

## 5.4 FG Calibration

After the calibration table for FG is created it is necessary to create a new Firmware for the charger and store it in the memory. A new setup for the control of the selected value table has to be created and checked with the chargers FG.

The setup consists of Kikusui device that is used for charging and discharging the battery and calculating SOC, Agilent multimeter to measure battery voltage and current that entes/exits the battery charger and FG, which measures the battery current, voltage and SOC. After the test is carried out it is necessary to compare the results of all three systems (Kikusui, FG on chip, multimeter setup.

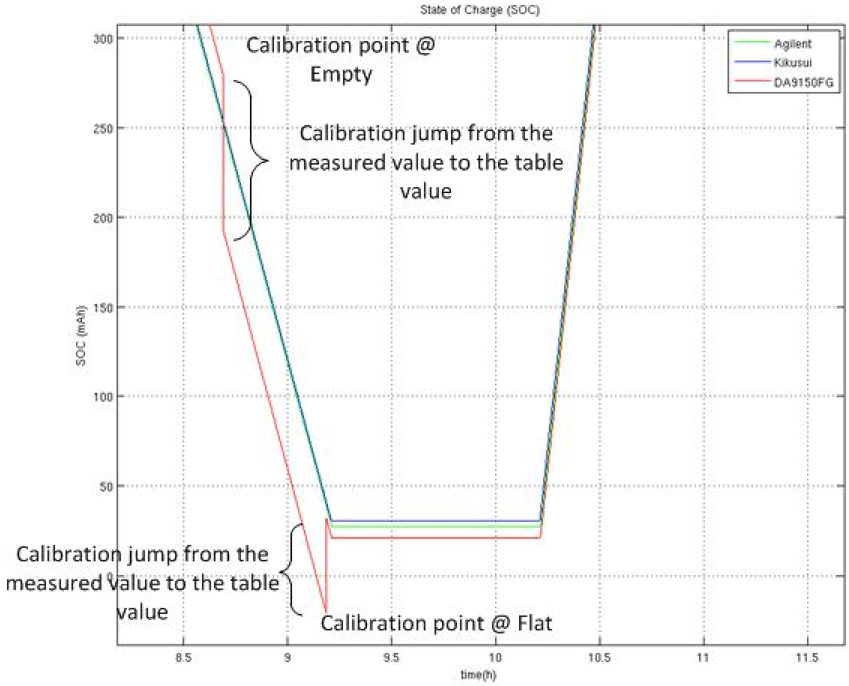


Figure 5.7: Calibration jumps of SOC

When the battery voltage drops to 3.4 V or 3.1 V FG access the lookup tables and performs the calibration. As the charts have five different values of the $C_{\text{rate}}$ and corresponding SOC, it is necessary to interpolate or extrapolate the values for each $C_{rate}$ and corresponding SOC that are different from these five. It is necessary to do the same mathematical operation in relation to the measured temperature. Firmware does this work by itself. First it should be mentioned that the FG, which is discharged to the end and filled to the max of that FCC, learns the new FCC during every cycle in which the battery is. The actual FCC value and the current which loads the battery at the time of calibration $C_{rate}$ is used for calculation. FG enters the tables and makes interpolation and extrapolation to find the exact value of the SOC at the measured temperature.

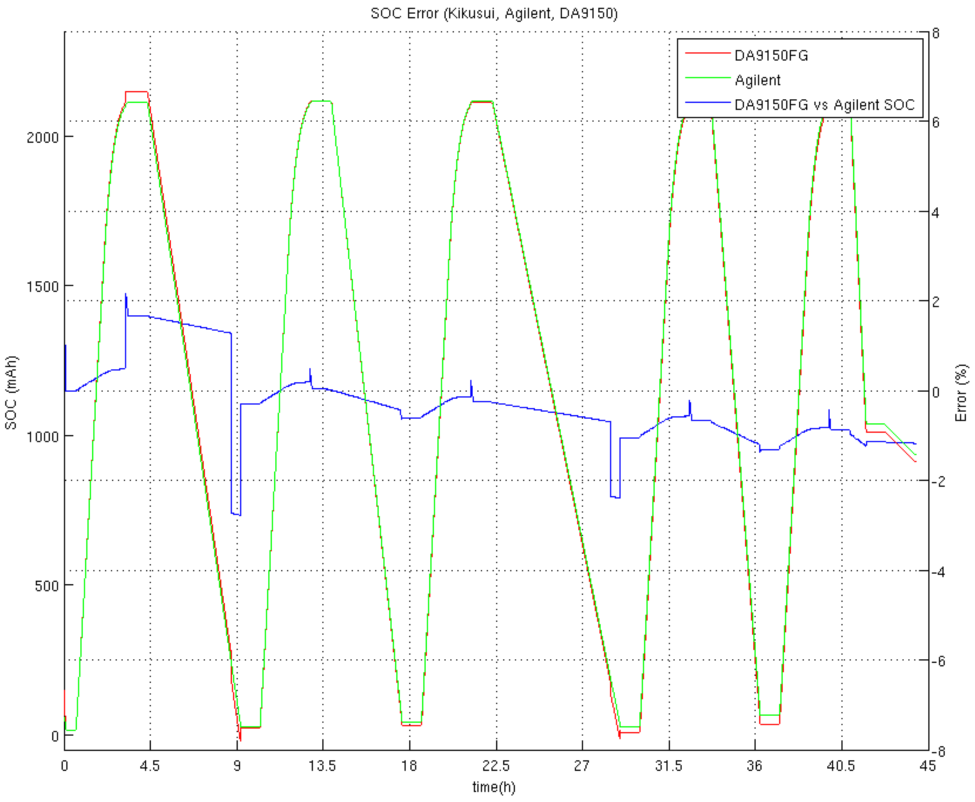


Figure 5.8: Calibration error - FG to the Reference value

On Figure 5.7 we can see exactly two jumps of SOC. The first is happening at the empty and the other at flat battery voltage. At this moment FG accesses the tables and calibrates. Battery calibration is done in real time.

Accuracy of the calibration is higher for lower $C_{rate}$. Figure 5.9 shows SOC deviation during FG Coulomb counting and calibration point at 3.4 V. For the FG calibration battery is discharged with 0.03C. Compared to the calibration based on discharging with higer $C_{rate}$ (Figure 5.7) here higher accuracy is achived.

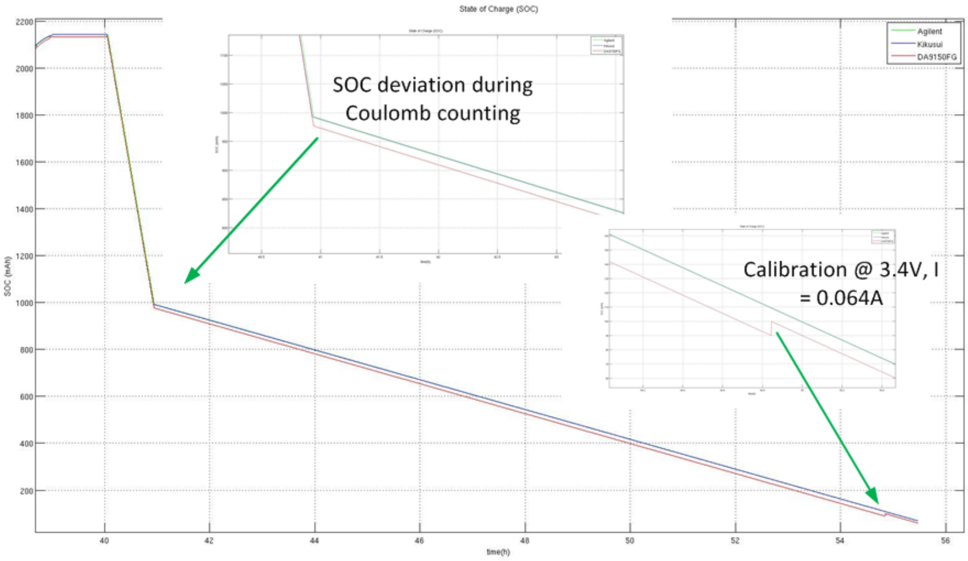


Figure 5.9: Calibration at 3.4V and 0.064A load

# Chapter 6

# Conclusion

After the test is done at a temperature of 25 °C and 45 °C and FG calibration the obtained result do not deviate much from the desired. The aim of objective characterization was reducing errors from the FG to a range within +/- 1 %, compared with the reference of the value measured by Kikusui and Agilent device. Results of this test show that the calibration error is within +/- 3 %, a one can see from the Figure 5.8. The reason probably lies in the deviation of the data processing. Assume that the setup which is used at characterization represents realistic behavior for charging and discharging batteries. During the data processing there are minor discrepancies such as incorrect FCC of the single battery, that is calculated $\mathrm{FCC}_{\mathrm{nominal}}$ over 10 batteries , then variations in interpolation and extrapolation values and the overlap of discharge curves during the drafting table for empty and flat battery voltage. The sum of all these small deviation leads to undesired deviations of the final value. During the test there was discharging with a current that is not represented in the tables directly but it is required to calculate FG by itself, $\mathrm{C}_{\mathrm{rate}}$ and SOC for that current, also. This may also be one of the reasons why the value of the error is higher than desired. Characterization of the battery is executed on only 5 different $\mathrm{C}_{\mathrm{rate}}$ and 8 temperatures (-5 °C, 0 °C, 5 °C, 10 °C, 15 °C, 25 °C, 35 °C, 45 °C). To increase the accuracy of the work of FG and reduce errors for future tests there will be used a larger number of discharge current and a large number of batteries as well as the temperature at which the test will be executed. Considering one BPChecker2000 and one control unit can control two Kikusui devices with each 10 channels (10 batteries) and one temperature chamber during the test. To get more data for increasing the accuracy it is necessary to use additional Kikusui devices and temperature chambers. This leads to an increase of cost for the tests. It is also possible to use only one Kikusui device and one temperature chamber, but seperating the batteries into two groups, with different currents and increased number of loops. This will achieve better resolution SOC but the time duration of the test would be considerably prolonged. The cause of the size of defect FG work also can be found in the battery for which the calibration is performed. As it showed during characterization all the batteries do not have equal performances - Case: battery $B_9$. Depending on value of the battery for which the calibration is performed for, there are value discrepancies.

# Bibliography

[1] Isidor Buchmann. When was the battery invented? battery ddefinition? comparison table of li-ion batteries. Battery University (http://batteryuniversity.com).

[2] Wikipedia. http://en.wikipedia.org/wiki/Voltaic_pile.

[3] Rizzi Michele Web Page. http://www.rizzimichele.it/wp-content/plugins/slick-social-share-buttons/css/images/tab_top_floating.png.

[4] David W. Ball. Introductory chemistry, v. 1.0. Flat World Education, Inc. Terms of Use.

[5] http://imgarcade.com/1/lithium-battery diagram/.

[6] Dipl. Chem. Carmen Meuser. *Physikalische und chemische Charakterisierung von Lithiumionenzellen.* PhD thesis, Fakultät Mathematik und Naturwissenschaften der Technischen Universität Dresden, July 2011.

[7] Kikusui Electronics Corporation. *Operation Manuel, Charge/Discharge Battery TEst System PFX2000 Series.* 1-1-3 Higashiyamata, Tsuzuki-ku, 224-0023, Japan, July 2012.

[8] Ltd. Battery Business Division Samsung SDI Co. Specification of product for lithium-ion rechargeable cell model : Icr18650-22p, Martch 2010.

[9] MIT Electric Vehicle Team. *A Guide to Understanding Battery Specifications,* 2008.

[10] Prof. Dr.-Ing Andreas Jossen. *Basiskurs Batterien.* Desing&Elektronik Entwicklerforum, Lehrstuhl für Elektrische Energiespeichertechnik (EES), Karlstrasse 45, 80333 München, Technische Universität München.

[11] Jugovic Dragana. Karakterizacija katodnih materijala LiMn2-xMxO4 sintetisanih ultrazvucnom sprej pirolizom. Master's thesis, Fakultet za fiziku hemiju Univerziteta u Beogradu, 2004.