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Online State of Health Estimation of Lithium-ion Batteries

Diploma Thesis, January 2020

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Abstract

Lithium-Ion batteries (Li-ion) are becoming more significant in powering modern electronic devices. Therefore it is of great interest how they are controlled and have their primary parameters estimated. This thesis seeks to investigate how modern battery management systems perform online State of Health (SOH) estimations on Li-ion batteries, as well as how precisely it can be done. An online estimation is performed while the battery is being used in a normal operation, and therefore when it is not possible to do a controlled full discharge. This involves describing the relevant characteristics of Li-ion batteries, and investigating the necessary relaxation time to get a precise voltage measurement, which influences the accuracy of the SOH estimation. Here a relaxation time of 20 min was found to be sufficient.

This thesis also investigates the influence the temperature of the cell has on the SOC-OCV curve, the capacity, as well as the internal resistance. For all tests, four fresh cells and four degraded cells were tested to investigate the influence the degradation of the cell had on the different battery parameters. The average amp-hour (Ah) capacity change compared to the capacity at $23°C$ was, for $5°C$ -2.87% for the fresh cells and -5.38% for the degraded cells. At $45°C$ it was $+0.37\%$ for the fresh cells, and $+2.00\%$ for the degraded cells. It was also found that the SOC-OCV had a very limited change as the cells aged, which made it possible to perform an SOC estimation of the degraded cells using the initial SOC-OCV curve for the fresh cells. The internal resistance was found to increase at $5°C$ and decrease at $45°C$, with the change being more noticeable for the degraded cells. It was also observed how the spread of the internal resistance was more significant for the degraded cells. It is critical that the cells are aged differently, as some cells experience a higher power dissipation and are thereby heated more as well as discharged faster, which limits the entire battery pack. This thesis also analyses how precise it is possible to perform online estimation of the SOH at different partial discharges. Here it was calculated that it could be estimated at an error percentage under 4% for set A and 2% for set B both with a discharge depth of over 40 %.

For the test, eight 18650-NMC cells from Samsung SDI was used. The cells were tested with a battery tester connected to the cells that was placed in a climate chamber where the temperature and humidity was controlled. All tests were carried out at Lithium Balance A/S, experts in the field of batteries and BMSs, which actively collaborate with knowledge, equipment availability and cells provision.

Keywords
Battery Management System, Li-ion battery cell, Online Estimation, State of Health (SOH)

Preface

Preface

This project was performed under the supervision of Mattia Marinelli, Andreas Thingvad, and Lisa Calearo, with the work being carried out between between September 2019 and January 2020 at the Department of Electrical Engineering of the Technical University of Denmark. This thesis constitutes to the work of 20 ECTS points and aims to give a contribution to the Danish Research Project "ACES - Across Continents Electric Vehicle Services". The project is done in collaboration with the firm Lithium Balance A/S, with supervision from Rasmus Viskinde and Sune Ebbesen.

Acknowledgements

I would like to thank my supervisors for all their help and guidance through the project, with a special thanks to Andreas Thingvad and Lisa Calearo for all the time they spend reading through my work. Finally a thanks to my boyfriend Joshua for his general support throughout the project.

Kgs. Lyngby, January, 2020

Nomenclature

Nomenclature **Acronyms**

SOH	State of Health
SOC	State of Charge
DOD	Depth of discharge
EV	Electric Vehicle
OCV	Open Circuit Voltage
BMS	Battery Management System
$Li-ion$	Lithium-Ion
Wh	Watt-hour
Ah	Ampere-hour
CC	Constant current
$CCCV$	Constant current constant voltage
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminum
OEM	Other Original Equipment Manufacturers

Symbols

Q_{Ah} Amp Hour Capacity

Q_{Wh} Watt hour Capacity

Q_{Wh}^{d} Watt hour Discharge Capacity

Q_{Wh}^{c} Watt hour Charge Capacity

Q_{full} Present Capacity

$Q_{nominal}$ Nominal Capacity

t_s Sampling time

ΔT Number of samples per hour

R_{int} Internal Resistance

V_T Terminal voltage

$V_{nominal}$ Nominal Voltage

V_{oc} Open Circuit Voltage

V_{max} Maximum Voltage

V_{min} Minimum/Cut off Voltage

η_{Wh} Energy Efficiency

I Current

CHAPTER 1

Introduction

Lithium ion (Li-ion) batteries are playing an increasingly significant role in powering and enabling modern electronic devices; from smaller batteries powering mobile phones, to electric vehicles (EV) and large scale grid connected energy storage systems. As we are depending more on them it also becomes increasingly important that the batteries are able to safely, reliably and efficiently provide power and energy when needed. Li-ion batteries however, have neither of those quantities without a well functioning battery management system (BMS). This is essential as the battery cells are functioning in a narrow voltage and temperature window, which is maintained by the BMS.

The BMS is the brain of the battery pack and makes sure that the cells are used in a way that optimises the energy capacity and limits the degradation.

This chapter goes through the thesis objective, description, and problem statement, as well as the history of Li-ion battery use.

1.1 Project Description

The thesis investigates how precisely it is possible to perform online estimation on State of Health (SOH) of Li-ion batteries.

1.1.1 Project Scope

This thesis investigates how precisely it is possible to do online estimation of SOH of Li-ion batteries. Online estimation is performed while the battery is being used in a normal operation without performing a controlled charge/discharge cycle.

This involves describing the relevant characteristics of Li-ion batteries, and investigating the necessary relaxation time to get a precise voltage measurement, which influences the accuracy of the SOH estimation. The thesis finally analyses how precise it is possible to perform online estimation of the SOH at different partial charges.

1.1.2 Problem Statement

The thesis will answer the following research questions:

- What physical quantities of lithium-ion battery cells are of interest?
- How do you measure and quantify the characteristics of the battery cells state of health (SOH), such as internal resistance and remaining capacity?

- How is SOH estimated by modern battery management systems?
- How does the open circuit voltage curve depend on the used relaxation time?
- Can the SOH be estimated based on changes in the open circuit voltage at partial discharge cycles and with what accuracy?
- What is the effect of the internal resistance and the temperature on the capacity measurements and can it be used to make better estimations?
- Is it possible to perform online capacity estimation during a normal electric vehicle charging process?

1.1.3 Thesis Outline

Chapter 1: Introduction
Describes the project, including problem statements and project scope.

Chapter 2: The Battery - Structure and modelling
Describes the battery. The most important parameters and how to model a battery.

Chapter 3: Battery Management System
Describes the primary functions of the BMS and how it estimates the battery parameters.

Chapter 4: Online State of Health Estimation
Describes a method of online state of health estimation and goes over what parameters to test.

Chapter 5: Test description
Describes the test setup used, as well as the specification and procedure of the different tests.

Chapter 6: Results
Presents the test results.

Chapter 7: Conclusion and Future Works
Presents the conclusion and future works.

1.2 Applications of Lithium-ion Batteries

Before lithium batteries, nickel-cadmium was the most used battery chemistry for portable batteries. In the early 1970s the first lithium batteries became available for consumers in cameras by Sony. Lithium is the lightest of all metals and has a much greater electrochemical voltage potential and energy density per weight than nickel-cadmium, but because of safety problems the first lithium batteries were non-rechargeable. This problem was overcome by using the lithium-ion instead of the lithium metal. Lithium-ion is safer and more stable to use, and could be recharged, as long as a protection circuit kept the battery parameters inside safe operating conditions. A Li-ion battery cell has a nominal voltage around 3.6 V, compared to the 1.2 V of the nickel-cadmium battery cell. This is preferred as a single Li-ion cell can provide a high enough voltage for a lot of consumer products. Compared to nickel-cadmium, Li-ion cells do not suffer from *memory effect* and have no need for *priming* which results in very low maintenance, as well as having only half of the self discharge. This is why the Li-ion battery cell has been an enabling technology of many portable devices such as mobile phones and increasingly also electric vehicles [1].

CHAPTER 2

The Battery - Structure and Modeling

This chapter explains the structure and modelling of a Li-ion battery, as well as the most important parameters.

2.1 Battery Cell Components

A battery cell is a device that converts the chemical energy from its active materials into electrical energy by an electrochemical oxidation-reduction reaction. Battery cells consist of three parts: the cathode, the anode and the separator as seen in Figure 2.1.1. A Li-ion battery works by having lithium ions flow from the cathode through the electrolyte to the anode under discharge and back again under charge. During a charge this creates a voltage difference that induces a current to flow from the negative to the positive terminal through the external load. The separator must be thin enough to enable a high flow of ions and thereby a high power, but thick enough to avoid short-circuiting of the cell [2].

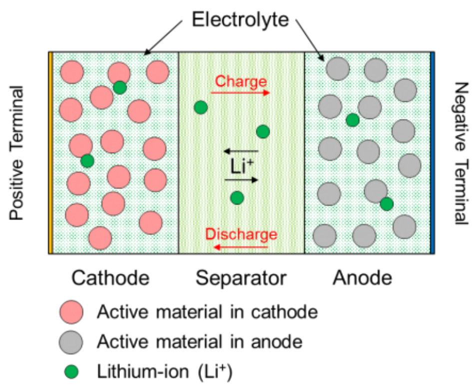


Figure 2.1.1: Cross-sectional view of Li-ion cell [3].

2.2 Physical Quantities of Lithium-ion Batteries

A Li-ion battery is a type of rechargeable battery which is commonly used for portable electronics and in EVs today [4]. The anode of most Li-ion batteries are carbon and graphite [4]. It is the material of the cathode that differs between different battery chemistries. The battery chemistry considered in this project is the Lithium Nickel Manganese Cobalt Oxide with the chemical formula $LiNiMnCoO_2$, often referred to as NMC or INR. Here the cathode consists of nickel-manganese-cobalt, which is characterized by a high specific energy and specific power capacity. These characteristics make it a good candidate to use in the batteries of EVs. NMC is used in the EVs manufactured by Nissan Leaf, Chevrolet Volt and BMW, and most other original equipment manufacturers (OEM) [4]. Another popular chemistry is nickel-cobalt-aluminium (NCA) which is used in some of Tesla's models. NCA has many similarities with NMC, but has a lower point of thermal runaway which makes more monitoring and thermal control necessary [4]. The performance of the 6 most used cell chemistries can be seen in Figure 2.2.1. The different Li-ion chemistries are compared for the 6 most important parameters: cost, specific power, life span, safety, performance, and specific energy.

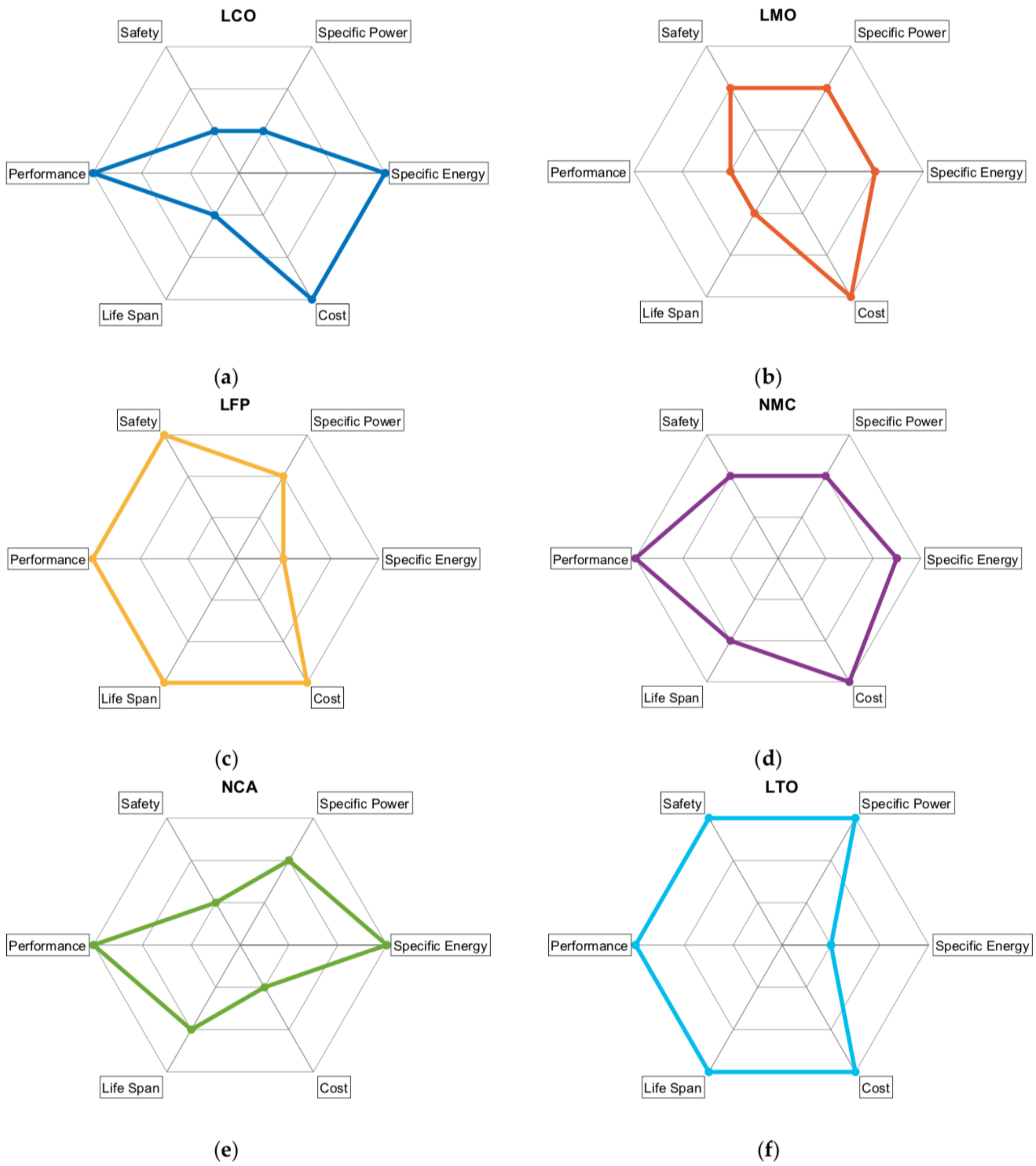


Figure 2.2.1: Lithium-ion chemistry performance comparison [5].

2.3 Battery Parameters

This section explains the different parameters of the battery cells, and the operating conditions that influence the performance.

2.3.1 Voltage levels

When speaking about batteries, the *voltage* is used in different situations as defined here:

- Terminal voltage is the voltage across the terminals of the cell.
- Nominal voltage is the rated voltage which the cell will have when at 50% state of charge (SOC). It is 3.6 V for the NMC cells used in this project.
- The open-circuit-voltage (OCV) is the same as the terminal voltage under no load conditions. It is a nonlinear function of the SOC.
- Maximum voltage is the set maximum voltage for the cell that is acceptable during charging.
- Minimum/cut off voltage is the minimum voltage when the battery has been fully discharged. The discharge-voltage is low enough to have the cell fully discharged, but without permanently harming the cell [2].

2.3.2 Relaxation Time

When a battery is connected to a load and discharged continuously, the voltage will decrease until it hits the set minimum voltage. When the discharge current is stopped, the terminal voltage will partially increase again. A part of the increase will occur instantaneously and can be explained by the change in current over the internal resistance of the battery cell. Due to the battery settling at this new state, the voltage will also have a slower increase until it reaches the OCV. In the same way, when the battery is charged, the voltage will increase, and then partially drop when the current is stopped.

It is therefore necessary to wait some time before the terminal voltage can be considered equal to the OCV and be used to find the SOC. The waiting period is called the relaxation time [6].

2.3.3 Battery Capacity

The battery capacity is the total charge energy stored in the battery and is most commonly specified in amp-hour (Ah). The Ah-capacity tells how much current it can deliver for an entire hour before the battery is drained. For example the 18650-NMC cells in this project have a capacity of 3 Ah, which means that it can deliver a current of 3 A for one hour before the battery cell is drained. 18650 is a standardized cell format. At constant discharge, the current is multiplied with the discharge time to get the Ah-capacity. It could therefore also deliver 1.5 A for 2 hours or 6 A for 30 minutes. This is however not the same as the delivered energy, as this also depends on the specific voltage. The energy delivered can be be approximated by multiplying the Ah-capacity with the nominal voltage, and thereby neglect the effect of the internal resistance. To get the exact energy, it is necessary to continuously calculate the power in W by multiplying the voltage and current and then integrate the power to get the energy in Wh. The Ah and the Wh capacity can for a time resolution of $t_s = 1$ s and $\Delta T = 3600$ s be calculated as

$$Q_{\text{Ah}} = \frac{1}{\Delta T} \sum_{k=0}^{\Delta T} I_k \cdot t_s \quad , \quad Q_{\text{Wh}} = \frac{1}{\Delta T} \sum_{k=0}^{\Delta T} I_k \cdot V_k \cdot t_s \tag{2.1}$$

Whether the battery capacity is described in available Ah or Wh depends on the intended use of the battery. For the manufacturer Ah is often used, but for real applications it is often more relevant to know Q_{Wh}, as it tells the amount of energy the battery is able to deliver.

It is easier to find Q_{Ah} as it is only necessary to integrate the current and as it is independent of the magnitude of the current. For Q_{Wh} it is necessary to know the cell voltage, which is dependent on the amount of charge stored in the battery and it is necessary to factor in the voltage drop over the internal resistance.

The capacity of a cell is always given at specific conditions since the batteries characteristics are highly dependent on its operating conditions. Capacity is highly dependent on both current and the temperature. At a lower temperature there will be a reduction in chemical conductivity leading to a lower capacity, as well as an increase in the internal resistance. At higher temperatures the internal resistance decreases and the capacity increases [2]. With a higher current there is a greater loss as heat dissipation in the internal resistance as a squared function of the current, I^2R. That means that the chargeable energy, Q^{c}_{Wh} is larger than the dischargeable energy, Q^{d}_{Wh}. The Q_{Ah} is however not affected.

This is also the reason why Q_{Ah} is preferred by the manufactures, as it gives a single number for the amount of Ah that can be charged and discharged, independent of the C-rate.

Energy Efficiency

The energy efficiency describes how much of the energy used to charge the battery can be discharged again. It is defined as the ratio of the discharged and charged Wh capacity as in Equation 2.2.

$$\eta_{Wh} = \frac{Q^{\text{d}}_{\text{Wh}}}{Q^{\text{c}}_{\text{Wh}}} \tag{2.2}$$

Discharge Modes

To be able to describe the battery capacity at a specific C-rate it is necessary to charge/discharge it with constant current. This mode is called constant-current (CC). The current is kept constant under discharge, and stops when the discharge voltage is reached. As the internal resistance causes a voltage drop, the voltage will increase again when the current is stopped. The OCV voltage is then still not at the minimum voltage and the battery not fully discharged. For higher currents, there is a larger voltage drop in the internal resistance, and the battery voltage will more quickly reach the minimum voltage, resulting in less useable capacity.

Therefore, to measure the actual energy capacity, it is necessary to reduce the current in the end of the charge. The current is reduced such that the terminal voltage is kept at the minimum or maximum voltage, depending on if it is during charging or discharging. This is called a constant-current-constant-voltage (CCCV) charge/discharge profile. With this method the battery is discharged with constant current until the discharge voltage is reached. Then the voltage is kept constant, as the current is reduced proportionally to the voltage drop. The current decreases until it hits a set cut-off current, where it is stopped. This is a slower method of discharging as the current is gradually decreased, and it is not useable for applications that require a constant current, but it is possible to get the true capacity of the battery.

Specific Energy, Energy Density and Specific Power

The specific energy is defined as the amount of energy per weight and is given in Wh/kg. Energy density is the amount of energy per volume and is given in Wh/l. Specific power is the amount of power the battery is able to deliver per weight and is given in W/kg.

C-rate

The current for charging and discharging a battery is often given as a C-rate. The C-rate is scaled to the nominal capacity of the battery, and defined as the current necessary to completely discharge the battery in one hour. So 1C will discharge the battery in one hour, 2C will discharge it in half an hour, and 0.5 C in two hours and so on. For the 3 Ah batteries in the project 1C will therefore be 3 A.

Internal Resistance

The internal resistance is the batteries opposition to the current flowing, and can be seen as the ohmic resistance of the cell. The resistance is not constant, and depends on the SOC and the temperature in the battery. The resistance can be estimated by measuring the change in the terminal voltage of the cell when the current is stepped . For low power battery applications the resistance is less of an issue as the current flowing through will be minimal, and therefore the voltage drop and the power loss is limited. For high power applications the current will be higher, which results in a bigger voltage drop. This can lead to premature termination of the charging process as the voltage falls under the minimum voltage earlier. There will also be a bigger power loss, which both waste energy and heats up the battery. In short, the internal resistance limits the power capabilities of the battery [2].

2.3.4 SOC and DOD

The SOC is defined as the level of charge left in the battery relative to its total capacity. It is given in percentage, where 0% is fully drained and 100% is fully charged. Alternatively DOD (depth of discharge) can be used. DOD is the opposite of SOC, where 100% is fully drained and 0% is fully charged. The SOC of the battery can not be measured directly but it can be estimated by different methods. The SOC is a nonlinear function of the OCV [2]. It is therefore possible to make a OCV-SOC curve showing the OCV at different SOC levels, and then compare the measured voltage to the curve. The problem with this method is that the battery cell needs to relax without a current for the OCV to stabilize and therefore get a good estimate. The OCV-SOC curve is also temperature dependent, and thus is necessary to have it defined at different temperatures [2]. There is also a hysteretic behaviour that affect the behaviour of the SOC-OCV relationship. The voltage of the cell is partly dependent on if it reached its SOC based on a charge or discharge. Even given time to fully relax there will still be a voltage difference. This effect needs to be accounted for when making SOC estimations based on either a charge or discharge [7]. Another method is by coulomb counting. Here the current in and out of the battery is measured. With this method it is necessary to know the total capacity and the initial SOC. This method can be summarized by formula 2.3 and 2.4 [7]. The charge measured is compared to the charge of the fully charged cell.

$$SOC(t) = \frac{Q(t)}{Q_{Ah,max} - Q_{Ah,min}} = \frac{Q(t)}{Q_{Ah,full}} \tag{2.3}$$

$$SOC(t) = \frac{1}{Q_{Ah,full}} \cdot \int_{t_0}^{t} I(t)dt \tag{2.4}$$

The accuracy of this method depends on the precision of the current measurement, as well as the estimation of the initial SOC. If it is measured over a long period, the error will accumulate and can cause a significant inaccuracy.

OCV dependent SOC estimations requires the device to be idle for the relaxation to take place and gives a good estimate of the SOC, while coulomb counting gives an accurate SOC estimate while in use, but only for short periods. Therefore most BMSs use a combination of the two methods.

It is the industry standard to define SOC based on the ampere-hour capacity, but it can also be calculated with respect to the Watt-hour capacity. For applications that are using specific power and not specific current such as EVs, it is necessary to calculate the SOC per Wh. This is because the voltage is lower at a lower SOC which in turn leads to a decrease in power. An EV could therefore drive more km on the highest 10% SOC than on the lowest, even though it is the same amount of current.

2.3.5 Battery Degradation

During their lifetime, batteries experience gradual degradation which leads to loss of capacity and higher internal resistance. This is partly due to mechanical and chemical changes of the electrodes. Many factors affect battery degradation, temperature and current being the main contributors. Battery degradation is the sum of two types of degradation: calendar and cycle aging [8]. Calendar aging includes all degradation processes independent of charge and discharge cycling [9]. It is dependent on the cell SOC, temperature, and time. Cycle aging is the cell degradation that happens every time the cell goes through a charge or discharge cycle. It is dependent on the temperature, the DOD, and the current [10]. The charge cycles are generally defined as equivalent cycles where partial charge cycles are added together to form full equivalent charge cycles [11].
The capacity fade in the battery reduces the charge capacity, and the increase in the internal resistance in the battery reduces the power capability.

2.3.6 SOH

The SOH is a measure that describes the general state of aging of the battery cell when compared to a new battery cell. There is not a universal consensus about how to define the SOH of a battery cell, as the main parameters depend on the application of the battery. The SOH definition can take into account several different parameters, for example:

- Energy capacity decrease compared to the capacity of a new battery.
- The increase of the internal resistance.
- The increase of battery self discharge.

End-of-life for a battery is when the battery performance has fallen under a set of minimum requirements. For a lot of manufacturers this is defined as when the energy capacity under specific conditions have fallen to 80 % of the rated charge capacity of a fresh cell. SOH is defined in formula 2.5. $Q_{nominal}$ is the initial capacity, and is know from initial testing or the battery cell manufacturing specification. Q_{full} is the current battery capacity and can be determined in Ah or Wh.

$$SOH = \frac{Q_{full}}{Q_{nominal}} \tag{2.5}$$

It is paramount to know the SOH of the cells in the battery pack, as it tells how much capacity is left and is usable in the pack, and when the battery, if necessary, needs to be replaced. To calculate the SOH it is necessary to know the initial capacity [7].

2.4 Electrical Circuit Model of Lithium-ion Batteries

Considering the Li-ion cell as an electrical circuit, the two main parameters are the voltage and the current, which can be measured and are then used for deriving the characterization of the battery. By integrating the current I, the Ah (amp-hour) can be calculated, and by integrating $I \cdot V$ the Wh (watt-hour) can be calculated. Because of this, the battery can be modelled as an electrical circuit. An ideal battery would just be an ideal voltage source in series with a load, without consideration for the internal parameters. But as the battery has an internal resistance, a resistance R_{int} is added in series with the voltage source. The model can be seen in figure 2.4.1. The internal resistance causes a voltage drop when the battery is connected to a current. This is the reason that the *terminal voltage* V_T and *open circuit voltage* V_{oc} is not the same under load conditions. The formula for the relation between V_{oc} and V_T can be seen in Equation 2.6. The battery has a linear behaviour where Ohms law describes the voltage drop over the resistance, and nonlinear behaviour where the voltage-source is dependent on the SOC of the battery.

$$V_T = V_{oc} - R_{int} \cdot I \tag{2.6}$$

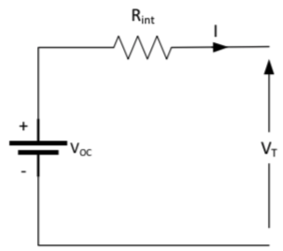


Figure 2.4.1: Simplified battery model [5].

To better describe the transient behaviour of the battery it is modelled as a Thevenin equivalent, with an ideal voltage source in series with an impedance. This model is known as a first order Thevenin model, and can be seen in Figure 2.4.2.

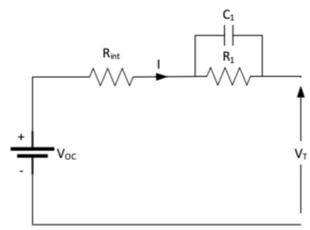


Figure 2.4.2: First order Thevenin battery model [5].

When a current is connected, C_1 will behave as a open circuit and the current will flow through R_{int} and R_1, both contributing to the voltage drop. When the current is stopped, the capacitor will behave as a short circuit, and the voltage drop will only come from R_{int}. As C_1 discharges, the voltage drop of R_1 will increase, and the overall voltage of the system increases. This behaviour can be seen for a charge and a discharge pulse in Figure 2.4.3.

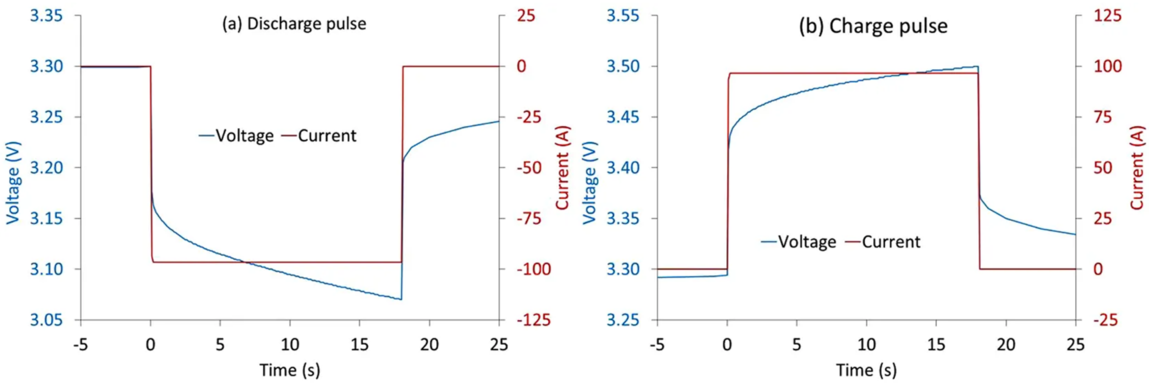


Figure 2.4.3: Battery voltage profile under current step [12].

2.4.1 Parallel and Series connected battery packs

In a battery pack the battery cells can either be placed in serial or parallel connections, or a combination of the two. When the cells are placed in series each cell adds its voltage to the total pack voltage. The same current will flow through the full series so the amount of Ah-capacity is the same as for the individual cell, but since the pack voltage increases with the number of cells, so does the total energy. When the cells are added in parallel, each cell adds its Ah capacity to the total pack Ah capacity. Thus to get a higher voltage the cells are added in series, and to get a higher Ah-capacity the cells are added in parallel. Often to get the desired voltage for the specific application cells are added in series. After the wanted voltage is reached, cells can be added in parallel to get the wanted energy capacity.

The parallel cells will have the same voltage, as the current will flow to the cells with the lowest voltage and charge them until they are equal. The parallel cells share current and the total internal resistance is decreased when more cells are added in parallel.

The series connected cells act as individual cells when discharged and the cell with the smallest capacity will be discharged first and then limit the whole string. The internal resistance of the pack is the sum of the internal resistance of each cell.

An example of a series and a parallel coupled 4-cell battery pack can be seen in Figure 2.4.4.

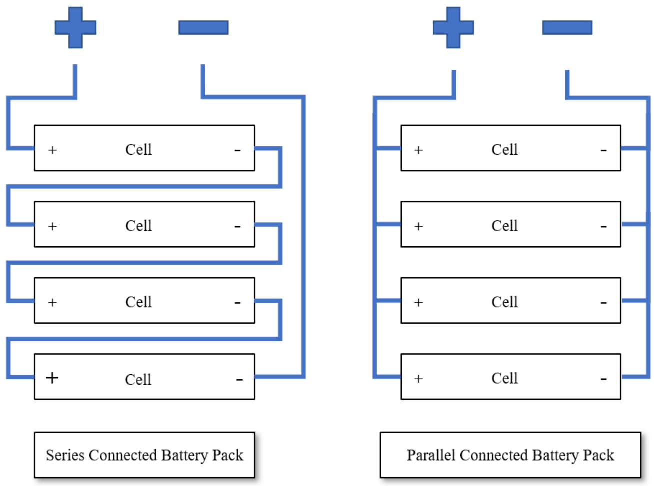


Figure 2.4.4: Series and Parallel connected battery pack.

CHAPTER 3

Battery Management System

A BMS is a control unit that performs monitoring and management of either a single cell or an entire battery pack. The primary job of the BMS is to maximize safety and make sure the cells deliver their best possible performance while prolonging battery life. It is essentially the brain of the battery pack.
This chapter looks at the most important functions of a modern BMS.

3.1 Safety

The BMS needs to cover any potential safety risk, as it can lead to the failure of the battery. This is primarily done by keeping the cells inside safe operating conditions, to make sure they do not get stressed. Li-ion batteries are very stable and reliable as long as they are kept within a small voltage and temperature window. However, if the cells leave this window it might cause overheating and damage, and in the worst case make the cells explode. A graph of the safe temperature and voltage window for safe operating conditions can be seen in Figure 3.1.1.

When the cell is overcharged to an over voltage state the separator between the anode and cathode can rupture which can result in a short circuit. This can also occur if the cell becomes too warm and will cause thermal runaway where the temperature of the battery increases uncontrollably. The process can end with the cell setting on fire [2]. This is the reason that stationary storage systems must demonstrate that a potential fire can be contained for it to live up to the safety regulations. This is done by short circuiting a cell to force thermal runaway. If the cells are undercharged to a lower voltage than their rated discharge voltage their capacity can be permanently reduced [13].

The BMS keeps the cell inside safe operating conditions by monitoring the state of the individual cell. This includes measuring the cell voltage and the temperature, as well as the current. This is essential with Li-ion cells, as they are highly sensitive to over- and undercharging and overheating, even by small overvoltages or a bigger current than what the cell is rated for [2].

The BMS protects the cell from:

- Overcurrent.
- Overvoltage during charging.
- Undervoltage during discharging.
- Over and under temperatures.

The BMS prevents a critical situation from arising by controlling an external switch to stop the current, or by communicating directly with the load or charger, requesting that the current drawn is reduced or completely terminated. An intelligent charger system will communicate the battery parameter specification with the BMS, so it can use a fitting charging profile. Some chargers can be programmed to charge at the maximum rate until the battery temperature reaches its limits, and then slowly reduce its charging. This can help to prevent overheating and extend battery time, while still having an efficient charging [13].

The temperature is not just limited with respect to the safety restrictions, but also to limit the calendar aging which increases significantly with high temperatures.

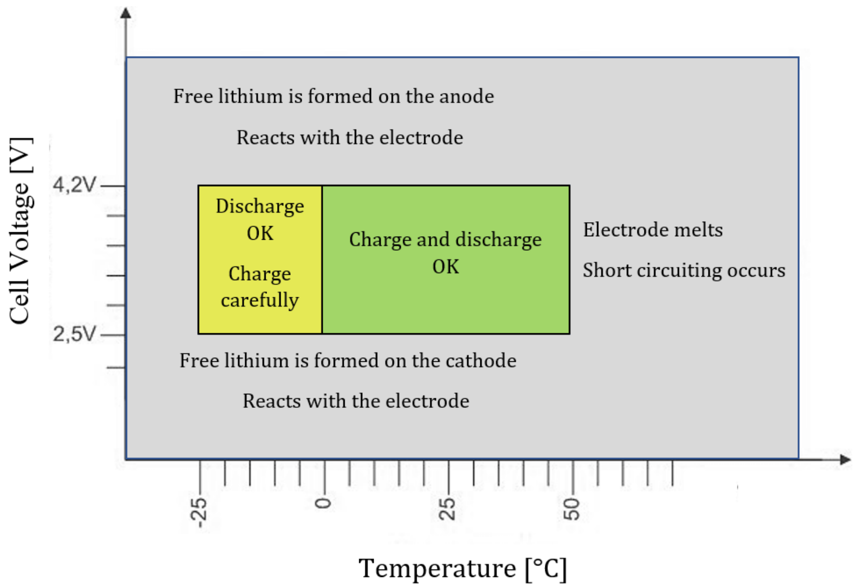


Figure 3.1.1: Temperature and voltage window for safe operating conditions

3.2 Communication

More advanced BMS units have an external communication data bus, so it can communicate with other systems, such as an EV or a computer. In EVs this is often done with CAN bus communication. The communication is also important in battery packs where it is necessary to externally log the parameters of the cells, to modify the BMS control parameters, and to do diagnostics and tests of the battery [7].

Advanced BMS have some memory, so it can store the battery history. This is important to evaluate the SOH and keep track of parameters like the number of discharge cycles, internal resistance and elapsed time. It can also be important for warranty issues, where it is possible to look at the history of the cell use.

3.3 Measurements

The BMS measures the cell and pack voltage, the pack current, the cell temperature, and does all calculations and management based on these variables. By integrating I and $V \cdot I$, Ah and Wh can be found, and by calculating the difference between OCV and V_T the internal resistance can be deduced. The current is often measured by a hall effect sensor or a shunt resistor sensor. The hall sensor measures the current by measuring the magnetic fields it produces, and then it produces an equivalent voltage. The shunts sensor works by measuring the voltage drop over a shunt resister in the circuit. The current is only measured once as it is the same for the string of cells. The voltage must be measured for each cell, to ensure that none of them are over or under charged, but voltage is also the simplest parameter to measure accurately. The temperature is measured by voltage drop over a thermister. The warmer it is, the lower its resistance will be, and the lower the voltage drop [7]. The temperature is measured at different zones of the battery pack in case the heat is not equally distributed [9]. The BMS measures the voltage on each side of the cells. By subtracting the two found voltages, the voltage of the each cell can be found. A block diagram over the different BMS measurements can be seen in figure 3.3.1.

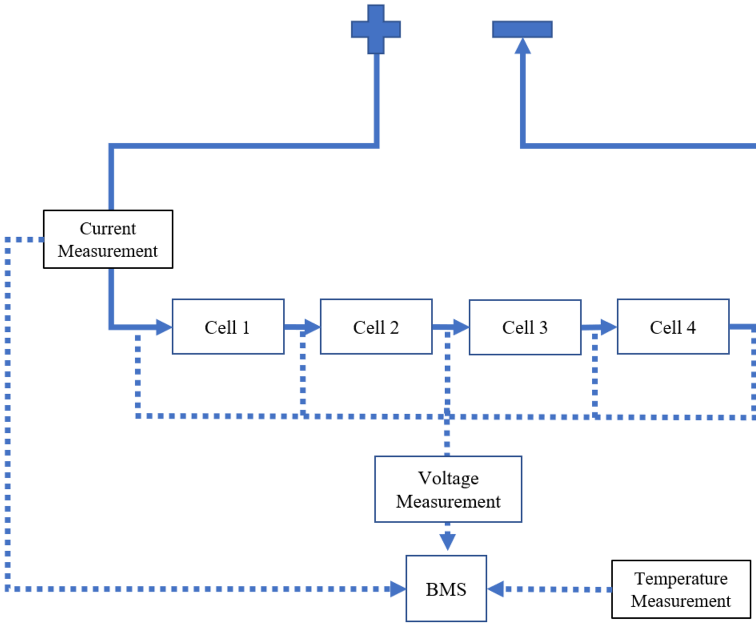


Figure 3.3.1: Block diagram over BMS measurements.

It is important to have accurate measurement to have the necessary safety and get the optimal performance of the battery. Inaccurate voltage measurements can lead to under or overcharging. Inaccuracy in the current measurement can lead to error in the SOC and SOH calculation.

3.4 Cell Balancing

To maximise usable battery capacity, and prevent cell degradation, the BMS can, through balancing, make sure that all the cells are kept at the same voltage/SOC.

In a fresh multi cell battery there will be small differences between cells. This is mainly because of production tolerances, as no two cells are made exactly the same. They may also have come from different batches and have experienced different heat exposures before being in operation. This can cause the cells to differ in both capacity and internal resistance.

Not balancing can cause different issues. When discharging, the current must be stopped when the first cell runs out of charge, even though other cells might have charge left in them. When charging, the current must be stopped when the first cell reaches its full maximum voltage at 100% SOC. Otherwise it will risk overcharging and damaging the cell [2]. Not all cells will be fully charged this way, and the cells will start discharging at different SOC levels. Because the worst cell is the only cell getting fully charged, the degradation will also be worse, as cells degrade faster at higher SOC [10]. This can have a self-reinforcing effect, that makes the already most degraded cells degrade even faster, and magnifies the cell-by-cell difference. This is a problem as it is the weakest cell that limits capacity of the battery. Balancing is a way of compensating for weaker cells, and minimizing the cell-to-cell difference.

This is not an issue with cells in parallel compared to cells in series. Cells in parallel self-balance to some degree, since the parallel connection keeps the cells at the same voltage. The current flows from the cell with the highest voltage to the ones with a lower voltage without an external voltage applied.

Balancing is most often done as passive balancing, or *bleeding* as it is also called. When the cell is fully charged a switch opens, and the current is instead dissipated as heat over a resistor. This is done through *bleeding*, or bypass, resisters. The bleeding continue until all cells are fully charged, and thereby all the cells will have the same SOC when the charge is complete. The method can be seen in Figure 3.4.1. The BMS controls a MOSFET, which is opened when the cell reaches the right voltage. In this form of balancing the energy goes to waste. Since the current through the resister have to be low to not cause overheating, it is a slow method. A faster balancing requires more current which generates more heat. A faster balancing also imposes a requirement for high power bleeding resister and high current rating on the MOSFETS that work as switches. The main advantages is that it is a simple and cheap form of balancing, which is why it is the most common method used [7].

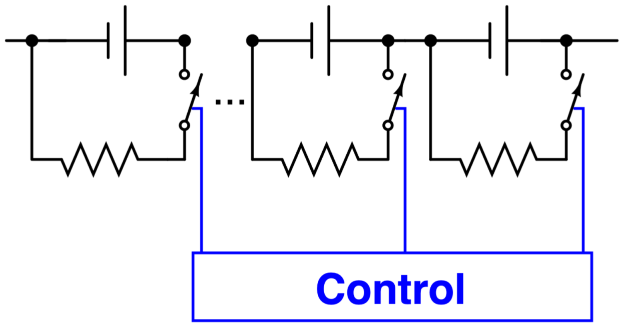


Figure 3.4.1: Model over passive balancing [14].

Another way of balancing is active balancing. With this method energy is being drawn from the fully charged cells and transferred to the cells with the lowest voltage. In this way the energy is not wasted, but conserved and used in the other cells. The disadvantage of this method is the more complex design, and the increased cost compared to passive balancing [7].

For smaller battery packs a simple solution that does not require balancing is to limit the depth of discharge (DOD) of the battery so the cells are never over- and under charged. It is cheaper as it does not require balancing electronics, but it is an inefficient use of the available cell capacity.

Once one cell in the battery pack have failed the entire pack must often be exchanged, which can be very costly. It can be problematic to replace the failed battery cell with a new cell, as the fresh cell will have entirely different characteristics than the other aged cells in the pack.

3.5 Thermal Management

As cells with a higher temperature degrade faster, it can be a problem with unbalanced thermal operating condition for the cells. It is therefore an important task of a BMS for bigger battery packs to secure a uniform heat distribution. The BMS measures the temperature at different areas of the battery pack and controls either active air or water cooling of the cells when necessary [7]. This can reduce the need for balancing, as it prevents the cells from degrading at different rates. It is also necessary to monitor the temperature to avoid thermal runaway by reducing the current when the cells overheat.

3.6 Parameter Estimation

This sections explains how the BMS estimates some of the core battery parameters. The same calculations are used in the test results section.

3.6.1 State of Charge Estimation

Estimating the SOC parameter is one of the key tasks of the BMS, as it is an indicator of the electrical energy left in the battery. The charge used is measured by coulomb counting. The discharged Ah is then added or subtracted from the "remaining capacity" counter, and compared to the full capacity. When the BMS detects a full charge, the "remaining capacity" counter will be set to the full capacity.

The problem with coulomb counting is that the measurement error is also accumulated over time, which can cause a big error in the SOC estimation after a long duration cycle if not calibrated. The calibration is done by finding the SOC estimation by comparing the voltage to the SOC-OCV curve. This is only possible when the battery have been relaxed for a long enough time so the terminal voltage have approached the OCV. As SOC-OCV is temperature dependent it is necessary to have multiple SOC-OCV curves defined at different temperatures [7]. An advanced BMS will use interpolation to find the right voltage if the temperature falls between one of the defined curves. A quality factor, k, can be set as part of the estimation to define significance of the calibration SOC when compared to the original estimated SOC. This can be seen on formula 3.1.

$$SOC_{\text{calibrated}} = (1-k) \cdot SOC_{\text{original}} + k \cdot (SOC_{\text{OCV}} - SOC_{\text{original}}) \tag{3.1}$$

3.6.2 State of Health Estimation

The total energy capacity can be calculated by integrating the current over a full discharge. $SOH_{\text{Ah,real}}$ is found by comparing the accumulated charge $Q_{\text{Ah,full}}$ to the nominal charge $Q_{\text{Ah,full}}$ as seen in formula 3.2. It is important to test at conditions comparable to how the initial conditions was found to get a precise estimate, as the capacity is dependent on the temperature [2].

$$SOH_{\text{real}} = \frac{Q_{\text{Ah,full}}}{Q_{\text{Ah,nominal}}} \tag{3.2}$$

As it can be rare that a battery in application goes through a full discharge before getting charged, it can be necessary to estimate the SOH based on a partial discharge. One method is to estimate the SOH based on two SOC-OCV calibrations, when the battery has been at rest for minimum 20 minutes, and the discharge between them. The relaxation time is necessary to get a good SOC estimation. The method compares the change in SOC found by the SOC-OCV calibration as seen in equation 3.3, to the change in SOC found by the coulomb counting as seen in equation 3.4. For this calculation, the coulomb counting estimate is based on the original capacity so when the voltage based SOC changes more than this, it is because of a capacity loss.

$$\Delta SOC_{CC} = SOC_{CC1} - SOC_{CC2} \tag{3.3}$$

$$\Delta SOC_{OCV} = SOC_{OCV1} - SOC_{OCV2} \tag{3.4}$$

By comparing ΔSOC_{OCV} and ΔSOC_{CC} the SOH can be estimated. The formula is shown in 3.5.

$$SOH_{\text{est}} = \frac{\Delta SOC_{\text{CC}}}{\Delta SOC_{\text{OCV}}} \cdot 100 \tag{3.5}$$

As the capacity is dependent on temperature and influenced by measurement uncertainty, the estimation might over- or underestimate the SOH. To prevent big variations in the calculated SOH it can be weighed down by a quality factor. This can be seen on 3.6. The quality factor k is chosen between [0,1].

$$SOH_{est,new} = (1-k) \cdot SOH_{est,old} + k \cdot \frac{\Delta SOC_{CC}}{\Delta SOC_{OCV}} \tag{3.6}$$

A very low quality factor might give more steady estimations, but it will also change more slowly, and it might make SOH_{est} lag behind SOH_{real}.

The BMS can set certain windows for when to do the SOH estimation, to ensure a high precision estimation. It can for example be when the battery is discharged from 100% SOC to 20% SOC, and only when the battery temperature is $25 \pm 5°C$. The more strict the window is, the more similar the parameters the estimation is calculated at will be, and the more comparable the different estimations will be. But for a more strict estimation window, SOH_{est} will be calculated less often, and might lack behind SOH_{real}. It is a trade off between high quality estimations, and more frequent estimations.

Different factors can add uncertainties to the SOH estimation. The estimation is only as good as the ΔSOC_{CC} and ΔSOC_{OCV} estimation. ΔSOC_{CC} depends on the precision of the current measurement. ΔSOC_{OCV} depends on the SOC-OCV curve. The reading will be more precise in areas of the curve where it is more steep and the voltage changes more per 1% SOC step. Here the accuracy of the voltage measurement is important. Another source of uncertainty is the change of the OCV-SOC over the battery life. In the results section it will be investigated whether the curve is different for new and aged cells.

CHAPTER 4

Online State of Health Estimation

Online SOH estimation is the method of estimating the SOH of a battery without doing a full discharge. In a lab or a garage the battery can be fully discharged so the exact Ah capacity, and thereby the SOH, can be found. However since a battery used in a normal application is rarely fully discharged, it is necessary to estimate the SOH on partial discharges.

For several applications that are using external charging equipment, it is easier to perform SOH during charging. During charging of e.g. EVs the current is often lower and more constant, which means that the temperature is more constant. When only looking at Ah capacity the charge and discharge capacity is close to the same, as the voltage drop does not have an influence. The charge capacity is however not investigated in this thesis as it would require further measurements of the SOC-OCV curve which is different during charging.

This chapter explains which parameters the SOH estimation might be dependent on, and what the thesis will test for.

4.1 SOH Estimation by Partial Discharges

By comparing the ΔSOC_{CC} found by coulomb counting to the $\Delta SOC_{\mathrm{OCV}}$ found by doing an SOC-OCV calibration before and after the partial discharge, the SOH can be derived. ΔSOC_{CC} is found by comparing the Ah discharged to the nominal capacity. This way the expected ΔSOC of the fresh cell is found. The real ΔSOC is then found by the SOC-OCV calibration, since the SOC-OCV relation changes only to a limited degree with the battery age. The ratio is the SOH.

The BMS can be set to only do a SOH estimation under very specific conditions. This could for example be when it is discharged over 80% at $25 \pm 5°C$. But the more narrow the window for estimations is, the more infrequent the estimations will be performed. It is therefore desirable that the estimations can be carried out under different operating conditions and still be comparable.

4.2 Parameters to Investigate

This thesis will investigate how dependable the battery is on different operating conditions, and what conditions needs to be considered when making a SOH estimation. As the cell dependency on its operating conditions might also depend on its level of degradation, the thesis will test both fresh cells that have not been used and aged cells that have been used for battery cycling. This section goes over the different parameters that this thesis investigates.

4.2.1 Relaxation Time

After the current is stopped the terminal voltage will approach the OCV. Since the terminal voltage is used as an estimate of the OCV, it is important to find out how long the battery needs to relax before the OCV curve has evened out, and can be considered equivalent to the OCV. As the necessary relaxation time is higher after a full discharge, this is investigated as the worst case. It also might depend on the C-rate used, which is why the OCV curve after a full discharge at different C-rates will be tested, and a fixed relaxation time for the rest of the experiments will be found.

4.2.2 Internal Resistance

As the cells age they experience a loss of capacity and an increase in internal resistance. Since the Ah is independent of the internal resistance, the increase in internal resistance, and thereby the loss of power, is not accounted for. The internal resistance is the main limiting factor on the Wh, since the Wh is affected by the power loss in the internal resistance. Since the Wh is the amount of energy available, it is an important parameter to consider. This thesis will therefore test the influence of the used C-rate, temperature and SOC level on the internal resistance. The loss of energy over a discharge can be seen on equation 4.1. Here ΔT being the number of samples per hour, t_s the sampling time, I_k the current and R_{int} the internal resistance.

$$Q_{\text{Wh,loss}} = \frac{1}{\Delta T} \sum_{k=0}^{\Delta T} I_k^2 \cdot R_{\text{int}} \cdot t_s \tag{4.1}$$

The internal resistance is found by comparing the terminal voltage V_T under load conditions to the terminal voltage right after the instantaneous voltage drop. In this way only the ohmic part of the internal resistance is counted. The found voltage drop is then divided by the current to find the resistance. The formula can be seen on 4.2.

$$R_{int} = \frac{V_{T_{Load}} - V_{T_{No\_load}}}{I} \tag{4.2}$$

4.2.3 Capacity

The capacity of the battery is dependent on the temperature. Therefore to be able to estimate SOH at different temperatures, it is necessary to know the precise influence. By knowing the influence it will be possible to convert the capacity, so estimations at different temperatures can be compared. This thesis investigates the discharge capacity at three different temperatures. Since the capacity can be found as the Ah and the Wh capacity, this thesis will investigate the relation of both.

4.2.4 SOC-OCV Curve

As the voltage of the battery is dependent on the temperature, it is necessary to define a SOC-OCV curve for different temperatures. This thesis will therefore investigate the variance of the SOC-OCV curve at different temperatures. The SOC-OCV is also tested for both new and degraded cells to see if/how much the SOC-OCV relation change as the cells age.

CHAPTER 5

Test Description

The chapter describes the test setup used, as well as the specification and procedure of the different tests.

5.1 Test Overview

All tests were carried out at Lithium Balance A/S, experts in the field of batteries and BMSs, which actively collaborate with knowledge, equipment availability and cells provision.

5.1.1 Test

Four main tests were performed:

- Test A: Influence of C-Rate on Relaxation Time.
- Test B: Influence of Temperature on Cell Capacity.
- Test C: Influence of Temperature on SOC-OCV Curve and Internal Resistance.
- Test D: Precision of SOH Estimation from Partial discharges.

5.1.2 Test Setup

The test setup consists of:

- PC with control software.
- CADEX C8000 Battery Testing System.
- CTS C-70/350 Climate Chamber.
- Battery cell setup.
- 8 INR18650-30Q Samsung battery cells.

A block diagram of the entire setup can be observed in Figure 5.1.1.

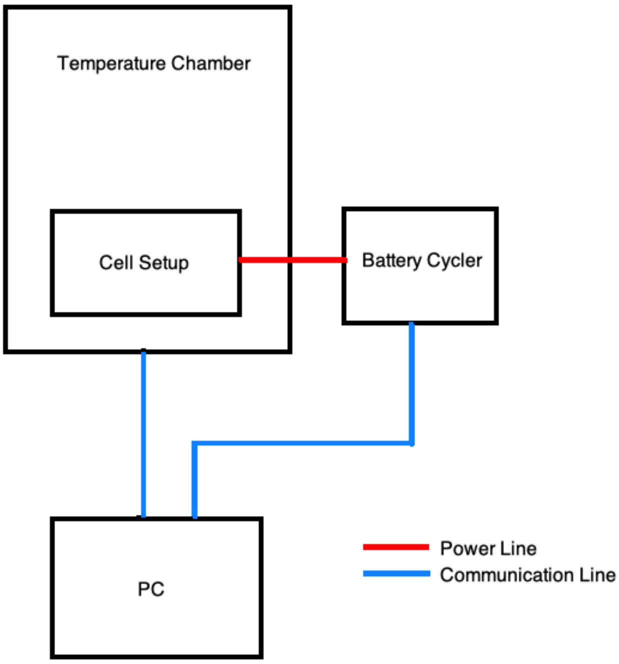


Figure 5.1.1: Block diagram test setup.

The tests are done on 8 INR18650-30Q (NMC) battery cells. NMC cells were chosen since they are a very popular cell chemistry, which is used from smaller battery systems to large battery packs in EVs. The cells are produced by Samsung SDI, who is a big distributor of battery cells. Four new cells, and four degraded cells with $\approx$ 90% SOH are used. From now on the fresh cells will be referred to as "set A", while the degraded cells will be referred to as "set B". The specifications of the cells are listed in Table 5.1.2, whereas Figure 5.1.2 shows the considered cells.

Figure 5.1.2: 18650 Cylindrical cell

Table 5.1.1: Specification of INR18650-30Q cells.

Item	Specification
Nominal discharge capacity	2.950 Ah
Nominal voltage	3.6 V
Minimum voltage	2.5 V
Maximum voltage	4.2 V

Initially the cells were tested to find their CC discharge capacity. The cells in set A has never been used but it is unknown how long time has passed since production. As some time has passed since production, they have experienced some calendar ageing as seen in table 5.1.2. The cells in set B were tested to find similar cells degraded to a SOH $\approx$ 90%. A table of the cell capacities as well as their SOH can be seen in Table 5.1.2.

In the data sheet the cells have their minimum discharge capacity specified as 2.950 Ah while being discharged by 0.2C (0.6 A). It also specifies that the discharge capacity is only 97% when discharged with 1.7C (5 A). In the presented test the cells were discharged with 1C which explains why the cells have a lower discharge capacity. This should only cause a difference of 2% SOH, so the rest of the degradation can be attributed to calendar aging.

Table 5.1.2: CC capacity and SOH of cells.

Cell	1C Discharge capacity at 23°C [Ah]	SOH [%]
A1	2.89	96.33
A2	2.92	97.33
A3	2.88	96.00
A4	2.90	96.66
B1	2.73	90.90
B2	2.72	90.77
B3	2.72	90.93
B4	2.72	90.70

The battery tester is a "CADEX C8000 Battery testing system", as shown in Figure 5.1.3. It has 4 isolated channels and is rated for 1.2 V - 36 V and 10 A per channel. It has a voltage accuracy of 0.1% and a current accuracy of 0.25% full scale, with a sample rate of 1 second [15]. The Battery tester is connected to the PC via ethernet and run through the BatteryLab PC software.

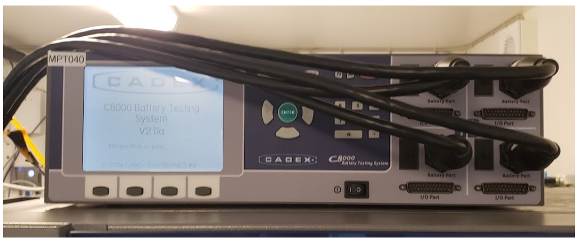


Figure 5.1.3: C8000 Battery Testing

The test is done in a "CTS C-70/350" Climate Chamber. The climate chamber has a temperature range of $-70°$C to $+180°$C, and a humidity range between 10% and 98% rH [16]. The climate chamber is connected to the PC via Ethernet and controlled by the PC software "CID". It can be seen in Figure 5.1.4.

Figure 5.1.4: CTS Climate Chamber.

The battery cells are connected to the battery tester via a copper clad PCB board. Plus and minus terminals are connected to each side of the battery cell and the temperature sensor are connected to the side of the battery cell. This setup can be seen in Figure 5.1.5.

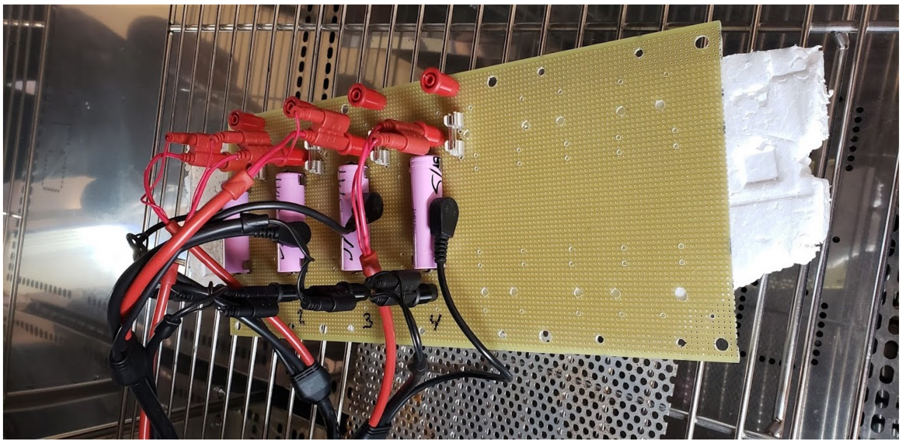


Figure 5.1.5: Battery Cell Test Setup

5.1.3 Test profiles

This sections explains the different charge and discharge profiles used in the testing.

Constant Current Constant Voltage (CCCV) The battery tester has a CCCV algorithm for charging cells to 100% but not for discharging, so a new algorithm was programmed such that it can be used for both. The cell is charged/discharged by constant current until maximum/minimum cell voltage is reached. Then the current decreases gradually with 0.1C until it hits the cut off current of 100 mA. A block diagram over the implemented CCCV algorithm can be seen in Figure 5.1.6.

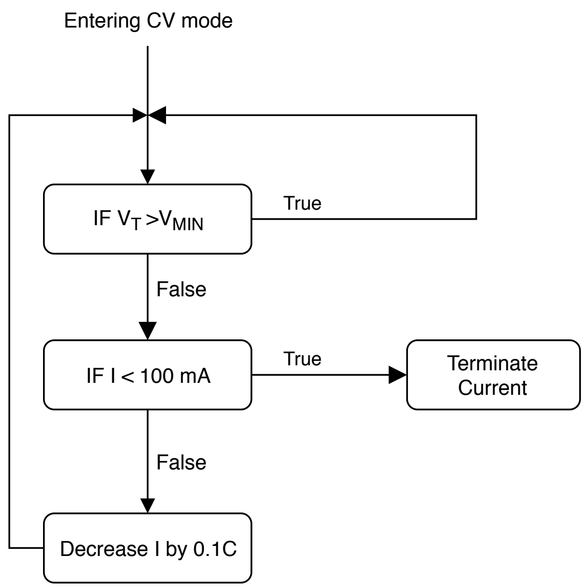


Figure 5.1.6: Block diagram over CCCV

Constant Current (CC) The cell is discharged at the specified C-rate, and the current is stopped once the cell reaches the minimum voltage.

5.1.4 Test Conditions

The cells are placed at the test temperature for a minimum of 12 hours to get a stabilised internal temperature, and the humidity is kept at 60% to follow the standard conditions of the INR18650-30Q data sheet. All test start with the cells being charged with CCCV followed by a 20 min relaxation time. This is done to ensure that the test is done at the same voltage baseline. The sets are tested one at a time on 4 isolated channels, with individual power profiles as well as voltage and current measurements, where the cell voltages and current are measured per second.

5.2 Dependency of Battery Parameters

5.2.1 Influence of C-Rate on Relaxation Time

Test Specification

The test objective is to find the impact the C-rate has on the relaxation time of the battery, and to derive the necessary relaxation time for a sufficiently accurate voltage measurement for the remaining tests profiles. The cell will be fully discharged at a C rate of 0.5C, 1C, and 2C. A temperature of 5°C is used to test the cells at the most extreme condition to which they will be exposed to during the following tests. After the discharge the cells will have a rest period of 60 min where the voltage is logged.

Test Procedure

Test A:

1. Place set A in test setup at 5°C and 60% humidity.
2. Discharge cells by CC at 0.5C
3. Rest for 60 min.
4. Fully charge cells by CCCV at 1C.
5. Stop measurement.

Repeat test A twice. First with discharging cells by CC at 1C and then with discharging cells by CC at 2C.
Repeat for set B.

5.2.2 Influence of Temperature on SOC-OCV Curve and Internal Resistance

Test Specification

The test objective is to find the influence the temperature has on the cell charge and discharge capacity. The cells are charged and discharged with CCCV at 1C, with an intermediate 20 min rest period. The test is done at $5°$C, $23°$C, and $45°$C.

Test Procedure

Test B:

1. Place set A in test setup at 5°C and 60% humidity.
2. Discharge cells by CCCV at 1C.
3. Rest for 20 min.
4. Charge cells by CCCV at 1C.
5. Rest for 20 min.
6. Stop measurement.

Repeat test B twice. First at a temperature of $23°C$and then at a temperature at $45°C$.
Repeat for set B.

5.2.3 Influence of Temperature on SOC-OCV Curve

Test Specification

The test objective is to determine the influence temperature have on the SOC-OCV curve and to find the internal resistance at different SOC levels. The cells are discharged with CC at 1C. The cells are discharged with steps of 0.3 Ah and a subsequent 20 min rest period until it reaches the minimum cell voltage. The cells are tested at $23°$C and $45°$C. The test was originally also meant to be done at $5°C$, but because of a fault in the battery tester the test was not performed.

Test procedure

Test C:

1. Place set A in test setup at 23°C and 60% humidity.
2. Repeat discharging cells by CC at 1C for 6 min or 0.3 Ah with subsequent 20 min rest until 0% SOC is reached.
3. Stop measurement.

Repeat test C with a temperature of $45°$C.
Repeat for set B.

5.3 Precision of SOH Estimation

5.3.1 Precision of SOH Estimation at Different Discharge Depths

The test objective is to find the precision of the SOH estimations at different discharge depths. The cells are discharged with CC at 1C. The cells are discharged with a DOD of 20%, 40%, 60%, and 80%. The cells are charged by CCCV between each discharge.

Test Procedure

Test D:

1. Place set A in test setup at 23°C and 60% humidity.
2. Discharge cells by CC at 1C for 12 min or 0.6 Ah.
3. Rest for 20 min.
4. Fully charge cells by CCCV at 1C.
5. Stop measurement.

Repeat part 4 three times. First with a DOD of 40% equal to 1.2 Ah, then with a DOD of 60% equal to 1.8 Ah, and last with a DOD of 80% equal to 2.4 Ah.
Repeat for set B.

5.4 MATLAB Data Processing

This section goes over the variables and code used for the data processing of the cells. All data processing is done using MATLAB_R2018b.

5.4.1 Variables

cell = Table with all logged variables.
Ah = Array with calculated Amp hour per second.
Duration_sec = Array with timestamp of test.
cell.mA = Array with logged current per second.
cell.mV = Array with logged voltage per second.
Ah_dis = Full discharge capacity.

Ah_acc = Array with accumulated amp hour per second.
SOC = Array with the SOC under discharge.
OCV = Array with the OCV under discharge.

5.4.2 MATLAB code

Calculate SOC based on the the discharged Ah

The following code is used to calculate the SOC based on the integrated Amp hour.

```
% Find SOC based on the integrated Amp hour. Ah_acc is compared to Ah_diss and multiplied by 100 to find the SOC.
for k = 1:length(Ah_acc)-1
    if Ah_acc(k) > 0
        SOC(k) = 100-(((Ah_acc(k)/Ah_dis))*100);
    else
        SOC(k) = 100;
    end
end
```

Calculate SOC Based on SOC-OCV Curve

Calculate ΔSOC_{OCV} based on the found SOC-OCV points. First the SOC-OCV are interpolated to get more OCV points.

```
% Use interpolation to find rest of SOC-OCV points
nodes = linspace(0,100,1000);     % Number of new points
SOC_OCV = interp1(SOC,OCV,nodes); % SOC_OCV is the new array containing the OCV at the node points.

% Calculate SOC based on voltage
i = 1;
while cell.mV(3119) > SOC_OCV(i) % The loop runs until the right OCV is found. i is now containing the SOC at the found OCV.
    i = i+1;
end
SOC_OCV = 100-i
```

Calculate SOC Based on Coulomb Counting

Calculate ΔSOC_{OCV}

```
for i = 1:length(cell_measurement)
   Ah(i)=((cell.Duration_sec(i)-cell.Duration_sec(i+1))/(60*60)) * (cell.mA(i)/1000); % The Ah is integrated
end
SOC_CC = ((sum(Ah)/Q_nominal)*100) % The accumulated Ah is compared to the nominal Ah capacity to find the SOC.
```

Calculate SOH and Percent Error

Find the SOH based on ΔSOC_{OCV} and ΔSOC_{OCV}, and find the percent error when compared to the real SOH.

```
SOH_est = SOC_CC/SOC_OCV % Find the SOH estimate
SOH_err = abs(1-(SOH_real-SOH_est)/SOH_real)*100; % Find the percent error
```

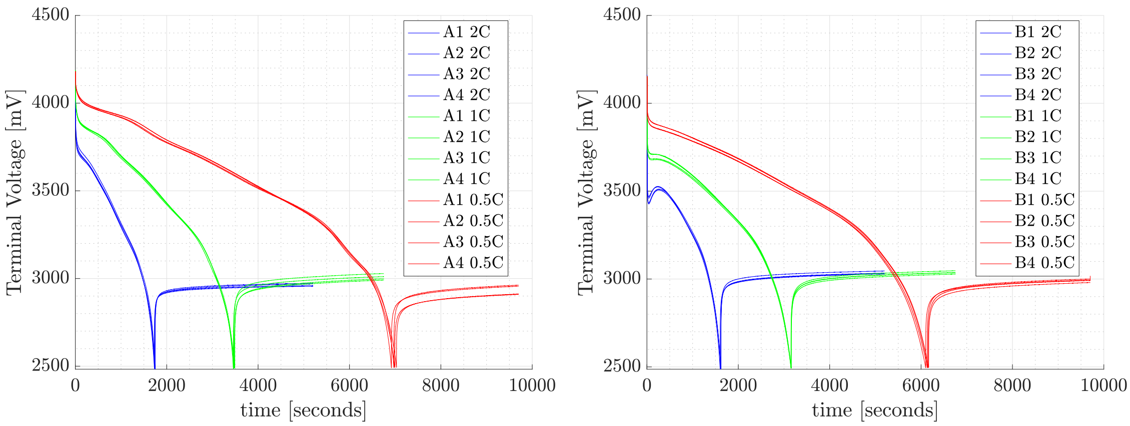
CHAPTER 6

Results

This chapter describes the results of each test performed. Each section ends with a discussion of the experimental results and the data processing.

6.1 Relaxation Time

In Figure 6.1.1a and 6.1.1b the voltage during the discharge of the cells with different C-rates can be observed. The cells are fully discharged at 5°C with a subsequent 60 min resting period. In the figures the influence of the used C-rate on the voltage drop can be seen. The discharges with a higher C-rate have a larger initial voltage drop, since the voltage drop is the current times the resistance. This is even clearer for set B that has a larger internal resistance. With the higher C-rate the cell voltages decreases faster, both because of the higher current causing faster discharge and for the increased voltage drop, leading the cells to reach their minimum voltage sooner. Set B at 2C has a slight voltage increase after the cells begin to discharge. This is caused by the increase in temperature of the cells, as they are heated by the dissipated power through the internal resistance of the cell. The effect is clear with a high C-rate and for set B with a higher internal resistance.

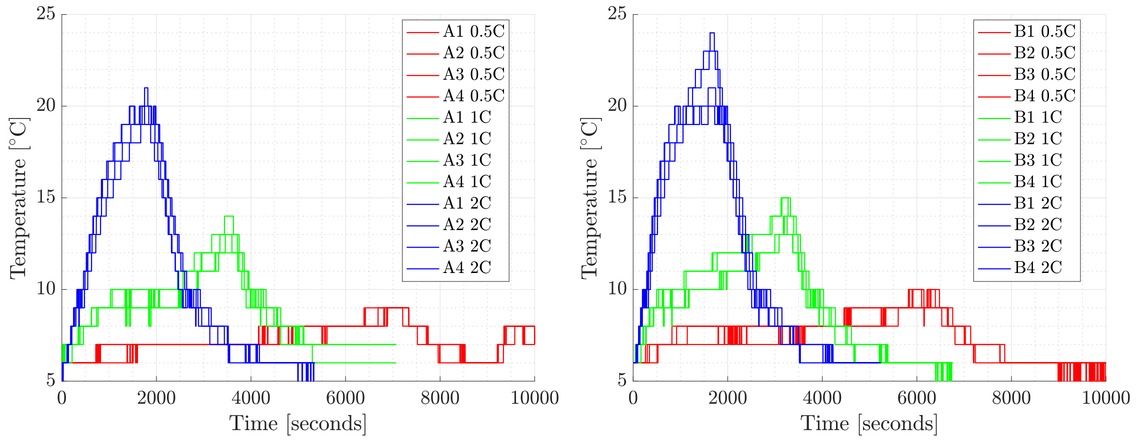


a Set A

b Set B

Figure 6.1.1: Voltage under discharge for different C-rates.

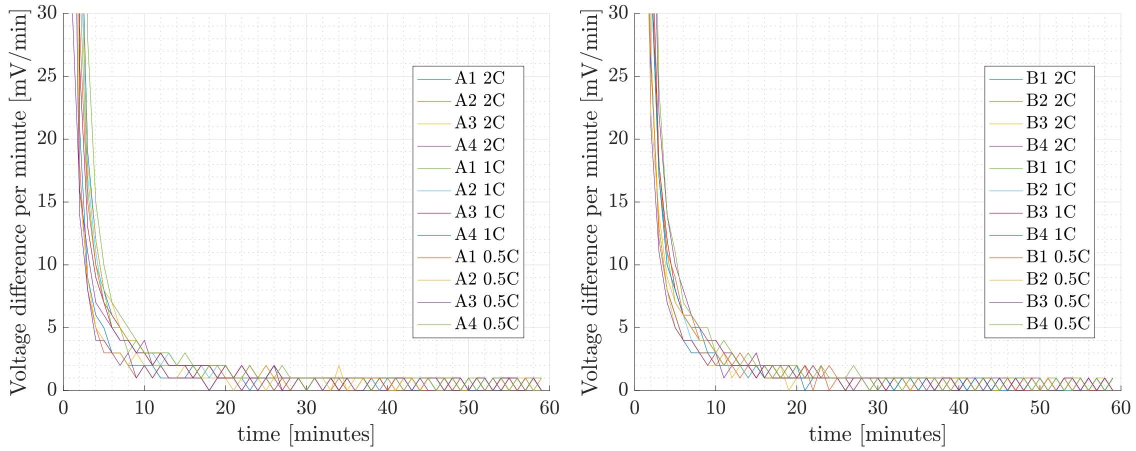
In figure 6.1.2a and 6.1.2b the temperature of the cells under discharge is plotted. Here the influence of the C-rate on the cell temperature is clear, while it can also be observed how the temperature is slightly increased for Set B for the same C-rates. It is also important to notice that the temperature of the cells is decreasing quickly again once the current is stopped, so the relaxation time can be compared at a similar temperature.



a Set A b Set B

Figure 6.1.2: Cell temperature for different C-rates.

To see the impact the C-rate have on the relaxation time, the differential of the voltage per minute after the current is stopped is compared to the time. The calculation can be seen in Figure 6.1.3a and 6.1.3b for set A and set B respectively. The relaxation time for both set A and set B is observed to be only dependent on the C-rate, to a limited and not significant extent. Even though the C-rate has a big influence on the terminal voltage and the discharge, the terminal voltage still stabilises quickly once the current is cut off. After 20 minutes both set A and B have a per minute change of less than 2 mV.



a Set A b Set B

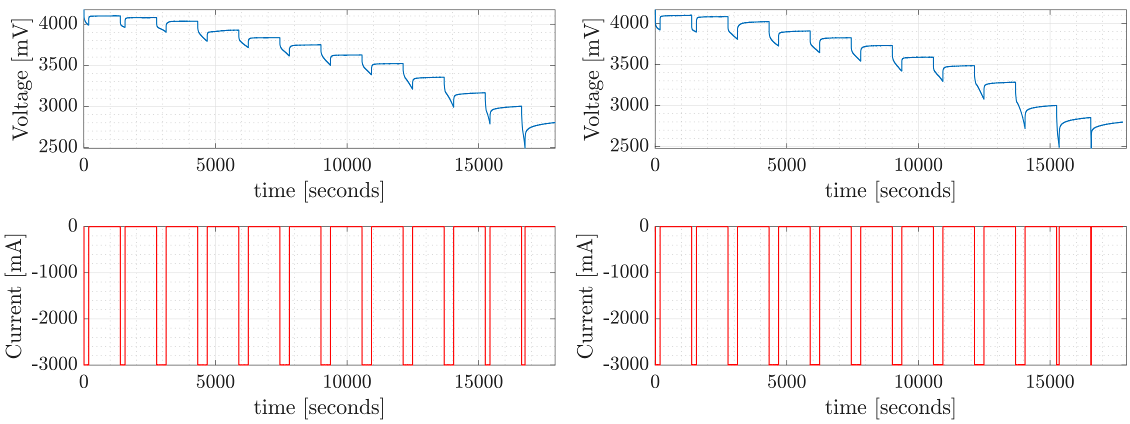
Figure 6.1.3: Voltage difference per minute for different C-rates.

6.1.1 Discussion

It is necessary to set a fixed relaxation time for the experiments so the terminal voltage readings can be compared. There is always a trade off between how long the batteries are allowed to rest, and how close the terminal voltage is to the OCV. For the rest of the experiments the relaxation time is set to 20 min, where the cells have a per minute change of less than 2 mV. This is a good trade off as the batteries have time to relax while having an acceptable resting time. The BMS has a limited measurement accuracy which means that very small voltage differences will not be appreciated.

6.2 Internal Resistance

The cells are tested to find the SOC-OCV curve, but the experimental data can also be used to determine the internal resistance at different SOC levels at 23°C and $45°$C. The terminal voltage and current for the test of a single cell in set A can be seen in Figure 6.2.1a and for a single cell in set B in Figure 6.2.1b. The cells are partially discharged with intermediate resting period to obtain the OCV.

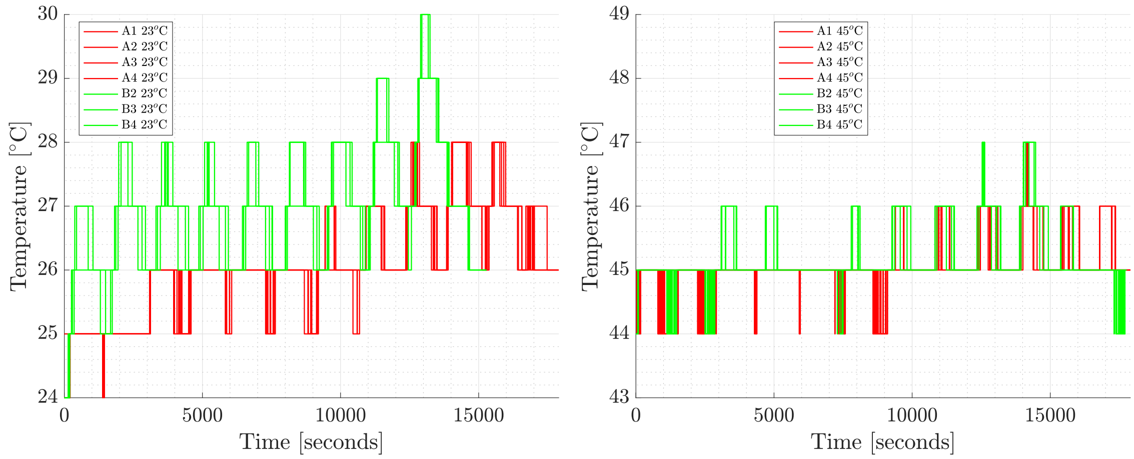


a Set A b Set B

Figure 6.2.1: Voltage and current under partial discharges.

The temperature of the cells can be seen in Figure 6.2.2a and 6.2.2a. The cells from each set are shown with the same color with red for set A and green for set B. This is because there are a very limited difference between the individual cells compared to the sets.

It is important to consider the temperature when testing for the internal resistance. Since the cells heat up when a current is flowing, the internal resistance might be influence more by the rise in temperature than by the parameter that is tested. For $45°$C both set A and set B only vary by maximum $\pm 2°$C through the test, which is considered negligible. For 23°C Set A vary by $\pm 5°$C and set B by $\pm 7°$C. This is a higher variance and might have to be considered when looking at the resulting internal resistance. Set B cells are heated more since they have a higher internal resistance than set A and therefore have a higher heat dissipation.

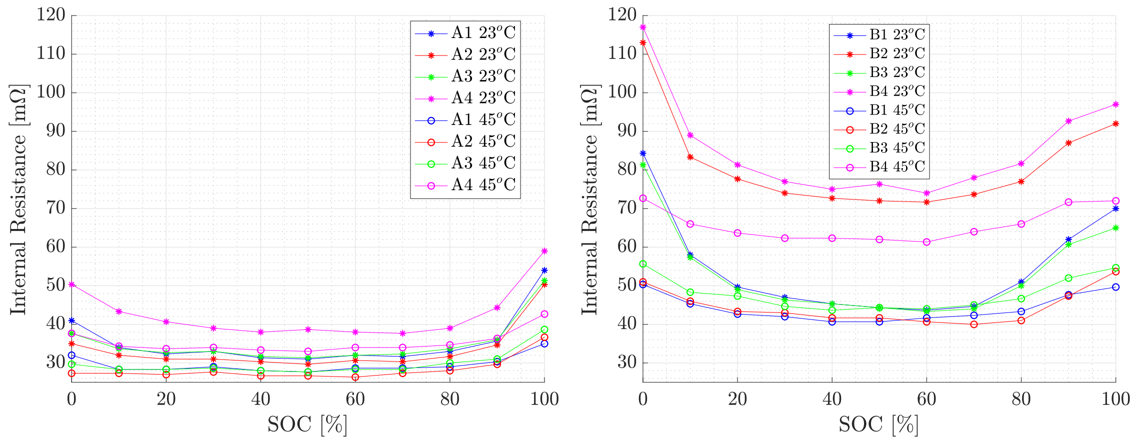


a Cell temperatures during discharge schedule at 23°C   b Cell temperatures during discharge schedule at 45°C

Figure 6.2.2: Temperature of each cell in set A and B under partial discharges for SOC-OCV curve.

Since this test is also used to determine the SOC-OCV curve at different temperatures, it is also important to note that the temperature increase during the tests are small compared to the difference between 23°C and 45°C.

On figure 6.2.3a and 6.2.3b R_{int} for set A and set B at different SOC levels can be seen. The cells in set B can be seen to have an increased R_{int}, compared to set A, as the cells have aged. R_{int} is lower at 45°C than at 23°C for each SOC point for each cell in both set A and set B. For set A R_{int} varies by a small amount between 10% and 90% SOC, but is increased when the battery is close to being fully charged or discharged. For set B R_{int} varies significantly more and is much more dependent on the SOC. R_{int} is only steady between 25% and 65% SOC, and they vary more at both high and low SOC. There is also significantly more spread between each cell of set B compared to set A. That the cells age differently is a big issue for large battery packs. That R_{int} differs from cell to cell leads to some cells getting more heated and getting discharged faster which limits the entire pack.



a Set A   b Set B

Figure 6.2.3: Internal Resistance at different SOC levels and temperatures.

C-rate	% loss at 26 [mΩ]	% loss at 52 [mΩ]
0.5	0.54	1.08
1	2.17	4.33
2	8.67	17.33

Table 6.2.1: Percentage Power loss.

For a lot of applications the battery end-of-life is defined as when the battery have reached a specific capacity loss and a maximum R_{int} increase. For a lot of manufacturers this is often set to 20% capacity fade, and/or when R_{int} have doubled its value. The initial R_{int} of the used cells is in the datasheet said to be minimum 26 mΩ, which would make its end-of-life R_{int} be $\approx$ 52 mΩ. The results of set B shows that 52 mΩ is not large compared to the found R_{int}.

The increase in R_{int} leads to an increase in power loss. $Q_{\text{Wh,loss}}$ can be founds based on the squared current and the internal resistance, and then compared to Q_{Wh}. For an full CC discharge at different C-rates the percentage of the energy lost during a discharge, $Q_{\text{Wh,loss}}$, compared to the initial Wh capacity Q_{Wh} is calculated. The result can be seen in Table 6.2.1 for a R_{int} of 26 mΩ and 52 mΩ. It can be seen that even for low C-rates, the higher internal resistance makes a big difference for the amount of energy lost. It increases significantly for high C-rates and where a C-rate of 2 gives an energy loss of 17% for an R_{int} of 52 mΩ.

6.2.1 Discussion

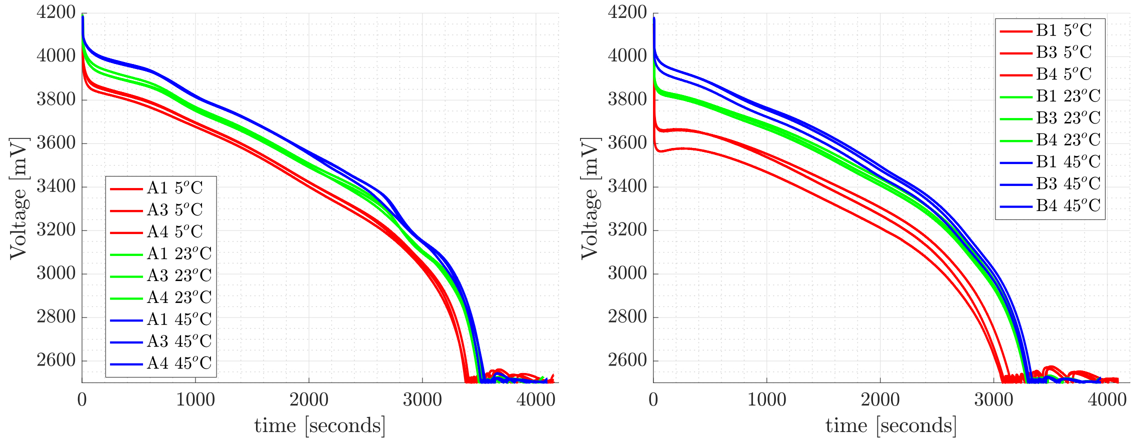
R_{int} has been found for different SOC point at 23°C and 45°C. The plots have shown how much the cells R_{int} vary under a discharge, and much more significantly the spread of R_{int} is as the cells age. The internal resistance increases significantly with temperature for these two temperatures but more experiments must be made to be able to interpolate to other temperatures.

The spread in internal resistance means that the cells does not reach the cut off voltage at the same time, which limits the capacity of the pack. It could however be a more limiting factor that some cells will reach the maximum temperature and result in limiting the available power of the pack.

As the Ah capacity is not dependent on R_{int}, its effect have been calculated for the Wh capacity. In Table 6.2.1 it is showed how important R_{int} is as parameter for high power use. For 0.5C current the percentage power loss is found to be 0.54 % for a fresh cell and 1.08% for a end-of-life cell. For a more high power use of 2C the percentage power loss is found to be 8.67% for a fresh cell and 17.33% for a end-of-life cell. Thus for high power operations the internal resistance is much more important to consider compared to a low power operation.

6.3 Capacity

In figure 6.3.1a and 6.3.1b the discharge voltage profile for set A and Set B can be seen for the different temperatures. The capacity test results can only be seen for cells A1, A3, A4 and B1, B3, B4. An error in the test equipment caused the data for the last 2 cells to be unusable. In the figure the initial voltage drop can be seen to increase as the temperature decreases. This is caused by the increase in internal resistance. At a lower temperature the internal resistance is higher, which cause an increased voltage drop. For set B the impact the temperature have on the initial voltage drop is even higher. As set B have a higher internal resistance, it is more affected by the temperature change. Both Set A and set B can be seen to end CC and enter CCCV discharge earlier at lower temperature. This is again be caused by the increase of the internal resistance, that causes the battery to reach its minimum voltage earlier.

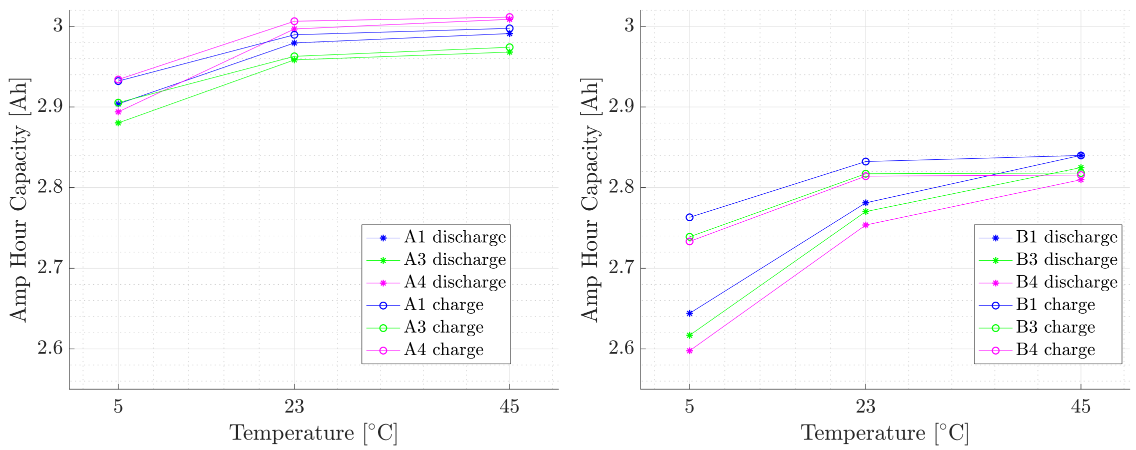


a Set A b Set B

Figure 6.3.1: Discharge profile for set A and set B at different temperatures.

In Figure 6.3.2a and 6.3.2b the Ah charge and discharge capacity for set A and B can be seen. For set A both charge and discharge capacity increases as the temperature increases. The difference between charge and discharge capacity decreases. At 45°C the difference is very limited. For set B the capacity for the cells are reduced compared to set A. The same behaviour can be seen for set B, but the difference between charge and discharge capacity is significantly increased at 5°C and at 23°C. At 45°C the difference is very limited.

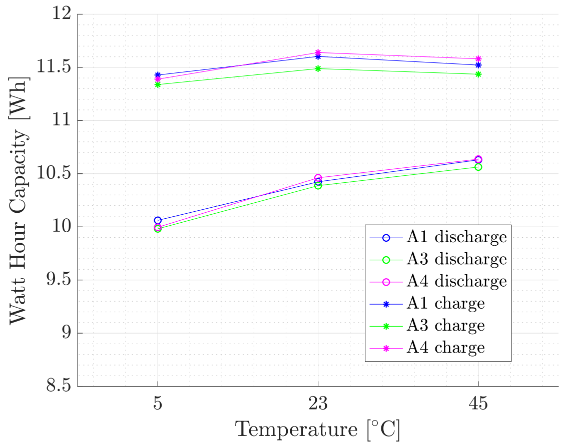
On average for set A the Ah discharge capacity changes 2.87% from 23°C to 5°C, and 0.37% from 23°C to 45°C. For set B the Ah discharge capacity changes 5.38% from 23°C to 5°C, and 2.00% from 23°C to 45°C.



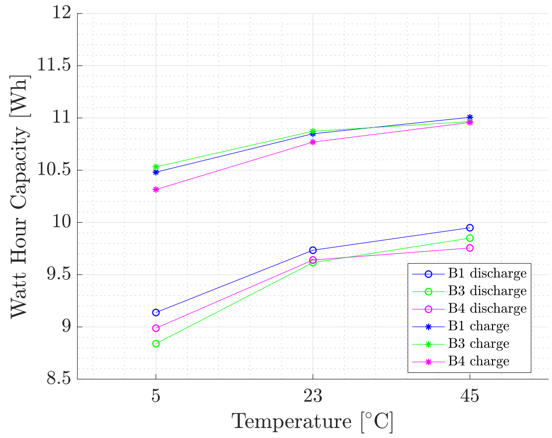
a Set A b Set B

Figure 6.3.2: Ah charge and discharge capacity at different temperatures.

In Figure 6.3.3a and 6.3.3a the Wh charge and discharge capacity can be seen. The significant difference between the charge and discharge capacity for set A and set B is explained by the power loss in the internal resistance, as it is charged and discharged. For both sets the difference between charge and discharge capacity is reduced as the temperature increases and the internal resistance decreases. For set B the spread of the Wh capacity of the cells is increased, as the cells have aged.



a Set A



b Set B

Figure 6.3.3: Wh charge and discharge capacity at different temperatures.

On average for set B the Wh discharge capacity changes 3.93% from 23°C and 5°C, and 1.73% from 23°C to 45°C. For set B the Wh discharge capacity changes 7.04% from 23°C to 5°C, and 1.90% from 23°C to 45°C.

In Table 6.3.1 the charge and discharge Wh and Ah capacity for each cell and temperature can be seen.

Table 6.3.1: Discharge and charge capacity.

Cell and temperature	Discharge [Ah]	Charge [Ah]	Discharge [Wh]	Charge [Wh]
A1 5°C	2.90	2.93	10.06	11.42
A3 5°C	2.88	2.90	9.98	11.33
A4 5°C	2.89	2.93	9.99	11.38
A1 23°C	2.97	2.98	10.42	11.60
A3 23°C	2.95	2.96	10.38	11.48
A4 23°C	2.99	3.00	10.46	11.63
A1 45°C	2.99	2.99	10.62	11.52
A3 45°C	2.96	2.97	10.56	11.43
A4 45°C	3.00	3.01	10.63	11.58
B1 5°C	2.64	2.76	9.13	10.48
B3 5°C	2.61	2.73	8.83	10.53
B4 5°C	2.59	2.73	8.98	10.31
B1 23°C	2.78	2.83	9.73	10.84
B3 23°C	2.77	2.81	9.61	10.87
B4 23°C	2.75	2.81	9.64	10.76
B1 45°C	2.84	2.83	9.94	11.00
B3 45°C	2.82	2.81	9.85	10.96
B4 45°C	2.80	2.81	9.75	10.95

6.3.1 Discussion

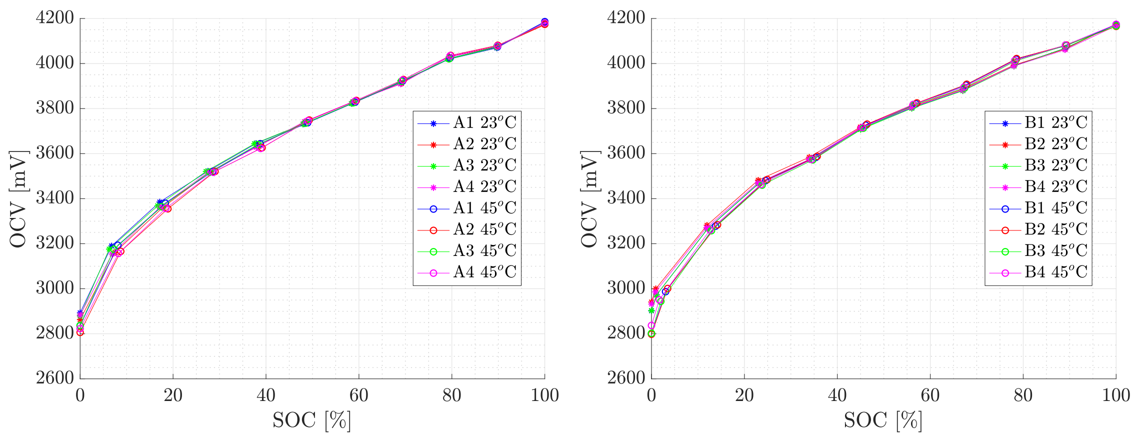
The results have shown the influence of the temperature on the capacity of the battery, and how the influence is increased for the aged cells. The change is bigger from 23°C - 5°C step, compared to the 23°C - 45°C step, for both sets. This behavior is more significant for the Wh capacity since it is dependent on the internal resistance.

The Ah capacity should be the same for charging and discharging capacity as it does not count the voltage drop. The discharge capacity is however generally a bit lower. This means that if the charge capacity can be measured it can be used to estimate the discharge capacity. For the Wh capacity there is a significant difference between charge and discharge capacity, so to be able to calculate one from the other it is necessary to know the internal resistance.

6.4 SOC-OCV curve

To find the SOC-OCV curve the cells are discharged with 10 partial discharges. Each discharge being 0.3 Ah. The partial discharges can be seen in Figure 6.2.1a and 6.2.1b. The SOC-OCV points are calculated by comparing the terminal voltage found after a 20 min relaxation time to the accumulated Ah. The Ah is compared to the full Ah capacity, and thereby the SOC-steps is found. Each OCV is then matched with the SOC. Since the SOC is found based on the same Ah-steps of each cell, the SOC-OCV points of set B will not be the same exact place. The steps of 0.3 Ah is chosen as it corresponds to 10% steps of a new cell, but since the cells in set B has a lower capacity each step will be slightly larger.

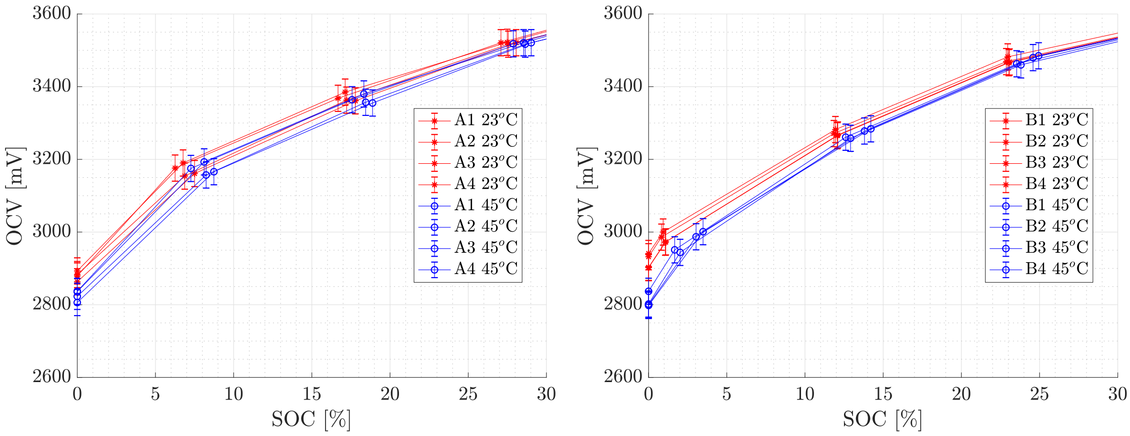
In Figure 6.4.1a and 6.4.1b the SOC-OCV curves for set A at $23°$C and $45°$C and set B at $23°$C and $45°$C is seen. For both sets there seems to be a limited variance between the temperatures. First at $\leq 30\%$ the curves divert to a noticeable degree.



a Set A b Set B

Figure 6.4.1: SOC-OCV curve for Set A and set B at different temperatures.

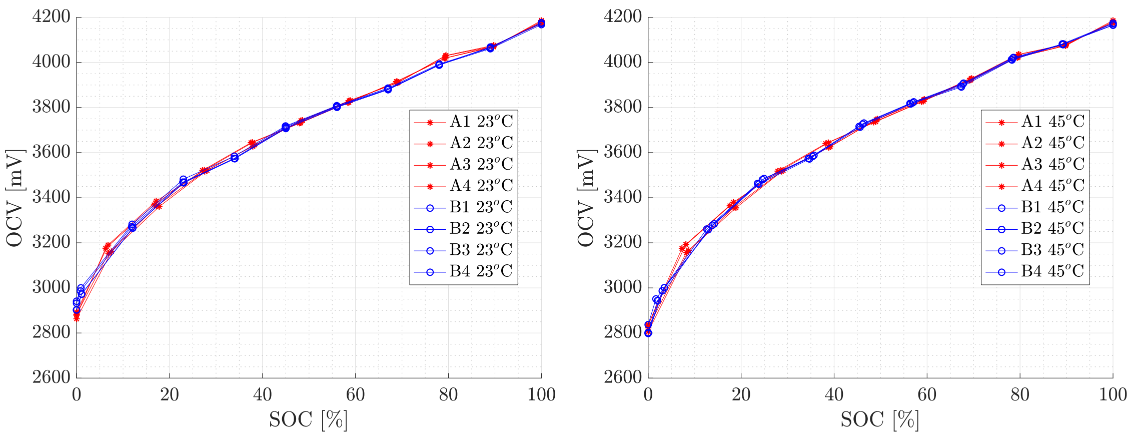
In Figure 6.4.2a and 6.4.2b the SOC-OCV curve for 0% to 30% SOC for both sets can be seen. The cells are plotted with an error bar of ±36mV showing the uncertainty of the voltage measurements. First after 10% they divert out of the uncertainty of measurements, this is especially noticeable for set B.



a Set A b Set B

Figure 6.4.2: 0% to 30% SOC-OCV curve for Set A and set B.

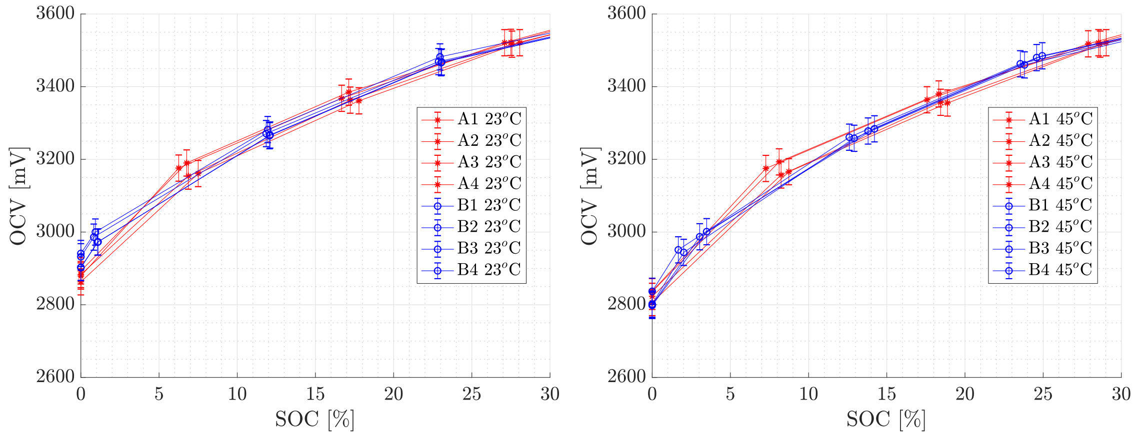
In Figure 6.4.3a and 6.4.3b the SOC-OCV curves for set A and set B at 23°C and 45°C is seen. For both temperatures there seems to be a very limited variance between the set A and B.



a 23°C b 45°C

Figure 6.4.3: SOC-OCV curve for Set A and Set B.

In Figure 6.4.4a and 6.4.4b the SOC-OCV curve for 0% to 30% SOC for both temperatures can be seen. Again the cells are plotted with an error bar of ±36mV. The curves divert when the SOC is under 10%, but since the data points are not at the same SOC level, it can not be concluded that the two curves would not follow the same behavior.



a 23°C b 45°C

Figure 6.4.4: 0% to 30% SOC-OCV curve for Set A and set B.

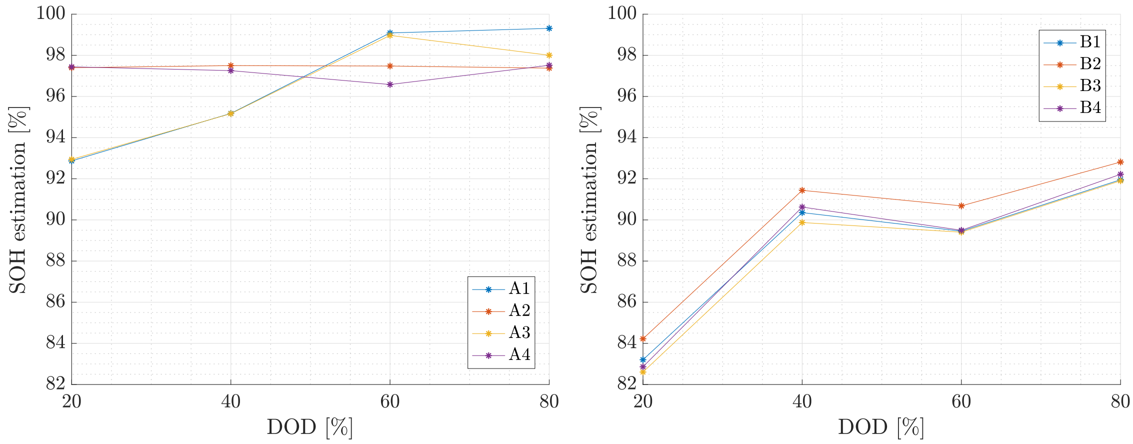
6.4.1 Discussion

Since the SOC-OCV points of set A and B are not found at the same SOC points it can be hard to conclude anything explicitly, but in general there only seems to be very limited change to the SOC-OCV curve as the cells age. The change is more significant, but still limited between the two different temperatures. The difference between 23°C and 45°C is slightly increased for set B at low SOC. Since the test was only done at 23°C and 45°C it is not possible to say how much a lower temperature at 5°C would increase the change of the SOC-OCV curve. This would need to be investigated further. It is an industry standard to define the SOC-OCV curves for different temperatures. This is necessary for high precision BMSs that need to estimate the SOC with a very small error margin.

6.5 SOH Estimation by Partial Discharges

The SOH estimation is done for Set A and set B at 23°C. The estimation is done at 20%, 40%, 60%, and 80% DOD, and calculated in the same way as described in Chapter 3 section 3.6.2 with formula 3.5. It is estimated with the SOC-OCV curve of set A, since that is what would be used in a real application, if the BMS only has the SOC-OCV curve for the new battery. All of the discharges are made in the same way with 1C Discharge at 23°C and calculating the Ah capacity.

In Figure 6.5.1a and 6.5.1b the estimations can be seen.



a Set A b Set B

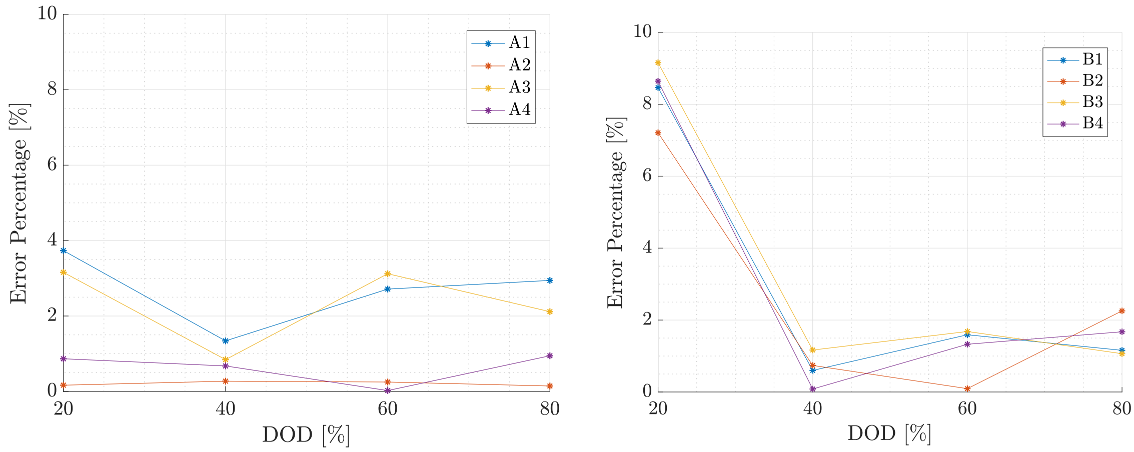
Figure 6.5.1: SOH estimation for Set A and set B.

The capacity of each cell measured during a full discharge is shown in the table. This is considered to be the accurate capacity and is used to calculate the estimation error of the capacity estimations from partial discharges.

Table 6.5.1: CC capacity and SOH of cells.

Cell	1C Discharge capacity at 23°C [Ah]	SOH [%]
A1	2.89	96.33
A2	2.92	97.33
A3	2.88	96.00
A4	2.90	96.66
B1	2.73	90.90
B2	2.72	90.77
B3	2.72	90.93
B4	2.72	90.70

In figure 6.5.2a and 6.5.2b the percentage error of the SOH estimate compared to the real SOH can be seen. For Set A there is not a clear behaviour between the cells, or a general increase in accuracy. The cells in set B follow a more clear behavior between the cells. For a DOD of 20% the error in the estimation between 7% and 9%. For a DOD at 40%, 60%, 80%, the error estimates are all under 2.1%.



a Set A

b Set B

Figure 6.5.2: Error percentage of SOH estimation at different DOD for set A and set B at 23°C.

6.5.1 Discussion

The test have shown the error percentage of the SOH estimations for set A and set B. The varying error percentage of some of the cells in set A might be because the cells are new. They thereby have a lower difference to estimate that might be more influence by the inaccuracy of the test equipment. For set B there was a decrease in error to under 2% from 20% DOD to 40% DOD but thereafter not a clear increase in accuracy. Considering the accuracy of measurements by the test equipment used the SOH have been estimated to a satisfying degree.

CHAPTER **7**

Conclusion and Future Works

7.1 Conclusion

This thesis investigated how a BMS can estimate the SOH based on partial discharge, as well as which battery parameters influence the estimation. This thesis explains that the SOH can be estimated based on a ΔSOC_{OCV} estimation based on the OCV compared to a ΔSOC_{CC} estimation based on coulomb counting. The SOC_{OCV} is dependent on the OCV measurement as well as the SOC-OCV curve. To get a precise OCV measurement the battery needs to relax for a certain time. By testing for the needed relaxation time at different C-rates, it was found that the relaxation time was not significantly dependant on the used C-rate or the level of degradation of the cell, and that 20 min was enough time for the cells to have a per minute change of under 2 mV. The OCV-SOC curve was tested for a set of fresh and a set of degraded cells at 23°C and $45°$C. The test have shown that there is very limited difference in the SOC-OCV relation between the fresh and the degraded cells, and that the initial SOC-OCV curve of the fresh cells can be used to make an accurate SOC_{OCV} estimation of the degraded cells. The test also showed very limited difference for the curves between 23°C and $45°$C, but since a test have not been done at $5°$C, the thesis is not able to conclude on how much it would change at lower temperature.

To be able to do SOH estimations at different scenarios, this thesis investigated how much the temperature influences the Ah discharge capacity. The average capacity change compared to capacity at 23°C was calculated. At $5°$C the capacity is decreased by 2.87% for the fresh cells and by 5.38% for the degraded cells. At $45°$C the capacity is increased by 0.37% for the fresh cells and by 2.00% for the degraded cells. For set A the capacity difference is insignificant at $45°$, but increases at $5°$C. The degraded cells are much more influenced by the temperature. As the cells discharge capacity have been shown to be dependent on the temperature, it is necessary to either incorporate the temperature into the SOH formula, or make SOH estimate at a smaller temperature window.

The SOH is often defined both as the loss of capacity and the increase in internal resistance. Because of this, the thesis investigated how big the internal resistance R_{int} was at different SOC levels at different temperatures. This was done to see how much R_{int} varied as the cells aged and how much the R_{int} influences the Wh capacity. The cells were found to vary significantly more when they aged, both between cells and at different SOC levels. For R_{int} of 52 mΩ at a full 0.5C discharge the cell had a percentage power loss at 1.08% compared to 17.33% for at full discharge at 2C, which shows how important R_{int} is for the calculation of the SOH of a battery in high power operation.

Lastly this thesis investigated how accurately the SOH could be estimated with the mentioned method at different discharges. For set A there was a variance and not a clear increase in accuracy both between the cells and the different DOD. For all the DOD the error percentage was under 4%. For set B there was a decrease in error to under 2% from 20% DOD to 40% DOD but thereafter not a clear increase in accuracy. The variance can be explained by the accuracy of measurements by the test equipment used. With the accuracy of measurements in mind the SOH have been estimated to a satisfying degree.

7.2 Future Work

For future testing the SOC-OCV could be repeated with more measurement points. Especially more points at high and low SOC, to better show the behavior for those areas. Set B could also be tested at smaller discharges, so its SOC points would line up with the SOC points of set A. By re-doing the tests at 5° it could be investigated how the SOC-OCV curves behave at lower temperatures, and get a better understanding of how dependent it is on the cell temperature. With this data R_{int} could also be found and its increase at 5° at different SOC levels could be quantified. All the tests could also be redone with different Li-ion cell chemistries to see what influence that would have on the results.

For future work it would be interesting to investigate if partial charges, instead of discharges, could help better estimate the SOH. Under charge, the current is both lower and constant, which might give a more precise estimation, if it is possible to convert from the charge to the discharge capacity. It could also be investigated how precisely the SOH with respect to Wh can be estimated and if by finding the SOH with respect to Ah, it is possible to convert it to Wh.

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