Improving Ultra Fast Charging of LiFePO\textsubscript{4} batteries at low temperatures with AC heating

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Rijswijk, May 7, 2010
Preface

Before you lies the report of the master thesis project of Wouter Smit. The subject of the project has been selected in cooperation with Wouter Robers, my daily supervisor at the young company Epyon and is closely related to the company activities of Epyon. In the document, a lot of battery technology specific expressions are used. Because battery technology is not treated extensively in the curriculum of Electrical Power Engineering at the TU Delft, an introduction to battery technology is included in Chapter 1. It is assumed that the reader has at least a basic knowledge on electrical engineering.

Acknowledgements

The author would like to thank:

- My daily supervisor at the TU Delft, dr. Jelena Gerber-Popović for her excellent guidance and support on writing this thesis

- My daily supervisor at Epyon, ir. Wouter Robers for his bright ideas on battery technology and guidance in difficult situations

- My family and my girlfriend for supporting the things I love to do

- My business partners for allowing me the time to complete this project

- All friends and colleagues
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5.1  Conclusions

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Abstract

The speed at which electric vehicle batteries can be charged usually depends on the available charging power. At low temperatures however, another bottleneck appears when the battery is unable to accept all available charging power. The charging speed is then limited by the battery. To fix this, the battery could be equipped with a heater so that the charging can take place at a higher temperature.

Using an experimental approach, the author tried to answer the following questions:

- How does temperature influence charging speed and battery degradation?
- What are the positive effects of the usage of battery heating?
- Is battery heating using AC an effective method from a battery point of view?
- Does AC heating cause battery degradation?

The most important conditions that apply in this project are:

- Evaluated battery technology is LiFePO4. This is one of the best suitable technologies for EV purposes today due to its high energy density, high power density and safety.
- The experiments are focused on Ultra Fast Charging (15 minutes). Battery heating can create a significant advantage in this operating mode.

Results

Measurements revealed a rapid decrease of charging performance below 10°C. Charging performance decreases to 70% at 0°C to as low as 20% at -20°C compared to the 25°C level. Ageing effects also showed a strong relation with temperature. Ultra Fast Charging at 0°C results in a five times higher ageing rate than doing the same at room temperature.

The available charging power is a practical power source for heating. Converting this power into a square wave using power electronics resulted into a battery current of about 17.5A RMS per 18650 cell. Although this current level is rather high (~16°C), measurements showed only little negative effects as a result of prolonged exposure to this current level.

Conclusions

Temperatures below 10°C significantly limit charging speed and battery lifetime. Due to this effect, AC battery heating is able to improve performance below 10°C. The performance improvement was determined as 25% at 0°C and even more at lower temperatures. Due to a significant increase in ageing effects below 10°C, also battery lifetime can be improved in an important amount.

Effects on battery lifetime due to the (AC) heating current and thermal cycles were found to be minimal. From the battery point of view, AC heating thus seems a good technique to improve performance and lifetime at low temperatures.
CHAPTER 1 Introduction & problem definition

After the invention of the automobile by Robert Anderson in the 1830s, it was not until the late 19th century when the interest in motor vehicles started to increase. Back then, electric propulsion was the preferred choice of many because it held the best cards in terms of comfort. The limited range of electric vehicles was not really an issue until later in the 1920s, when a demand developed for long-range vehicles. The low price of oil and several inventions on the field of the petrol powered car then resulted into a decline of the electric vehicle [1].

During recent decades however, the general public developed an increasing awareness on the effects of pollution caused by the massive use of fossil fuels. The public opinion on environmental issues is now stimulating the development of technology required for clean mobility more than ever before. Examples of progress in this field are recent announcements from various prominent car manufacturers to introduce full-electric consumer cars on the market. Most of these announced models have a range of about 160 km, which is far less than the average range of petrol cars. This and other issues such as the lack of public charging stations currently limit the adoption rate of electric vehicles, but as more people and companies are starting to trust the concept of clean electric mobility, this might change in the near future.

Battery technology is a matter of great importance for car makers since most consumers demand an equal level of comfort and costs for electric vehicles as for petrol powered cars. With current battery technology, not all demands can be satisfied so new developments are needed to allow a broad acceptance of electric vehicles. Bringing down the battery costs per kWh is an important challenge to be addressed as well as developing battery lifetime extending technologies.

The rapidly emerging market in electric vehicles comes with numerous challenges. One of these challenges that has received only little attention thus far is involved with charging a vehicle’s battery at low temperatures. The study presented in this thesis will give insight into the issues playing a role when a battery is attempted to be charged quickly at low temperatures. In this document, the term Ultra Fast Charging (UFC) will be used frequently and is defined as a recharge in 15 minutes. This definition will be used as a basis for experiments and calculations.

Epyon focuses on the development of technologies that assist in making the best possible usage of vehicle batteries. Ultra Fast Charging receives special attention because it is thought that this is key functionality for the acceptance of electric cars. The ability to charge quickly enables EV owners to cover large distances without the necessity to wait hours for a standard charge.

Battery heating has been suggested as a possible solution for the low temperature issues. Using an experimental approach, the usability of battery heating is evaluated. A specific heating method using AC will receive extra attention due to its attractive property to heat a battery through the internal resistance. The project will be focused on the effects of heating on the battery.
1.1 Battery basics and history

The modern development of batteries started with the Voltaic pile, invented by the Italian physicist Alessandro Volta in 1800 [1]. Since the invention of the first Voltaic pile, the battery has become a common power source for many household and industrial applications and is now a multi-billion dollar industry [2]. In today’s society, the battery has become important: from mobile phones to (hybrid) electric vehicles [3], batteries can be found everywhere.

A battery, which is actually an electric cell, is a device that produces electricity from a chemical reaction. Strictly speaking, a battery consists of two or more cells connected in series or parallel, but the term is generally used for a single cell. A cell consists of a negative electrode; an electrolyte, which conducts ions; a separator, also an ion conductor; and a positive electrode. A wide variation of chemicals can be used to generate the ions, where carbon-zinc and lead-acid are popular combinations [4], [5].

While battery technology has been in development for more then 200 years, ideal batteries still do not exist today. When one speaks of an ideal battery, one assumes an inexhaustible pool of energy in a small package that is cheap, safe and clean [6]. Furthermore, a battery must have a certain power density in order to fulfil its function properly; that is, the battery should deliver its energy as fast as demanded by its application.

1.1.1 Battery classification

Batteries are classified into two broad categories, each type with its own advantages and disadvantages [7].

- *Primary batteries* irreversibly (within limits of practicality) transform chemical energy to electrical energy. When the initial supply of reactants is exhausted, energy cannot be readily restored to the battery by electrical means [5].

- *Secondary batteries* can be recharged; that is, their chemical reactions can be reversed by supplying electrical energy to the cell, restoring the original composition [8].

As the title says, this thesis deals with batteries which can be recharged and hence, the focus lies on the secondary batteries. Batteries may be optimised in various ways, for example, one can make a trade-off between capacity and power of the battery. A second classification can be made in this way:

- *High capacity batteries* are optimised having a high energy storage capacity but cannot be charged and discharged as fast as a high power batteries. This type of battery can be found in most handheld applications like mobile phones and laptops.

- *High power batteries* are optimised having fast charging and discharging capability but have less energy storage capacity than high capacity batteries. This type of battery can be found in power tools and (hybrid) electric vehicles.

Because this second categorisation is a result of an optimisation of the internal battery structure, in-between solutions are also possible [9].
1.1.2 State-of-the-art battery technology

Lots of different battery chemistries have been developed in the last 200 years, each having its own specific properties. Some of these chemistries found their way into our society because they were most attractive not only in terms of energy density but also service life, load characteristics, maintenance requirements, self-discharge and operational costs. Examples of four well known secondary battery types are [10]:

<table>
<thead>
<tr>
<th>Type</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-Acid</td>
<td>Car starter batteries, solar energy storage</td>
</tr>
<tr>
<td>Nickel Cadmium (NiCd)</td>
<td>RC Racing, electric tools</td>
</tr>
<tr>
<td>Nickel Metal Hydride (NiMH)</td>
<td>Hybrid electric vehicles</td>
</tr>
<tr>
<td>Lithium-Ion (Li-ion)</td>
<td>Mobile phones, electric vehicles</td>
</tr>
</tbody>
</table>

This thesis will be focused on Lithium Iron Phosphate (LiFePO4) batteries which is a type of Li-ion high power secondary battery and has been selected by market leaders such as General Motors to be the battery technology for upcoming hybrid electric vehicles [11]. LiFePO4 batteries are particularly suitable for Ultra Fast Charging and the technology has reached a mass production stage [12]. Most manufacturers produce LiFePO4 batteries in cylindrical form factors such as the popular 18650 type, but also other form factors are possible. A cross section of a cylindrical battery is shown in Figure 1.1. In chapter 2, the internal functioning of batteries is explained in more detail.

![Cylindrical Li-Ion Battery](image_url)

Figure 1.1 – Internal structure of a cylindrical Li-ion battery [13]
1.2 Battery properties

Because the ideal battery only exists in theory, one should be aware of the characteristics and limitations of practical batteries. In electric circuit theory, a battery is often modelled as a voltage source, sometimes added with an equivalent series resistance (ESR). This electric circuit model has in fact all properties of an ideal battery; it is never depleted and it can deliver as much current as required (when the ESR is absent). For electric circuit modelling, this ideal model will suffice in most cases. In real applications, one should be aware of the battery limits for several reasons such as size, costs, lifetime, safety etc.

The properties of a real battery depend on many factors including internal chemistry, current drain, temperature, battery history and usage [14]. The electrode materials in a battery determine the (rated) cell voltage while the type of electrolyte has influence on the ESR. A rechargeable NiCd pile has a rated voltage of 1.2 Volt, whereas a Li-ion cell operates at a rated voltage of 3.6 Volt.

The speed of chemical processes depend on temperature. Since batteries operate due to a chemical process, the properties of a battery vary with temperature. At very low temperatures, batteries will cease to function due to low reaction speed or frozen electrolyte [15].

Depending on many factors like environmental temperature, discharge depth and the current levels used for charging and discharging, batteries degrade. During a battery’s lifetime, the properties of a battery deteriorate. Affected parameters are, among others, useful capacity and ESR. More on the various processes influencing battery properties can be found in chapter CHAPTER 2.

1.2.1 Battery State Of Life

The useful life of a battery ends when its performance falls below a certain predefined level. This level depends on the application which is powered by the battery. For many applications has been decided that the end of useful battery life is reached when the useful capacity falls below 80% of the initial useful capacity [16]. Other applications may define the useful battery life in more detail, for example by specifying the maximum internal resistance. To give more insight in the remaining useful battery life, the State of Life (SOL) could be determined for a specific application and battery. The SOL is a single parameter representation for a battery which reflects the ability to fulfil its function in a specific application. The determination of the SOL can be done by different algorithms with varying accuracy. It should be noted that high accuracy goes hand in hand with high effort and costs [17].

1.2.2 Battery lifetime guarantee

For many electric mobility applications the useful battery life must be guaranteed for business models to work. The battery pack is often the most expensive part of an electric car and also a big factor in the cost of a hybrid electric car. For this reason, the battery should last the entire lifetime of the car. Currently, battery manufacturers must be able to guarantee around 10 years of battery service life before they are allowed to supply battery packs for (hybrid) electric vehicles [18].
CHAPTER 1: Introduction & problem definition

The complex nature of batteries with all kinds of environmental parameters influencing its properties makes it a tough job for battery manufacturers to guarantee long service life, especially in the harsh automotive environment where temperature extremes (-40°C...+105°C for liquid cooled parts) and vibrations are present.

Various techniques are used to guarantee a certain battery lifetime. To compensate for capacity decrease, Dynamic Depth Of Discharge (DOD) control can be used. This technique uses a slightly over-dimensional battery to compensate the capacity fade over the years. If an application needs a capacity of say 10 kWh, the capacity of the new battery is chosen to be slightly larger, for example 12 kWh. The available capacity is then electronically limited to 10 kWh so the user does not notice any decrease in capacity until, years later, the real battery capacity falls below 10 kWh [19].

Another technique used to guarantee battery lifetime is model based battery lifetime prediction. With this technique, the lifetime is calculated with the help of an accurate model of the battery, exposing it to typical operating conditions. With the availability of increasing computing power, this method is gaining popularity [20]. Active temperature control may also be used to prevent excessive battery ageing due to temperature extremes [21].

1.3 Ultra Fast Charging

Many of today’s products like power tools use the term “fast charging” to indicate that the product charges faster than other products using regular charging. Regular charging has been known technology for years and is used for rechargeable batteries that are not optimised for high power applications. The rechargeable NiCd and NiMH piles are good examples of regular charging batteries. With regular charging, batteries are typically charged within 8-12 hours, with fast charging is usually meant one to a few hours. There are however no general accepted definitions of these terms.

Ultra Fast Charging (UFC) applications take the opportunity to charge in the time of (coffee) breaks, typically 15 minutes. In this way, charging time is so short that it does not interfere with business processes. UFC systems can be seen as a combination of three distinguishable parts [22]:

- **High power Lithium-ion batteries**
  High power Lithium-ion batteries are currently the most advanced energy storage systems suitable for Ultra Fast Charging.

- **Advanced power conversion technology**
  Ultra Fast Charging requires high amounts of energy to flow into the storage medium in a short amount of time (high power). This means very high system efficiency and good thermal management are absolute musts. On-board chargers also need a high power density. To achieve such high goals, state-of-the-art techniques are required.

- **Intelligent charge control system**
  The intelligent charge control system chooses the best charging strategy in order to guarantee the objected battery lifetime and safety. The charging strategy is calculated by an algorithm which combines actual and historical data of the battery, objected lifetime and recommended operating conditions and calculates the maximum charging speed at each moment.
1.4 Problem definition & project goals

As already explained in section 1.2, the properties of batteries vary with temperature. For most battery types, including Li-ion, the ESR has a negative temperature coefficient [23]. This means that the charging speed will decrease with temperature. The problem is here that the battery cannot be charged as fast as necessary when the battery temperature falls below a certain level. To cope with this problem, some companies add heaters in their battery packs to improve performance at low temperatures [21].

With battery heating, cold batteries can be heated before charging, improving the properties of the battery. The proposed heating method uses alternating current (AC) to heat the battery internally through its internal resistance.

The primary goal of the project is thus to determine the feasibility of the AC heating method when used for Li-ion (LiFePO₄ in particular) batteries.

By investigating the following matters, an attempt is made to fulfil the project goal:

- The effect of temperature on battery performance should be evaluated so that the charging speed with and without heating system can be compared.
- The effects on battery degradation have to be evaluated because batteries should not degrade faster due to the exposure to the AC currents needed for heating, compared to charging without AC heating.
- The relation of heating speed (time) to the ac current must be determined. It is assumed that larger currents will result in more dissipation and hence faster heating.
- The total time needed for the charging process with heating should be less then the time needed for the charging process without heating, respecting the manufacturers safety limits. It should be checked if this is the case.

To limit the scope of the project, the following matters are not investigated:

- Search for the optimum frequency of the heating current.
- Search for a suitable power source to provide the necessary heating power in the right quality (frequency, voltage, current).
- Study on the cables, plugs and interconnections of the battery.

All batteries used in tests will be 18650 sample cells described in the datasheet in APPENDIX E. These cells are of the LiFePO₄ chemistry and are already being used for UFC purposes [22].
1.5 Thesis outline

In this chapter, the problem has been defined within its context. In Chapter 2, more specific information on the research topics will be presented that has been found in the course of a literature survey. The chapter will specify the state of the art in more detail and concludes with the research questions and approach.

The nature of the topic requires a lot of experimental work in order to get a better understanding of low temperature battery operation. Chapter 3 will present an analysis of the research questions. The research questions are split in relations that have one input and one output parameter. Subsequently, a number of experiments are presented that are each designed to gain knowledge on one such relation. A summarised version of the measurement results is given after each experiment description.

Chapter 4 will discuss the author’s interpretation of the experimental results that were previously presented. The chapter is divided into three main parts. In section 4.1, the influence of low temperatures on battery performance and lifetime is explained. Section 4.2 will explain the properties of AC heating and its influence on battery performance. The last part of chapter 4, section 4.3 deals with ageing effects that are possibly introduced by AC heating. In this way, both positive and negative properties of AC heating are reviewed to give the reader a balanced set of information.

The conclusions of the project will be revisited in Chapter 5. A number of additional topics related to AC battery heating that are useful to investigate but did not get attention in this project are presented in paragraph 5.2, future work.
CHAPTER 1: Introduction & problem definition
CHAPTER 2  Technical background and research approach

As a first step in understanding the internal functioning of LiFePO$_4$ batteries, a literature survey has been done. The first part of this chapter, paragraph 2.1, summarises this literature survey and provides more technical information regarding battery technology. The state of the art of AC heating is discussed in section 2.2. The last part of this chapter, section 2.3, is dedicated to the research plan.

Batteries rely on chemical processes to store and retrieve electrical energy. It is trivial to say that the reaction speed of chemical processes depends on temperature and therefore that the properties of batteries are also temperature dependent. From literature [24] but also from everyday experience is known that the effect of temperature on battery performance can be dramatic. An example of a situation where the effect of temperature on battery performance becomes noticeable is starting a car at ambient temperatures below 0°C. Due to this effect, a degraded car battery which is still able to start a car at higher temperatures might suddenly fail to start the car on an icy winter morning.

In 1951, J.B. Godshalk et. al. filed a patent “Method and apparatus for treating batteries” which was granted in 1954 [25]. The patent describes the method of heating batteries by sending AC current through the battery such that heat is generated inside the battery by effect of dissipation in its internal resistance. In the patent is explained that the properties of cold batteries can be improved by heating the battery. In this way, the internal resistance of the battery is decreased, lowering the losses and improving the useful battery capacity.

The method as described by Godshalk et. al. was tested with lead-acid batteries. Because the heat is generated inside the battery as a result of current flowing through the internal structure of the battery, of which the resistance is larger than zero, this method can be applied to all types of secondary batteries. It is however not said that the method will work adequately for all types of secondary batteries as this is determined by the battery properties and application specific needs.

A more recent attempt to use the AC heating method is done by Daimler on NiMH batteries. Daimler has filed a patent on a system using high frequency switching power electronics to generate AC currents through a battery [26]. The effect of this high frequency heating method on the battery lifetime was not discussed.

From section 1.4 one can conclude that a good understanding of the behaviour of batteries under the applicable operating conditions is essential in determining the feasibility of the AC heating method. For the modern LiFePO$_4$ battery chemistry, little test data is available on the effects of AC on the lifetime of the battery. On the effect of alternating currents on LiFePO$_4$ at temperatures below 0°C no test data has been found by the author.

More information on battery technology and battery heating will be presented in the upcoming sections 2.1 and 2.2.
2.1 Battery ageing and modelling – Literature survey

In this paragraph the current state of knowledge on battery failure modes and battery modelling is given. Different types of battery modelling will be discussed in paragraphs 2.1.1 up to 2.1.3 and paragraphs 2.1.4 up to 2.1.6 will deal with the various ageing effects present in batteries.

2.1.1 Internal battery structure

2.1.1.1 Electrode potentials

Figure 2.1 shows the general structure of a cylindrical 18650 cell. The anode, cathode and separator layers can be distinguished. More difficult to see is that the anode layers are slightly shifted towards the top-cap and the cathode layers are slightly shifted towards the bottom cap. The layer shifting facilitates the connection between the electrodes and the battery terminals.

![Cylindrical Li-ion Battery](image)

Figure 2.1 - Dissection of a cylindrical Li-ion battery [12]

Electrode potential, denoted as $E$ in electrochemistry, according to an IUPAC definition is the electromotive force of a cell built of two electrodes [27]:

- on the left-hand side is the standard hydrogen electrode, and
- on the right-hand side is the electrode of which the potential is being defined
CHAPTER 2: Technical background and research approach

Then, by convention:

$$E_{\text{Cell}} = E_{\text{Light}} - E_{\text{Ref}}$$  \hspace{1cm} (2.1)

From the above, for the cell with the standard hydrogen electrode (potential of 0 by convention), one obtains:

$$E_{\text{Cell}} = E_{\text{Light}} - 0 = E_{\text{Electrode}}$$  \hspace{1cm} (2.2)

In most electrochemical cells, hydrogen is not used as an electrode material. Therefore, both the anode and cathode potential are usually referred to a (virtual) hydrogen electrode according to the IUPAC definition. As the hydrogen reference electrode is just a definition, also other references can be chosen for convenience. Independent of the reference electrode potential, the total (open circuit) cell voltage will be the same and is defined as:

$$E_{\text{Cell}} = (E_{\text{Anode}} - E_{\text{Ref}}) - (E_{\text{Cathode}} - E_{\text{Ref}}) = E_{\text{Anode}} - E_{\text{Cathode}}$$  \hspace{1cm} (2.3)

It would be very useful if one has the ability to determine the anode and cathode potentials of a battery during charging. If this was possible, the situation where lithium plating (see also paragraph 2.1.5.2 for more on lithium plating) occurs could be detected and the charging profile adjusted so that lithium plating is avoided.

According to [28], it is possible to measure the internal potentials of a battery, but it is very cumbersome in an assembled cell. The only way to measure the internal potentials is by placing a reference electrode between the anode and cathode, which is nearly impossible in a rolled cell like 18650 cells. So, practically it is not possible to measure the internal potentials of an 18650 cell.
CHAPTER 2: Technical background and research approach

2.1.1.2 Internal resistance mechanisms

The internal resistance of a LiFePO4 battery consists of multiple components as explained in [23]. The following components may be considered:

- Metal part of electrodes
- Anode/electrolyte interface
- Cathode/electrolyte interface
- Charge transfer through electrolyte

A minor part of the resistance is determined by the internal metallic structure of the electrodes and interconnections. A slight dependence on temperature can be observed due to the PTC behaviour of metals, but this effect is not significant. A variation in resistance of the metal part as a result of ageing is also not expected because the metal parts do not change over time.

The biggest part of the internal resistance is caused by the conductivity of the electrolyte and interface layers of the electrodes [23]. The speed of chemical processes depends on temperature and this affects the internal resistance. As a result of ageing (shelf life), the chemical properties of the electrolyte change, causing a change in internal resistance. Another ageing effect is caused by charge cycling which causes a reduction of active electrode area and hence an increase in internal resistance [16].

2.1.2 Battery thermodynamics

When a battery is charged or discharged, heat can either be generated or absorbed. There are three heat generation factors of importance:

- Reaction heat, \( Q_r \)
- Polarization heat, \( Q_{pc}, Q_{pd} \)
- Joule heat, \( Q_j \)

The reaction heat is the heat generated or absorbed by the chemical energy storage process (intercalation). The polarization heat is the heat generated by the polarization process of the battery materials, a distinction is made between the polarisation heat during charging \( (Q_{pc}) \) and during discharging \( (Q_{pd}) \). The Joule heat is the heat generated in the ohmic resistance of the battery materials.

The total heat generated during charging, \( Q_c \), can be expressed as:

\[
Q_c = Q_r + Q_{pc} + Q_j
\]  

And the total heat generated during discharging, \( Q_d \), as:

\[
Q_d = Q_r + Q_{pd} + Q_j
\]

Graphically, this can be represented as in Figure 2.2 where it can be seen that the discharge process is purely exothermic. The charge process is partly endothermic.
Because the $Q_r$ and $Q_{pc}$ are linearly dependent on the battery current and $Q_c$ is quadratic, the net heat generated in the battery can be positive or negative during charging. For low charge currents, the battery cools down during charging. Beyond a certain charging current where $(Q_{pc} + Q_c) > Q_r$, the battery will heat up during charging [29].

![Figure 2.2 - Heat intake and release model of Li-ion batteries during charge and discharge process [26]](image)

In [30] is explained that the internal heating of cylindrical cells may be approximated by an adiabatic model as depicted in Figure 2.3, where $W$ is the thermal energy flow and $C_{Th}$ is the thermal capacity of the battery. Due to the layered structure of a cylindrical cell, the heat is generated evenly throughout the internal structure of the cell.

![Figure 2.3 - Simple adiabatic model of a battery](image)

Note that the amount of heat generated depends on the operating mode (charging, discharging), current ($I^2R$, quadratic relation), SOC and temperature. The adiabatic model is only a first order approximation. Figure 2.4 shows the measured battery temperature for four different discharge rates (crosses) and the predicted temperature according to the adiabatic model (straight lines). In the figure, it can be seen that an adiabatic model can be used as an approximation, but it is not very accurate.
2.1.2.1 Thermal capacity of batteries

In [30] is shown that the specific heat capacity of an 18650 cell has a value of about 1,03 J/gK. With a weight of 39 grams of the 18650 sample cell, this results in a heat capacity of about 40 J/K for the total cell.

Under adiabatic conditions, the heating of a cell requires 40 J/K. In practice more energy is needed due to heat losses to the environment. The required heating power to heat an object within a certain interval may be calculated by using equation 2.6.

\[
P = (T_{\text{end}} - T_{\text{start}}) \cdot \frac{C}{t}\]

(2.6)

Where \(T_{\text{start}}\) and \(T_{\text{end}}\) are the battery temperatures prior to and after heating respectively, \(C\) is the thermal capacity of the battery, \(t\) is the heating interval and \(P\) the heating power. For example, if one wants to heat an 18650 cell from -20°C to 0°C, 800 Joules are needed in the case of adiabatic heating. To do this in 60 seconds, a heating power of 13 Watts is required.
2.1.3 Electrical modelling

In reference [31], a battery model is proposed in which three important effects are incorporated. Figure 2.5 shows the model where the following three effects are modelled as electrical elements:

- Ohmic resistance due to the electrodes, connections and electrolyte \( (R_i) \)
- Double layer capacitance effect \( (R_{DL}, C_D) \)
- Diffusion effect \( (R_K, C_K) \)

![Figure 2.5 - Simple equivalent circuit diagram of a battery [29]](image)

In Figure 2.5, \( U_B \) and \( I_B \) are the terminal voltage and current of the battery respectively. The voltage \( U_0 \) is the open circuit voltage which is determined by the electrode potentials.

With the help of a battery tester, the values of the different elements in the model can be determined. Reference [31] shows that the time constants of the double layer capacity effect and the diffusion effect differ at least an order of magnitude, so they are not difficult to obtain from measurement data.

For a Sony US18650 cell, which has a comparable internal structure to the cell tested in this project, the model parameters have been determined of a model like the one depicted in Figure 2.5 without the diffusion effect. The time constant of the parasitic double layer capacitance was found to be 160ms while the total internal resistance \( (R_i + R_{DL}) \) was about 150 mOhm [32].

2.1.4 Operating modes with accelerated ageing

Battery powered applications are designed to have a certain life expectancy of the battery. Due to the complexity of battery lifetime calculations, this is not done for most applications where the battery costs are only a minor part of the total system costs. In the case of a battery failure, the battery is simply replaced without serious economical issues. Lead-acid car starter batteries are a good example of this practice.

For Ultra Fast Charge capable products, the battery costs are much more significant in the total system costs and hence much effort is put into creating an optimal trade-off between battery costs and battery lifetime. In this case, it has a lot of advantages to know the operating modes of batteries where accelerated ageing occurs. As shown in
Table 2.1, one can distinguish at least four modes where accelerated ageing occurs [20],[33],[34].

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Process</th>
<th>Effect(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High temperature</td>
<td>Decomposition of electrolyte and active electrode materials</td>
<td>Increased cell resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreased capacity</td>
</tr>
<tr>
<td>High cell voltage</td>
<td>Decomposition of electrolyte</td>
<td>Increased cell resistance</td>
</tr>
<tr>
<td>Very high and very low SOC</td>
<td>Loss of active electrode area</td>
<td>Increased cell resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreased capacity</td>
</tr>
<tr>
<td>Too high or too low anode potential</td>
<td>Lithium plating</td>
<td>Increased cell resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreased capacity</td>
</tr>
</tbody>
</table>

Note that the states of the first three modes are not hard to detect. Most battery management systems (BMS) can do this. The state of the last mode in Table 2.1 however is difficult to determine as was explained in paragraph 2.1.1.1. This mode is of high importance when charging at low temperature due to the elevated risk of lithium plating, also see paragraph 2.1.5.2. A conservative method to deal with the lack of information on electrode potentials is to apply a charge current derating for charging at low temperatures [35]. This method is far from optimal because the derating should follow the life condition of the battery, which is also difficult to determine. A charge current derating without knowledge of the actual internal state of the battery must be conservative because it should be valid during the entire lifetime of the battery. Such a conservative approach will most certainly result in an undesirably long charging time.

2.1.5 Effect of temperature on battery operation

2.1.5.1 High temperature operation

A lot of research has been done on the ageing of batteries [36] but a direct link between cell temperature during charging and the battery lifetime has not been found in literature. On the other hand, a link between the battery lifetime and operating temperature is reported for the case that a battery is held at its float voltage [21]. The float voltage is the recommended voltage to keep a battery in its fully charged state. The float lifetime (lifetime of the battery when it is held at its float voltage) can be modelled quite accurately by Arrhenius’ equation 2.7. According to Arrhenius’ equation the float lifetime decreases exponentially with an increase of the operating temperature. The process modelled by Arrhenius’ equation is the chemical conversion of active electrolyte materials into inactive materials. The loss of active electrolyte materials causes an increase of the cell resistance and a decrease of energy storage capacity, both effects are irreversible [37].

\[
k = C \cdot e^{\left(\frac{-E_a}{RT}\right)}
\]  

(2.7)
In equation 2.7, k is the rate of a chemical process (here: battery ageing), C is a constant, \(E_A\) is the system’s activation energy (J), R is the gas constant (8.3143 J/mol K) and \(T\) is the temperature in Kelvin.

Because battery ageing is a cumulative process, it is possible to use an accumulating damage model where the ageing speed increases at higher temperatures, as stated by Arrhenius’ equation. By using such a model, one can compare ageing effects at different temperatures and predict float life for various temperature profiles.

The temperature dependence of battery ageing is a parameter which is different for every battery chemistry and physical battery properties. The amount of temperature dependence is put into the Arrhenius equation by the Activation Energy \(E_A\) parameter. For LiFePO\(_4\), \(E_A\) is about 0.6 eV (13.8 kcal/mol) which is about the same as the \(E_A\) of valve regulated lead-acid (VRLA) batteries. The higher the \(E_A\), the stronger the temperature dependence of the battery ageing becomes. If one needs to design a battery system suitable for operation in different climate zones, batteries with a low \(E_A\) are a good choice due to their low susceptibility for changes in temperature. An example of a battery technology with a low activation energy is NiCd [21].

The exponential nature of battery ageing as a function of temperature tells us that the ageing mechanism is only significant at higher temperatures. When a battery is designed to operate at room temperature, it is safe to assume that the ageing rate according to Arrhenius’ equation is not significant at temperatures below 0°C.

2.1.5.2 Low temperature operation

From charge and discharge tests it is observed [38] that charging at a high rate at low temperatures causes increased capacity fading. This ageing mechanism differs from the one described by Arrhenius’ equation. In this case, the capacity decrease is caused by lithium plating, a process where solid lithium is deposited on the graphite anode. In normal operation of a LiFePO\(_4\) battery, lithium ions intercalate into the graphite anode during charging. In LiFePO\(_4\) batteries, intercalation of lithium ions happens when the anode potential is in the range of 0.05-0.3V versus the potential of Li\(^+\)/Li [34]. The anode potential of a battery cannot be measured at the exterior [28], therefore a battery should be operated according to the manufacturers recommendation to make sure that the anode potential will stay in the proper range. This can be done when two basic rules are applied:

- The maximum cell voltage should not exceed the manufacturers’ recommended value
- The charging current should not exceed the manufacturers’ recommended value

By following these rules, the level of lithium plating is acceptable for normal usage.

When a battery is operated at a low temperature, its performance will decrease due to the lower reaction speed of the involved chemicals. The lower reaction speed effectuates into a higher internal resistance [30]. During charging, a higher internal resistance will result in higher cell voltages. When the maximum cell voltage is fixed, charge current derating is needed at low cell temperatures to keep the cell voltage below the limit; this mode is also called constant voltage charging (CV). For subzero temperatures, this derating poses serious constraints on the Ultra Fast Charging capability of a battery.
2.1.6 Charging speed related effects

A general observation in the world of Li-ion batteries is the relation between charging speed and cycle lifetime. Two well known relations exist:

- Faster charging decreases cycle lifetime
- Using a larger part of the battery capacity decreases cycle lifetime

While these relations imply that faster charging and using a bigger part of the battery’s capacity has a negative effect on the cycle life of the battery, it only gives an indication of what to expect, these relations are not linear. Reference [34] gives more insight in the effect of charging speed on battery cycle life. While the article does not deal specifically with Ultra Fast Charging, it gives information on situations that should be avoided. Two processes are mentioned that damage the battery:

- Decomposition of electrolyte
- Lithium plating

During charging at very low State Of Charge (SOC) (< 10%) care must be taken to avoid excessive heating of cells because of the higher internal resistance at low SOC. Secondly, lithium plating must be avoided because this process reduces available capacity and battery safety because of the deposited pure lithium. The risk of lithium plating is the highest during charging when both the SOC and charging current are high. With Ultra Fast Charging, this situation is entered earlier than with regular charging due to the high charging current. Therefore, it is important to have a good charging profile during Ultra Fast Charging. A charging profile is a set of rules which set the maximum charge current and –voltage in different charge stages. A charging profile can be programmed to ensure a lower charge current at low and high SOC, reducing cell heating and lithium plating.
2.2 State of the art

This paragraph presents more information on technologies and effects regarding battery design and AC battery heating. Paragraph 2.2.1 presents the most important tradeoffs that have to be made when matching a battery to an application. Methods of AC heating will be discussed in 2.2.2. More on the effects of AC heating a battery and the modelling of these effects is presented in paragraphs 2.2.3 and 2.2.4.

2.2.1 The Power Capacity Lifetime balance

An engineer instructed to design a battery for a given application is usually given a number of constraints. Examples of such constraints are:

- Cost
- Size
- Weight

In most situations, these constraints are determined by the market (costs), geometry (size) and regulations. A good design specification also includes the following three properties of the battery:

- The power level (during charging and discharging);
- The energy storage capacity;
- The minimum battery lifetime.

Figure 2.6 visualises that these three properties are tightly linked. Changing one of the three will always effect at least one of the other two.

![Figure 2.6 - Power-Capacity-Lifetime (PCL) triangle](image)

The PCL triangle is a graphical representation of the interaction between its components. If, for a given battery, one of the properties is increased, at least one of the other properties must be decreased to keep the triangle balanced. In order to keep costs down, the engineer must be able to approach the optimum balance of the PCL triangle for a given application. In this way, the most cost effective battery is found.
To ensure that the expected lifetime is reached, it is crucial to have a set of rules to prevent excessive battery degradation. A first set of rules can be found in the battery datasheet and is known as the Safe Operating Area (SOA). The limits of the SOA should never be exceeded due to safety reasons. The set of rules that the SOA brings is not sufficient to ensure a certain lifetime. To do that, an extra set of rules is needed that define the usage of the battery. This set of rules will be called the Desired Operating Area (DOA). In Figure 2.7, the relation between SOA and DOA is graphically shown.

![Diagram showing SOA and DOA](image)

**Figure 2.7 – Visualization of SOA and DOA**

In Figure 2.7 can be seen that the circumference of the SOA is fixed but that of the DOA is not. Varying the circumference of the DOA is the same as changing the equilibrium of the PCL triangle; a larger DOA results in better performance but also reduces battery lifetime.

The three numbered circular regions in Figure 2.7 indicate the different operating areas:

1. Safe operation at normal ageing rate
2. Safe operation at increased ageing rate
3. Unsafe operation

For most applications it is difficult to ensure completely that operating area 2 is never entered. If the battery is slightly over dimensioned, such exceptions are allowed from time to time.
2.2.2 Methods of battery heating

Basically, there are only two basic options to heat a battery:

- External heating of the battery with an external heat source
- Internal heating by sending current through the battery

Current methods for operating batteries at low temperatures employ means for heating the battery from an external source, such as warm air heating, liquid heating, and thermal jackets. Each of these systems warm the battery by heating the external surface of the battery. By applying heat to the external surface, a significant amount of heat is lost to the environment. Moreover, external heating systems usually require a significant amount of space in a battery pack [26].

Reference [39] describes a heating system for electric vehicle batteries. The system comprises of a set of electric heating elements located near the vehicle batteries. The energy needed for the generation of heat is retrieved from the batteries.

Another method to heat a battery pack, but also cooling at the same time by using forced air is described by [40]. With this method, a not further specified source of heated or cooled air is needed. For hybrid electric vehicles, hot air can be obtained from the internal combustion engine. In full electric vehicles, heat can only be generated electrically. Using electrically heated air is not very efficient because a lot of heat is lost when the used air is disposed of to the environment.

With an internal battery heating system as is described in [26], a number of disadvantages of heating a battery pack with an external heat source can be circumvented. An internal heating system can save valuable space in a battery pack and is able to do its work more efficient because the heat is only generated at the place where it is needed.

A major point of concern with internal battery heating is the negative temperature coefficient of the internal cell resistance. When cells are placed in a parallel configuration, the cell with the lowest internal resistance will carry the highest current and hence heat up the quickest. This is a known problem in battery pack design and should be considered carefully when designing internal cell heating systems. A good thermal coupling between adjacent cells can help to reduce temperature differences in battery packs.

Heating a battery externally has other thermal properties than internal battery heating. The difference between those two methods is graphically shown in Figure 2.8 and Figure 2.9. In the case of external heating, thermal energy is applied at the exterior of the battery (J) and will gradually find its way to the most inner layers of the battery structure depicted by thermal capacities of the layers ($C_{th}$) and the thermal resistance between the layers ($R_{th}$). Due to the temperature gradient inside the battery, not all layers have identical performance and ageing rates.
2.2.3 Effects of AC heating on battery lifetime

Heating of batteries before charging can be used to give the battery better properties during the charging process. When the short term effects are considered, the health state of the battery can be regarded as constant. During heating with AC, no charging takes place, so the SOC is also constant. With these two states being constant, the battery can be modelled as an electric circuit as depicted in Figure 2.5 having temperature dependent component values. When both the electrical and thermal behaviour are known, the two can be placed in closed loop in such a way that the electrical circuit parameters are updated when the temperature changes. In this way, heating cycles can be simulated. Because the component values of the model in Figure 2.5 are not hard to determine, it should be possible to measure them automatically. This enables a possible heating power supply to adjust its output to the battery parameters in order to provide optimum heating for a wide range of batteries.
CHAPTER 2: Technical background and research approach

The usefulness of the AC heating method does not solely depend on the short term performance. When designing applications using AC heating, insight is needed into the long term effects on the batteries as well. Insight is gained by performing tests to acquire data on the property changes during battery lifetime. This is necessary because the method must work with both new and aged batteries.

When AC currents are used for battery heating, frequencies of 1Hz and above are generally used to avoid the influence of chemical processes which have much larger time constants, as discussed in paragraph 2.1.3. This means that the effective DOD is much less than 0.5% and the question should be asked if the extrapolation of the results of measurements at 0.5% DOD yield valid results.

Available research material on the effects of AC currents on batteries is limited. The most applicable material that has been found by the author deals with the effects of cycling with reduced DOD down to 0.5% DOD. A relation is discussed between DOD and charge/discharge cycles in reference [41]. Under typical AC-heating conditions, even smaller DOD values are used. If, for example, a frequency of 1 Hz is used and the measurement results of reference [41] are linearly extrapolated for this frequency, an estimated lifetime is obtained of >100 years continuous duty. Because such a lifetime implies that AC heating is not harmful for Li-ion batteries, the validity of this hypothesis should definitely be checked by measurements.

2.2.4 Choice of heating current frequency

Other than the relation mentioned in paragraph 2.2.3, little is known on the long term effects of the used frequency. Due to limits of practicality, not all frequencies are suitable for a technical implementation of an AC heating system. One could use the power line frequency and use passive circuits like transformers for the heating system. Another system could use power electronics and use frequencies in the kHz range. In order to save time, one could limit the search for a good heating frequency range to the range that can be implemented in a practical manner. When the AC-heating method proves to be effective and feasible, it would be useful to search for the least damaging operating conditions. This search does not lie within the scope of the project.
CHAPTER 2:  Technical background and research approach

2.3 Research approach

This section of the document will define the objectives of this thesis project. First a short description of terms used in the research plan is given in paragraph 2.3.1. Then, a few topics are explained to provide the right context for the research goal in 2.3.2. Paragraph 2.3.3 contains the research questions and the research approach will be given in paragraph 2.3.4.

2.3.1 Definitions

This paragraph contains a short listing of terms used further on in this chapter. The terms are explained shortly to give a better understanding of the research objectives.

2.3.1.1 Battery pack

A structure built out of multiple elements (cells) connected in such a way that the potential of each element can be used to its full extent but manifests itself as a single element to the outside world.

2.3.1.2 Lithium Iron Phosphate (LiFePO₄)

State of the art cathode material used for rechargeable batteries. Usually used in combination with carbon anode material. Lithium Iron Phosphate batteries usually have high energy density and high power density and have good safety properties.

2.3.1.3 Internal resistance

Internal resistance is a concept used to model the change in the terminal voltage of a battery that occurs when terminal current is absorbed or delivered by the battery.

2.3.1.4 Charging time

In order to make a fair comparison of the effects of different charging methods, the environmental parameters must be equal for all methods. When charging methods without and including heating are compared, it is fair to define the charging time as the time needed for heating plus the time needed for electrically charging the battery.

2.3.1.5 Ultra Fast Charging (UFC)

In paragraph 1.3, Ultra Fast Charging is defined as charging a battery in 5 to 60 minutes. A typical value is 15 minutes since this is the most common period for coffee breaks.

2.3.1.6 UFC threshold temperature

Temperature below which UFC performance drops below 80% of its nominal value at room temperature.
2.3.1.7 AC heating

The method of heating a battery by generating heat in the battery’s internal structure as a result of alternating current flowing through the battery.

2.3.1.8 Energy efficiency

In the context of AC heating, energy efficiency is the ratio between energy the total amount of energy required by the power electronics that generate the AC heating current to the energy that is converted to heat inside the battery.

2.3.1.9 Battery lifetime

The period in which a battery is able to perform its duty under normal operating conditions.

2.3.1.10 Ageing mechanism

Irreversible process that decrease the battery lifetime.

2.3.1.11 Ageing damage

Result of irreversible processes that decrease the battery lifetime.

2.3.1.12 State of Charge (SOC)

Single parameter representation of the internal energy level of a battery. SOC has usually a value between 0% and 100%, indicating the ‘battery empty’ level and the ‘battery full’ level respectively.

2.3.1.13 State Of Life (SOL)

The SOL is a single parameter representation which reflects the remaining useful battery life. A new battery has by definition a SOL of unity value. If at a certain moment, the battery becomes degraded in a way that it cannot fulfil its intended function anymore, the useful battery life has ended and the SOL has become zero.

2.3.1.14 Total Cost of Ownership (TCO)

A financial estimate of the direct and indirect costs of a product or system.
2.3.2 Boundary conditions

This paragraph has been added to define the scope of the project. Due to the high complexity of the internal processes of batteries, the scope of this project will be limited when compared to the large amount of knowledge on batteries. The information given in this paragraph should be seen as a frame of reference to assist the reader in getting a clearer view of the research objectives. A few project related topics are briefly discussed to achieve this.

2.3.2.1 Choice of heating frequency

The behaviour and implementation of an AC heating system will depend on the frequency range in which the system is operating. The operating frequency could be a function of battery age, temperature and SOC. The optimum operating frequency could be defined as the frequency where the fastest heating is possible at acceptable lifetime decrease.

The determination of the optimum heating frequency will not be a part of this project. Instead, a likely candidate will be chosen according to a few assumptions made on basic measurements, available technology and good engineering practice. A few guidelines to be followed are:

- High impedance at heating frequency
- Low losses in power converter
- Low audible noise
- Small component size

Due to confidentiality reasons, the establishment of the frequency used in the experiments has been laid out in APPENDIX C.

2.3.2.2 Battery interconnections

The design of an AC heating system is not limited to just adding a power supply for the heating current. All components where the heating current flows have to be able to handle this current level. High power Li-ion batteries are optimised to have a high power density and hence have low losses during normal operation. A safe assumption would be that the currents needed for heating are larger than in normal operation. The battery interconnections need to be able to handle the current level needed for heating. If the heating power supply is located off-board, all charge cabling and connectors should be designed for the heating current level as well.

2.3.2.3 Degradation of battery performance

The ageing of batteries is an important issue in total cost of ownership calculations. A heating system could provide faster charging in low temperature environments, but this has little value if the lifetime of the battery is not preserved. One of the aspects looked upon in this thesis project is therefore to assess the potential of the AC heating technique with respect to the lifetime of the battery.
2.3.2.4 Fixed charging time

For Ultra Fast Charging applications, the total time needed to complete the charging cycle is fixed. Unlike for most slow charging applications, the charging time of Ultra Fast Charging systems is a tight constraint in the product specification. UFC systems are sold mainly in a business-to-business fashion. Customers are interested in UFC systems because they are able to reduce the total cost of ownership (TCO) of battery powered systems. In order to realise such a reduction of TCO, Ultra Fast Charging systems are tightly fit into the customer’s business process. If one customer works with coffee breaks of 15 minutes, a charging time of 15 minutes is a good match. When an installed UFC system requires more time to charge than specified, it could happen that personnel is waiting for the charge cycle to complete, which increases the TCO.

Due to the high investment costs involved with UFC systems, customers demand control over the TCO. A fixed charge time gives an extra level of control and simplifies the calculation of the TCO. In order to make a good comparison between the two charging methods, the total time of the charging process will be kept constant in the experiments. This automatically implies that in case of charging with AC heating, less time is available for charging and a higher charge current is needed to obtain the same amount of transferred energy as with charging without heating.

2.3.2.5 Power supply technologies

Different technologies for generating AC currents for heating purposes have been described in literature. The most attractive technology available at the moment of writing would be a power electronic converter because of its high power density. The selection of the power supply will not be a part of this thesis project because there are already some solutions present and currently, the largest knowledge gap lies at the ageing processes.
2.3.3 Research questions

The project aims to get more insight into the technical and economical feasibility of the AC heating method used to increase battery performance at low temperatures. As has been showed in previous paragraphs, there are many questions to be answered to get a good understanding of the subject. Because the scope of the complete subject is too large for a thesis project, the focus will lie on two research questions. The goal of the project will be to provide an answer to these research questions, being:

<table>
<thead>
<tr>
<th>RQ1:</th>
<th>Will an AC heating system be able to increase the battery performance and lifetime of Ultra Fast Charging LiFePO₄ battery systems used in cold environments?</th>
</tr>
</thead>
</table>

**Hypothesis:** If LiFePO₄ batteries are heated with AC before initiating Ultra Fast Charging, then the battery will have better UFC performance and a longer lifetime.

<table>
<thead>
<tr>
<th>RQ2:</th>
<th>How is the lifetime of LiFePO₄ batteries influenced by Ultra Fast Charging at sub-nominal temperatures?</th>
</tr>
</thead>
</table>

**Hypothesis:** Ageing speed depends on many factors, among which the battery voltage during charging. Temperature has an effect on the batteries' internal resistance which in turn influences the voltage during charging. It is expected that a relation exists between battery voltage and current during charging and the battery lifetime.

It is the author's point of view that these research questions cover the most important topics to be investigated regarding the current state of knowledge on AC heating for UFC battery systems. Additionally there are other research questions to be answered to get a good understanding of all aspects of AC heated battery systems. A few examples of such questions are listed below. Due to the limited time available for this project, the research and analysis on these topics is regarded as future work. A few examples of topics for future work are:

- What will be the size of the hardware needed for the integration of an AC heating system into a battery pack?
- What level of energy efficiency can be reached for different implementations?
- Which frequency is the most attractive to use when hardware costs are considered?
- Which frequency is the most attractive to use when hardware size is considered?

Any new information resulting from the research on the main topic which could be valuable in answering these questions will be given in the next chapter. This could form a basis for further work on the topic.
2.3.4 Project approach

Two possible approaches to obtain a model of a battery which is able to reflect the consequences of Ultra Fast Charging and AC heating are given here:

1. Theoretical approach

Develop a model which is able to show the ageing effects on batteries as a result of AC heating and Ultra Fast Charging. The model must be constructed by using current literature and information from battery manufacturers. With help of some experiments, the model is verified.

2. Experimental approach

By use of the results of a number of carefully selected experiments, a model is built which is able to show the ageing effects on batteries as a result of AC heating and Ultra Fast Charging. The accuracy of the model has to be verified by using one or more tests other than the test used for modelling.

Choice for experimental approach

In paragraph 2.2.2 has been explained that the modelling of ageing effects of batteries is difficult due to the high complexity of battery chemistry and the inaccessibility of the internal battery structure. The limited amount of available research material on the particular subject of battery ageing combined with low temperatures and AC heating complicates the method of theory based modelling. The research approach of theory based modelling is therefore not suitable for application in this master thesis project.

To find an answer to the research question, an experimental approach is chosen. A number of experiments will be done to gain knowledge on the behaviour of LiFePO4 batteries under AC heating conditions. With help of the experimental data and the available literature, the author will attempt to construct a model which can represent the ageing processes caused by AC heating. The final goal will be to find an answer to the research questions in paragraph 2.3.3.

The path leading to the project goals is schematically depicted in the flowchart in Figure 2.10. After start, the temperature dependency of UFC performance will be determined in experiment E1. The obtained information is used to define the temperature below which the UFC performance becomes unacceptable. This temperature is used as a base for subsequent tests. Experiments E2, E5 and E6 are used to check the influence of various ageing mechanisms on UFC performance. Other performance figures are obtained by experiments E3 and E4. The last experiment, E7, is planned to find an answer to RQ2.

To simplify the experiments and to achieve more accurate results, as much parameters as possible will be held constant during the experiments. An attempt is made to separate the ageing effects caused by Ultra Fast Charging and the ageing effects caused by AC heating.
CHAPTER 2: Technical background and research approach

Figure 2.10 – Experiment flowchart
CHAPTER 2: Technical background and research approach

The flowchart displayed in Figure 2.10 consists of various steps needed to reach the objectives laid out in paragraph 2.3.3. Seven experiments are shown in Figure 2.10:

E1 Determine the UFC performance as a function of temperature for a new cell.

E2 Measure the battery degradation as a result of Ultra Fast Charging at the UFC threshold temperature.

E3 Determine the heating speed as a function of the current magnitude.

E4 Same as E1, but for an aged cell (aged by E2).

E5 Measure the battery degradation as a result of AC heating current exposure. Two tests are done, one at -20°C and one at the UFC threshold temperature defined in E1.

E6 Measure the battery degradation as a result of temperature cycling. The temperature is cycled between -20°C and the UFC threshold temperature.

E7 Determine the relation between temperature and battery degradation, with a focus on low temperature Ultra Fast Charging.

In addition to these experiments, other steps are required to answer the research question. The choice of the frequency of the heating current for example will not be based on measurements in this project due to the large amount of time involved. Instead, a frequency is chosen out of other constraints as being a ‘best guess’. Further research is needed to find an optimum frequency. A complete description of all experiments, test setups and constraints, as well as experimental results is given in the next chapter.
CHAPTER 2: Technical background and research approach
CHAPTER 3  Experimental investigation of the effects of low temperatures and AC heating on Li-ion batteries

In this part of the thesis report, the experimental work is elaborated on. First the research questions are analysed. The result of this analysis is a set of relations which will be investigated by a set of experiments. This experimental approach and analysis can be found in paragraph 3.1. A description of all experiments and their respective results are covered in paragraph 3.2. The experimental setups and equipment used for the experiments is covered in APPENDIX B.

3.1 Experimental approach

3.1.1 Analysis of the main research questions

Although the experimental work has been split up in several distinct experiments, the work should be seen as one unit. The goal of this unit of experimental work is to obtain information that leads to answering the research questions that have been defined in paragraph 2.3.3:

RQ1. Will an AC heating system be able to increase the battery performance and lifetime of Ultra Fast Charging LiFePO₄ battery systems used in cold environments?

RQ2. How is the lifetime of LiFePO₄ batteries influenced by Ultra Fast Charging at sub-nominal temperatures?

Upon analysing these questions, one can find various dependencies between parameters hidden inside these research questions. Therefore, designing a single experiment to find answers to this questions is rather complex. A more structured approach would be to find the dependencies of interest and design experiment(s) to test each dependency separately.

In RQ1, the following parameters can be found:

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Parameter type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Chemistry Type</td>
<td>Input</td>
</tr>
<tr>
<td>Operating mode (Charging, Discharging)</td>
<td>Input</td>
</tr>
<tr>
<td>Operating current</td>
<td>Input</td>
</tr>
<tr>
<td>Temperature</td>
<td>Input</td>
</tr>
<tr>
<td>Heating system used (Yes, No)</td>
<td>Input</td>
</tr>
<tr>
<td>Charging time</td>
<td>Input</td>
</tr>
<tr>
<td>Charging performance</td>
<td>Output</td>
</tr>
<tr>
<td>Cycle life</td>
<td>Output</td>
</tr>
</tbody>
</table>

Logically, with the above list of 6 input and 2 output parameters, 6x2=12 relations can be found, each one relating one input to one output parameter. Characterizing all
CHAPTER 3: Experimental investigation of the effects of low temperatures and AC heating on Li-ion batteries

these relations would take too much time for this project and is also not necessary to answer the questions. Some input parameters may be fixed, such as the battery chemistry type which is LiFePO₄ throughout the project. Also the operating mode of the battery is fixed; only the effects of charging are investigated.

In order to limit the number of relations to be investigated even more, the operating current parameter is combined with the heating system parameter. This is fair because in the case of heating assisted charging, some time is lost for the heating of the cell. To compensate for this lost time, the operating current is increased in such a way that a charging time of 15 minutes is obtained.

With only 2 input- and 2 output parameters left, 4 relations remain to be investigated:

<table>
<thead>
<tr>
<th>Input parameter:</th>
<th>Output parameter:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating system used (Yes, No)</td>
<td>Charging performance</td>
</tr>
<tr>
<td>Heating system used (Yes, No)</td>
<td>Cycle life</td>
</tr>
<tr>
<td>Temperature</td>
<td>Charging performance</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cycle life</td>
</tr>
</tbody>
</table>

As the main goal of RQ1 is to investigate the influence of using an AC battery heating system, the first two relations are the most important. The third and last relation are investigated to judge the usefulness of battery heaters.

A total of seven experiments have been defined to obtain test data that should give more insight into the relations defined in Table 3.2. The experiments are numbered
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chronologically and a detailed description of all experiments will be given in the next paragraph. The targets of the experimental part of the project are shown in Figure 3.1, these can be seen as sub-goals of the project. When these sub-goals are completed it should be possible to reach the main project goal, answering RQ1.

In RQ2, the following parameters can be found:

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Parameter type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Chemistry Type</td>
<td>Input</td>
</tr>
<tr>
<td>Operating mode (Charging, Discharging)</td>
<td>Input</td>
</tr>
<tr>
<td>Operating current</td>
<td>Input</td>
</tr>
<tr>
<td>Temperature</td>
<td>Input</td>
</tr>
<tr>
<td>Charging time</td>
<td>Input</td>
</tr>
<tr>
<td>Cycle life</td>
<td>Output</td>
</tr>
</tbody>
</table>

With 1 output and 5 input parameters, 5 relations can be distinguished in Table 3.3. The most important relation for answering RQ2 is the relation between temperature and cycle life. In order to focus the research work to this relation, all input variables except the cell temperature will be fixed.

With help of multiple ageing tests at fixed temperatures in the sub-nominal range (between 0°C and +30°C), an attempt is made to define the influence of temperature on the ageing of LiFePO4 batteries under UFC conditions. These ageing tests are identical to Experiment E2, except for the temperature at which they are performed. The tests at temperatures other than in experiment E2 are listed as experiment E7.

3.1.2 General experiment properties

For all experiments, batteries will be used that are of the same type and manufacturing batch. In this paragraph, the most important properties of these batteries will be given and the typical charge/discharge profile for UFC use is explained.

The manufacturers' recommended charging parameters can be found in the product data sheet. The parameters relevant for this project are given in Table 3.4.

<table>
<thead>
<tr>
<th>Nominal capacity</th>
<th>1,1 Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. recommended charge current</td>
<td>5A</td>
</tr>
<tr>
<td>Discharge cut-off voltage</td>
<td>2,0V</td>
</tr>
<tr>
<td>Charge cut-off voltage</td>
<td>3,6V</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-30°C to +60°C</td>
</tr>
</tbody>
</table>

It has already been explained in paragraph 2.3.2.4 that in the case of AC heating assisted charging, the actual time available for charging is slightly less than in the case of non AC heating assisted charging. For compensation of the lost time due to heating, the maximum current has to be higher in the case of AC heating assisted charging in order to get the same amount of charge transferred in 15 minutes. In order to have some headroom for this compensation, the maximum charge current is chosen slightly lower than the maximum charge current defined in the data sheet.

A maximum charge current of 4,4A is used for all experiments.
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This allows for an increase in the charge current to 5.0A when a good battery lifetime comparison has to be made between the AC-assisted and non-AC-assisted charging at an equal charging time of 15 minutes.

3.1.3 State Of Life

In the different experiments, cells are put under different kinds of stress which will result in a degradation of performance of the cell. To be able to compare the degradation effects as a result of different kinds of stress such as charge cycling, temperature cycling and exposure to alternating currents, one should be able to measure the state of life (SOL) of the battery. The SOL is a single parameter representation which reflects the remaining useful battery life. A new battery has by definition a SOL of unity value. If at a certain moment, the battery becomes degraded in a way that it cannot fulfill its intended function anymore, the useful battery life has ended and the SOL has become zero.

The only applications which lie within the scope of this project are those with the ability to charge ultra fast. In typical UFC applications, the charging time is (much) shorter than the discharging time of its battery. As the battery in such an application is degrading as a result of normal usage, the effects of this degradation will be felt primarily in the UFC performance: the application needs more time to acquire sufficient energy. Hence it would be logical to use a measure for the UFC performance of a battery as a basis for calculating the SOL.

3.1.4 Calculating the State Of Life

The first step in the calculation of the SOL of a battery is the determination of the new system performance (100% SOL) and the performance level at which the battery should be replaced (0% SOL). The parameter on which this decision is based may vary depending on the application. For UFC systems with fixed charging intervals, it is practical to base the SOL calculation on the amount of charge that can be transferred to the battery during the charging interval while respecting the limits of safe operation.

The determination of the SOL should be done at operating conditions where the lowest performance is expected. This makes sure that if acceptable performance is measured at this point, the performance will be acceptable for all other allowable operating conditions as well.

**Determination of 100% SOL:**
- Find the operating conditions with lowest UFC performance.
- Measure the performance at these operating conditions for a new battery (system).
- Define measured performance level as 100% SOL.

**Determination of 0% SOL:**
- Based on the system specifications, determine the minimum performance level as a portion of the 100% SOL performance.
- The minimum accepted performance level is defined as 0% SOL.
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Determination of the SOL of an active system:
- Measure the UFC performance at the same operating conditions at which the 100% SOL measurement was done.
- The SOL of the system can be calculated by:

$$SOL(t) = \frac{Performance(t) - Performance_{New}}{Performance_{New} - Performance_{Reject}} \cdot 100\% \quad (3.1)$$

In the above SOL calculation, it is assumed that the operating conditions with the lowest UFC performance are known. In the design process of an UFC battery system, the lowest temperature at which the system must be UFC capable has effect on the amount of over dimensioning of the battery. Obviously, over-dimensioning increases the total system costs as well. The use of an AC heating system raises the lowest UFC battery temperature, while it reduces battery over-dimensioning.

3.1.5 Definition and measurement of UFC performance

Because Ultra Fast Charging is all about performance, it should be clear how this performance is defined. The term Ultra Fast Charging already reveals the essence of the performance indicator: it consists of a measure for ‘Fastness’ (time) and a measure for ‘Charge’ (electric charge). Paragraph (2.3.1) gives a typical value of 15 minutes for the duration of an UFC charge cycle, so the performance indicator for Ultra Fast Charging can be defined as follows:

| UFC performance | The amount of electric charge which can be transferred to a battery in a fixed interval without exceeding the safe operating area of the battery. |

Note that the UFC performance is a snapshot of the performance of a specific battery and that the measured value depends on the state of the battery (temperature, SOL etc.) at the time the snapshot is made. Hence care must be taken when measurements of UFC performance are being compared.

To determine the UFC performance of a cell, a cycle profile has been made which is repeated at various temperatures. The cycle profile used in this experiment is defined as showed in Table 3.5 and graphically as in Figure 3.2.

| Table 3.5 – Description of cycle profile used for the determination of the UFC performance |
| Phase 1 | Constant current discharging down to 2.0 V @ 50 mA |
| Phase 2 | Constant current charging at 4.4 A, stop if voltage reaches 3.6 V |
| Phase 3 | Constant voltage charging at 3.6 V, stop if current drops below 50 mA |
| Phase 4 | Constant current discharging down to 2.0 V @ 275 mA |
UFC performance is defined as the amount of transferred charge after the first 15 minutes of charging. Determination of the transferred charge out of measurement data is straightforward. In Figure 3.2 can be seen that this is only a matter of integrating the current during the first 15 minutes of the charge process, displayed as regions 2 (CC part) and 3 (CV part). Charge counting is the most common way to determine the state of charge of a Li-ion battery. Using the transferred energy would be less suitable due to the temperature dependency of the terminal voltage, which is needed to calculate the transferred energy.
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3.2 Experiments and results

3.2.1 Experiment 1: Influence of temperature on UFC performance

For the design of an UFC capable battery system, it is important to know the relation between charging performance and temperature. When a performance guarantee must be given for the charging speed of a given application at temperatures much lower than room temperature, battery over-dimensioning might be needed. For economical reasons, over dimensioning should be minimised.

This experiment has been set up to find the charging performance versus temperature of an unused test cell. The results of this experiment can be used for three different purposes, being:

1. To show the relevance of battery heating by presenting the impact of temperature on charging performance in a simple way.
2. To find the lowest temperature at which the UFC performance is still acceptable.
3. To be able to minimise battery over-dimensioning

3.2.1.1 Description of experiment

Test description: Measurement of UFC performance vs. temperature

Deliverables: Graph of the UFC performance as a function of temperature.

Description of test setup: A single, new, 18650 cell will be placed into a temperature controlled environment. The battery charge- and discharge current is provided by a battery tester.

At every temperature, the cell is cycled with the cycle pattern described in section 3.1.5.

The UFC performance will be calculated for every temperature by analysing the test-data.

Test conditions: Fixed temperature -20°C .. +25°C / 5°C steps
Max. charge current: 4,4A
Charge cut-off voltage: 3,6V
Discharge current: 550mA
Discharge cut-off voltage: 2,0V

Duration of the test: 10 cycles at ~2 Cycles per day (manual temperature change after each cycle is required) = 5 days

Equipment needed: Temperature regulated environment
New 18650 sample cell
Battery cycle tester
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3.2.1.2 Experimental results

The experiment has been set up to find the charging performance versus temperature of an unused test cell. This test cell has been cycled at temperatures ranging from -20°C to +25°C with 5°C increments. Figure 3.3 shows the transferred charge after 15 minutes of charging for every measurement. The curve has been normalised with the +25°C measurement as this is the nominal operating temperature of the cell.

![Graph showing transferred charge vs temperature](image)

Figure 3.3 - UFC performance as a function of temperature

A widely accepted rule of thumb for useful battery life is defined as the moment where less than 80% of the original battery capacity is remaining, also see paragraph 1.2.1. Because capacity and performance are closely related, an equivalent rule exists for the battery performance. When battery performance drops to less than 80% of the initial performance, the performance is said to be unacceptable. Note that both capacity and performance needs to be determined for each distinct application.

For the tested cell in this experiment, 5°C turned out to be the critical temperature below which the UFC performance becomes unacceptable. In order to be on the safe side when cells are used that have a different state of life, or have a slightly lower performance due to other reasons like a manufacturing defect, the minimum temperature at which UFC is performed is chosen to be 10°C. Batteries operating at lower environmental temperatures should be heated until a temperature of 10°C has been reached. At this temperature, the UFC performance is considered as adequate.
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3.2.2 Experiment 2: UFC cycle life at 10°C

The results of experiment 1 showed that the tested cell has an adequate UFC performance down to 10°C. In this experiment, the cycle life of an 18650 sample cell will be evaluated when cycled with a typical UFC pattern at a temperature of 10°C. The result of this test will be a curve showing the usable battery capacity as the number of cycles progresses. In a later stage, this curve can be compared with curves obtained with charge cycling under other conditions.

3.2.2.1 Description of experiment

Test description: Measurement of UFC performance vs. number of charge/discharge cycles.

Deliverables: UFC performance curve as a function of the number of charge/discharge cycles.

Description of test setup: A single, new, 18650 sample cell will be placed into a temperature controlled environment. The battery charge- and discharge current is provided by a battery tester. Every cycle, the UFC performance is determined according to the method described in section 3.1.5.

Test conditions: Constant temperature 10°C
Charge current: 4,4A
Charge cut-off voltage: 3,6V
Discharge current: 550mA
Discharge cut-off voltage: 2,0V

Duration of the test: One cycle (as in Figure 3.2) takes about 110 minutes to complete under the conditions above. According to company proprietary test data, the battery is expected to have a lifetime of somewhere between 1000 and 3000 cycles under these conditions. It is assumed that 500 cycles should therefore be enough to observe the ageing trend. The total duration is then calculated as:
500 cycles * 110 minutes = 55000 minutes = 38 days non stop

Equipment needed: Temperature regulated environment
New 18650 sample cell
Battery cycle tester
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3.2.2.2 Experimental results

Experiment 2 was done to determine the UFC performance of an 18650 sample cell at lowered environmental temperature (+10°C) during its lifetime. The obtained results thereof will be used as a reference; the performance decrease due to other effects will be compared with the results measured in this experiment.

![Graph: Normalized UFC capacity versus # cycles](image)

**Figure 3.4 - UFC performance as a function of charge/discharge cycles**

Figure 3.4 displays the measured capacity during the ageing process. The cell has been aged with UFC cycles of 4C/15 minutes charging and 0.5C discharging. In this way, the charging process will be the main contributor to the total performance degradation. This is important because the influence of the discharging process does not lie within the project scope.

During the ageing of the tested cell, measurements of the UFC performance were done every 50 cycles. In Figure 3.4, the capacity measurements are shown and a linear approximation is made using the least square method. Due to the limited time available for testing, not more than 500 cycles could be evaluated. The test data clearly shows a decreasing trend for the UFC performance as a function of the number of cycles. By extrapolation of the current dataset, it can be assumed with reasonable certainty that the UFC performance will most likely fall below 80% of its initial value after about 2000 cycles.
3.2.3 Experiment 3: AC heating speed test

The properties of AC heating assisted charging are compared to regular (UFC) charging. When a new application is planned to be equipped with an AC heating system, it is important to know how much current is required to heat a battery within a particular timeframe. In this experiment, a cell is heated over a temperature range with a constant current. The amount of dissipation is calculated with help of a thermal model of the test setup and the measured temperature of the cell during heating. By using the assumption that the internal resistance of the cell behaves Ohmic, the required current for a range of heating speeds is then calculated.

3.2.3.1 Description of experiment

Test description: Measurement of the power dissipation in a cell resulting from AC current at various temperatures.

Deliverables: Graph of heating speed vs. temperature

Description of test setup: A single, new 18650 sample cell is brought to a temperature of -20°C and is equipped with thermal isolation to reduce thermal contact with the environment. The cell is then heated by the application of a constant AC current and the cell temperature is measured.

Test conditions: Environmental temperature -20°C
Temperature window: -20°C .. +20°C
Heating current: 17,5 A RMS
State Of Charge ~20%

Duration of the test: One day

Equipment needed: Temperature regulated environment
New 18650 sample cell
AC generator circuit
AC Decoupling inductor
DC power supply for charging the battery
Power supply
3.2.3.2 Experimental results

During the experiment, the cell temperature has been measured every 10 seconds. These measurements are shown Figure 3.5. The exponential pattern of the measurements suggests that the test setup behaves like a first order system. In paragraph 4.2, a more detailed interpretation of the measured data can be found.
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3.2.4 Experiment 4: Influence of temperature on UFC performance for an aged cell

This is basically the same experiment as Experiment 1, carried out with an aged cell instead of a new cell. The results of the measurements will be compared to that of Experiment 1 to determine the influence of SOL on the UFC performance. To speed up the experiment, less measurements will be done. Because the trend of the behaviour is known from Experiment 1, only the most important points can be measured to obtain an adequate comparison between the data.

3.2.4.1 Description of experiment

Test description: Measurement of UFC performance vs. temperature

Deliverables: Graph of the UFC performance as a function of temperature.

Description of test setup: A single, aged, 18650 sample cell will be placed into a temperature controlled environment. The battery charge- and discharge current is provided by a battery tester. At every temperature, the cell is cycled with the cycle pattern described in section 3.1.5. The UFC performance will be calculated for every temperature by analyzing the test-data.

Test conditions: Fixed temperature -20°C, -5°C, +10°C, +25°C
Max. charge current: 4.4A
Charge cut-off voltage: 3.6V
Discharge current: 550mA
Discharge cut-off voltage: 2.0V

Duration of the test: 4 cycles at 2 Cycles / day (manual temperature change) = 2 days

Equipment needed: Temperature regulated environment
Aged 18650 sample cell
Battery cycle tester

3.2.4.2 Experimental results

Due to a planning conflict, no testing hardware was available to carry out this test. Results from experiment 7 can be used instead, but these are less accurate and available at fewer temperatures.
3.2.5 Experiment 5: AC Current degradation test

With this experiment an attempt is made to measure the influence of AC currents on the SOL of a battery. To make sure that only the effects of the AC current are measured, the tested cells are kept at a constant temperature to avoid temperature cycling. The effects of temperature cycling will be measured in Experiment 6.

3.2.5.1 Description of experiment

Purpose of the test: Try to find a direct relation between high AC currents and battery degradation.

Test conditions:
- Constant temperature: -20°C, 10°C
- Constant current: 17.5A RMS
- Constant frequency: (confidential)
- Constant SOC: ~20%

Duration of the test: The number of charge cycles of UFC applications during the entire battery lifetime varies, but is usually a few thousand. For this test, 5000 cycles is chosen, representing 5 years of operation at 3 cycles a day. The heating time is estimated at 2 minutes, which is applicable for environmental temperatures around 0°C.

5000 cycles * 2 minutes heating * 2 temperatures
= 20000 minutes
= 14 days

Description of test setup: A single, new, 18650 sample cell will be placed into a temperature controlled environment. Because of the high dissipation of the cell, it has to be actively cooled. The heating current will be provided by a power electronic circuit as described in APPENDIX B.

Before and after the AC current exposure, the cells are cycled with the cycle pattern described in section 3.1.5. The UFC performance will be calculated by analyzing these measurements.

Equipment needed:
- Freezer
- Two new 18650 sample cells
- Temperature regulated environment for 1 cell
- AC source
- DC power supply for charging the battery
- Volt meter
- Oscilloscope with current probe
- Battery tester capacity for capacity measurement
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3.2.5.2 Experimental results

For each cell, a number of capacity measurements were done before and after the exposure to seven days continuous AC current. The capacity measurements were repeated a few times to eliminate possible noise. Measurement results for the cell exposed to AC current at +10°C are displayed in Table 3.6 and Table 3.7. For the other cell that has been exposed to AC current at -20°C, the results are displayed in Table 3.8 and Table 3.9.

Results of +10°C AC exposure test:

Table 3.6 - Measurement of UFC performance prior to AC exposure (new cell)

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>989</td>
</tr>
<tr>
<td>2</td>
<td>990</td>
</tr>
<tr>
<td>3</td>
<td>990</td>
</tr>
<tr>
<td>4</td>
<td>991</td>
</tr>
</tbody>
</table>

Table 3.7 - Measurement of UFC performance after 1 week AC exposure at +10°C

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>975</td>
</tr>
<tr>
<td>2</td>
<td>970</td>
</tr>
<tr>
<td>3</td>
<td>972</td>
</tr>
<tr>
<td>4</td>
<td>978</td>
</tr>
</tbody>
</table>

Results of -20°C AC exposure test:

Table 3.8 - Measurement of UFC performance prior to AC exposure (new cell)

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>974</td>
</tr>
<tr>
<td>2</td>
<td>972</td>
</tr>
<tr>
<td>3</td>
<td>974</td>
</tr>
<tr>
<td>4</td>
<td>974</td>
</tr>
</tbody>
</table>

Table 3.9 - Measurement of UFC performance after 1 week AC exposure at -20°C

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>985</td>
</tr>
<tr>
<td>2</td>
<td>987</td>
</tr>
<tr>
<td>3</td>
<td>986</td>
</tr>
<tr>
<td>4</td>
<td>986</td>
</tr>
</tbody>
</table>

Note that the cell that has been exposed to AC current at -20°C showed a minor increase in measured capacity after exposure. This seems not realistic and is therefore considered as a measurement error. More on this topic and the interpretation of the results is discussed in section 4.3.2.
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3.2.6 Experiment 6: Thermal cycling test

The thermal cycling test is used to investigate the influence of thermal cycling as a result of pre-heating on the SOL of the battery. A new cell will be exposed to 2500 thermal cycles after which the influence on the SOL will be determined.

3.2.6.1 Description of experiment

Purpose of the test: Try to find a relation between thermal cycling and SOL.

Test conditions: Variable temperature -20°C .. +10°C
                Constant SOC ~20%

Duration of the test: 20 minutes (3 min. heating, 17 min. cooling) per cycle
                      2500 cycles = 1 month

Description of test setup: A single, new, 18650 sample cell will be placed into a temperature regulated brass block equipped with software for thermal cycling. The brass block setup is placed inside a freezer.

Before and after the thermal cycling, the cells are cycled with the cycle pattern described in section 3.1.5. The UFC performance will be calculated by analyzing these measurements.

Equipment needed:
- Freezer
- Regulator block with temperature cycling software
- One 18650 sample cell
- Battery tester capacity for capacity measurement

3.2.6.2 Experimental results

Like in the previous experiment, a number of capacity measurements were done before and after exposure to the thermal cycles. Table 3.10 and Table 3.11 show the results. The interpretation of these results is discussed in section 4.3.1.

Table 3.10 - Measurement of UFC performance prior to thermal cycling

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1002</td>
</tr>
<tr>
<td>2</td>
<td>1002</td>
</tr>
<tr>
<td>3</td>
<td>1001</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 3.11 - Measurement of UFC performance after 2500 thermal cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>UFC performance [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>998</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>1002</td>
</tr>
</tbody>
</table>
CHAPTER 3: Experimental investigation of the effects of low temperatures and AC heating on Li-ion batteries

3.2.7 Experiment 7: UFC cycle life test at 0°C ... +30°C

The last experiment has been designed to investigate the relation between temperature and ageing effects at various sub-nominal battery temperatures. The experiment is basically identical to Experiment 2, except for the number of cells that will be tested and the environmental temperatures of those cells. The cycle life of the 18650 sample cells will be evaluated by cycling them with a typical UFC pattern at temperatures between 0°C and +30°C with increments of 10°C. As test results for +10°C are already obtained in Experiment 2, the remaining temperatures for this test are 0°C, +20°C and +30°C.

The results of this test will be curves showing the UFC performance as the number of cycles progresses for all temperatures tested. It is the intention to use the obtained results to build a theory on the dominant ageing mechanism present at the test conditions.

3.2.7.1 Description of experiment

Test description: Measurement of UFC performance vs. number of charge/discharge cycles at temperatures in the range of 0°C and +30°C.

Deliverables: UFC performance curves as a function of the number of charge/discharge cycles.

Description of test setup: Three new 18650 sample cells will be placed into a temperature controlled environment at 0°C, +20°C and +30°C.

The battery charge- and discharge current is provided by a battery tester. Every cycle, the UFC performance is determined using the method described in section 3.1.5.

Test conditions:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant temperature</td>
<td>0°C, +20°C, +30°C</td>
</tr>
<tr>
<td>Charge current</td>
<td>4.4A</td>
</tr>
<tr>
<td>Charge cut-off voltage</td>
<td>3.6V</td>
</tr>
<tr>
<td>Discharge current</td>
<td>275mA</td>
</tr>
<tr>
<td>Discharge cut-off voltage</td>
<td>2.0V</td>
</tr>
</tbody>
</table>

Duration of the test: One cycle (as in Figure 3.2) takes about 220 minutes to complete under the conditions above. The battery is expected to have a lifetime of somewhere between 1000 and 3000 cycles under these conditions. A number of 500 cycles should therefore be enough to observe the ageing trend. The total duration is then calculated as:

\[ 500 \text{ cycles} \times 220 \text{ minutes} = 110000 \text{ minutes} = 76 \text{ days non stop} \]

Equipment needed: 3x Temperature regulated environment
1x Deep Freezer (for 0°C test)
3x New 18650 sample cell
3xBattery cycle tester
CHAPTER 3: Experimental investigation of the effects of low temperatures and AC heating on Li-ion batteries

3.2.7.2 Experimental results

In this experiment, three previously unused cells have been exposed to identical UFC charge/discharge patterns. The cells are placed in a temperature controlled environment at temperatures of 0°C, 20°C and 30°C. With help of the results of these tests and those of experiment E2, an attempt will be made to identify the relation between temperature and capacity fading at sub-nominal operating temperatures.

The data points, displayed in Figure 3.6, are fitted with a linear approximation, which is extrapolated to get a feeling for the ageing effects after 2500 cycles. More figures of the results of this experiment can be found in APPENDIX D. The interpretation of the results can be found in section 4.3.3.

![UFC performance as a function of temperature for unused cells (measured) and aged cells (extrapolated)](image)

Figure 3.6 – Observed and predicted UFC performance at various temperatures
CHAPTER 4: Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

CHAPTER 4 Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

In this chapter, the background information and experimental results presented in the previous chapters will be discussed to support the final conclusions.

The two most important issues that currently exist in this field of low temperature Ultra Fast Charging are lower performance and increased ageing. These two issues will be addressed separately in paragraphs 4.1 and 4.3 respectively, while paragraph 4.2 will discuss the thermal behaviour of an AC heating system. The chapter will be concluded with a more detailed view of the relation between temperature and battery ageing.

4.1 Effects of sub-nominal temperatures on UFC performance

In chapter 2, UFC performance has been defined as the amount of electric charge that can be transferred to a battery in a fixed interval without exceeding the safe operating area (also see paragraph 2.2.1) of the battery. The length of this interval has been set to 15 minutes for all experiments in this project.

In this section, the experimental results on low temperature battery performance will be discussed (experiments E1, E2 and E7). These results show the effects of sub-nominal temperatures on both the short-term and long-term UFC performance and shows why a heating system can be beneficial under these conditions.

4.1.1 Short term UFC performance

The effect of temperature on the properties of batteries has been investigated in various research projects [23],[42]. Experimental results show that the internal resistance, which is an important performance indicator, is strongly dependent on temperature. The increase of internal resistance is particularly noticeable at temperatures below nominal as specified in the battery datasheet. In order to quantify the effect of temperature on the battery performance, the UFC performance of a widely used battery type has been experimentally determined for the sub-nominal temperature range.

The measured UFC performance is depicted in Figure 4.1. For convenience, all points are normalised with the 25°C measurement which is the nominal operating temperature of the tested cell. The effect of temperature on UFC performance is clearly noticeable at temperatures lower than 10°C. Below 0°C, the performance reaches dramatically low levels.
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![Graph showing normalized transferred charge vs. temperature]

**Figure 4.1 - UFC performance as a function of temperature**

Because the decrease in UFC performance seems to be quite linear in the temperature region between -20°C and +5°C, the data in Figure 4.1 suggests that charging the battery becomes impossible below -30°C. This observation is consistent with performance measurements of Li-ion batteries in [43]. According to [15], the main cause of the poor performance is a low value of the Lithium diffusivity in the carbon electrode. Since most electrolytes solidify (and ions become immobilised) at temperatures lower than -30°C, most batteries cannot be used at these temperatures anyway.

### 4.1.2 Long term UFC performance

Previous section has described the reversible influence of temperature on battery performance. Temperature has also effect on the long term performance of batteries. There are several temperature related non-reversible processes known to have a permanent negative effect on battery performance. Examples of such processes are:

- Lithium plating
- Electrolyte decomposition
- Loss of active electrode material
- Current collector corrosion

A more complete overview is given in reference [44], where it is also explained that the lithium plating process is enhanced at low temperature and high charge rates.
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Lithium plating is the (unintended) deposition of metallic lithium onto active electrode areas (also see paragraph 2.1.5.2). Because both active electrode area and active materials are lost, lithium plating has a negative effect on both battery capacity and power. For UFC applications, both loss in capacity and power capability will reflect into the UFC performance, but cannot be distinguished individually as the UFC performance is a single parameter representation.

The impact of battery temperature during Ultra Fast Charging on degradation was measured in experiments E2 and E7 by cycling various samples with the same cycle pattern in a temperature controlled environment at different temperatures ranging between 0°C and 30°C.

Figure 4.2 shows the measurements of an ageing test part of experiment E7. The small dots show the measured UFC performance of each cycle. Averaging is used to reduce measurement noise and artefacts introduced by the 100% DOD cycles done after each 50 cycles. Due to the periodicity of the artefacts, averaging has been done over the first and last 50 cycles. The averages are shown in Figure 4.2 as two big squares. Finally a linear approximation of the degradation is made using the two averages, plotted as a solid black line in the figure.

![Measured and approximated UFC performance](Image)

Figure 4.2 – Measured UFC performance during degradation test at 0°C and the linear approximation.
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The same linearization method has been applied to the results of the ageing experiments at other temperatures. In Figure 4.3, the linear approximations of UFC performance degradation is plotted for all tested temperatures. From this figure, it is clearly noticeable that the degradation at the lowest temperature is the most severe.

![Linearized UFC performance at different temperatures](image)

Figure 4.3 – Linear approximations at four different temperatures of UFC performance as a function of the number of cycles.

Another way of presenting the acquired data that is more suitable for showing the effect of temperature on performance degradation is plotting the per-cycle degradation as a function of temperature. Because batteries are usually rejected when the performance drops to a certain fraction of its initial performance, it is best to express per-cycle degradation as a percentage of the initial (new battery) performance. This is because temperature is also directly related with performance as can be seen in Figure 4.3 when looking at the performance of the batteries during the first cycle. Figure 4.4 shows the relative performance degradation per cycle using the same experimental data as in Figure 4.3.

Due to confidentiality, this figure has been moved to APPENDIX D.

Figure 4.4 - UFC Ageing rate as a function of temperature
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The impact of low temperatures on the ageing rate is visible in Figure 4.4. The high ageing rate below 10°C indicates that an application operating at such temperatures might benefit from a battery heating system when ageing effects are considered.

Note: The measured value for the per-cycle UFC performance decrease at 10°C in Figure 4.4 is expected to be too low by the author. This is because the data for this point has been obtained in experiment E2, whereas all other points were obtained in experiment E7. The difference is that experiment E2 used a higher setting for the discharge current than experiment E7. Because the discharge stops at a fixed terminal voltage, a higher discharge current will cause less deep discharges and hence less transferred charge during charging. The author believes that the 10°C point in Figure 4.4 could be slightly higher if the discharge current had been identical to the level used in experiment E7.

In order to check the assumption that the effect shown in Figure 4.4 is primarily caused by lithium plating, the tested cells could be disassembled to search for evidence of metallic lithium. Due to the safety risks involved with metallic lithium and nano-structured materials, such a disassembly may only be done by chemical experts and with proper safety precautions. Doing so is however recommended for future work.
CHAPTER 4: Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

4.2 Effects of AC heating on performance

Results of experiments E2 and E7 show that charging batteries at lower temperatures increases ageing effects, which reduces Ageing effects at 0°C that impact UFC performance are almost five times higher than at 30°C (Figure 4.4). Moreover, low temperatures have a direct but reversible effect an UFC performance. The UFC performance of new cells as a function of temperature was measured to be 30% less at 0°C and almost 80% less at -20°C when compared to the level at 25°C (Figure 4.1).

To overcome these issues, battery heating can be used. The principle of battery heating is simple: the temperature of a battery is increased so that the battery can be operated at a temperature where its properties are more favourable.

One of the objectives of this project is to show if AC battery heating can reduce the low-temperature ageing effects. With help of the results of experiments E1, E3, E5 and E6, two aspects of AC battery heating have been investigated:

- Heating performance
- Ageing effects introduced by AC heating

This paragraph will focus on the heating performance and will conclude with an estimation of the performance improvement that battery heating can bring in UFC systems. The ageing effects introduced by AC heating will be covered in section 4.3.

4.2.1 Influence of battery temperature on the power dissipation of an AC heater

The basic idea of internal battery heating is straightforward: the temperature of the internal structure of the battery is raised to enhance its physical and chemical properties. In its most basic form, the battery can be seen as a lumped thermal capacitance \( C_T \). The internal battery resistance acts as a heating element: electrically it acts as a resistor \( (R_I) \) and thermally as a heat source \( (P_{\text{heating}}) \). Schematically, the internal battery heating process is depicted in Figure 4.5. Note that heat losses to the environment are represented by resistance \( R_{Te} \) and that the heat is supposed to spread evenly and instantaneous throughout the battery (lumped \( C_T \)).

![Figure 4.5 - Electrical and thermal circuit diagram of internal heated battery](image-url)
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Figure 4.6 – Block diagram of internal battery heating process

The thermal model in Figure 4.5 is converted to the Simulink model shown in Figure 4.6. Simulation results of this model in Simulink were verified with data obtained in experiment E3 to check the assumption that the test setup can be modelled by the linear thermal circuit of Figure 4.5. The test setup used to do this verification contained a partially thermally insulated 18650 cell that was heated by a current of 17.5A RMS. Due to the imperfect thermal isolation in the test setup, heat losses from cell to environment were present. Figure 4.7 shows the temperature of the cell during the test.

Figure 4.7 – Measured cell temperature and linear model curve fittings

In Figure 4.7, two first order exponential fits in red and green are shown. The fitted curves match well with the measurements so a first order thermal model like the one in Figure 4.5 predicts the battery temperature accurately.

With help of the curvatures found with the measurements shown in Figure 4.7, a value for $R_e$ can be found. The value of $C_T$ is known from the battery’s datasheet.
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The total amount of thermal energy available for heating in the case when no thermal losses to the environment are present ($P_{\text{heating}}$), cannot be determined directly from Figure 4.7, but can be obtained from $P_{\text{Total}}$ and $P_{\text{Losses}}$. The temperature difference between two subsequent samples in the red curve gives a representation of the heating power flowing into $C_T$ ($P_{\text{Total}}$). Equation 4.1 explains this procedure where $t_s$ is the sampling time, in this case 10 seconds.

$$P_{\text{Total}} = \frac{T_{n+1} - T_n}{t_s}$$  \hspace{1cm} (4.1)

The same procedure can be used on the samples under the green curve to obtain $P_{\text{Losses}}$. By using the power balance like showed in Figure 4.7, the net heating power that is generated inside the battery, $P_{\text{heating}}$, is now found by equation 4.2:

$$P_{\text{heating}} = P_{\text{Total}} - P_{\text{Losses}}$$  \hspace{1cm} (4.2)

Figure 4.8 shows the result of the evaluation of $P_{\text{heating}}$ for all samples.

![Determination of total heating power using regression on measured cell temperature during heating and cooling](image)

**Figure 4.8 - Calculation of $P_{\text{total}}$ for temperature range -20°C...+20°C using the power balance**

The internal power dissipation as a result of the battery current ($P_{\text{heating}}$) is about 8 Watts in the temperature range between -20°C and +20°C. A slight temperature dependence in $P_{\text{heating}}$ is visible but the assumption of a constant heating power will suffice in most cases.
4.2.2 Customising the heating interval

The used current level of 17.5A RMS results in a temperature rise of 30°C in about four minutes time, as can be seen in Figure 4.7. Altering the current level changes the time needed for heating. Figure 4.9 shows the relation between current and the heating interval. When choosing the desired heating period, one should be aware that higher currents result in faster heating but also in larger power electronics. Also the battery (inter)connections should be able to handle the desired current level.

![Diagram showing current required for a ΔT of 30°C as a function of the heating interval](image)

**Figure 4.9 – Relation between heating speed and battery current**
CHAPTER 4: Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

4.2.3 Effect of battery heating on UFC performance

Paragraph 4.1.1 revealed that the UFC performance drops dramatically at temperatures below 10°C for the tested battery type. A battery heater can be used to elevate the battery temperature in the first minutes of the charging process. For AC heating, this implies that during the heating interval, the battery cannot be charged because all available energy is used to heat the battery. Figure 4.10 shows a typical time schedule for the charging process of a UFC application with battery heating. It can be seen that colder batteries require more time to reach the temperature where charging is initiated (here +10°C). As a result, less time is available for charging.

![Figure 4.10 - Time schedule for a UFC charge cycle with AC heating](image)

In Figure 4.11 the same UFC performance values as used to construct Figure 4.1 are used for the “original performance”. The “improved performance” is then calculated as a portion of the +10°C original performance, where the portion is determined by the amount of time that is used for charging during the 15 minutes (see Figure 4.11).

Figure 4.11 shows that battery heating (improved performance) effectively improves UFC performance, especially for temperatures below 0°C.

![Figure 4.11 - Expected performance improvement for UFC application using battery heating](image)
CHAPTER 4: Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

4.3 Ageing effects introduced by AC heating

Paragraph 4.2 showed the influence of AC battery heating on charging performance. In some cases, batteries can be charged faster with AC heating, even if some charging time is used for heating instead of charging. Another property of AC heating is its potential to reduce ageing effects for batteries operating at low temperatures. This paragraph will show the influence of AC heating on battery degradation.

Three different processes have been investigated that are expected to be present in a typical situation where batteries are heated with AC prior to Ultra Fast Charging. These three processes are:

- Ageing due to thermal cycling
- Ageing due to AC heating current
- Ageing due to UFC cycling

A number of experiments have been designed to measure the contribution to the total battery performance degradation of each process separately. The results of those experiments are discussed in the next three sections. Each section is dedicated to one of the above mentioned ageing processes.

4.3.1 Battery ageing due to thermal cycling

For mechanical structures, thermal cycling is a possible cause of failure. Changes in temperature make materials expand or shrink. A badly chosen form factor or combination of materials could lead to high mechanical stresses which could in turn lead to micro fractures in the material. The operation of Li-ion batteries depends on nano-scale structures on the electrodes, hence micro fractures could affect the properties of a battery as a whole.

Because heating a battery inherently creates a thermal cycle, it is interesting to know how much degradation this will cause. For this purpose, experiment E6 in which a UFC capable cell was exposed to 2500 thermal cycles was set up. This number of cycles was chosen because UFC systems are usually designed for a few thousand charge-cycles (the actual number depends on the application). Another reason not to choose more than 2500 thermal cycles was due to the duration of the experiment.

The measurement results presented in paragraph 3.2.6.2 show no evidence of reduction in UFC performance due to thermal cycles. It seems therefore that the kind of thermal cycling applied in experiment E6 does not introduce obstacles for AC heating. Although not much literature is available on the effect of thermal cycling on batteries at low temperatures, reference [45] notes that extreme temperature cycling can cause a failure of the battery seal integrity, which increases the potential of electrolyte leakage.

4.3.2 Battery ageing due to AC heating current

Another possible cause of battery degradation due to AC heating is the effect of the battery current used to heat the battery on the internal structure. Alternating current can be seen as a large number of small charge and discharge cycles. Measurements on several types of Li-ion batteries have revealed that the number of charge / discharge
cycles depends on the depth of discharge. For DOD between 50% and 100%, the number of cycles is approximated by equation 4.2:

\[ N(DOD) \approx N_{100\%} \left( \frac{100\%}{DOD} \right)^C \]  \hspace{1cm} (4.3)

where \( N \) is the number of attainable charge / discharge cycles, \( N_{100\%} \) is the number of charge / discharge cycles when a DOD of 100% is used, \( C \) is a constant and DOD is the actual DOD used. Experimental results in [41] show that \( C \) has an approximate value of 2 for the tested types of Li-ion batteries.

In periodic charge/discharge operation like AC heating, the lifetime of a battery (\( T_{life} \)) is evaluated by the product of the total number of cycles \( N \) and the cycle period \( T_{cycle} \):

\[ T_{life} = N \cdot T_{cycle} \]  \hspace{1cm} (4.4)

The duration of one cycle depends on the depth of discharge. Under equal charge and discharge conditions, the cycle period is linearly dependent on the depth of discharge:

\[ T_{cycle} = T_{100\%} \cdot DOD \]  \hspace{1cm} (4.5)

By combining equations 4.3, 4.3 and 4.4, a single expression for \( T_{life} \) is obtained where \( T_{cycle} \) and \( N \) are eliminated. Assuming \( C = 2 \), one obtains:

\[ T_{life} = N_{100\%} \cdot T_{100\%} \cdot \frac{100\%}{DOD} \]  \hspace{1cm} (4.6)

According to equation 4.5, battery lifetime is inversely proportional with DOD. In order to write this relation in terms of frequency of the battery current, DOD has to be written in terms of frequency. At a charge current of 1C, a battery is ideally completely charged in one hour. The same applies for a discharge cycle at 1C, so a charge/discharge cycle will take 2 hours which is equivalent to a frequency of 1/7200 Hz. When the charge/discharge current is fixed to 1C, the relation between DOD and frequency is inversely proportional:

\[ f = \frac{100\%}{DOD} \cdot \frac{1}{7200} \]  \hspace{1cm} (4.7)

Merging equation 4.5 and 4.6 results in equation 4.7 which shows a linear relation between lifetime and frequency. This relation is also graphically depicted in Figure 4.12.

\[ T_{life} = N_{100\%} \cdot T_{100\%} \cdot 7200 \cdot f \]  \hspace{1cm} (4.8)
CHAPTER 4: Discussion on the effects of low temperatures and AC heating on the performance and lifetime of Li-ion batteries

Although the trend of relation 4.7 has not been backed by measurements, the most important observation that can be made for this project is that battery currents with a frequency higher than 0.1 Hz will have a negligible effect on the battery lifetime.

During experiments in [41], batteries were cycled at 0.5% DOD, which, according to equation 4.6, corresponds to a frequency of 1/36 Hz. After a few months of continuous cycling (experiment E5), no noticeable degradation was found which could be attributed to the low-DOD cycles. Another set of measurements has been acquired as part of this project in Experiment 5. In this experiment, the frequency was higher (and hence lower DOD). Here again, no evidence was found for battery degradation as a result of the application of high frequency battery currents. When looking at the trend in Figure 4.12, this is an expected result.

Note: In experiment 5, the 10°C measurements show a performance drop of 1.6% after 1 week but the -20°C measurements show a performance gain of 1.3% after the same period of testing. The author believes however that it is not likely that the experimental conditions are able to improve the performance of a battery. A temperature difference was thought to be a possible cause of measurement variations, but the experimental data revealed that the temperatures were identical in all cases. An explanation which is ought to be plausible by the author is a difference in contact resistance between the performance measurements.
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4.3.3 Battery ageing due to UFC cycling

The third and last process that is suspected to be a cause of battery performance degradation is charge cycling. Charge cycle tests are common practice to determine the capacity and life expectancy of batteries. Battery manufacturers run such tests to advertise their products in the datasheet. For temperatures below nominal operating temperature however, this data is either not available or not published. This is also the case for the battery type used in this project. The data therefore needed to be obtained by own experiments.

In paragraph 4.1.2, the effects of UFC charge cycling at low temperatures were discussed. In this discussion was revealed that temperatures below 10°C have considerable (negative) impact on ageing. In contradiction to the effects of thermal cycling and prolonged exposure to high level AC currents, the effects of low temperature Ultra Fast Charging cannot be neglected.

4.3.4 Combined ageing effect

Three different processes that are expected to be present in a typical situation where batteries are heated with AC prior to Ultra Fast Charging were discussed in paragraphs 4.3.1, 4.3.2 and 4.3.3. When the results of the experiments on the three effects are compared, one can conclude that by far the most UFC performance degradation is caused by charge cycling.

This observation is in favour of the AC battery heating method, because it implies that:

- Ultra Fast Charging a battery at 10°C instead of 0°C reduces ageing effects.
  Therefore:
  - Heating a battery of 0°C to 10°C prior to Ultra Fast Charging reduces ageing effects.
    And:
    - The newly introduced ageing effects due to AC heating (thermal cycling and AC heating current exposure) do not significantly counteract the positive effects of charging at a higher temperature

From this perspective, AC heating thus seems a method that has potential benefits through its abilities to reduce ageing effects during Ultra Fast Charging and to increase UFC performance. The effects of temperature cycling and AC heating current exposure were marked as potential show-stoppers but experimental results showed no signs of increased battery ageing as a result thereof.
CHAPTER 5 Conclusions and future work

In chapter 2, two research questions were presented that would form the basis of the experimental investigation of the thesis project. For the reader’s convenience, these research questions are repeated here. Following each research question, the conclusions drawn from the experimental work in previous sections are revisited. The chapter will be concluded with recommended topics for future work.

5.1 Conclusions

In section 2.3.3, the first research question and its associated hypotheses were formulated as follows:

<table>
<thead>
<tr>
<th>RQ1:</th>
<th>Will an AC heating system be able to increase the battery performance and lifetime of Ultra Fast Charging LiFePO₄ battery systems used in cold environments?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis:</td>
<td>If LiFePO₄ batteries are heated with AC before initiating Ultra Fast Charging, then the battery will have better UFC performance and a longer lifetime.</td>
</tr>
</tbody>
</table>

Experimental results on the effects of low temperature on battery performance and lifetime were discussed in section 4.1. The results showed a significant reduction in UFC performance for temperatures below 10°C. Also battery lifetime is reduced by a large amount when batteries are charged ultra fast below 10°C. The reduction of both performance and lifetime at low temperatures are in line with the hypothesis and endorse the potential of battery heating.

AC battery heating is a specific implementation of battery heating that has the ability to heat a battery internally, which is faster than conventional heating methods. In order to be able to judge whether the way is worse than the disease, it has been investigated how much battery degradation is caused by AC heating. From the discussion in section 4.3 can be concluded that additional degradation caused by AC heating is minimal.

In section 4.2 has been verified that the tested battery type can indeed be heated within a few minutes by a high level AC current. Moreover, it is shown in that section that any time lost by heating the battery is gradually compensated through the UFC performance gained by heating the battery.

By combining the above mentioned conclusions, the hypothesis on the first research question can be confirmed. This means that AC battery heating can be regarded as an effective and feasible technique when looked from a battery point of view. A feasibility study on the implementation of a power electronic converter for AC battery heating is still subject to future work.
The second research question and its hypothesis as formulated in section 2.3.3 sounds:

| RQ2: | How is the lifetime of LiFePO₄ batteries influenced by Ultra Fast Charging at sub-nominal temperatures? |

Hypothesis: Ageing speed depends on many factors, among which the battery voltage during charging. Temperature has an effect on the batteries’ internal resistance which in turn influences the voltage during charging. It is expected that a relation exists between battery voltage and current during charging and the battery lifetime.

Most Li-ion batteries are designed to operate efficiently at room temperature (25°C) and also have an acceptable lifetime at this temperature. For Li-ion batteries, temperatures ranging from 0°C to 30°C can therefore be considered as sub-nominal. Paragraph 4.1.2 discussed the experimental results on the effects of Ultra Fast Charging on battery ageing for several temperatures between 0°C and 30°C. The observed trend for this effect is shown in APPENDIX D. From the figure it is directly clear that below 10°C, battery ageing clearly increases and hence the battery lifetime is reduced.

The hypotheses of RQ2 could not be confirmed by using the experimental results obtained in this project. Because battery voltage and current were fixed during the experiments, a relation between these parameters and battery lifetime could not be found in the results. More important is however to conclude that the experimental results were useful to find an answer to RQ2 itself. The hypotheses of RQ2 could have been more strictly defined by just predicting the effect of temperature on battery lifetime under the specified conditions.
5.2 Future work

Following the investigations described in this thesis, a number of projects can be taken up that bring the knowledge of AC battery heating to a higher level:

- Investigation of technical possibilities for the generation of alternating currents in batteries. A higher level of understanding is required in at least the following subjects, in order to determine the practical feasibility of AC heating:
  - Search for the optimal frequency of the heating current. It is likely that different frequencies exist with their own optimum. For example:
    - Frequency with the lowest ageing
    - Frequency with the highest power dissipation
    - Frequency where power electronics is the smallest
    - Etc.
  - How small can the power electronics be made for an AC generation circuit. The size and weight of the power electronics is crucial when placed on-board.
  - What will be the costs of the required power electronics?
  - What is a realistic efficiency for such a power electronic converter? It is hard to beat the efficiency of a resistor but the advantages of AC heating might allow a lower efficiency.

- Develop a better understanding of the physical processes that take place inside the battery during Ultra Fast Charging at low temperatures. It would be useful to study the interior of a battery to search for evidence of physical processes like lithium plating. For other battery types, AC heating might behave differently than for the battery type used in this project. A better understanding of the internal ageing processes could also make it easier to predict the effects of AC heating on other battery types.

- Through more extensive testing, the relation between temperature and ageing rate can be defined in more detail. Such knowledge is very useful to design the most cost-effective battery solution for every low temperature application.

- The experimental work in this project is focused on single-cell measurements. Practical systems are usually built with a large number of cells. An investigation of the properties of AC heating in multiple-cell arrangements is therefore recommended.
CHAPTER 5: Conclusions and future work
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