Modeling and Analysis of the Interaction of Batteries and Power Electronic Converters

RUDI SOARES

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Tryck: Universitetsservice US AB
To my mother
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Stockholm, May 2019
Rudi Soares
“I think that it is a relatively good approximation to truth — which is much too complicated to allow anything but approximations — that mathematical ideas originate in empirics.”

- John von Neumann
Abstract

This thesis deals with the interaction of batteries and power electronic converters in automotive applications. Even if the additional heating caused by (unwanted) alternating currents is disregarded, there has been a concern that alternating currents can be harmful for batteries. For that reason, alternating currents can be filtered using capacitors and/or by sophisticated hardware. In this work, the concern whether alternating currents are harmful to batteries is studied particular focus on large, lithium-ion cells for use in automotive applications.

First, the harmonic content in the battery current of two, commercial hybrid-electric busses were measured and analysed. The most prominent harmonic had a peak magnitude higher than 10% of the maximum direct current level (160 A) arising at frequencies below 150 Hz. The maximum amplitude detected of a harmonic caused by the voltage source converter's switching action was around 10 A and occurred at a frequency of 2 kHz.

An experimental setup with alternating current capability for evaluating large lithium-ion cells has been designed and built. Twelve lithium-ion cells were cycled at a rate of 1 C during approximately 2000 cycles (corresponding to approximately one year). The cells were cycled with an superimposed alternating current of 1 Hz, 100 Hz, or 1 kHz while the rest of the cells were cycled with direct current (only), injected with alternating current (only), or no current at all (calendar aging). No negative effects caused by the alternating current was identified in terms of capacity fade and power fade for the tested lithium-ion cells.

A comparison between sinusoidal current-ripple charging and conventional constant-current constant-voltage charging was also carried out. Three lithium-ion cells were cycled (ten times) with different ac currents superimposed during charge. The results were analyzed statistically and no significant improvements in terms of charging time or charging efficiency were observed in any of the charging tests using an superimposed ac current.

The injection of alternating currents into batteries for heating purposes has also been studied and a control method for battery heating using an ac current was proposed. The proposed controller is applicable regardless of the LIB’s subsequent impedance nature (capacitive, inductive or resistive). Further, a design process for the generation of magnified
alternating currents in dc-dc converters was presented. By matching the switching frequency with the frequency where the LCL filter and the battery resonate, the current flowing in the semiconductors and the switching frequency could be reduced. In a small experimental setup using a single lithium-ion cell, using an LCL-resonant circuit and a full-bridge switch arrangement, magnifications of up to 15.7 was reached. This allowed for a loss reduction in the semiconductors of up to 75%, when compared to an equivalent dc-dc converter enabled to produce a non-magnified ac current.

**Keywords:** Alternating current, aging, electric vehicles, harmonics, lithium-ion batteries, power converter, resonant filters, ripple, temperature control.
Sammanfattning

Denna avhandling behandlar interaktionen mellan batterier och kraftelektroniska omvandlare i fordonssapplikationer. Även om den tillförda (och oönskade) värmeökningen på grund en växelströmskomponent förbises så har det funnits oro att växelströmskomponenter kan vara skadliga för batterier. För att minska växelströmskomponenternas eventuella inverkan kan dessa strömmar filtreras med hjälp av kondensatorer och/eller annan hårdvara. I detta arbete studeras huruvida växelströmskomponenter är skadliga med särskilt fokus fäst vid stora, lithiumjonceller avsedda för fordonssapplikationer.

Först uppmättes övertonsinnehållet i batteriströmmen i två kommersiella hybridelektriska bussar. Den mest framträdande övertonen nådde en magnitude som var större än 10% av dc-strömmens maximala värde (160 A) och uppstod vid en frekvens lägre än 150 Hz. Den största uppmätta amplituden på grund av den kraftelektroniska omvandlarens switchning var cirka 10 A och uppstod vid en frekvens på 2 kHz.

En experimentuppsättning för att laddcykla stora lithiumjonceller med en pålagd växelströmskomponent har designats och konstruerats. Tolv lithiumjonceller laddcyklades vid 1 C under ungefär 1 år vilket motsvarade cirka 2000 cyklar. Frekvenserna på de celler som laddcyklades med en pålagd växelströmskomponent var 1 Hz, 100 Hz och 1 kHz. De resterade cellerna laddcyklades med en dc-ström eller utan någon ström (motsvarande kalendeåldring). Inga negativa effekter (i termer av kapacitets eller effektminskning) orsakade av de pålagda växelströmskomponenterna kunde identifieras under försöket.

En jämförelse mellan laddning med en pålagd växelströmskomponent och konventionell konstant-ström-konstant-spänningsladdning har också utförts. Tre lithiumjonceller laddcyklades tio gånger med olika växelströmskomponenter pålagda under laddfasen. Resulterande data analyserades statistiskt och inga signifikanta förbättringar i termer av ladd tid eller laddeffektivitet kunde observeras jämfört med laddcykling utan en pålagd växelströmskomponent.

Injektion av en växelströmskomponent med avsikt att värma upp lithiumjonceller har även studerats och en styrmetod för att åstadkomma detta har föreslagits. Den framstagna styrmetoden kan appliceras oberoende av
litiumjoncellens impedanskarakteristik (kapacitiv, inductive eller resistiv). Vidare har en metodik för generering av en förstärkt växelströmskomponent med utnyttjande av ett LCL-filter studerats. Genom att matcha switchfrekvensen med den frekvens där LVL-filtret och battericellen resonerar kan strömmen i krafthalvledarna (och switchfrekvensen) begränsas. I en mindre experimentuppställning kopplad till en litiumjoncell erhölls en strömförstärkning på upp till 15.7 gånger vilket möjliggjorde en minskning av förlusterna i krafthalvledarna med 75% jämfört med om den förstärka strömmen hade passerat krafthalvledarna.

**Nyckelord:** Elfordon, kraftelektroniska omvandlare, litiumjonbatterier, resonanta filter, temperaturstyrning, växelström, åldring, övertoner.
Publications and manuscripts

List of appended papers


List of related papers


Contribution of individual authors

In general, the order of the authors in each publication reflects the level of responsibility and involvement of the author in the corresponding publication. Thus, the first author contributed the most for the publication. However, the following contributions should be recognized:
In [Paper II], the manuscript was mainly compiled by the third author.
In [Paper IV], the majority of the work prior to the preparation of the manuscript should be attributed equally to the first two authors. The final graphical user interface design, also addressed in [Paper R.III], as well as, the offset compensation analysis, and the lithium-ion cell characterization were carried out by the second author.
In [Paper V], the second author carried out the literature review and proposed the idea leading to the publication. The contributions for the experimental work are identical to the ones of [Paper IV].
In [Paper VI], the majority of the work prior to the preparation of the manuscript should be attributed equally to the first two authors. The second author contributed with the literature review, the proposal of fundamental concepts, and discussion of the results. The contributions for the experimental work are identical to the ones of [Paper IV].
In [Paper VII], the physics-based FEM model (based on the work presented in [1]) was edited by the second author.
List of abbreviations used in this thesis

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ac</td>
<td>Alternating current</td>
</tr>
<tr>
<td>BOL</td>
<td>Beginning of life</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller area network</td>
</tr>
<tr>
<td>CRG</td>
<td>Current ripple generator</td>
</tr>
<tr>
<td>dc</td>
<td>Direct current</td>
</tr>
<tr>
<td>DCG</td>
<td>Direct current generator</td>
</tr>
<tr>
<td>DoD</td>
<td>Dept-of-discharge</td>
</tr>
<tr>
<td>EIS</td>
<td>Electrochemical impedance spectroscopy</td>
</tr>
<tr>
<td>EOL</td>
<td>End of life</td>
</tr>
<tr>
<td>EM</td>
<td>Electric machine</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>GITT</td>
<td>Galvanic intermittent titration technique</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
</tr>
<tr>
<td>HPPC</td>
<td>Hybrid pulse power current</td>
</tr>
<tr>
<td>ICA</td>
<td>Incremental capacity analysis</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-gate bipolar transistor</td>
</tr>
<tr>
<td>KTH</td>
<td>Royal Institute of Technology</td>
</tr>
<tr>
<td>LIB</td>
<td>Lithium-ion battery</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal-oxide-semiconductor field-effect transistor</td>
</tr>
<tr>
<td>NI</td>
<td>National Instruments</td>
</tr>
<tr>
<td>NMC</td>
<td>Nickel-manganese cobalt oxide</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel-metal hydrate</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional integral (control)</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>SEI</td>
<td>Solid electrolyte interface</td>
</tr>
<tr>
<td>SMPC</td>
<td>Switched-mode power converters</td>
</tr>
<tr>
<td>SOC</td>
<td>State-of-charge</td>
</tr>
<tr>
<td>SOH</td>
<td>State-of-health</td>
</tr>
<tr>
<td>SPL</td>
<td>Sustainable Power Laboratory</td>
</tr>
<tr>
<td>STFT</td>
<td>Short-time Fourier transform</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage source converter</td>
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Chapter 1

Introduction

This chapter introduces the thesis by providing a background and the motivations. An outline of the thesis is given, and a list of the main contributions and findings is provided.

1.1 Background

Batteries currently power the majority of all electronic mobile devices. Particularly, lithium-ion batteries (LIBs) have been a key enabling technology in the new generations of electric vehicles (EVs), mobile phones, drones, and power tools [2]. Additionally, LIBs are now been used in heavier propelled systems such as piloted electric aircrafts [3]. Also, with the rise of renewable energy production, LIBs are increasingly being considered as a peaker replacement option in grid storage applications [4]. With the enormous applicability of LIBs and thanks to new developments of LIB technology, LIBs will likely continue to improve and dominate the above mentioned markets for the next years to come [5].

Despite of the recent advances in LIB technology, LIBs are still expensive components with an uncertain and relatively short lifetime. An example of this may be found while observing LIBs’ warranties. Commonly, the default warranty time stipulated for a mobile phone’s LIB is one year [6]. Hence, users willing to extend their experience on mobile phones often have to rely on bulky external battery banks (a market that keeps growing [7]). In the EV market, the latter solution is not admissible and in order to meet the expectation of
CHAPTER 1. INTRODUCTION

the average consumer, a battery warranty time of around 8 years or 100 000 miles is now being practiced [8]. However, there is a risk that such warranties are accomplished at the expense of oversizing the LIB. This oversizing is due to the fact that the lifetime of a LIB is associated to large state-of-charge (SOC) intervals (or deep depth-of-discharges (DoDs)) [9]. Hence, to avoid LIB aging while maintaining an attractive warranty time, the applications using LIBs are bulkier and heavier (and therefore more expensive) than wished by the consumers.

Another inherent weakness of LIBs is that they experience a reduction of life time and cannot be used safely at low and high temperatures (subzero and more than 40 °C). To be operated in such temperature ranges, LIBs have to be “blinded” from the ambient temperatures and surveyed so that the cell temperature is kept within certain temperature limits. Today, this is accomplished with the use of additional heating and cooling systems. This increases the system complexity, namely in the packaging of LIBs, which subsequently increases the volume, the weight and the price of the corresponding applications.

Considering the massive adoption of LIBs in the above mentioned markets, relatively minor improvements in terms of LIB aging and cell temperature management systems, as well as, minor advances in the power electronics interacting with batteries, may have significant impact in large sectors which are part of the life style lived in the majority of today’s societies.

This thesis is part of a collaboration between Scania AB, and the departments of Electric Power and Energy Systems and Applied Electrochemistry at KTH Royal Institute of Technology. The work has been funded by the Swedish Energy Agency (research grant number 37434-1), Scania AB, and the Swedish Electromobility Center.

1.2 A collaboration between electric power engineering and applied electrochemistry

This doctoral thesis is a result from a collaboration between electric power engineering and applied electrochemistry regarding batteries and their use in heavy hybrid electric vehicles. Generally, applied electrochemistry includes the study of the physical and chemical phenomena occurring in batter-
A COLLABORATION BETWEEN ELECTRIC POWER ENGINEERING AND APPLIED ELECTROCHEMISTRY

ies while electric power engineering focus on the apparatus (electronic devices such as power converters or measurement instruments) involved in the utilization of batteries. Specifically, the study and modeling of batteries’ aging mechanisms, for example by carrying out post-mortem studies on aged battery cells, are examples of tasks commonly carried out by electrochemists. Such knowledge is fundamental to comprehend the conditions in which the batteries should be utilized.

The design and commission of battery related electronic devices, typically falls into the realm of electric power engineering. Through a power converter, a load or a source (e.g., an electric motor or a grid connection) may be connected to a battery so that energy can be transferred. This task should be accomplished in a safe manner while preserving the battery’s well being. Ergo, electric power engineering may only create battery related devices that interact in conscientious manner with batteries if applied electrochemistry knowledge is available. Despite the obviousness of this claim, as it will be possible to verify in this thesis, this is often not the case.

Today, due to their efficiency attributes, switched-mode power converters (SMPCs) are commonly used to operate (charge-discharge) batteries. SMPCs use switching devices such as IGBT, and/or MOSFET, which turn on and off at some high frequency (normally at several kHz). The batteries either supply or receive energy during the conduction state of the SMPC’s switches. However, the energy transfer due to this switching action if not filtered results in current ripple in the battery. A convenient way to treat ripple is by identifying its main components as a sum of harmonics (ac currents). This sum of harmonics, also called harmonic content, has been historically (and it is still today by many) assumed to be harmful for batteries [10–13]. This perception led to the development of sophisticated hardware and methods intended to filter ac currents in batteries [14–20] (just to cite some relevant examples among the probably hundreds of papers and technical notes from the last decades that could be cited). At a first glance this is a natural way to address the topic, after all, batteries are often designed and operated according to direct current (dc) principles [21]. Nonetheless, batteries’ electrochemical reactions occur at a wide range of time scales [22] as is illustrated in Figure 1.1. Another way highlight this dualistic (dc and ac) view, is by acknowledging that for the batteries’ electrochemistry, the concept of ac or dc current is linked with the concept of how quickly the charging (of dc current) is switched to the discharging (of dc current). Now, when compared with calender aged batteries,
batteries charge cycled with dc currents clearly show patterns of accelerated age [23–25]. Hence, at what frequency (the charging is reversed to discharging and vice-versa) does an certain level of ac current age a battery?

Figure 1.1: LIB effects due to charging-discharging current occurring at different time scales. The figure is reproduced from [Paper III].

### 1.3 Outline of the thesis

This PhD thesis is in the form of a compilation thesis. The main chapters in this thesis are therefore kept brief and serve to introduce the background and the fundamental concepts required to understand this thesis contributions. The detailed scientific contributions belonging to this thesis are presented in the appended publications.

The outline of the thesis is as follows:

**Chapter 1** introduces the thesis by giving a background to the thesis topic and presents its main objectives. A list of the main scientific contributions is also provided.

**Chapter 2** shortly goes through some fundamental concepts in battery technology.

**Chapter 3** connects the main contributions into a research path. Short summaries and highlights of the appended publications are provided.

**Chapter 4** draws the conclusions of the research carried out within this thesis and suggests ideas for future work.

**Appendix** collects and sequences the most relevant publications carried out in this thesis.
1.4 Main contributions and findings

This thesis has resulted in the following original scientific and engineering contributions:

- The harmonic content in the battery current from two commercial hybrid-electric busses were measured and analysed. From this data, it was found that the harmonic with the corresponding largest magnitude reached a magnitude of approximately 10% of the maximum dc-current level. The corresponding frequency range was around 100 Hz.

- An experimental setup with alternating current capability for evaluating large lithium-ion batteries cells was designed, built, commissioned, and used during a one-year long charge-cycling experiment. This setup allows a variety of cell-characterization tests and was the main tool used to collect data analyzed in this work.

- Sinusoidal ripple-current charging when compared with the conventional constant-current constant-voltage charging strategy, was suggested in [26] to improve charging time and charging efficiency of the lithium-ion batteries. In the work presented in [Paper V], it was demonstrated that the superposition of an alternating current to the charging current does not enhance the charging process in terms of charging time or efficiency.

- Results from a one-year charge-cycling study demonstrated that, when compared with dc cycling, cycling with superimposed current ripples (from 1 Hz to 1 kHz) appear to have a negligible effect on capacity fade and power fade of lithium-ion battery cells. Further, incremental capacity analysis revealed no difference between the cells cycled only with dc current and cells cycled with to several different superimposed ac currents.
  
  - Considering that ac currents appear to have a negligible impact on the life time of lithium-ion batteries, the filtering requirements of the dc-links used in power converters may be reduced. This could result in cost savings in industries producing electric mobile devices.

- The knowledge regarding the injection of alternating currents into batteries for heating purposes is improved and a control method for battery heating using alternating current was proposed.
– In this context, methods to model lithium-ion battery (electrically and thermally) envisioning onboard utilization were recommended.

– The proposed controller is suitable in any kind of LIB pack operated at any frequency regardless of the LIB’s subsequent impedance nature (capacitive, inductive or resistive).

• A design process intended for ac current magnification, applied to voltage source converters driving an resonate filter was proposed. It uses a multi-objective algorithm for finding the highest current magnification while keeping the impedance driven by the voltage source converter to a minimum. In this fashion, optimal operating conditions for the voltage source converter, such as operating frequency, as well as optimal filter sizes can be identified.

– In a context of using alternating current to heat batteries, it was empirically demonstrated that by using an LCL resonant filter for ac current magnification, the semiconductor losses of the tested dc-dc converter could be reduced up to 75% when compared with an equivalent dc-dc converter without ac current magnification ability.
Chapter 2

Fundamentals

This chapter provides fundamental aspects regarding batteries, specifically, the operating principles and the main aging mechanisms of lithium-ion batteries are briefly reviewed. Additionally, the methods used in this thesis to model lithium-ion batteries (electrically and thermally) are exemplified. Finally, this chapter shortly reviews the fundamental technologies involved in electric powertrains and in dc-links.

2.1 Batteries

Batteries are composed of one or more electrochemical cells. The cells can be arranged in series or in parallel on a terminal collector where a source or a sink may be connected. Because batteries (typically) are composed of multiple cells, a battery management system (BMS) is used to control and survey the cells’ voltage, capacity, power, and temperature [27]. In more sophisticated BMSs, estimations of the battery state-of-charge (SOC) as well as its state-of-health (SOH) may be computed for monitoring and protection purposes [28]. Fundamentally, a battery is a device that converts chemical energy into electrical energy. This conversion is accomplished via an electrochemical oxidation-reduction (redox) reaction [21]. Although in this thesis, only rechargeable batteries are considered, batteries may not be rechargeable. There are many types of rechargeable batteries, and they are best known by the materials composing them. For instance, lead-acid, nickel cadmium, nickel-metal hydrate
(NiMH), sodium sulphur, and lithium-ion batteries common examples. Further, within each battery chemistry, specific features such as energy or power densities, longevity, and safety may be enhanced. To achieve such purposes, different materials may compose the positive electrode and the negative electrode. In turn, this leads to a sub-categorization of batteries. For example, to enhance longevity, nickel cobalt manganese (LiNiMnCoO$_2$, also know as NMC) may be used in the positive electrode of a LIB and, because of this, this battery type is typically known by the acronym NMC. In contrast, even if different materials such as lithium titanate (LTO) and graphite (LiC$_6$, the most common material found in the negative electrodes of LIBs) may compose the negative electrode, traditionally they have no reflection on the LIB’s abbreviation.

When compared with other types of battery chemistries, LIBs offer higher performances in terms of output voltage levels, energy and power densities, as well as very low self-discharge rates. Due to these qualities, they are commonly used in applications such as traction of electric and hybrid electric vehicles (HEVs) [29]. Even so, it is worth pointing out that when compared, for instance, with NiMH batteries, LIBs are less tolerant to low and high temperatures (subzero and more than 40°C) and are less tolerant of misuse, like overcharging and overdischarging. Subjecting the cell to these conditions may reduce the LIB’s life time, cause battery overheating and, in a worst case scenario, cause fires or explosions [30]. This fact leaves room for other types of batteries to maintain certain positions in the market such as in grid applications [31].

This thesis is mostly carried out using NMC LIB (provided by Scania AB). However, in much lesser extent, NiMH batteries (provided by Nilar AB) have also been tested and analysed during the course of this thesis.

### 2.2 Lithium-ion battery operating principles

In this thesis, the terms anode and cathode are avoided while the terms positive electrode and negative electrode are preferred. From the user point of view, the cell voltage has a fixed polarity. Likewise, the selected terminology avoids confusions since the selected terms remain fixed regardless the direction of the energy transfer, i.e., if the cell is being charged or discharged.

A LIB cell structure may be schematically represented by a positive and a negative electrode, an electrolyte, and a separator. Each of the electrodes is
2.2. LITHIUM-ION BATTERY OPERATING PRINCIPLES

comprised of an active chemical material and a current collector. As mentioned in Section 2.1, graphite is typically used for the negative electrode whereas for the positive electrode, a metal oxide such as NMC can be used. The main electrochemical processes occurring in the electrodes are intercalation (insertion of lithium-ions (represented in Figure 2.1 by Li$^+$s)) and deintercalation (removal of lithium-ions). When such processes happen, in parallel with the lithium-ions, and at the same exact rate, electrons (e$^-$) flow as an electric current from one current collector to the other through a path outside of the cell. For example, during the discharging process, one lithium atom stored in the negative electrode looses (through a redox reaction) one electron. Now, attracted by the positive electrode, the free electron travels through the graphite into the current collector and proceeds to the externally connected circuit. Simultaneously, one lithium-ion flows through the electrolyte, passes the separator and reaches the positive electrode. Intercalation is followed, and the unification (again by means of a redox reaction) of the lithium-ion with an electron occurs in the metal oxide. Thereby, since the potential between lithium and the negative electrode is lower than the potential between lithium and the positive electrode, energy is removed from the cell. The charging process may be described in an analogous fashion to the discharging process [21]. Both electrodes are in fact stacks of layers designed to store charges. These layers should last as long as possible, giving the LIB longevity, and their materials have to be electrically conductive. Subsequently, also the current collectors are made of highly conductive metals, typically copper or aluminium. However, the positive and negative electrodes, since they have different potentials, must be electrically isolated in order to prevent short-circuits. For this purpose a separator is used. The separator must facilitate the permeability in the flow of lithium-ions. For this reason, the separator as well as the lithium-ions are immersed in an electrolyte. This permeability is achieved using a porous material which should allow the lithium-ions to cross through with minimal resistance while maintaining the electrodes physically isolated [21]. The flow of lithium-ions as well as the flow of electrons occurs when a voltage supply or an impedance is applied across the cell terminals. Figure 2.1 illustrates a LIB cell structure.
2.3 Aging mechanisms

The aging of a LIB is mainly measured by its loss in capacity (the ability to store energy) and in its increase of impedance (which results in a reduction of the LIB’s ability to accept/provide power) \[21\]. These evolutions occur regardless of whether the LIB is in use or not and in the latter case, aging may be termed calendar aging. Also, aging may be accelerated by factors such as the average level of SOC throughout the cell’s life \[33\], the current rates used,
2.3. AGING MECHANISMS

and temperature experienced during utilization [34], to state some examples. The degradation of a LIB may occur in any of the cell’s parts. However, when operated, the parts subjected to the most substantial degradation are the electrodes. From the two electrodes, aging typically is more severe in the negative electrode, and that is why the aging mechanisms on this electrode are the most well studied. The two main aging mechanisms are the formation of solid-electrolyte interphase (SEI) and lithium plating which are briefly described below.

**Formation of solid-electrolyte interphase**

The formation of SEI occurs mostly in the negative electrode, especially if it is made from graphite [35]. It occurs because graphite has a low potential to lithium, a factor that increases the overall specific energy of the cell, but that makes the electrolyte prone to decomposition reactions [36]. These reactions consume lithium by turning it into a solid electrolyte layer at the surface of the graphite. This process is chronic since the decomposition reactions are not reversible. Hence, the lithium is permanently lost which results in a reduction of the LIB cell’s capacity. However, some fortunate side effects occur. As the SEI layer grows, it becomes harder for additional SEI layer to form. This is because the surface of the electrode becomes impermeable to the electrolyte, reducing the decomposition reactions between the electrolyte and the graphite. Subsequently, short-circuits between positive and negative electrodes are less likely in these parts of the LIB cell. The SEI layer is permeable to lithium-ions allowing the remaining cyclable lithium to be used for its original purpose [37,38]. However, while charging and discharging the LIB cell, the lithium intercalates and deintercalates in the respective electrodes. This enlarges and shrinks the volume of the layers of graphite and may cause the SEI layer to crack. Through the SEI fissures, the electrolyte may reach the graphite again which, as previously explained, may consume more functional lithium and create further SEI layers [37,38]. This is one of the reasons why LIBs are not very tolerant to misuse. The formation process of the SEI layer is enhanced with the increase of temperature [39].

**Lithium plating**

As the formation of SEI, lithium plating mainly affects the negative electrode. Lithium plating occurs during the charging process when the lithium-
ions attempt to intercalate into the graphite layers. There are two main reasons for this. One is related to charge intensity, namely when a LIB is being charged with a high current and the lithium-ions are forced to move at a faster reaction rate (redox reaction during intercalation) then the reaction rate that they may be physically intercalated. These unsuccessful intercalations result in accumulated metallic lithium atoms (lithium-ions unified with electrons but not intercalated) on the surface of the graphite [37]. This issue represents a main challenge in applications where LIBs are subjected to fast charging rates. The other situation where lithium plating occurs is when LIBs are charged at low temperatures (for instance subzero temperatures) [40]. At low temperature, the potential of graphite to lithium falls below the necessary potential for successful redox reactions to happen. Again, by decreasing the rate of successful redox reactions (lithium-ions united with electrons and intercalated), metallic lithium atoms accumulate on the surface of the graphite. Once converted into metallic lithium, the lithium cannot be separated in lithium-ions and electrons which results in the reduction of the LIB cell’s capacity. Moreover, by accumulating in the surface of the negative electrode, the metallic lithium can grow in a dendrite which may pierce the separator and cause an electrical short-circuit, leading to potentially dangerous thermal runaway [41]. This problem is one of the main challenges that applications requiring the usage of LIBs in subzero temperatures are confronted with.

2.4 Lithium-ion battery electric modeling

Commonly, the electrical behaviour of LIBs is represented using equivalent electric circuits [42]. The exact selection of the components belonging to the equivalent electric circuit depends on the frequency region under study for the LIB [43–45]. From the many possible circuits, the dual polarization circuit model, as depicted in Figure 2.2, is one of the most used and thus is here shown as an example. The dual polarization circuit model may represent a wide range of frequencies since it is composed by R L C circuit elements, namely: a resistor ($R_0$) in series with an inductor ($L_1$) and in series with two branches of a resistor in parallel with a capacitor, ($R_2 C_2$) and ($R_3 C_3$), respectively. In order to consider the SOC of a LIB cell, a voltage source ($E_{LIB}$) is added to the circuit model. The term $E_{LIB}$ is not considered in an ac circuit analysis.
Transfer functions are another possible representation for LIBs. Equation (2.1),

\[ Z_{\text{model}}(s) \approx \frac{s^2 + n_1 s + n_0}{d_2 s^2 + d_1 s + d_0}, \]  

elexemplifies a transfer function with two poles and two zeros. This way to characterize LIBs has the advantage of not fixing the modeled transfer function to a certain impedance structure (as the dual polarization circuit does). Depending on the frequency region to be modeled, the imaginary part of the impedance is either positive or negative (that is to say, inductive or capacitive), which influences circuit model selection.

Regardless of the selected model representation, its parameters have to be determined. This can be done by collecting electrochemical impedance spectroscopy (EIS) data. To demonstrate this process, EIS measurements were carried out for a LIB cell in its beginning of life (BOL). The large (28 Ah) cell was mounted into a set of pressure plates. Before the EIS data acquisition, the cell was set to its nominal voltage of 3.67 V corresponding to a SOC level of 50%. The EIS measurements were repeated from -30 to +30 °C in steps of 10 °C. The data were collected using a frequency response analyzer (Zahner IM6 KG) operated with a voltage perturbation of 10 mV and with a frequency sweep from 10 kHz down to 100 mHz. Figure 2.3 shows the EIS data plotted in a Nyquist plot (blue lines).
The obtained impedance data was fitted to (2.1) in Matlab\textsuperscript{1} using the \textit{tfest} command. To improve further the accuracy of the coefficients of (2.1), the selected frequency region for the fit may be narrowed down. The narrower the selected frequency region, the more accurate the transfer function coefficients (zeros and poles) become. To demonstrate this process, the frequency selected and used for the fit was from 5 to 50 Hz. The curve fitting results are shown in Figure 2.3 by the red lines plotted on top of the $Z_{\text{EIS}}$ data (blue lines). Figure 2.4 shows the model coefficients for the fitted situation as function of temperature.

Figure 2.3: (a) Nyquist plot of all the measured EIS from $0.1-10^4$ Hz (blue curves) and model fitted using data region from 5–50 Hz (red curves); (b) is a zoom of (a).

\textsuperscript{1}Matlab is a registered trademark of The Mathworks, Natick, MA, U.S.A.
2.5 Lithium-ion battery thermal modeling

To model heat transfer in LIBs, commonly two methods are used: finite element method (FEM) and thermal impedance networks [46]. When using the FEM method, each material constituting the different parts of the LIB volume may be modeled which enables an accurate prediction of the heat distribution provided that the loss distribution is known accurately. However, this comes at the expense of elaborated and repetitive numerical calculations and their subsequent computation costs. This method is typically used in LIB design [47]. A detailed description of a physics-based FEM model of the LIB cell used in this thesis may be found in [1].

In contrast, thermal impedance networks predict thermal transients in as-
CHAPTER 2. FUNDAMENTALS

sumed uniform volumes using analytical formulae [48]. This simplification allows for a low computational low-cost, which can be attractive when adopted in on-board (in-vehicle) applications.

In thermal impedance networks, the heat generation, $\dot{q}$ [J/s], is represented by the electrical analogue of a current source while (the electrical analogue of) a voltage source sets a temperature level in [$^\circ$C]. Capacitances $C_{th}$ [J/$^\circ$C] represent heat accumulation in a material and can be computed using the specific heat capacity $c_{th,spec}$ [J/($^\circ$C·kg)] and mass $m$ [kg], like shown in

$$C_{th} = c_{th,spec}m. \quad (2.2)$$

Thermal resistances $R_{th}$ [$^\circ$C/W] represent the opposition to heat flow of a material through a certain surface $A$ [m$^2$]. In a similar fashion, $R_{th}$ may be calculated using specific thermal conductivity $G_{th,spec}$ [W/($^\circ$C·kg)] as

$$R_{th} = \frac{m}{A \ G_{th,spec}}. \quad (2.3)$$

The rate of the heat generated in the interior of a LIB cell, $\dot{q}$ [W], may be categorized as entropic or ohmic heat [49]. Entropic heat is caused by electro-chemical processes named by charge transfer overpotential and mass transfer overpotential. These processes are slow, and typically arise for currents with frequencies below 1 kHz [11, 21]. In contrast, ohmic heat occurs regardless of the frequency of the current flowing in the LIB. It is dependent on the real part of the LIB’s impedance at a certain frequency and certain temperature (here addressed as $\Re(Z_{batt})$, denoting the real part of the LIB cells’ impedance), and the root-mean-square value of the injected ac current amplitude ($i_{rms}$).

By considering frequencies higher than 1 kHz and, therefore, the rate of generated heat can be expressed as

$$\dot{q} = \Re(Z_{batt})i_{rms}^2. \quad (2.4)$$

The link between heat generation, thermal capacitances, and thermal resistances is given by

$$\dot{q} = C_{th}\frac{d\Delta T}{dt} + \Delta T \frac{1}{R_{th}}, \quad (2.5)$$

where $\Delta T$ [$^\circ$C] is the temperature difference between two points, for instance the cell’s center of mass and the cell’s surface.
To exemplify the characterization of the thermal impedance network parameters, the LIB cell used in Section 2.4 was encapsulated with EPE-foam (to allow more expressive thermal transients). Different well known empirical tests, such as calorimetric tests, or abrupt ambient change tests may be carried out to extract the model parameters [50]. However, here an injected ac current was used as a method to extract the parameters of a simple $R_{th}$ and $C_{th}$ model, as presented in Figure 2.5. The temperature transient (here called $T_{fit}$) resulting due to an injected ac current was measured. Two tests were done by injecting 1 kHz of alternating current, with 0.5 and 1 C-rate amplitudes respectively were performed. The ac current had a sinusoidal shape, meaning that for instance 1 C-rate corresponds to 28 $A_{rms}$ which is equivalent to 39.6 $A_{peak}$. The tests were conducted at a starting temperature of approximately $-20 \, ^\circ C$, and were preceded by a 10 h of rest. Figure 2.6 depicts the measure data (red lines) and the result of the thermal characterization (blue lines) of LIB cell under test. The corresponding values are also found in Table 2.1.

The thermal impedance fitted parameters $R_{th}$ and $C_{th}$ were computed by fitting the measured data with a an RC exponential function, here represented by $T_{fit}$ found in (2.6), the rate of generated power is modelled by $\Re(Z_{batt})t_{rms}^2$ (as found in (2.4)), and where $T_0$ is the initial temperature

$$T_{fit} = T_0 + \Re(Z_{EIS}(f))t_{rms}^2 \times (R_{th} - R_{th} - R_{th}C_{th}).$$

(2.6)
**CHAPTER 2. FUNDAMENTALS**

Temperature $°C$  
time [hours]  
Temperature $°C$  
time [hours]  
Temperature $°C$  
time [hours]

Figure 2.6: Thermal characterization tests: at -20 $°C$ with 0.5 and 1 C-rate, 1 kHz of ac current.

Table 2.1: Fitted thermal parameters.

<table>
<thead>
<tr>
<th></th>
<th>$R_{th}$ $[°C/W]$</th>
<th>$C_{th}$ $[J/°C]$</th>
<th>$\tau = R_{th}C_{th}$ $[s]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 C-rate, 1 kHz, -20 $°C$</td>
<td>6.4</td>
<td>798</td>
<td>5110</td>
</tr>
<tr>
<td>1 C-rate, 1 kHz, -20 $°C$</td>
<td>6.5</td>
<td>823</td>
<td>5349</td>
</tr>
</tbody>
</table>

2.6 Electric powertrains

An electric powertrain is a group of electric components that deliver power to the wheels in an electric or hybrid electric vehicle. It is typically composed of a LIB, a three phase voltage source converter (VSC), and an electric machine (EM). Depending on the application, it may act alone or in parallel with a mechanical drivetrain. The mechanical drivetrain may be composed of an internal combustion engine (ICE), a torsional damper, a clutch, and a gear box. When the mechanical and electric powertrain act together, the drivetrain may be called an hybrid drivetrain. Figure 2.7 shows a schematic of the parallel hybrid drive train studied in [Paper I] which is here used as an example.
Different converter topologies have been suggested for use in electric powertrains. This includes two- and multi-level VSCs, current source converters [51], as well as, matrix converters [52]. However, two-level VSCs using a dc-link are, by far, the most adopted solution used in electric powertrains [53]. Figure 2.8 shows a schematic of a two level voltage source converters and its associated dc-link.
CHAPTER 2. FUNDAMENTALS

2.7 Dc-links

The purpose of the dc-link is to decouple the two sides of the power converter and maintain the dc-voltage has constant (or slowly varying) level as needed. As shown in Figure 2.8, the left side of the dc-link is connected to a battery and therefore dc power is used, while the right side of the power converter is connected to an EM and therefore uses ac power. By this decoupling of the two sides of the power converter, essentially two goals are aimed. One is the protection the battery against ripple currents [16,20]. The other aim is to protect the devices powered at the dc-link from electromagnetic interferences (EMI) [54,55].
Capacitors are the main components found in a dc-link [56,57]. Depending on the magnitude and frequency of the ripple currents, the capacitors may be a bulky and heavy component, which reduces the modularity of electrical system. Hence, dc-links may increase the volume, weight and cost of their
2.8 Summary of chapter

Some of the main fundamental aspects regarding batteries, the electric powertrain, and their interaction were provided in this chapter. Specifically, the operating principles and the main aging mechanisms of lithium-ion batteries were briefly reviewed. Methods to model electrical and thermal behaviour of lithium-ion batteries were also presented. Finally, the chapter is concluded.
with a short review of the fundamental technologies involved in electric pow-
ertrains and associated dc-links.
Chapter 3

The research path

In this chapter, an overview of the research conducted in this doctoral project is presented. The chapter provides short summaries as well as some of the highlights of the main contributions found in the publications appended in this thesis. Details not covered in the publications are also given as well. This chapter intends to give a sense of how the publications are connected in a research path.

3.1 The sequence of investigations

The investigations belonging to this thesis started by questioning the impact of ac currents in LIBs. Before subjecting the LIBs with different harmonic contents, a sense of what kind of ac currents dominated in the intended application was first needed. To address this issue, in-vehicle measurements on two commercial HEV Scania busses were performed. Subsequently, the data obtained from the two measurements were used as specifications for an experimental setup constructed over two years at the Sustainable Power Laboratory (SPL) at KTH. With the experimental setup in operation, several research questions could be addressed. The long term effects of ac current in LIBs were analysed, sinusoidal ripple charging was challenged, ac current heating was explored, and variations of the experimental setup were used to propose dc-dc converter designs aimed for ac current heating applications. Figure 3.1 illustrates the mentioned research topics and links them to the collection of publications appended.
3.2 In-vehicle current ripple measurements

Understanding the characteristics of real-world LIB ac currents could provide initial insights for the progress of this thesis. Scania provided two commercial HEVs (passenger busses) which could be used at Scania’s test track in Södertälje. With the available opportunity, battery current data was measurements and analysed and are presented in [Paper I and II].
3.2. IN-VEHICLE CURRENT RIPPLE MEASUREMENTS

To acquire ac current spectra data in-vehicle, the Dewetron acquisition system (depicted in Figure 3.2 d)) was used. The dc-link voltage was measured with the differential voltage probe shown in Figure 3.2 (c)). Since the LIB current measurement was of utmost importance, three methods for measuring the LIB current were used, a shunt resistor (depicted in Figure 3.2 (a)), a Rogowski coil (depicted in Figure 3.2 (a)), and a Hall-effect current probe (depicted in Figure 3.2 (b)). The strategy payed-off since for safety reasons, Scania did not allow the measurement with the shunt resistor, and for unknown reasons the Rogowski data got partially corrupted. Thus, the data presented in [Paper I and II] was harvested using the Hall-effect current probe.

The Dewetron acquisition system was chosen since it allowed long periods of recording data while sampling at 200 kSamples/s. Synchronously with the acquisition of data (sampled at a high rate), the HEV’s controlled area network (CAN) communication bus (sampled at 200 kHz) was logged and all the available HEV’s CAN signals were recorded. Thus, signals like ICE torque, shaft speed, and LIB monitoring CAN signals were also saved. To keep the amount of recorded data within reasonable limits, specific driving situations with 10’s of seconds in time length were measured. The instrumentation used in the in-vehicle measurements can be visualized in Figure 3.2.

In [Paper I] a spectral analysis of the collected LIB current data is presented. Figure 3.3 (a) depicts the spectrogram of a driving situation lasting for approximately 44 s where the HEV was accelerated from standstill to around 30 km/h and then braked down to standstill again (repeated four times). The goal of this driving pattern was to recreate a driving situation that can be found in city traffic. The spectral analysis shown in Figure 3.3 (a) helped to understand the relation between the LIB current harmonics and how they varied with different driving situations. It was found that the most prominent harmonic was a frequency corresponding to five times the shaft speed of the electrical machine (red trace from Figure 3.3 (b)). This harmonic reached a peak magnitude of approximately 17.6 A (more than 10% of maximum the dc current level) and alternated with a maximum frequency of 150 Hz. Further details of this analysis may be found in [Paper I].
CHAPTER 3. THE RESEARCH PATH

3.3 Design of the experimental setup

In [Paper IV] main procedures encountered in the design of the experimental setup with alternating current capability for evaluating large lithium-ion battery cells are presented. The key specifications of the experimental setup are also reported in Table 3.1.

The main reason why it was decided to construct the experimental setup was due to the lack of commercial options. When this doctoral project was commenced, at least to the knowledge of the author, LIB cell testers with a high (28 Ah) ac current capability operating at frequencies above 200 Hz were presently not available in the market. The experimental setup incorporates relevant lithium-ion battery cell characterization routines, namely hybrid pulse power current (HPPC), incremental capacity analysis (ICA), and galvanic intermittent titration technique (GITT). Despite of several technical challenges encountered during the construction of the experimental setup, because the experimental setup was built “in house”, it was easy to modify/adapt/disassemble/assemble. This flexibility proved valuable since it allowed the author to engage in unplanned “research detours”, where [Paper VIII]
3.3. DESIGN OF THE EXPERIMENTAL SETUP

Figure 3.3: Spectrogram and matching harmonic curves for the driving situation resembling city driving (0 to 1500 Hz zoom). This figure is reproduced from [Paper I].

and [Paper R.III.], are examples. Paper IV] includes the work found in [Papers III, R.II., and R.III.]. In [Paper III] and [Paper R.I.], preliminary and short-term tests of ac currents in LIB cells were carried out. Some design aspects of the setup were described as well. The focus of [Paper IV] is the hardware and the measurement capabilities of the experimental setup.
Also, a special emphasis to the measurements errors due to the setup’s instrumentation is given. The goal was to recorded the engineering work invested (during around two years) in the construction of setup. Finally, [Paper III] addressed the quality of the tests that can be achieved using the experimental setup and, in similar fashion, the different characterization techniques were described in detail. Figure 3.4 shows a photograph of the setup together with the climate chamber.

### Table 3.1: Experimental setup specification summary.

<table>
<thead>
<tr>
<th><strong>Targeted Cell Capacity</strong></th>
<th>28 Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneous cells</td>
<td>16</td>
</tr>
<tr>
<td>Controlled temperature</td>
<td>Yes</td>
</tr>
<tr>
<td>Availability</td>
<td>24 h—7 days—during months</td>
</tr>
<tr>
<td>Operation modes</td>
<td>Cycling, HPPC, ICA, GITT</td>
</tr>
<tr>
<td>dc current</td>
<td>60 A per channel</td>
</tr>
<tr>
<td>ac current</td>
<td>60 A_{peak} per channel</td>
</tr>
<tr>
<td>Ripple waveform shape</td>
<td>Flexible up to 2 kHz, triangular up to 70 kHz</td>
</tr>
</tbody>
</table>

3.4 Sinusoidal ripple charging

The goal of [Paper V] was to challenge the main conclusions found in [26] from where the following citation is taken:
“Compared with the conventional constant-current constant-voltage charging strategy, the charging time, the charging efficiency, the maximum rising temperature, and the lifetime of the Li-ion battery are improved by about 17%, 1.9% 45.8%, and 16.1%, respectively.”

To test the findings reported in [26], the minimal impedance (found through EIS characterization and here called $f_{Z_{\text{min}}}$) of three LIB cells was determined. LIB NMC cells with nominal c-rate of 25 Ah were charged with a dc current, as well as, with dc current plus superimposed ac current, where the ac current was alternating at $f_{Z_{\text{min}}}$. Thereby, the tests performed in [26] were reproduced. Further, three different shapes, i.e., sinusoidal (SIN), triangular
3.4. SINUSOIDAL RIPPLE CHARGING

Figure 3.4: Photograph of the experimental setup connected to the climate chamber used during the tests.

(TRI) and square (SQR) shapes were used to alternate the ac current. For each LIB cell, these tests were carried out ten times, so a statistical analysis eliminating/reducing possible measurement errors could be done. Details may be found in [Paper V] and the main results of these tests may be observed in Figure 3.5.

Based on the statistical analysis of the results, as well as results from a physics-based FEM model of the LIB cell under test, it was found that neither the charge time, nor the energy efficiency were improved by superimposing an alternating current during the charging process. For the evaluated metrics chosen in [26], it was concluded that simple dc charging is still a more performing method of charging LIBs. This results holds regardless of the three selected ac waveforms.
The null hypothesis is that each of the charging modes SIN, TRI, and SQR is not different from the dc mode. Additionally, if any of the charging modes had caused significantly higher internal temperatures, this would have resulted in lower energy efficiency for that charging mode. Since no significant difference in energy efficiency was found, this also supports that internal temperature differences are small.

The above-mentioned results are summarized in Table III.

Figure 3.5: (a) Mean energy efficiency, (b) mean charge time, (c) mean current, and (d) mean cell temperature during charge for each charging mode. The error bars represent the standard error of the mean. The figure is reproduced from [Paper V]

### 3.5 Aging of lithium-ion batteries due to ac currents

The effect of different frequencies on the aging of NMC/graphite 28 Ah commercial prismatic LIB cells is reported in [Paper VI]. The findings were obtained after completing approximately 2000 cycles, and by periodically characterized the LIB cells using HPPC, ICA, and EIS. The experiment divides the LIB cells in two groups. In the first group, the LIB cells were cycled, either with superimposed ac current, or cycled only with dc current. The second group of LIB cells were used for control and subjected either to no current or an ac-current component only. All the cycled cells were cycled using 1 C-rate and...
3.5. AGING OF LITHIUM-ION BATTERIES DUE TO AC CURRENTS

all LIB cells subjected to an ac current, the ac current had a peak amplitude of 21 A. The tested frequencies were 1 Hz, 100 Hz, and 1 kHz. The control group was only subjected to an ac current, where the current alternated at 100 Hz. The tests were terminated after the capacity of the cell decreased to about 80%. Figure 3.6 shows the results of the normalized capacity fade as a function of number of completed cycles.

As it may be observed in Figure 3.6, when compared with the LIB cells cycled only with dc current, no significant negative effect of ac currents on ca-

Figure 3.6: Normalized capacity fade as a function of number of completed cycles. Filled markers show the average of two cells from a certain test group, while hollow markers show data from a single cell from that test group. The error bars represent the full data range for each group. The upper x-axis shows total time in hours. The figure is reproduced from [Paper VI].
CHAPTER 3. THE RESEARCH PATH

Pacity fade was observed. Similarly, it was found that the ac currents had no measurable impact in power fade and that no difference in aging mechanism was detected when using the above mentioned non-invasive electrochemical methods. Details may be found in [Paper VI]. Since these results were not in agreement with some of the relevant publications available on the topic, a revision and comparison of with the results presented in [10,13,59–63] is also included in [Paper VI].

3.6 Using ac currents to heat batteries

With the insights provided by the findings presented in [Paper VI], the research path was directed towards the development of the injection of ac current for heating LIBs. This technique tries to tackle one of the weakness of LIBs which is their “aversion” to be charged at subzero temperatures. If charged at subzero temperatures, LIBs experience significant loss in power capability and rapidly age [37,38,64–66]. Since around the year 2015 the injection of ac current with the purpose of generating heat in the interior of LIB cell has been receiving considerable attention [67–74]. This technique is potentially competing with convectional heating systems which typically are utilizing some fluid circulation around the LIB cell’s outer surface. With the publication of [75], the interest in this technique increased, since in [75] it has been shown that the injection of ac current may require less energy per mass and per degree of temperature increased than in conventional heating systems.

In [Paper VII] the design of a closed-loop temperature controller is outlined. The proposed temperature controller can be applied in any kind of LIB pack operated at any frequency regardless of the LIB’s subsequent impedance nature (capacitive, inductive or resistive). One the intents of [Paper VII] is to demonstrate that the controller is immune to uncertainties rising from the aging of the LIB cells. The developed temperature controller uses BOL electrical models. Yet, it still accurately controls the temperature in the interior of aged LIB cells during transient and steady state. In [Paper VII] it is shown that when compared, the experimental results and the results predicted by the thermal model, a good match is achieved. This accomplishment may be observed in Figure 3.7. Such temperature controller may be valued in applications like the one presented in [69], where accurate control during temperature transient is needed.
3.7 INTRODUCTION OF MAGNIFIED AC CURRENT INTO DC-DC BATTERY CHARGERS

The design proposed for the temperature controller relies on an electric model and on the simple thermal model described in Sections 2.4 and 2.5 of this thesis.

Finally, Paper VII includes a short discussion regarding the experimentally found uniform temperature distribution (supported with thermal simulations using the physics-based electrochemical model) and the placement of the temperature sensors, their inevitable measurement error when compared with the temperature at the interior of the cell.

3.7 Integration of magnified ac current into DC-DC battery chargers

By understanding the potential of heating batteries using ac currents, in Paper VIII it is advocated for the magnification of ac currents as the a potential up grade in battery chargers. As addressed in Paper VIII, for safety and longevity reasons, in subzero temperatures, LIBs can only be charged after pre-commissioning their temperature. Therefore, in such conditions fast charging depends on fast heating. In Paper VII, it is shown the potential advantages of integrating magnified ac currents into dc-dc converters is put in scope. This was done by proposing the use of transformerless resonant filters as ac current magnifiers. The magnification of ac current may be achieved by exciting the output filter and the LIB with their resonant frequency. Paper VIII demonstrates a method which optimally calculates the converter’s specifications (operating frequency, component sizes). It proposes the use of a multi-objective algorithm where specifically two objectives are simultaneously optimized, i.e., maximize the ac current magnification and minimize the circuit impedance. The purpose of these design objects is to maximize the generated heat in the battery while minimizing semi-conductor losses.

One of the highlights of Paper VIII is the exemplification and validation of the optimization used in the design method. We exemplified it using gain spectroscopy (GS) (for both simulations and experiment). In the laboratory, GS was achieved using the experimental setup’s VSC injecting a controlled chirp current signal similar to the one used for the regular EIS. The difference was that instead of measuring voltage and current and then calculating the impedance, in case of a GS, two currents are measured and their ratio is determined over a certain frequency range. Sample simulations and experimental
Figure 3.7: Implemented and modeled temperature controller performance using a reference temperature step. (a) Cell’s temperature measured by implanted K-type sensors (1, 2 and 3 with green, cyan and pink lines respectively); cell’s temperature measured by the PT100 sensor (black line); simulated cell’s temperature (blue line); (b) Measured current reference (red line); simulated current reference (purple line). This figure is reproduced from [Paper VII].
3.8. SUMMARY OF CHAPTER

results are illustrated in Figure 3.8. [Paper VIII] is concluded with a topological survey where the proposed

method was used to design dc-dc converters based in half- and full-bridge switch arrangements. It is demonstrated that by using an LCL circuit and a full-bridge switch arrangement, magnifications of up to 15.7 may be reached. Further, by matching the switching frequency with the frequency where the LCL and the battery resonate, the stress in semiconductors could be decreased. This allowed a loss reduction in the semiconductors of up to 75% when compared with an equivalent DC-DC converter.

3.8 Summary of chapter

A summary and some of the highlights of the main contributions found in the publications appended in this thesis were presented in this chapter. The

![Figure 3.8: Comparison of Bode plots of $G_{Gain}$ for experimental and simulation results. This figure is reproduced from [Paper VIII].](image-url)
motivations and the rationale linking the publications in a research path were also pointed out.
Chapter 4

Conclusion and Future Work

This thesis reports the work carried out in a doctoral project which starts by acquiring in-vehicle (HEV) battery harmonic current data. With the frequencies and amplitudes found in the current circulating through the HEV’s battery, an experimental setup with alternating current capability for evaluating large lithium-ion batteries cells was designed. This setup allowed the collection of large amounts of data which, in turn expanded the understanding of the effects of ac currents on charging performance, on the life time of LIBs, and on the viability of using an injected ac current as a heating method for LIBs.

The harmonic currents of the batteries of two commercial hybrid vehicles were measured. The spectral analysis of the in-vehicle battery harmonic currents data revealed several harmonic currents with different amplitudes and frequencies. The most prominent harmonic had a peak magnitude higher than 10% of the maximum dc-current level (160 A) arising at frequencies below 150 Hz. The origin of this harmonic was not confirmed, but it is suspected that it could originate from an eccentricity of the resolver. It was also found that the magnitude of the dominating harmonic increased significantly when the EM reached the field-weakening operating range. This makes magnitude prediction more complicated since the dynamics of the current/torque control implemented in the converter controller must be considered. The maximum amplitude detected in a harmonic due to the VSC’s switching frequency was around 10 A at 2 kHz which is not insignificant. In parallel to the in-vehicle
measurement, an experimental setup with alternating current capability suited for large lithium-ion battery cells was designed, built, and commissioned. The experimental setup allowed long term charge-cycling testing. Particularly, a one-year study demonstrated that when compared with dc cycling, cycling with a superimposed ac current (where frequencies the 1 Hz, 100 Hz and to 1 kHz where tested) have negligible impact on capacity and power fade of LIB cells. Further, the incremental capacity analysis carried out indicated no difference in aging mechanisms between the cells cycled with dc current only and the LIB cells cycled a superimposed ac current. This finding could mean that the filtering requirements of the dc-links used in the power converter may be reduced if EMI requirements are not the limiting factor. This may, hence, represent a potential saving in terms of system cost for industries producing electric mobile devices.

In addition to the LIB cell aging tests, the experimental setup was used to challenge the sinusoidal ripple charging technique. The comparison between sinusoidal current-ripple charging and conventional constant-current constant-voltage charging was done using three LIB cells and repeating ten times a full cycle with different ac currents superimposed during charge. The results were analyzed statistically, and no significant improvements in the charging time as well as in terms of charging efficiency, were observed in any of the charging tests using an superimposed ac current.

With the insight that ac current could have negligible impact on LIB’s life time the research path changed. Now, instead of trying to understand how much ac currents should be filtered, the new path was to understand whether ac currents can be exploited to obtain any system advantage. Hence, the injection of ac currents into batteries for heating purposes was studied and a control method for battery heating using ac current was proposed. In this context, methods to model lithium-ion battery (electrically and thermally) envisioning onboard utilization were recommended. The proposed controller could be applicable regardless of the LIB’s subsequent impedance nature (capacitive, inductive or resistive). Further, injection of alternating current was proposed as an option method to characterize the parameters of a lumped element thermal model. By applying this thermal model, the proposed temperature controller has shown to be immune to uncertainties rising from the aging of the lithium-ion battery cells. This knowledge intended to help regarding the viability of this technique, and may accompany this technique in its path to commercial adoption.
Motivated by the potential of the above mentioned heating technique, and considering that LIB fast charging in subzero temperatures depends on fast heating, a design process enabling the generation of magnified ac currents in dc-dc converters was proposed. This is achieved by exciting the dc-dc converter output filter and the LIB with their resonant frequency. It uses a multi-objective algorithm for finding the highest current magnification while keeping the impedance driven by dc-dc converter to a minimum. In this way, optimal operating conditions for the dc-dc converter, such as operating frequency, as well as optimal filter sizes may be found. Using the proposed design method, a topological survey of dc-dc converters with magnified ac current capability composed by half- and full-bridge switch arrangements is carried out. It was demonstrated that by using an LCL resonant circuit and a full-bridge switch arrangement, magnifications of up to 15.7 may be reached. Further, by matching the switching frequency with the frequency where the LCL and the battery resonate, the stress in semiconductors could be decreased. This allowed a loss reduction in the semiconductors of up to 75% when compared with an equivalent dc-dc converter.

4.1 Future Work

This thesis demonstrated the negligible impact of ac currents in LIBs, specifically in power optimized NMC LIB types of cells. The data was collected by testing the LIB cells with a cycling current of 1 c-rate at 40 °C. Considering that different batteries chemistries are more and more available in the market, the repetition in ac current aging tests in different battery chemistries is recommend. Additionally, and with particular interest for the follow-up of this thesis, the investigation of the long term effects of large ac current in LIBs under subzero temperature should be carried out. Comprehending the formation of lithium planing at high ac currents rates (4 c-rates, maybe even higher) will be determinate for the demonstration of the commercial viability of heating LIBs by injecting ac current.

All the laboratory tests carried for this thesis were carried out at the cell level. However, if LIB cell level tests are indicated for understanding, for instance the impact of ac current in LIBs lifetime, they are insufficient to understand thermal behaviours of LIBs in real applications. Therefore, thermal modelsof LIB packs used in a real applications, where packaging characteristics as well as the cooling systems may be modelled, could provide a deeper understanding of
the performance of the injection of ac current technique as a practical heating method. Also, by moving the investigation towards LIB packs, a topological survey where the modularity to the LIB pack may be use as an advantage. In this context, an algorithm proposing the optimal thermal and energy management of the LIB pack could be proposed.

The experimental setup used for testing dc-dc converters with integrated ac magnification was assembled with off-the-shelf components. It aimed the implementation of a design method and the verification of dc-dc converter performance hypothesis, such as ac current magnification and semiconductor loss mitigation, rather than to develop a commercial product. While prototyping is a normal task in a doctoral thesis, it is also a caveat when circuit performance are extracted as if in a final commercial product. The development of that experimental setup used none optimized inductors and the components were not packed so that their stray resistances could be minimized. Hence, the case study presented in [Paper VIII] (which is representative for the prototype there shown) can be improved.

Within the study of the integration of magnified ac current into dc-dc converters, several follow-up investigation may be made. A topological survey of the applicability of different resonant circuits, the integration of magnified ac current in different circuit topologies used in battery packs, such as modular multilevel converters, as well as, extending the understanding of best control practices (for example PI versus and resonant controller) could be explored.
Bibliography


BIBLIOGRAPHY


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