A Battery Management Unit

Master of Science Thesis in the programmes Integrated Electronic System Design & Secure and Dependable Computer Systems

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Preface

This thesis was done as a part of the Masters programme in Computer Science and Engineering at Chalmers University of Technology.

We would like to thank QRTECH for giving us the opportunity to work in this exciting field. Special thanks to our project supervisor at QRTECH, Linus Lundin, for all his guidance and support. We would also like to thank Texas Instruments and the group working on the bq76PL537 for all their help and ABATEL, our supplier and sponsor of the battery cells. We are also grateful for the feedback on the thesis from our examiner Jan Jonsson.

And last, but not least, a big thanks to friends and family for their support.

Abstract

Emissions from vehicles and decreasing oil resources are pressing matters in today's society. Electric vehicles are considered, by some, to be the solution to those problems. For years the available batteries have been too heavy and inefficient to be used in commercial electric vehicles. This thesis considers a new cell technology, $LiFePO_4$, which was investigated and implemented into a battery pack for a prototype electric go-cart. The $LiFePO_4$ cells need to be supervised by an efficient Battery Management Unit to function. The Battery Management Unit implemented in this thesis was based on minimal hardware combined with a prototype board for active cell balancing. The results show that it is possible to build such a lightweight Battery Management Unit, but with the loss of accuracy in the system.

Keywords: State of charge, Battery Management, $LiFePO_4$, Li-Ion, active cell balancing, electric vehicle

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List of Abbreviations

ADC	Analog to Digital Converter
Ah	Ampere hours
BMU	Battery Management Unit
CRC	Cyclic Redundancy Check
DOD	Depth of Discharge
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
kWh	Kilowatt hours
LED	Light Emitting Diode
MISO	Master input - Slave output
MOSI	Master output - Slave input
SCLK	SPI Clock Signal
SOC	State of Charge
SOH	State of Health
SPI	Serial Peripheral Interface Bus
SS	SPI Slave Select
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
V_{OC}	Open Circuit Voltage

Li-Ion battery technologies

LCO	Lithium-Cobalt
$LiFePO_4$	Lithium-Iron-Phosphate
LMO	Lithium- Manganese
MCO	Manganese-Cobalt

Other battery technologies

Pb	Lead-acid
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal-Hydride

1. Introduction

The combination of the worlds need for lower emissions, non-fossil energy sources and the development of battery technologies has opened up new possibilities for the future of automotives. With hybrid electric vehicles already on the market, the automotive industry is looking at pure electric vehicles to meet these global demands [1][2]. Today's battery technologies have a higher energy per weight ratio but the new chemical structures bring on new challenges concerning battery management and safety [1]. One of the technologies with the highest energy density is the Lithium-Ion cell [1][3]. Although it has been used for years, this technology is still expensive. When used as a single energy source in an electric vehicle a large amount of cells is needed. Therefore, the need to prolong the battery lifetime, as well as using its full capacity, is of the utmost importance. A new type of Lithium-Ion cell technology is used in the project.

QRTECH AB is a Swedish company focused on developing embedded systems. The company has years of experience working in the automotive industry. An electric vehicle was designed by QRTECH to test new technologies for future automotive projects. With a smaller electric vehicle, such as the QRTECH go-cart, new ideas and technologies can be implemented and tested quicker and at a lesser cost. Old implementations in the go-cart can be easily extended or substituted with newer technologies.

The aim of this thesis was to produce a battery pack with a battery management unit for the above mentioned go-cart. This included designing and assembling the battery pack from single cells, responsibility for safety functions, set-up and programming of the hardware.

Starting with the background for the project and the history of electric vehicles this first chapter summarizes the basics in electric vehicle technology: its advantages and limitations, cell technologies and the need for intelligent battery management systems. The outline for the project with methods and limitations are described at the end of this chapter.

1.1 Background

Some might think the electric vehicles (EVs) of today are ultramodern and somewhat futuristic, but the truth is the dawn of the electric vehicle (EV) belongs to a different century altogether. The history of the EV began in the early 1800s. By the mid 30's both Volta's invention of the battery and the electric motor by Faraday had been engineered into the first electric road vehicle [1].

Both the design of the cars and the battery technologies evolved during the 19th century. For instance, the discovery of the first re-chargeable battery in 1859 by Gaston Planté [1][4][5] furthered the development of EVs. The main principle of Planté's lead-acid battery has not changed since those early years and it is still the most used battery technology today [4]. The lead-acid battery made it possible to store higher amounts of energy, but with the cost of increased weight. Despite this weight limitation, EVs were still competitive and held a third of the automotive market in the early 1900s [1]. The competing technologies at that time were fuel and steam. The golden age of the EV ended in 1912 when the cost and the limited driving range could no longer compete against the popularity of the gasoline car. In the United States, EVs were quickly overrun by Fords new Model T [1]. With the smaller market share, the cost of producing EVs increased even more and many companies ended up bankrupt [1].

Since then there has been limited amount of EVs and hybrid EVs built by automotive companies, most of them mainly for research [5].

With the pressure on decreasing emissions and oil dependence, hybrid EVs are becoming more common, not just as prototypes, but also as consumer vehicles [5]. The successful Toyota Prius model is an example of that. It is a series-parallel hybrid [6] that combines the advantages of EVs with today's combustion engines. In such a hybrid set-up, the cars run on an electrical engine when at start-stop and low speed driving, while using fossil fuels for longer rides at higher speeds, as well as for re-charging the battery. Today it is possible to build lighter vehicles, use re-generative braking and more energy efficient batteries. Even so, pure EVs have a minimal share of the consumer market due to problems concerning top speed, range, safety and charge times. A pure EV on the market in 2010 is the "Think City" car by Think that has a top speed of 100km/h, a maximum range of 180km and a charge time of 13 hours[1] [7].

The largest cost item in an EV is the battery needed to run the electric engine, but even with the higher capacities of Lithium-Ion (Li-Ion) batteries EVs cannot compete against fuel vehicles. For example, the Boston-Power battery Swing has an energy density of 180 Wh/kg [8] which is high for batteries, but low compared to a conventional fuel such as Diesel with an energy density of 12700 Wh/kg [9].

Today's battery technologies have advantages, but they also bring new challenges. The Li-Ion technology gives a more reliable and steady current, but is highly sensitive for under and over voltage. These cause degradation of the battery and, in worst case, even explosion due to thermal runaway [10]. Thermal runaway is further discussed in section *2.23 Temperature*.

1.2 Battery Management Unit

The management of the battery in an EV is of great importance since improving battery life-time will reduce cost as well as runtime for the vehicle. The battery status must be known and managed to achieve a longer lifetime and a higher level of safety and reliability. Even with $LiFePO_4$ cells that are more reliable than earlier Li-Ion cell technologies, the risk of thermal runaway, explosion and early degradation remains [11]. The cells in an EV battery pack are expensive; today they are the largest cost item in an EV. Any deterioration in lifetime or capacity leads to a need for more cells to compensate for the loss. Therefore, the cells in a battery pack have to be controlled individually in order to optimize the stored energy. Safety and reliability in the automotive industry are of greatest importance and the high energy density in a battery is a critical safety concern. Measures have to be taken to protect the battery itself, the vehicle, its passengers and the surrounding environment. An intelligent Battery Management Unit (BMU) can control and manage cells individually, thus prolonging the lifetime, increasing the capacity and managing the safety of the battery.

[1] 13 hours when charging at 230V and 14A

1.3 Method

This section describes the method used in the project for this master thesis.

Part 1- Studies

The first part of the project consisted of exhaustive studies in electrical and hybrid vehicles and different available battery and BMU technologies, such as balancing algorithms and management. This included testing different algorithms and electronics for the final BMU. Since the project includes so many different areas, a large amount of time was spent on planning how to realize the project.

Part 2 - Implementation

The second part of the project consisted of an implementation phase of the found solution for a battery pack. In addition to the development of software and assembly of hardware, the cells for the project needed to be found. Before the software implementation, a BMU prototype was simulated using Matlab and Simulink. In Excel different algorithms for active cell balancing were simulated and analyzed. The different parts of the project, both software and hardware, were built piecewise to ease troubleshooting. During the project, the software was developed for and tested on a smaller platform with fewer cells. A reason for this was that only 6 cells were available at the beginning of the project.

Part 3- Finalization

The software needed to be altered to fit the final cell set-up and the devices at hand. Testing was done throughout the process. The final step was to combine the implemented BMU and the battery cells into a complete battery pack.

1.4 Scope

The project for the thesis consisted of modelling and simulating a minimal BMU and the programming and assembly of the control unit and battery pack. The main goal of this project was to develop a small, cost efficient and safe battery management unit to be implemented in an electric go-cart. The use of active cell balancing, as well as balancing in general, is a complex area which will be discussed throughout this thesis. An evaluation board with active cell balancing from Texas Instruments was used.

The main difficulties in the project were to find algorithms for cell balancing and to implement the final system on limited hardware. Therefore, the focus of the project was on finalizing the actual battery pack. Although testing, simulation and analysis of the software and hardware was done throughout the thesis, deeper analysis of the final battery pack was outside the scope of this thesis.

1.5 Limitations

The cell technology implemented in this project is the $LiFePO_4$. Although other cells or energy sources could be considered for an EV, this was a choice made by QRTECH. The $LiFePO_4$ cells are, at the moment, the most stable technology with a sufficient amount of energy to be interesting for EV developments in the near future. One of the major reasons for developing EVs is to lower emissions and the environmental effects caused by the conventional cars used in today's society. This report does not take into account the environmental impacts caused by the $LiFePO_4$ cells nor does it focus on energy sources for charging the batteries.

The BMU in this project will not include a State of Health (SOH) since the cells for the go-cart will be changed over time. A simple SOH could be implemented, but would require batteries to be tagged and for the user to notify the BMU which cells are in use. Instead, implementing a small, efficient and accurate State of Charge to be run on limited hardware will be the objective.

Even though temperatures greatly effect the performance and capacity of Li-Ion cells, the implemented State of Charge (SOC) will not take into account any temperature changes. It is assumed that the prototype will only be used within the optimal temperature range of +20-30°C. The safety functions in a real EV should monitor the battery pack temperature and signal if it reaches a critical level. The battery pack for the go-cart will only consist of a smaller amount of cells. Therefore, it will not be necessary to monitor the pack temperature.

In this project both active and passive cell balancing schemes are considered, but the final implementation only includes active cell balancing. Balancing could be done at any time and the aim is to even out voltage differences between cells. Due to the complexities of balancing algorithms within active cell balancing, the project will only focus on balancing cells after a full charge and without a connected load.

Since the implementation phase of the project consists of constructing a battery pack for an EV, the main focus in this report will be on EVs, even though HEVs will be discussed.

As stated in *1.4 Scope*, the project will focus on the design and implementation of a BMU. Although some tests will be done, major testing and analysis of the BMU and battery will be outside the scope of this project.

The go-cart at QRTECH is being built in parallel with this thesis project. Therefore, it will not be possible to test the final battery pack in the go-cart within the limits of this thesis. Further tests and integration of the system into the go-cart will be continued by QRTECH.

1.6 Organization

Chapter 2 with sections 2.1-2.3 summarizes the theory in battery technologies, electric vehicle implementations and the charging of batteries. Chapter 2 then continues with sections 2.4-2.5 which address safety issues and environmental aspects concerning battery driven vehicles.

Chapter 3 contains the theory of Battery Management Units. The basics of a BMU are described in this section, with a greater focus on its core functions: State of Charge in section 3.1 and Cell balancing in section 3.2. Sections 3.3 and onwards summarize the safety, reliability and fault tolerance concerning a BMU.

Chapter 4 describes the project for this thesis. It begins with a short description of the go-cart at QRTECH for which the battery pack is designed for. It then, continues with the design of the battery pack. An overview of the final system is described in section 4.2. In sections 4.3, the implemented BMU and SOC for the go-cart are presented.

The results of the project are discussed in chapter 5.

Finally in chapter 6, some of the conclusions from the project are stated. This includes both the implementation and the field of EVs.

2. Theory of batteries

This chapter covers theories in the field of EVs, the different available batteries, charging, Battery Management Units (BMU) and State of Charge (SOC) technologies. It also includes a section concerning the safety and recycling in relation to EVs.

2.1 Battery construction

Many different battery technologies have evolved since the 1800s and Volta's first battery [5]. No matter what technology a battery is based on, the main idea is still the same: to convert chemical energy into electric energy.

2.11 Primary and secondary cells

A battery consists of one or more cells. Cells are usually classified as primary or secondary cells. Primary cells are not re-chargeable, their chemical structure will not tolerate re-charging and so an empty battery of this type will need to be discarded. The advantages of primary cells are low cost, long shelf-life and ease of use [4]. Secondary cells are more complicated than primary cells and do not have the advantages of primary cells. Even their energy density is lower, but they are re-chargeable and can be re-used. This makes secondary cells a better candidate for portable applications, EVs and other high energy consuming products [4]. There are different secondary battery types and Lithium-Ion is the umbrella term for the lithium technology.

2.12 Cell structure

A cell consists of an electrolyte and two electrodes called anode and cathode. The anode is the reducing electrode and gives up electrons [4]. The cathode is the oxidizing electrode due to its ability to accept electrons [4]. The electrolyte and electrodes can be constructed of different materials and the cell technologies are named based on these. A common electrolyte usually consists of a liquid such as water containing dissolved salts, acids or alkalis to improve ionic conductivity. There are also technologies based on dry or gel electrolytes. In a discharging battery connected to an electric circuit, electrons move from the negative electrode to the positive electrode through the load circuit. During charge, the process is reversed and the electrodes change tasks, causing the electrons to move in the opposite direction. This charging process converts electric energy back to chemical energy.

An important factor affecting the performance of a cell is the internal impedance. The impedance consists of different types of resistance due to the chemical structures in the cell. These consume a part of the available energy in a cell and emit heat, causing a voltage drop during operation (also called IR drop or Ohmic Polarization). Weight and active material may differ in cells due to imperfect production processes, causing the impedance to differ even between cells within a production series [12]. The theoretical energy stored in a cell is only theoretical and is, at its best, available at low operation currents where the effects of the internal impedance are small [4]. For many applications, especially EVs, low currents are not an option. Cells for a battery pack should be chosen from the same production series to at least minimize the differences stated above. Cell differences have great impact in EV battery packs which contain hundreds of cells. Even small imbalances will affect the EVs performance and the lifetime of its battery pack [13].

2.13 Cell set-up

In general, a battery consists of one or more cells connected in series and/or parallel set-ups. By connecting cells in parallel, the total capacity of the battery increases, but the voltage remains unchanged. Connecting cells in series causes the total voltage to increase while the capacity stays the same. Combinations of series and parallel set-ups are common and designed to fit the application at hand [14]. In the case of EVs it is common to have more than 100 cells in series to get the desired voltage of 300-400 V. The need for higher capacity also requires the cells to be connected in parallel. The possible connections are shown in figure 1.

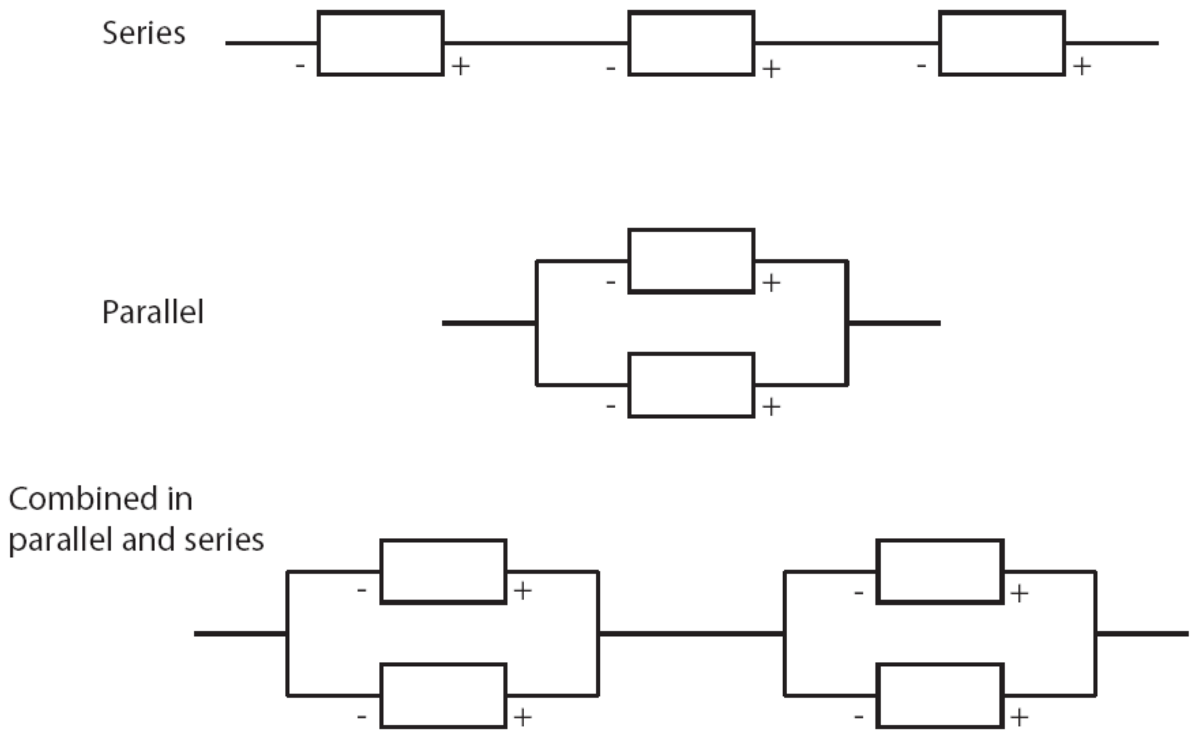


Figure 1. Different cell connections.

2.14 C rate

C rate is used to indicate the charge and discharge currents for a battery cell [4]. Manufacturers specify the rates for cells they develop as an indication of what rates are feasible without damaging the cells. A discharge rate of 1C means that the current delivered by the battery will discharge the battery in one hour. If a greater discharge rate is used, the time to discharge the battery will be shorter, i.e. one divided by the C rate (in hours). When choosing a battery it is important to decide what discharge and charge currents will be used, so that the battery used will manage the currents for the system and the charger.

$$h = \frac{1}{C}$$

Where *h* represents the time in hours for discharging at rate C. For example discharging a battery with the capacity of 20 Ah, at 1C will discharge the battery with a constant current of 20 A. The total discharge time will then be 1 hour. If using a C-rate of 5C for the same battery, the constant current will be 100 A with a discharge time of 1/5 hour, i.e. 12 minutes.

2.15 The $LiFePO_4$ battery technology

Due to lithium's high density of power and energy, it is a perfect candidate as an electrode material [4][15]. Power density is a measure of energy throughput during discharge and energy density is the amount of stored energy. Only Aluminum and Magnesium have better properties, however lithium is preferred because of its low reactivity and better mechanical characteristics [4]. Even so, lithium still reacts strongly with water, releasing hydrogen and forming lithium hydroxide [16]. This reaction emits heat and may ignite the hydrogen and cause the lithium to burn. It should, therefore, be handled with care and the electrolyte in Lithium batteries should preferably be non-aqueous[2] [4].

A Li-Ion battery cell contains other compounds than lithium, the actual amount of lithium is as small as 3% [17]. When discharging a Li-Ion cell, the electrons in the electrode are released and move through the external circuit providing energy, while the ions move through the electrolyte. When charging a cell, the work is reversed, thus moving the ions back through the electrolyte creating a swinging motion. The Li-Ion batteries are sometimes referred to as swing batteries due to the swinging movement of the ions [1]. There are many different Li-Ion cells with varying compound set-ups, for example, $LiCoO_2$, $LiMn_2O_4$ and $LiFePO_4$, and others.

[2] The Lithium-Water battery is an exception

Battery type	Maximum energy density (Wh/kg)	Voltage (V) [7]	Self-discharge Loss of capacity % per month	Examples of usage
Lead-acid	35 [3]	2	4-5% [4]	Car batteries
Nickel-metal hydride	70 [3]	1.2	25-30% [4]	EV, HEV [5]
Lithium-solid polymer	200 [3]	3.7	5% [6]	Laptops, mobile phones
$LiFePO_4$	90-110 [7]	3.2 [8]	3% [8]	New technology

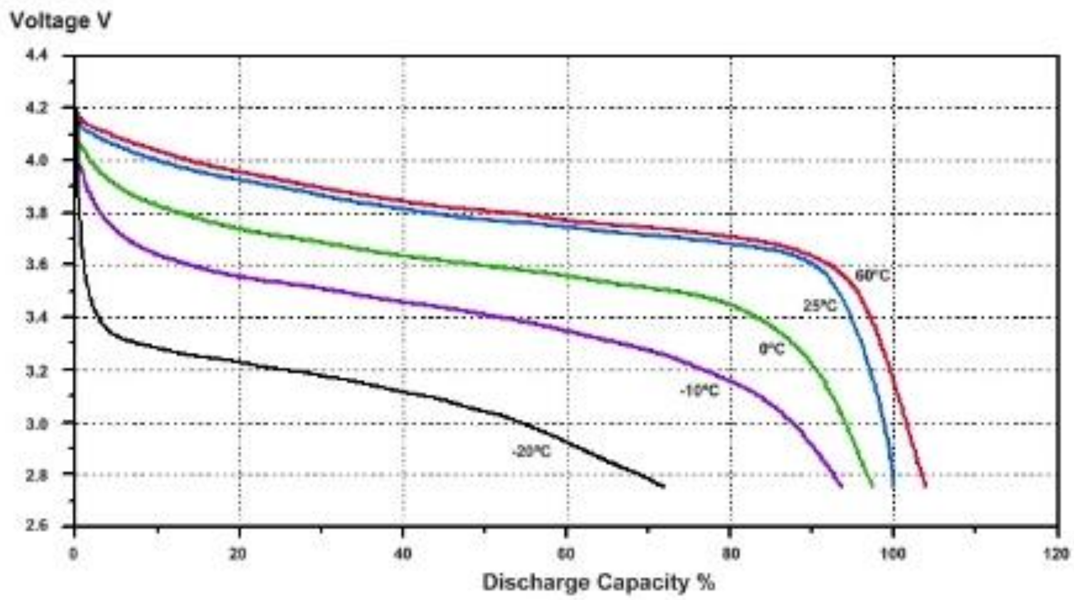
Table 1. Table of battery properties. Note that the energy density of diesel is about 12 700 Wh/kg [9].

Li-Ion cells can be produced in different shapes and have a higher energy density than many other battery technologies [1], see *Table 1 Table of battery properties* for a comparison. This makes them a suitable candidate for EV implementations, where both weight and space are major issues. An advantage of the Li-Ion technologies is the low self-discharge rates, about 5% of its capacity per month [18]. Self-discharge is a loss of capacity over time due to parasitic reactions in the chemicals of a cell [18]. The rate of the self-discharge depends on the temperature affecting the cell. The capacity loss is not permanent and can be regained by charging, but the self-discharge of the battery continues afterwards, both when in use and in storage. Other technologies used in hybrid and pure EVs have much higher self-discharge rates, for example valve regulated lead-acid (15%) and nickel metal hydride (25%) [18].

Li-Ion does not suffer from memory effects like other technologies do [1]. Memory effects decrease battery capacity due to faulty charge and discharge procedures [4]. For instance, a NiCd battery exposed to repetitive shallow discharges will have a lower voltage when the previously unused material is fully discharged [18]. This type of memory effect or voltage depression, as it is also called, can be reversed by maintenance charge cycles. Maintenance cycles are not needed for Li-Ion cells. However, the Li-Ion technology has its disadvantages: high production costs, the need for temperature monitoring and protection against under and over voltage. These factors contribute to the need for a BMU, to monitor and control a Li-Ion battery.

[3] The Electric Car - Development and future of battery, hybrid and fuel-cell cars (1)
[4] Electropaedia (21)
[5] For example in Toyota Prius (6)
[6] ABATEL (40)
[7] Wikipedia (39)
[8] Shenzhen Mottcell Battery Technology Co. (36)

A $LiFePO_4$ (Lithium-iron-phosphate) cell is an application within the Li-Ion technology. It is named after the chemical compounds of its electrode material. The use of iron in the electrode makes the cells more stable than other Li-Ion technologies and less prone to thermal runaway [4][19]. It is common for Li-Ion technologies to be effected by temperature; an example of how the capacity is effected can be seen in graph 1. Compared to other Li-Ion technologies, the $LiFePO_4$ cell has a lower voltage and energy density, but on the other hand it has a lower capacity loss over time. Even though $LiFePO_4$ batteries can withstand higher temperatures than other technologies, their performance is still affected by temperature changes.



Graph 1. The effects of temperature on the capacity of a Li-Ion ($LiCoO_2$) battery [20].

2.2 Batteries in EV

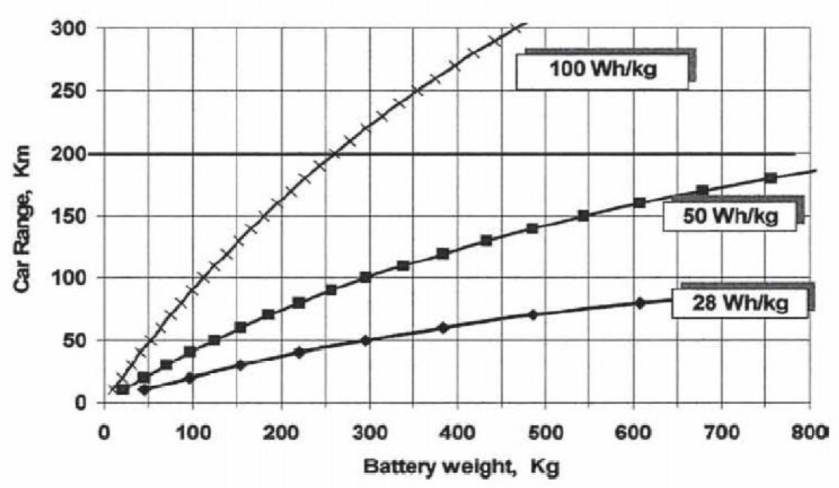
In this section, the batteries in an EV are evaluated with a focus on the cost of the battery, weight and temperature considerations. The last section contains some identifications of large power consumers in a car, which need to be considered in an EV.

2.21 Economics of EV

Batteries used in EVs are often produced in small demonstration series and therefore the cost for producing a battery pack for a vehicle becomes high. The lifetime of the batteries varies between technologies and an EV battery pack may not last even 10 years. The cost of the battery pack is one of the largest disadvantages with EVs today.

2.22 Weight of batteries

Weight of batteries is a big disadvantage compared to gasoline which has a higher energy density than any of the battery technologies used today. A range of 100 km for an electrical vehicle requires over 400 kg of lead-acid batteries, about 200 kg of nickel-metal hydride (NiMH) batteries or about 120 kg of Lithium-Ion (Li-Ion) batteries [1]. A typical gasoline car, on the other hand, may only need about 10 liters for the same range. Development is needed to improve battery performance and weight to make EVs more comparable to conventional cars.



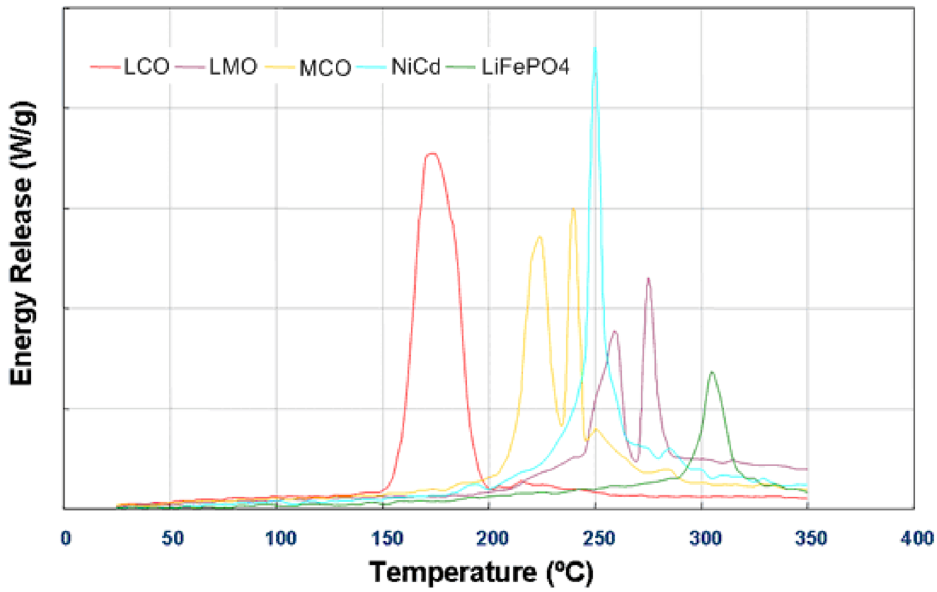
Graph 2. Describing the relation between range and battery weight [5]

Since the weight of the battery itself affects the performance and range of an EV, the battery material has to be light but still contain enough energy. While the range for an EV increases with the size of the battery, its weight might become intolerable. According to *Industrial applications of batteries: from cars to aerospace and energy storage* [5], the most important parameters when considering a battery technology for EVs are energy density and specific energy. The only probable technology to exceed a 200km range is Lithium since these batteries have an energy density over 100Wh/kg [5].

2.23 Temperature

Temperature affects battery cells' chemical structures and are of importance both during use and storage. The temperature ranges for storage and operation differ between technologies and manufacturers, with some cell technologies being more sensitive than others. Storing cells in a too hot or cold environment will damage the cells and cause a decrease in their total capacity shortening their shelf-life [4]. Over usage or overcharging at temperatures outside the cell's operational range may cause permanent damage to the chemical structure of the cells making them inoperable [4]. A low temperature during discharge of a cell causes a reduction of the chemical activity and an increase of its inner resistance [4]. Examples of the impact on capacity by different temperatures can be seen in graph 1.

At high temperatures, the chemical activity in a cell will increase and its inner resistance decrease. This can cause higher self-discharge rates and a decrease of the cell's capacity. It is not only the surrounding temperature that can be damaging, but also the heat produced by the individual cells inside the battery pack. Discharging at high rates may cause anomalous effects leading the cell to heat above its operational temperature range [4]. If over-heated, some cell technologies, such as NiCd, can dry out and short circuit [4], while others, such as LCO cells, could rupture and explode as a result of thermal runaway [13]. Thermal runaway is a chemical reaction caused in heated cells where the inner temperature causes more heat to be exerted leading the cell to be exposed to hundreds of degrees Celsius. Some Li-Ion technologies are especially prone to thermal runaway and caution should be taken during usage [1]. As seen in graph 3, $LiFePO_4$ is a safer technology due to its low energy release at high temperatures.



Graph 3. The graph shows the energy release for different cell technologies when thermal runaway occurs [21]. *The top of the curves, in order from the left: LCO, MCO, NiCd, LMO and* $LiFePO_4$.

Heaters and air-conditioners can be used to maintain a battery's optimum operating temperature and avoid the negative effects stated above. However, heaters and air-conditioners consume a lot of power and will affect the EVs operating range [1].

2.24 Power consumption in a car

Essential functions such as lighting, instrumentation and windshield wipers are necessary for the safety of a car. These features, however, consume energy and therefore the performance in distance when used in an EV may decrease. As mentioned in section *2.23 Temperature*, heating and air-conditioning for the battery may also be necessary. Other functionalities taken for granted in modern cars are power steering, front and rear window defrost, electrical windows, door looks, media functions and many other features [1]. All functions need to be considered when constructing an electrical vehicle for the consumer market.

2.3 Charging

This chapter discusses the charging of an EV and describes the different methods used today. It also considers some of the difficulties faced when designing charging methods. Only the charging technologies available to Li-Ion batteries have been accounted for in this section.

2.31 Charging technologies

Not all charging methods are suitable for Li-Ion cells due to their sensitivity to overheating and under and over voltage. Compared to other technologies, the amount of parasitic processes is low, thus minimizing the benefits of using more complex charging methods [4]. For example, pulse charging would minimize the gas forming in a cell, but this is not a problem in the non aqueous Li-Ion [4]. Overcharging is wasteful and damages both Li-Ion batteries and other technologies [18]. According to *Electric vehicle battery systems* [18], overcharging is most likely the biggest factor in reducing battery life [18].

Charging can be done at different rates, see *2.14 C rate* above. When considering charging methods for an EV, the most common rate being discussed is slow charge. In general, a typical car is used during the day and has range of 40 km with an average energy consumption of 0.2 kWh per km [1]. With an optimal discharge rate of 80% this gives a total of 10 kWh needed for the average commuter car per day and could easily be charged over night during an 8 hour period [1]. This does, however, raise the question of fast charging EV batteries when needed. At the moment, battery and EV manufacturers are working on enabling fast and flexible charging for Li-Ion cells. Some have had successful results with fast charging, for example the Think car company that has managed to charge from zero to 80 percent capacity in 15 minutes [22]. Still, little is known of the long-term effects of such charging. Other research is focused on changing the chemical structures in the Li-Ion cells to improve their charge performance [23][24].

Some charging methods are described below.

Constant voltage

A constant voltage is applied until the battery voltage matches the charge voltage. This method, combined with safety functions, can be used to charge Li-Ion batteries as long as the current is limited. [18][21]

Constant current:

The voltage over the battery is varied during charging while the current maintains a fixed rate. Charging is aborted when the battery voltage reaches its maximum value. This way of charging makes it possible to keep track of the current input to the battery. On the other hand, charging with a high current may cause overheating and electrolyte leakage in some batteries [18]. This method can be used for Li-Ion batteries as long as the voltage is kept within range; if the voltage reaches the over voltage limit safety functions should abort charging. This charging method is mostly used for nickel metal hydride batteries. [18][21]

Pulse charge:

Charging the battery with a current pulse enables the charge rate to be more controlled. Between pulses there is a short rest period. Voltage measurements can be done during pauses, preferably at the end of the rest periods when the chemicals have stabilized a little. The downside of this charging method is the duration; the pauses between pulses increase the charge time compared to other charging methods. This method can be applied to Li-Ion, but is mainly used for lead-acid batteries. [18][21]

Combined charge

Many EV charging systems combine constant voltage and constant current charging methods. At first, constant voltage is applied to fill up the main part of the battery. Then a small constant current is used for fine tuning, slowly charging the battery to its full capacity. Combining the two reduces the risk of overcharging and damaging the battery. [18][21]

2.32 Effects of overcharging

Overcharging damages Li-Ion cells and can result in degraded cell capacity [13]. But early charge termination due to safety functions against overloading may also have negative effects on the available cell capacity. The safety functions abort charging as soon as one cell reaches its over voltage threshold. The other cells will then be undercharged thus resulting in a reduced available capacity [25]. These problems could be solved by intelligent cell balancing, increasing both the available capacity and the battery's lifetime.

2.33 Re-generative braking

Cars used in city and suburban traffic are subject to a large amount of repetitive start and stop motions. Re-generative braking can be used to store energy otherwise lost when braking and provide up to 15 percent extra range for a car [1][18]. The electric motor in an EV can be used as a generator [1], as in the Toyota Prius hybrid EV [6]. To capture the momentum at deceleration the generator is used to convert kinetic energy back to electric energy [18]. When braking, the generator supplies the battery with a current which enables charging during drive [1]. Both hybrid and pure EVs can benefit from re-generative braking.

Although it has energy saving benefits, re-generative braking exposes the battery to sudden and high currents forcing it to fast charge [18]. This could be a problem with some battery technologies, for example Li-Ion, where fast charging could damage the cells.

2.4 Safety of batteries in electric vehicles

In the case of a car crash, it is important that the battery does not cause further damage. Therefore, collision zones and guards for the battery need to be designed, to keep the battery intact and in a safe place. Batteries and cables can be damaged and injure passengers with acids, high temperatures and electric shocks [1]. One way to avoid injuries caused by the batteries is to isolate the electric system and separate it from the vehicle chassis [1].

When short-circuits occur the energy stored in a battery is converted into heat within the battery pack [4]. To prevent this, the terminals should be isolated and preferably have different connectors to avoid mix-ups [4]. Additional protection against short-circuiting could be fuses, circuit breakers and temperature sensors.

2.5 Environmental effects and recycling

Lithium compositions, especially Lithium-Ion, in batteries are a fairly new technology. Therefore, the long term usage and effects it might have on the environment are still unknown. According to *New metals and metalloids in society [*26] there was still no recycling of lithium in Sweden in 1999 and readings done at that time show minimal amounts of lithium in the environment. On the other hand, Lithium-Ion is known to be a neurotoxin in humans and long term exposure could lead to death [16].

For battery powered EVs to be environmentally acceptable, recycling methods are needed for the batteries, especially when they may contain toxic material. Examples of batteries that contain toxic materials are lead-acid batteries, nickel-cadmium batteries and Lithium-Ion batteries [1]. At the time of recycling, it is important to gather all the components of the battery, not only the most hazardous materials [17]. Even materials that are not dangerous may have large effects at high concentrations if they spread or leak out of control [17]. For example, in lead acid batteries, not only is lead a hazard, but also the electrolyte containing sulfuric acid as well [17].

Even if the batteries are spent and thrown away, there may still be some remaining power. This can be a risk if the batteries are not handled correctly during recycling [27]. The materials can be toxic and need to be handled correctly to avoid injuries and environmental impacts [27]. Since the beginning of lithium battery recycling in the USA, there have been great improvements, from basic collection for disposal to more advanced material separation [28]. There are advantages and disadvantages with all recycling methods. One method described in *Recycling the Lithium battery* [27] just melts the batteries with common metal smelting. This method blends batteries into metals. This mixture of different metals can be refined and separated by specialized companies [27]. Another method developed by Toxco Inc. is said to recover 98 percent of the available lithium [28]. It is recovered as lithium carbonate which can be converted into electrolyte and re-used in lithium batteries [28].

Recycling rates and recycling methods of batteries have been improved and developed over time caused by new demands and new battery technologies. For instance, lead acid batteries which have been used for a long time have a recycling rate that is better than 90 percent[9] [17]. The recycling process is easier and requires less energy with nickel-cadmium and acid batteries compared to zinc and lithium batteries [17] because cadmium and lead oxide are more easily reduced back to pure metal.

[9] In the United States

3. Theory of Battery Management Units

A Battery Management Unit (BMU) monitors and controls a battery pack. The basic functionalities in a BMU consist of safety functions, voltage and current measuring, State of Charge (SOC) and temperature monitoring.

For Li-Ion battery packs, battery management is essential. Due to the nature of the Li-Ion technology, the cells need to be controlled individually. For example, without a BMU, a Li-Ion cell could easily be discharged under its voltage limit and be irreversibly damaged. As mentioned in the introductory section *1.2 Battery Management Unit*, individual control over the cells also enables optimization of the stored energy, improving lifetime, safety and cost of the battery pack. In an EV, a BMU is needed to keep track of the battery's capacity status and also to increase the safety and reliability of the vehicle.

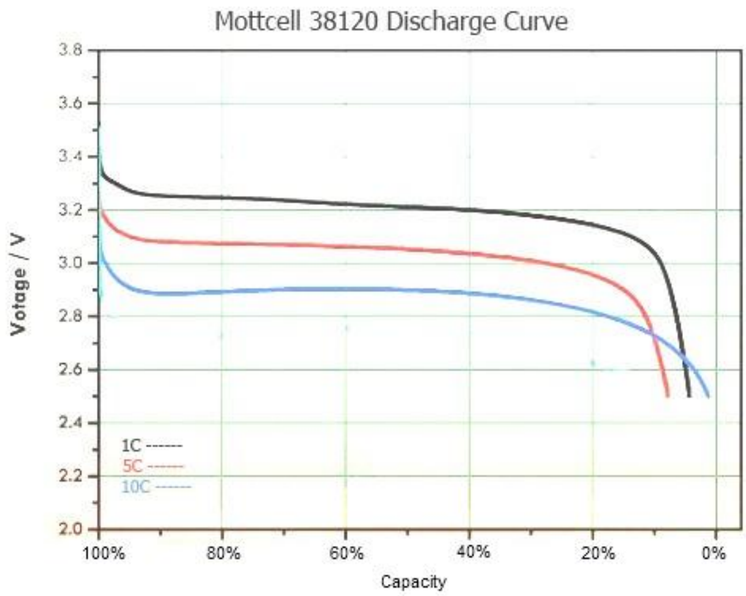
3.1 State of Charge SOC

To know how much capacity remains in a battery the SOC (State of Charge) is needed. SOC in an EV is the same as a fuel gauge in a combustion engine; it is a measurement of the remaining capacity of what the battery can deliver. SOC is usually stated as an estimation of the remaining capacity, where 100% represents a fully charged battery. There are different ways to measure the SOC, voltage and coulomb measuring being the most common.

3.11 Voltage measuring

The voltage of a battery is fairly easy to measure, but the quality of the estimated SOC based on voltage measuring is hard to determine. For a Li-Ion battery where the charge and discharge curves are relatively flat it is especially hard to use voltage measuring. As seen in Graph 4 below the differences in voltage are small during most of the cells capacity. This causes difficulty in estimating the capacity based on voltage. Small measuring errors could cause large errors in the SOC [1].

In many implementations the battery voltage is measured and then used in a reference look-up table to gain the estimated SOC value. The simplicity of this method has become a standard, even though the method is unsatisfactory [1]. Charge and discharge curves depend on both temperature and current rates, which cause SOC estimation based on voltage measuring to be erroneous.



Graph 4. Discharge curve for a 10Ah $LiFePO_4$ cell. The voltage differences are small during most of the cells capacity. See, for instance, the range 30-90% capacity where it is very difficult to estimate capacity based on voltage since the difference is only a few mV.

Voltage measuring can be done on an open circuit voltage (OCV) or when a load is applied. When no load is applied and the battery is stable the OCV method displays a battery's correct voltage level. See figure 2 on examples of OCV and a circuit with a load. When the battery is used, i.e. a load or a charger is connected the accuracy of the voltage measurement depends on the current. High currents increase the error in the voltage measurements. This is caused by hysteresis, i.e. slowness in the battery's chemical process.

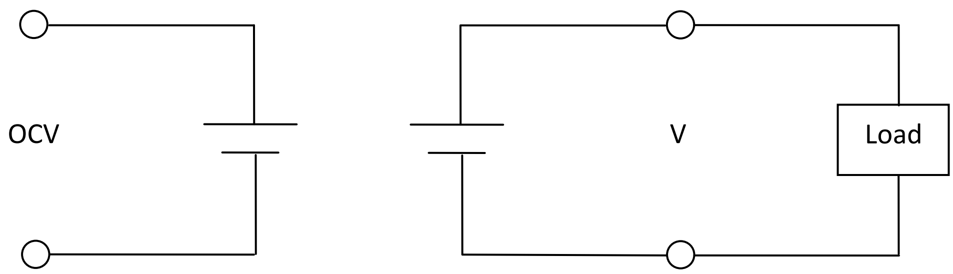


Figure 2. The left figure shows a circuit on which open circuit voltage (OCV) measuring can be done. The right side figure shows a circuit with a connected load.

3.12 Coulomb measurement

SOC can be estimated by keeping track of the in and out flowing currents of the battery. The usual implementation of this method involves integration and is therefore a more expensive solution. Integration requires more hardware and calculations to give an accurate estimation. Another issue with Coulomb measurement (also called Coulomb counting) is how to manage sudden current spikes. If the sampling frequency is too low currents spikes can be missed and the coulomb counter will be inaccurate. This causes the SOC to drift away from its real value. To minimize the errors due to drifting problems, the coulomb counter could be reset or re-calibrated to its real value. When this is done the SOC will be accurate again.

3.13 Other possibilities to determine SOC

The difficulties concerning accuracy in SOC estimation have necessitated the development of more techniques other than basic voltage and current measuring. Some methods could include a battery cell model which can be used to correct the estimated SOC during runtime. Other SOC estimations use more advanced methods such as neural networks [29], fuzzy logic and readings of the chemical compositions and impedance of the cell [21]. Although there is research within those areas, their actual implementation in real applications is unknown. Other methods that currently have been used are filters, especially Kalman filters which improve the estimation accuracy [30].

3.14 SOC dependability

A well defined SOC model should consider the changes in the battery's capacity due to temperature variations and the battery's aging counted in charge cycles [10]. It is also important to be aware that high temperatures damage the battery and cause it to age prematurely. Batteries are considered aged and should not be used when the maximum capacity is at 80% of its original capacity [1]. The error in the SOC estimation will increase if the present capacity is used as the full capacity in SOC calculations. The decreasing capacity must be considered when designing a SOC model.

The use of only voltage measuring cannot be seen as a sufficient method for SOC estimation. Many implementations combine Coulomb and voltage measurement, some with other techniques as well.

3.2 Cell balancing

Even batteries produced from the same batch will never be identical [13]; there are always small differences in self-discharge rate, capacity and impedance [4][13][14]. Therefore, the cells in a battery pack may have different voltage levels after the battery has been fully charged. To avoid damaging the cells due to imbalance in the battery pack, cell balancing is used to reduce the difference in voltage between the cells. This gives cells longer lifetime and more available capacity [14][25].

The differences between cells are especially important for Li-Ion batteries, since they are sensitive to overcharging and deep discharge [11][13]. Imbalance in Lead-acid, NiMH and NiCd batteries due to overcharging can be handled by a chemical short-circuit [25].

Over voltage safety functions will abort charging of the battery when any cell reaches its overvoltage threshold. Therefore, other cells may stay undercharged. One consequence is that the battery's full capacity will not be available for discharge. The same occurs when the weakest cell reaches the lower threshold, resulting in capacity not being used. This is shown in figure 3.

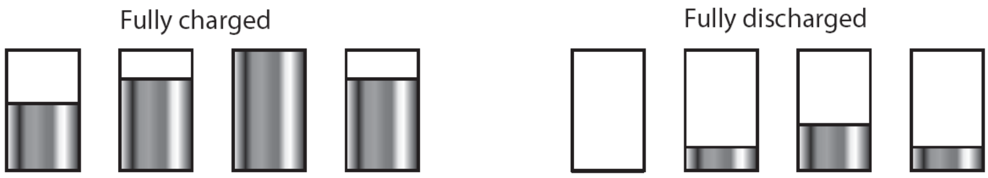


Figure 3. Example of imbalance in a battery pack. The four leftmost cells represent a fully charged, unbalanced battery pack. The right four cells represent the same battery pack, but after a full discharge.

Without balancing, the different cell capacities will start to drift with every charge-discharge cycle, leading to a decrease in the battery packs total capacity [25]. Balancing is designed to improve battery performance [25], but a wrongly implemented balancing can lead to an accelerated cell degradation [13][25].

Balancing efficiency is effected by the current [31]. Too low currents effect the time needed to even out the cell voltages, while too high currents make balancing hard to accomplish. This occurs because high currents can be difficult to control and the attempt to balance can do more damage than good. The best performance can be accomplished by high currents at the start and lower currents towards the end of the balancing process.

3.21 Balancing in parallel and series connected cells

When all cells are in parallel, the voltages are forced to be equal according to Kirchhoff's circuit laws [32] and hence no balancing is needed [14]. The same laws conclude that when the cells are connected in series the voltages will differ. Therefore the series connected cells will need balancing. Cell balancing can be done in two different ways: passive and active balancing. The most common way of balancing is passive [14].

3.22 Passive cell balancing

Passive balancing, also called current bypass, is performed by burning up energy through a resistor as heat [13][14], the circuit layout can be seen in figure 4.

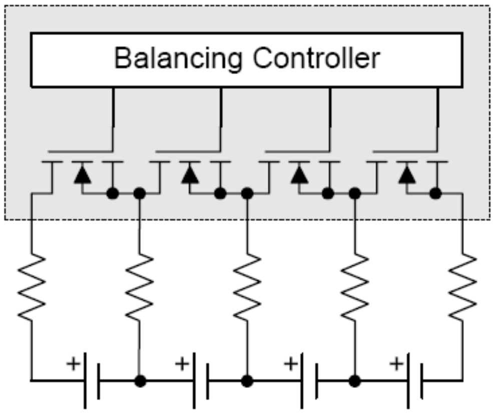


Figure 4. Example of a passive balancing circuit. The Balancing Controller is used to control which cells to bleed out into the resistors. [25]

To even out differences between cells with passive cell balancing, the lowest cell determines the level of capacity after balancing. Figure 5 shows the capacity after passive cell balancing. In this example the total capacity is only half after completed balancing. Passive balancing should not be applied during discharge since it reduces the available capacity of the battery.

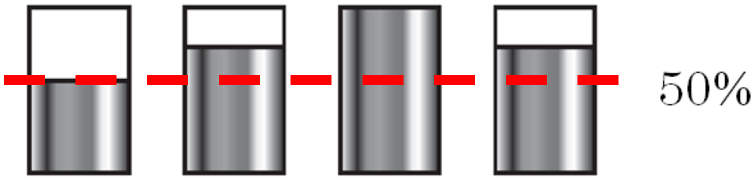


Figure 5. Example of passive balancing. The capacity is only 50% after passive balancing since the excess energy is wasted through resistors.

Disadvantages of passive cell balancing

- Balancing can only be done when charging or after charging [13][14]
- Energy is wasted as heat [13][14]
- Cooling may be necessary since the resistors emit heat [14]

3.23 Active cell balancing

The difference between active and passive balancing is that active balancing recycles energy. It passes energy from a cell with higher voltage to a cell with lower voltage. Figure 6 shows the capacity after active cell balancing.

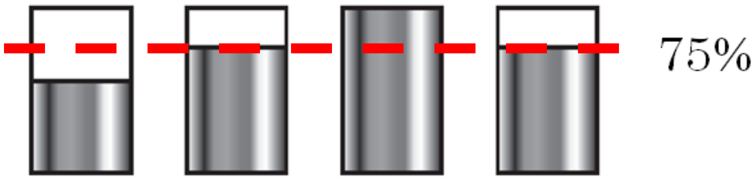


Figure 6. Example of active balancing. After active cell balancing the available capacity is 75 %, which is much higher than after passive cell balancing.

A major advantage compared to passive balancing, is that active balancing can be used during both charging and discharging [25]. An example of an active balancing circuit can be found in figure 7. There are different implementation methods of active balancing and these are described below.

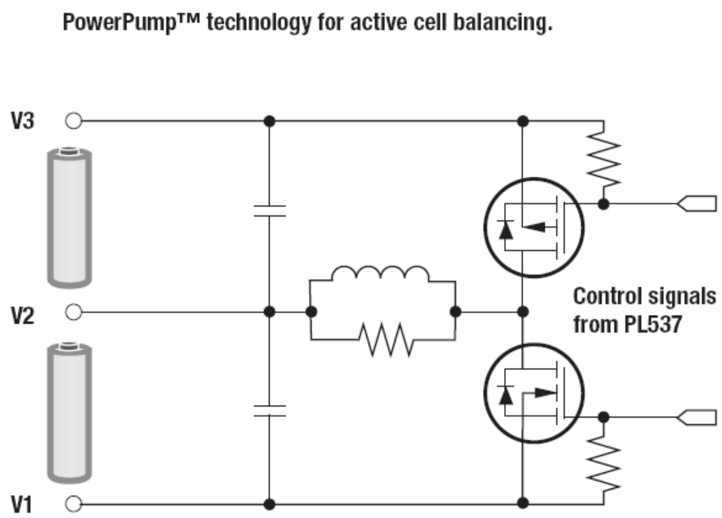


Figure 7. Active cell balancing circuit from Texas instruments illustrating PowerPump [33]. *Control signals choose from which cell to pump current.*

Charge shuttle

Active balancing with a charge shuttle is done by loading capacitors with the excess energy from the higher voltage cells. A switching circuit will then provide the lower cells with that energy. Unfortunately, there is an energy loss of about 50 percent due to capacitor charging [25].

Inductive shuttle

Inductive shuttle balancing is a much faster method than charge shuttle balancing [21]. It uses inductors to transfer energy between cells. Instead of transferring small charges between cells, it takes the overcharge from one cell to top up the cells which have less charge [21].

Disadvantages of active cell balancing

- More expensive than passive cell balancing because it needs more hardware [13]

- The profit in energy when using charge shuttle might, at best, be only 50% [25]

3.24 Algorithms for cell balancing

With the improvement of cell balancing methods, comes a need for more advanced algorithms in order to successfully execute and control balancing. Algorithms for this are hard to implement and depend upon the structure of the cell balancing circuit.

Passive balancing is simpler to implement algorithms for, since the energy is burned up. The algorithm may need to spread balancing over time to avoid the heating problems.

Active balancing transfers current to other cells. A difficulty can be hardware limitations, so the currents need to be transferred along many cells to reach its destination. Therefore, intelligent algorithms are needed. No standards for active cell balancing are available since few manufacturers manage this technique.

3.3 Safety Functions in BMU

Safety functions must be implemented and work correctly to ensure that no one gets hurt and that the BMU and battery cells are not damaged. If a battery cell has too low a cell voltage, it may result in voltage reversal [4]. The consequences of reversal can be venting or rupturing depending on battery type [4]. Under voltage can be prevented by measuring the voltage. In some cases, if there are weak battery cells in the battery pack, individual voltage measurements may be needed to detect low voltage. The cells should be monitored and not allowed to drop below the lower voltage threshold, thus minimizing the risk of voltage reversal. Cell balancing or use of diodes will also make reversal improbable [4].

Charging above a cell's over voltage threshold can lead to a degradation of the cells and, in worst case, cause them to explode or catch fire [25]. If one cell explodes or ignites, it is likely that the other cells will do so as well, due to thermal runaway [25]. According to *Electropaedia* [21] the most likely reason for a cell to break down is heat. To avoid this, besides monitoring the battery pack, air-conditioners can be used to maintain the right operating temperature. An important fact when deciding the cooling system is for the battery pack to have a proper design [4] and that each cell can be cooled, i.e. it is possible for the air to circulate.

The use of individual cell voltage measurements leads to a better precision in SOC and balancing, increasing the battery lifetime and capacity. It is important to follow the manufacturer's suggested cell voltage thresholds to avoid degradation of performance and improve safety.

3.4 Reliability and fault tolerance

It is common for EVs to have more than 100 cells in series to get the desired voltage of 300-400 V. The need for higher capacity also forces cells to be connected in parallel, which leads to even more cells in a battery pack. Depending on the battery technology and manufacturer used, the number of cells may vary. When a failure occurs it is important that the system, i.e. the EV, can still function or fail in a safe way. To fail in a safe way, redundancy should be implemented in the system. If a cell fails it should be disabled or disconnected from the battery pack. In this chapter, some failures, risks, their effects and prevention methods are presented.

3.41 Battery pack

The battery pack is protected by the BMU. Failure of cells cannot be completely avoided by using a BMU, but, in the case of a failure, the BMU can detect and carry out precautions to minimize the damage.

A short-circuit inside a battery cell, while rare [21], cannot be prevented by the BMU, fuses or other external safety functions. The risk with internal short-circuit is total failure of the cell and can be minimized by operating the battery pack within its recommended temperature range [21].

In the case of high pressure[10] caused by abuse or faulty sensors, the BMU cannot act. Instead, a safety vent should be installed to prevent the battery from rupturing. In the case of an accident, *Electropaedia* [21] states that EV batteries in general are a lower hazard than a full tank of petrol.

In a Li-Ion battery pack that lacks a proper BMU, exchanging old or damaged cells will not improve the battery. Instead, charging and discharging the battery with the new cell will cause an accelerated degradation of the weaker cells. The exchanged cell will not increase the SOC because the SOC is, in general, measured by the weakest cell [34]. Therefore, the whole battery pack should be replaced when a cell fails [21].

The quality of the cells in the battery pack will also determine the failure rate. Higher quality cells improve the whole battery pack. A battery pack contains a lot of series and parallel connections and the failure rate of the whole battery pack is the sum of all failure rates of the components (in this case battery cells and cables). Therefore, testing is needed to confirm the quality and reliability of the cells and identify potential risks and hazards [21]. Different battery technologies have their own specific cell construction, thus failing differently [21]. The likelihood of failure in new cell technologies is higher since they often are produced manually [21]. This increases the differences in cell capacity and inner resistance compared to cells that have been mass-produced. Other failure possibilities are aging and abuse [21]. Often a single failure does not directly lead to a complete breakdown of the cell, instead it usually degrades the cells performance, i.e. reduced capacity, higher self-discharge etcetera [21]. According to [21], the different failure modes when a complete breakdown occurs are: open circuit, short circuit, explosion and fire. The failure mode cannot be predicted beforehand and depends on the circumstances [21].

Improvements of lithium batteries have made them more reliable and safer to use [21]. Their cell chemistry and more reliable manufacturing process are two of the improvements. The BMU introduction has also improved the safety and enabled better operating conditions for the battery cells.

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[10] Not all batteries.

Further improvements on the reliability of the battery pack can be performed by:

- Using cells with higher capacity and C-rate than specified for the project to reduce the risk of wear out
- Substituting larger cells for smaller cells connected in parallel. Using parallel batteries has the following benefits: in general they have lower failure rate, in case of failure it has less stored energy that can damage the system and a failure of one cell will not cause the entire battery pack to fail [21]
- Implementing redundancy so that a single failure can be contained and the EV can continue to operate. This can be done by dividing the battery pack into sections that can be bypassed in case of failure [21]

3.42 BMU

As mentioned previously, the BMU monitors the battery pack and protects it from under-/overvoltage and damaging temperatures. In the case of failure of the BMU caused, for example, by sensor failures or loss of power, it is possible that the battery pack may be overcharged or over discharged. This can be improved by redundancy in the BMU.

It is important that the BMU can detect insulation problems within the battery pack and shut down the battery to avoid current leakage [18]. An inertia switch disconnects the battery pack when it senses a fast deceleration as in a car accident [18].

3.43 Charging methods

An EV battery can be charged in two ways: conductive and inductive coupling [18]. The big differences between the methods are that conductive coupling uses a physical cable while inductive coupling uses inductive transmission caused by electromagnetic fields. An EV is going to be used in all weather and the safety of charging is important. In the case of inductive charging, the driver does not come in contact with any electrical interfaces. Conductive coupling must be proper isolated and the user should not be able to short-circuit the EV or the charging equipment [18]. It is also necessary to not connect or disconnect cables to the EV during charging, in order to avoid electrical arcs [18]. To protect users, the charging equipment should have a ground-fault circuit [18]. In inductive charging, this problem is minimized since no cables are used.

4. Project implementation

In this chapter, the implementation of the project is described and the design choices are justified. First the choices regarding the assembly of the battery pack are discussed, such as the connections and the specific cell for the implementation. This is then followed by an overview of the system design, descriptions of the hardware and communication between devices. Finally, the BMU implementation with its different parts is introduced.

4.1 Battery

The battery chapter describes the requirements of the battery needed to run the go-cart. The cells that were chosen and the design of the battery pack are described in section 4.12. Section 4.13 and 4.14 cover charging and possible extensions of the battery pack respectively.

4.11 Go-cart specification and battery requirements

The battery pack requirements are based on the electric go-cart developed by QRTECH and have the following specifications:

Engine power (P_{max}): 10 kW
Average effect ($P_{average}$): 5 kW
Engine voltage (U): 48 V

Given the engine specifications above, the battery requirements can be calculated by Joule's law:

$$P = U * I$$
$$I = \frac{P}{U}$$

In this case, the formulas give the following max and average current that can be drawn by the engine:

$$I_{max} = \frac{P_{max}}{U} = 208.3\ A$$
$$I_{average} = \frac{P_{average}}{U} = 104.167\ A$$

The required battery in the electric go-cart must be able to cope with at least the calculated current. The capacity of a battery states how much energy is stored inside the battery in Ampere hours (Ah). A comparison can be done against C-rate, see section 2.14, that describes the load under which the battery is charged and discharged. An example of Ah: a 10 Ah battery can be used for two hours if a load of 5 A is drawn. In this project the battery will be discharged with a much higher current, so the capacity needs to be higher than 10 Ah. For a drive time between 5-8 minutes[11], the battery capacity must be 20 Ah. Calculation of time is shown below:

$$\frac{Battery\ capacity\ (Ah)}{Discharge\ rate\ (A)} = hours$$

The shortest driving time is when the highest current I_{max} is drawn and the driving time will increase when the current decreases. The calculated $I_{average}$ gives us an average of the time for driving, see the calculations below:

$$\text{hours}_{\text{min}} = \frac{20\ Ah}{208.3\ A} = 0{,}096\ h = 5.8\ min$$

$$\text{hours}_{\text{average}} = \frac{20\ Ah}{104.167\ A} = 0{,}192\ h = 11.5\ min$$

Note that the max current (I_{max}) will only be drawn for a short period, i.e. for a couple of seconds. The average is a more likely estimation. Another important aspect in selecting cells is to keep down the weight and volume, since the battery pack will be placed on a go-cart.

Figure 8. The electric go-cart at QRTECH [35]

4.12 Cell specification and design of battery pack

At the time of writing, $LiFePO_4$ is considered by many to be the near future battery technology for EVs [19][1]. As stated previously, $LiFePO_4$ cells provide enough capacity and power to be applicable in modern EVs. It also has lower weight and is safer than other battery technologies.

[11] Specification by QRTECH (35)

After the cell requirement for the project was determined, the right batteries needed to be located through a cell manufacturer. Appendix C contains a list of all $LiFePO_4$ cell suppliers that were considered. ABATEL, a consultancy firm within battery solutions, provided the project with cells from Shenzhen Mottcell Battery Technology.

Cell specification

The cells used in the project will be parallel connected to achieve the desired capacity of 20 Ah. The parallel cell pack has following specifications:

Voltage:	3.2 V
Capacity:	20 Ah
Constant current:	≤200 A
Max current:	≤300 A
Cycle life:	2000 cycles[12]
Min / max voltage:	2.0 V / 3.65 V
Internal resistance:	<10 mΩ
Self discharge:	3% per month[13]
Weight:	700 g

A more detailed description of the cells can be found in Appendix B.

The decision to have two cells in parallel was made to reduce the exhaustion which can occur with a single cell, as described in section *3.41 Battery pack*. Other cells that were considered for the implementation had 20 Ah per cell, but the discharge current rates were lower. Therefore, they could not be used in the go-cart since it needs high currents rates. To achieve the required voltage of 48 V for the engine, a series connection was also needed in the battery pack. Since each cell has a nominal voltage of 3.2 the battery pack needed 15 series connected cells. The total weight for the battery pack was 15*0.7 = 10.5 kg, which is quite low.

[12] Higher than 70% of its capacity, see Appendix C
[13] Temperature 25±5°C

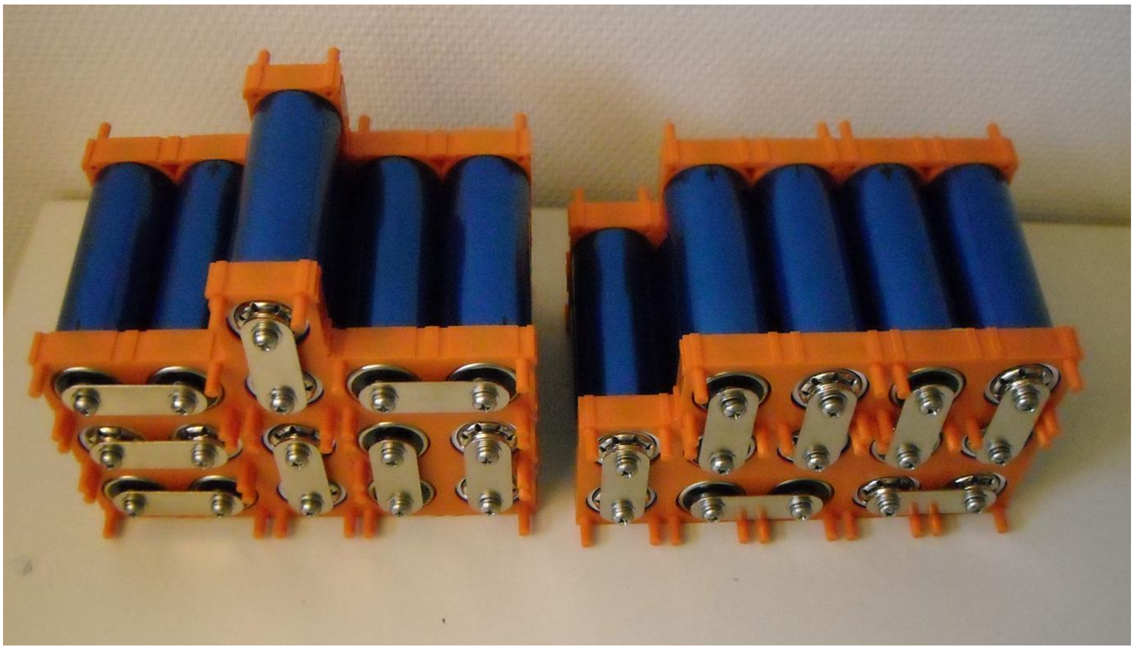
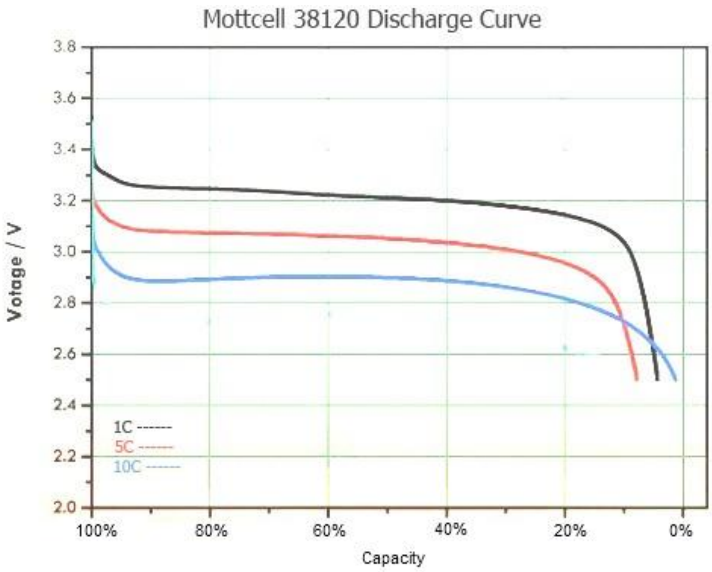


Figure 9. Picture of the $LiFePO_4$ battery pack. The cells are shown connected in parallel.

Discharge curves

Discharge curves are constructed by discharging the battery pack at different C-rates. These curves were needed to design and test a SOC. Graph 5 below shows the discharge curves for the $LiFePO_4$cell used in this project. The top curve represents discharging a cell at 1 C, which in this case means discharging for 1 hour at a constant current of 20 A. The middle curve represents discharging at 5 C, i.e. five times faster discharging than the top curve. Thus, the middle curve discharges with a constant current of 200A which takes about 12 minutes.



Graph 5. The discharge curve for the $LiFePO_4$ battery cells used in the project [36].

4.13 Charging method for the battery pack

The battery pack is charged with a power supply using a constant voltage of 48 V and a constant current of max 10 A. Safety functions will abort charging if any cell reaches the over voltage limit of 3.6 V. The nominal voltage of a $LiFePO_4$ cell is about 3.2 V, but it can sustain higher voltages. The cells used in this project have a top limit of 3.6 V. As stated in section *3.3 Safety Functions in BMU*, charging above its limit will damage the cell. To charge the battery at 10 A to 100% of its capacity will take about 2 hours[14].

After a charge, the battery is left to rest. A period of 30 minutes is enough for the cells to stabilize and result in more accurate voltage readings [37]. Balancing takes place after the rest period. Now the SOC can be investigated to see if a new round of charging should be performed. High imbalance can cause the capacity to be much lower than feasible, see chapter 3.2.

4.14 Extending the battery pack

To boost the capacity and range of the go-cart, more cells can be connected in parallel. Although it would not require major changes to the implemented BMU, a higher capacity would increase the cost, space and weight of the battery pack. These three factors limit the range of the go-cart, but the main idea with this master thesis was to construct a battery pack for testing, not to enable the same speed or range as in a real car.

Extensions to a battery pack to increase its voltage can be managed by extending the BMU and adding more balancing boards. Only minor changes to the BMU would be needed since the code is generic.

4.2 System design

The final system consists of four distinctive parts: the balancing board, the control unit, the power switch and the current transducer. These together realize the BMU and the active balancing for the battery pack. The system has a minimal design, only consisting of the most fundamental functions needed to supervise and control the battery pack. The BMU includes functionality for SOC, safety and active cell balancing for $LiFePO_4$ cells.

[14] The SOC will never be allowed to be less than 20%

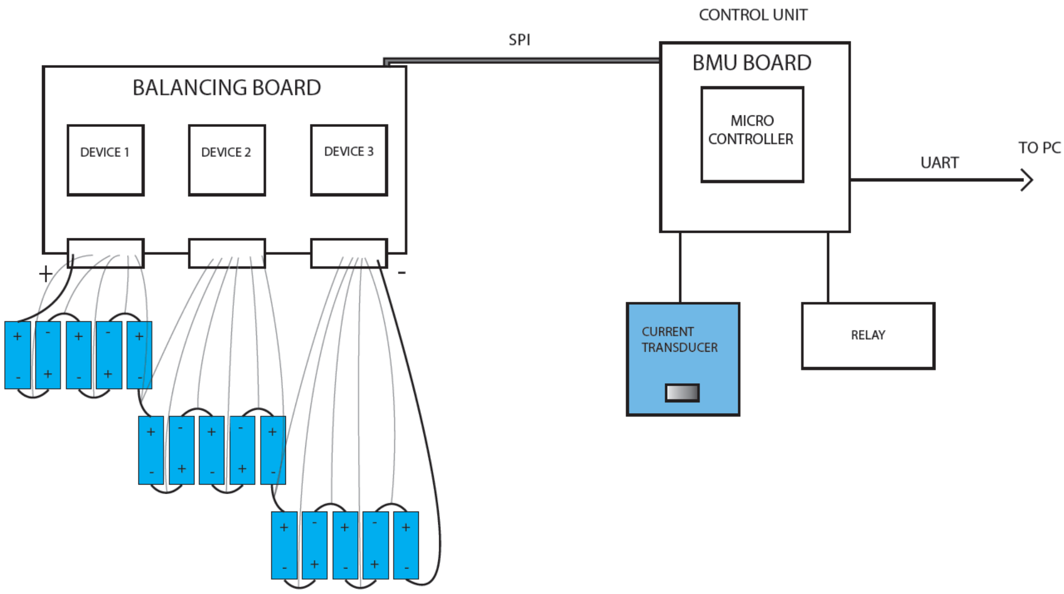


Figure 10. Overview of the implemented system.

As seen in figure 10 the system consists of two major blocks, the control unit and the balancing board. The control unit contains a microcontroller on a BMU board and works as the host of the system, with the balancing board as slave. The balancing board has 3 devices, which control 5 cells each. The cells are connected as stated in the previous section *4.1 Battery.* The relay is the power switch for the system; it is used to cut off the power to the engine or charger. It is controlled by safety functions inside the BMU. A current transducer is needed to measure the current through the battery, for more details on this see the section below about the *Current Transducer*. The communications interface and protocol between the control unit and the balancing board are described in section *4.22 Communication*. In debug mode, the communication to the PC is used for printing messages. The communication to the control unit from the PC is handled by a hardware programmer from Atmel and is not described in this thesis.

4.21 Hardware design

The main reason for starting this project at QRTECH was to try out new technology, ideas and hardware. Since QRTECH has previously worked on similar, but larger BMU projects, they had experience in this field and could suggest hardware fitting the project. Through QRTECHs contact with Texas Instruments, the project was supplied with a brand new prototype unit, bq76PL537, with active balancing and internal voltage measuring. The prototype was examined and tested to see if it could be integrated in the project. Since the results were adequate and active balancing is highly interesting, the rest of the project was designed around the prototype. Previous EV projects at QRTECH had lead to the development of a circuit board for a BMU. This circuit board was also to be tested in the project and became the base for the projects control unit. As stated in the introduction, one of the main goals was to implement a small, but yet efficient BMU. Therefore, the choice of control unit fell upon the

Atmel Mega 168. The microcontroller and other hardware used in this project are described in the following sections.

Control unit

An 8-bit microcontroller from Atmel was used as the control unit. The Atmel Mega 168 (ATmega168) was chosen by QRTECH for the project first and foremost due to its compatibility with their previously designed BMU board. More general benefits of the ATmega168 are low cost and low power consumption [38]. ATmega168 also has an internal Analog to Digital Converter (ADC) which was needed for this project. The ADC was used for converting the measurements from current flows; for further details see *Current transducer* below. The main drawback of the ATmega168 is the limited memory space which greatly affected the layout of the project. The available memory had massive impact on the system design in general, forcing the BMU to be slimmed down to its core functions. While the limited memory affected every aspect of the design, the performance of the ATmega168 had the largest impact on the SOC design. Floating point operations and large integration calculations had to be excluded. These, in turn, effect the accuracy of the SOC estimation.

In the final implementation, the ATmega168 included the BMU and initialization of the balancing board. The implemented BMU had control over charging procedures, SOC, balancing algorithm and safety functions. For debugging purposes, a UART communications interface was used to output messages on a PC. The software was programmed in C with AVR Studio and debugged in Eclipse.

Current transducer

A HASS 100-S current transducer was used to measure the current flow in and out of the battery. The current transducer surrounds the power cable and senses the magnetic field caused by the current. A current in the range +/- 300A can be measured and the HASS 100-S outputs a voltage between 0-5V. The zero reference voltage is 2,5 V. The voltage output can be converted through the Atmega168 internal ADC to a digital representation. The digital value is then converted to a value representing the current. Those currents can then be used for current counting within the BMU.

BMU board

The BMU circuit board was developed by QRTECH for EV implementations. The board suited the project and was chosen as the base of the control unit. It consists of a printed circuit board and component schematics. Before it could be used, the components had to be ordered, assembled and soldered by hand. The components used were diodes and resistors for protection, LEDs for indication, USB interface for debugging purposes, a power converter to supply the board with 5 V and filters to reduce noise. After each major group of components had been soldered, the voltages were measured to check if they were properly mounted. The final BMU board can be seen in figure 11.

It was not possible to test the BMU board fully until the ATmega168 had been soldered and programmed. Some difficulties with setting-up the board were caused by differences in the schematics and the printed circuit board. For instance, some of the connections on the board from the ATmega168 were mixed up causing errors. Re-soldering had to be done to set-up a proper SPI connection for the ATmega168.

A logic analyzer called Logic from Saleae was used for debugging both the soldering and the programs on ATmega168. When Logic is hooked to wires it listens to digital signals and displays these in a GUI in Windows. This enables the user to actually see the communication between devices. Logic samples the signals and the user can scroll back and forth in time to see all the signals that passed through the wires. This made it possible to see if errors in the communication were due to programming errors in the control unit, errors in other devices or soldering errors. Soldering errors were usually noticed when no signals went through at all or if correct signals appeared on the wrong wires.

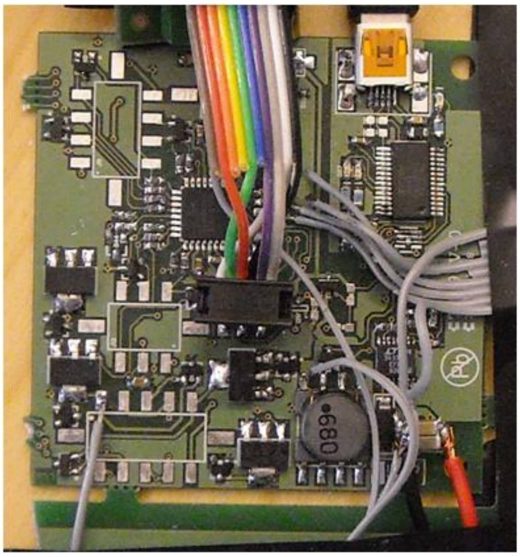


Figure 11. Picture of the final BMU board. The ATmega168 microcontroller can be seen on the top left side of the multicolored data bus.

Balancing Board

For the project an evaluation board, bq76PL537, from Texas Instruments was used. With the balancing board, up to 18 cells can be connected in series. For the final implementation of the project, only 15 cells in series were used. The balancing board has a separate ADC for every cell to provide the user with voltage measurements from each cell in the battery pack. The BMU controls the balancing board through an SPI communication.

One big advantage with the bq76PL537 is that it has circuits for active cell balancing. More details about the implementations of active cell balancing can be read in section *4.32 Balancing*. Texas Instrument also included a graphical user interface (GUI) to communicate with the evaluation board. It initiates communication to the evaluation board and makes it possible for the user to see all registers, change settings and start balancing.

4.22 Communication

Communication between the control unit and the balancing board is enabled by a Serial Peripheral Interface Bus (SPI). For debugging purposes between the control unit and the PC, a Universal asynchronous receiver/transmitter (UART) and Universal Serial Bus (USB) were used. Only the SPI implementation is described since it is the communications interface between devices.

Serial Peripheral Interface Bus (SPI)

A SPI is a full duplex four wire serial bus commonly used in communication between hardware devices. As seen in figure 12 below, the interface consists of a clock signal (SCLK), Slave Select (SS), Master output - Slave Input (MOSI) and Master input - Slave output (MISO).

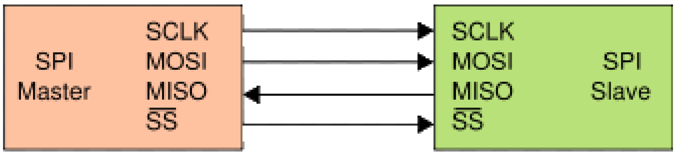


Figure 12. Picture of a SPI master – slave set-up [39].

The master uses the SS to signal to the slave that it wants to communicate. In this project, the control unit is set as master and the balancing board as slave. The balancing board itself has many devices, but these have an internal device selection which can be accessed through software. A more detailed description of the communication with the balancing board can be found in the next section *Communications protocol*. The SS signal is pulled high when no communication is in process and low when transferring data. This prevents erroneous data from being read when no communication is supposed to be in progress. The SCKL is supplied by the master and is only used when transmitting data over the MOSI and MISO wires.

When writing data to the SPI send buffer inside the Atmega168 it automatically starts to generate a clock signal on the SCKL wire. At the same time, the message is shifted out on the wire, sending it bit by bit over the MOSI. The data is clocked out from the master and into the slave on every falling edge. After each transmission, the SCLK is turned off. The reason for this is to reset the clock to prevent it from drifting, causing errors in the communication.

The SPI does not provide hardware acknowledgement which is a disadvantage; instead the master could be talking to nothing without knowing it. The balancing board, on the other hand, echoes the message back to the host. Therefore, the project implementation has software that checks the received data from the slave. Every time the master reads from or writes to the slave, the slave replies on MISO with the data it has received. The control unit checks the message, to see that the transfer did not causes errors and that the slave did not misinterpret the command.

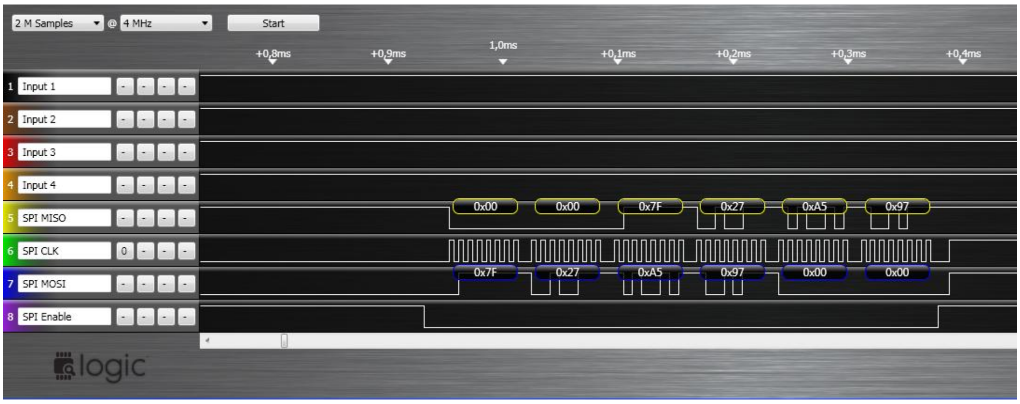


Figure 13. Example of SPI communication between the balancing board and the control unit. The picture shows a broadcast write packet.

Communications protocol

The communication protocol was developed for the balancing board by Texas Instruments. The protocol supports two packet structures, one each for read and write, which include Cyclic Redundancy Check (CRC).

Write packet

0	Device Address	1
	Register Address	
	Data	
	CRC	
	<NULL> PAD	
	<NULL> PAD	

Read packet

0	Device Address	0
	Start Register Address	
	Read length	
	Read byte 1	
	. . .	
	Read byte n	
	CRC	
	<NULL> PAD	
	<NULL> PAD	

Figure 14. Describes the write and read packet structures [33].

It is only possible to write 1 byte at a time to the balancing board registers, therefore a write packet has a fixed size of 6 bytes. As seen in figure 14, the first byte is the device address. This is the internal device select, since the board consists of 3 devices. The address 0x7F is reserved for broadcast writes, which means that all 3 devices on the board will execute a write at the same time. The 0x00 address is reserved for un-addressed devices. The second byte is the register address to which the control unit wants to write. The third byte consists of the byte that is to be written. The forth byte is the CRC, which is used on both sides of the communication. The CRC helps to prevent erroneous data from being written or read at both ends. The last two bytes are both 0x00, i.e. empty padding bytes. These are used to enable the read-back functionality, see the example in figure 13.

The differences between read and write packets are caused by the fact that the balancing board accepts multiple byte reads. Broadcast reads are not possible. The read packet is similar to write, but it consists of 6+n bytes, where n is the number of data bytes to be read. As in the write packet the two first bytes are the device and register addresses. In a read packet, the register address is the starting address for the multiple read. The third byte is the length of the read in bytes, i.e. the number of registers to be read. This is then followed by n+3 empty bytes for the read data, CRC and padding bytes. The CRC is not used when sending the read packet, instead the CRC from the read is checked by the host.

4.3 BMU

As described in section *4.21 Hardware design*, the BMU was implemented in an 8-bit microcontroller. It included the SOC, control over measurements and balancing, balancing algorithms and safety functions. The following sections explain the implementation choices in detail and the chapter ends with suggestions of probable modifications to the BMU.

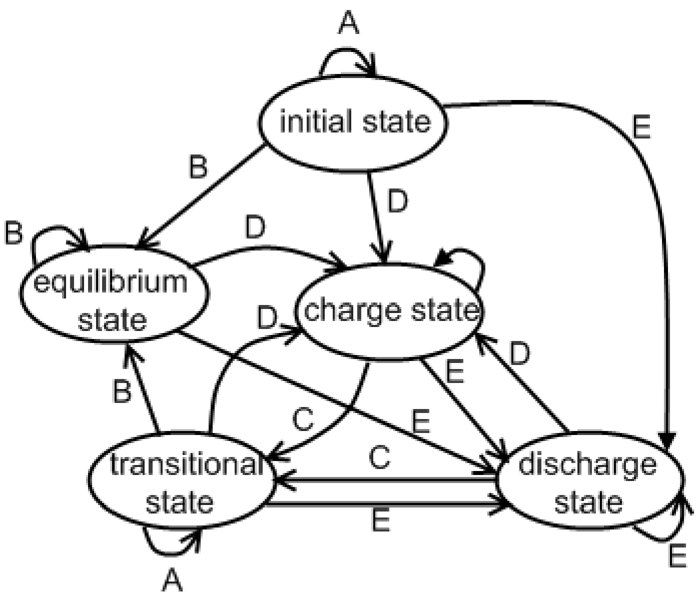
4.31 SOC

The final SOC model was strictly limited by the hardware in the project. This excluded more advanced SOC methods and algorithms from being implemented. Instead, it had to be small and efficient while still providing an accurate battery status.

As a starting point, QRTECH provided the project with a Matlab Simulink SOC model used in real electric cars. The SOC model considers more than 30 different parameters and includes a battery cell as a reference model for its self-correcting algorithms. Although the final implementation would not include this model, it enabled simulations for a better understanding of SOC.

Due to the limitations in the hardware, the implemented SOC was focused on the classic SOC estimation methods, namely voltage and current measuring. As stated in chapter 3, basing a SOC estimation purely on voltage or current measuring is prone to be error. Voltage measurement is inaccurate during load while the accuracy of current counting is dependent on initial value and the frequency of measurements and calculations. Therefore, combining these methods as proposed by Pop, Bergveld et al. [10], overcomes the greater disadvantages and allows for a more accurate SOC estimation.

The basic idea of Pop, Bergveld et al. [10] is to use voltage and current measurement only when they are in their accurate zones. For this, they suggest an algorithm to keep track of which SOC estimation method to use in all possible states of a battery. Their work uses a combination of voltage measuring and book-keeping. Book-keeping keeps track of the currents for the coulomb counter and decides the transitions between the different states in the algorithm. The 5 states for the battery are: Initial state, Charge state, Discharge state, Transition state and Equilibrium state. This algorithm enables the SOC estimation to be decided by different types of readings depending on which state it is in. For more details concerning the states and the transitions, consult the graph below.

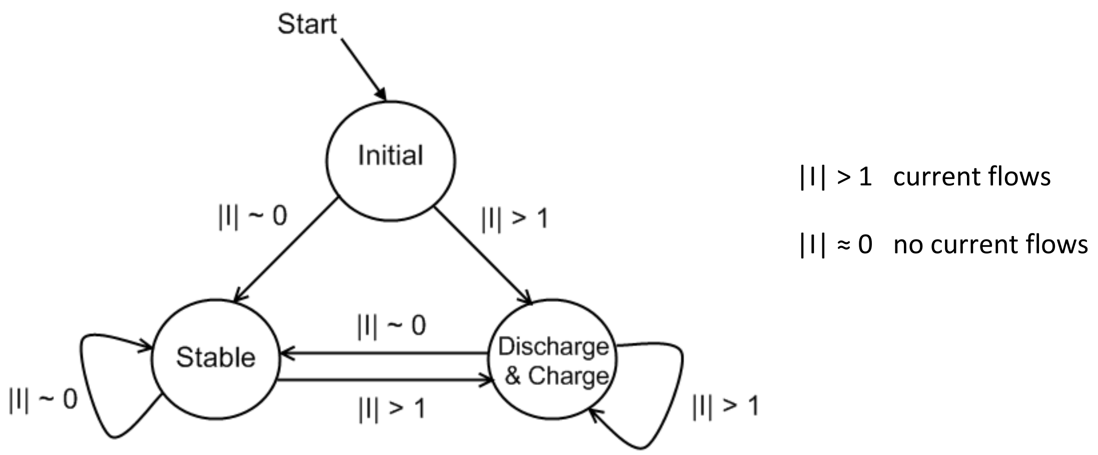


A) $|I| < I_{lim}$ and voltage not stable
B) $|I| < I_{lim}$ and voltage stable
C) $|I| \leq I_{lim}$
D) $I > I_{lim}$
E) $I < -I_{lim}$

Graph 6. Graph of state transitions as suggested by Pop, Bergveld et al. [10]

As in the state graph above, voltage measuring is used when the cells are stable, thus giving an accurate reading of its SOC. Current counting on the other hand, is used while discharging and charging the battery. For the go-cart SOC, the original algorithm and model by Pop, Bergveld et al. was simplified and altered to fit the implementation at hand.

In the implementation, current counting is used to keep track of the current while in discharge or charge modes, see graph 7. Voltage measurement is used when the battery is considered stable, for instance if the current has been lower than 1A for 25 minutes. The SOC then re-reads the voltages and converts the voltage of the lowest cell to a SOC value for the whole battery. In the software, this is done by using a look-up table based on data from a discharge curve for the cell in use. Since there are not enough measurement points to work with, if a voltage is between two values in the look-up table linear interpolation is used to find the probable SOC value. Although the discharge curve, see graph 5, is non-linear in some areas, it is assumed that since the data points are close enough the relation between points are linear. Since floating point calculations are excluded in the implementation, any constants needed for the functions are pre-calculated, rounded and re-formatted. The look-up table returns a SOC value between 0-100. The typical value for the SOC will be in the range 20-80.



Graph 7. A graph of state transitions as implemented in the project. The SOC estimation is begun in the Initial state, where voltage measuring is used to determine the SOC value. Depending on the current flows it will transfer between states Stable and Discharge & Charge.

4.32 Balancing

Active cell balancing is a more preferable option than passive due to its ability to balance both during charge and discharge with minimal energy losses. Although a prototype board for active balancing from Texas Instruments was supplied for the project, some difficulties and challenges still remained. Next follows some limitations, methods and other considerations that were made to implement balancing in our project. A balancing algorithm was also designed and implemented.

Limitations

Balancing will only be done after charging to simplify the implementation. If balancing is desired while driving the go-cart, more powerful microcontrollers would be required. As described in the section *Balancing algorithm*, the algorithm is fairly simple.

Pre-balancing

Before the cells are going to be connected to a battery pack, all cells are connected in parallel. This was done to achieve an initial balancing. This lead to the voltage differences between the cells automatically evening out according to Kirchhoff's circuit laws, see section 3.21. Since this is not a practical balancing solution for an EV that has hundreds of cells in series, this was only done as an experiment. For the go-cart, this basic parallel balancing scheme is only used once, before they are connected into the final battery pack.

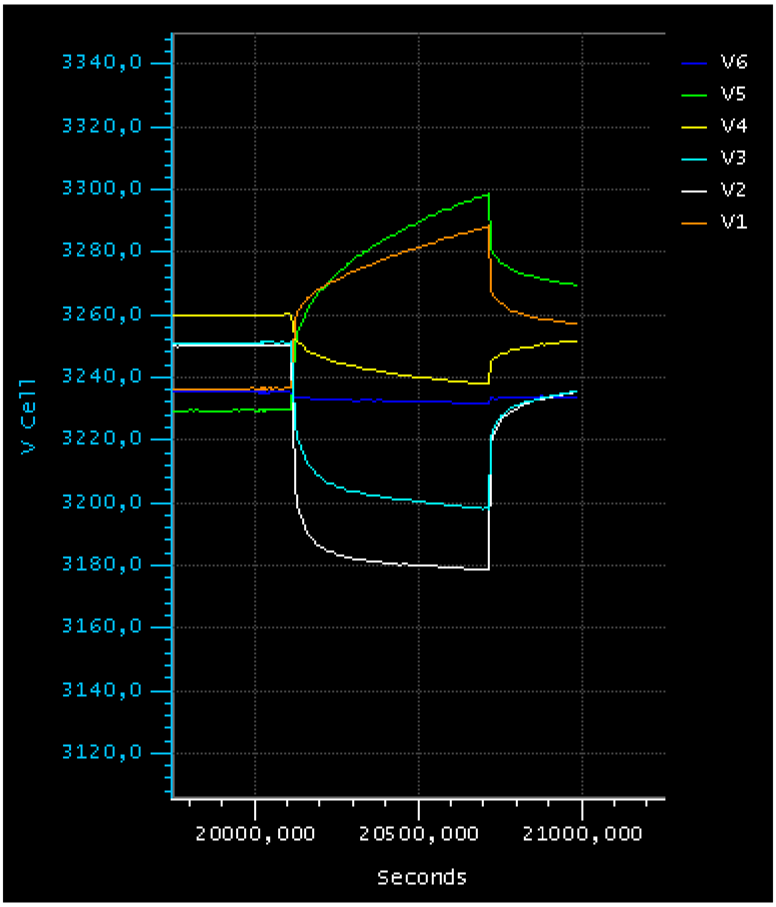
Balancing board

As mentioned in *Balancing board* under section *4.21 Hardware design*, Texas Instruments has a prototype, bq76PL537, with active cell balancing technology. On the board, active balancing is done by shuffling currents between neighboring cells. This method, named PowerPump by

Texas Instruments, is done by inductive charge transfer [13]. The performance of the components in the PowerPump determines the time needed to balance.

In order to balance with the balancing board the direction of the balancing current needs to be set. One register for north and one register for south exist. Balancing inside the device pack can be done fairly simply. Hardware disables balancing in opposite directions, i.e. if both cell 4 receives current from cell 5 and cell 4 transmits current to cell 5, a current collision occurs. In this evaluation prototype, it is important that balancing between devices is correctly set-up, because no such prevention exists to prevent a collision.

An algorithm for active balancing had to be implemented in the host. During development of the algorithm, the GUI from Texas Instruments was used to analyze how the balancing could be done. Graph 8 shows how 10 minutes balancing effects the voltages of the cells. In the test phase of the implementation, only device1 was used to balance and check parameters for the implementation of the control unit. One reason for this was that only 6 cells were available at the project start and another was that it is easier to develop on a smaller platform.



Graph 8. Example of balancing in the Texas Instruments GUI for 10 minutes. Cell2, with voltage V2, is being discharged into cell1 and can be seen in the graph as the lowest voltage when

discharging. Cell1, with voltage V1, is the second highest cell being charged. After charging, about 30 minutes is needed for the cells to stabilize. Therefore, the voltages just after balancing, as shown at the end of the graph, are not yet accurate.

Balancing algorithm

The algorithm should balance both between devices and in the device pack. To simplify the implementation of the balancing, two different algorithms were designed, one for balancing between devices and one for balancing in the device pack.

Balancing between devices

First the device with highest voltage balances its current to the device with lowest voltage. The direction in north and south registers need to be set. In max and min devices the directions are decided before the balancing of the device, namely by choosing to forward current to the lowest cell in the device and draw current from the cell with highest voltage.

After a balancing period, directions are recalculated, i.e. to choose new max and min devices. Also, new min and max cells are located within those devices. Then balancing starts again and is finished when the differences between devices are smaller than the decided limit. A rest period of 30 minutes must now occur to allow the voltages to stabilize. One difficulty with the device to device balancing algorithm is to avoid collisions between devices, since no safety mechanisms are implemented in the hardware.

Balancing in device pack

After the balancing between devices is complete, balancing in the device pack will be performed. Two possible solutions exist, all cells balance to the lowest or balance to a local minimum. After modeling cell balancing in Excel, it was decided to choose the latter option. The chosen algorithm to be implemented has simpler calculations and seems to be more effective when small cell differences exist. The main idea is to avoid drift caused by complex and untested algorithms.

4.33 Safety

In order to avoid under and over voltages, safety functions need to be implemented. During all the states of the go-cart (charging, balancing, driving), safety checks are continuously executed to determine under and over voltages. All states are aborted by sending signals to a relay that disables the battery connection to the electric co-cart. Fuses are also used to limit the current drawn.

4.34 Extending the BMU

During the project many alterations to the BMU were discussed. Due to the limitations of this thesis, many of them could not be implemented during the project. Instead, some of the suggestions are listed in this section with a short description of the main idea and the probable benefits of the changes.

Improvements of SOC

The implemented SOC accuracy will decrease over time and it does not contain any advanced self-correcting algorithms. Therefore, it will keep drifting away from its real value when discharging due to the drift in the current counter. Many papers that were studied made use of filters such as Kalman filters. By using filters, it should be possible to better the accuracy of the SOC. A microcontroller with higher capacity would be needed for such an improvement.

It would be interesting to use parallel processors for a BMU project. The accuracy of the current counting is dependent on the frequency of its readings. If one micro controller would be programmed to only do current counting, the frequency would be higher than on the ATmega168. At the moment, there are too many other functions that need to run in sequence between current readings. This type of parallelism could also be implemented in a single ATmega168 if re-writing the software to be driven by interrupts.

Voltage measurements for SOC estimation could be used more often if there was a correcting algorithm for the voltage levels. The algorithm could calculate the difference between the real and the measured voltage. Then, a more accurate SOC could be accomplished. This would require a larger and faster microcontroller to handle more detailed information about the cells.

Improvements of balancing

Balancing algorithms can be more optimized to perform better. Also the balancing algorithm can be executed several times with rest period between, to minimize drift caused by hysteresis. Balancing can also be performed several times, before, during and after charging.

4.4 Tools

A varied set of software tools were used during the project. Only the major ones are listed below.

AVR Studio

AVR Studio is a free Integrated Development Environment (IDE) for developing 8-bit AVR applications in Windows environments [38]. It has support for the ATmega168 which was used in the project. AVR Studio includes an assembler, a compiler, a simulator and a debugging interface.

Eclipse

Eclipse is a free IDE for various programming languages. It can be extended with different plug-ins. In this project Eclipse Galileo, C/C++ Development Tools and an external C compiler were used to program and debug software for the BMU.

Matlab, Simulink and Real Time Workshop

A broad description of Matlab is that it is a program used for numerical computing. It can be used for instance manipulating matrixes, plotting graphs and calculating equations. Simulink, an add-on for Matlab, is a graphical block diagramming tool that was used to simulate a BMU model. In Simulink, it is possible to simulate certain scenarios which can occur in a BMU. For instance, it was possible to see if safety functions were working properly and what the SOC value was during a simulated run. Simulink combined with the add-on Real Time Workshop made it possible to generate C code from models. Since Real Time Workshop has support for the ATmega168 it was used for generating code. The generated code was examined in the project, but never used in the final implementation.

Microsoft Office Excel

Excel is a spreadsheet application. It can handle both basic calculations and programs. A simulation of a balancing algorithm in Excel was provided by Texas Instruments. Therefore, the rest of the simulations for the balancing algorithms were also implemented in Excel. The program was used for data calculations and for simulating cell balancing algorithms.

Saleae Logic analyzer

Saleae Logic analyzer consists of a GUI and a hardware analyzer which is coupled in the communication wires between devices. The analyzer listens to signals passing between the devices and proved to be helpful when troubleshooting communication between devices.

5. Discussion

The magnitude of this project was not discovered until long after it had begun. The abundance of new articles published within the fields of battery management units, electric vehicles and cell technologies show that improving battery systems is indeed an important and pressing matter. Many difficulties remain in these fields and they are far too great to all be considered given the limitations of this thesis. This project narrowed its focus instead to an investigation of the available technologies and their applications in electric vehicles.

Today, most of the Li-Ion cell manufacturers are located in Asia. This creates difficulties in ordering new cell technologies, such as the LiFePO4. It can be hard to locate good suppliers and manufacturers. Since most production facilities are located in Asia, the time between order and delivery may be longer than expected. Obtaining cells that match their specifications accurately may prove difficult, let alone finding the correct specifications, discharge curves and other important technical data. It is, therefore, important to properly test the new cells before integrating them into a commercial product. The first large Li-Ion battery factory in Europe is to open in 2010, which may speed up the use of and research in new battery technologies. During the project, a large amount of time was taken to locate suitable cells for the battery pack. A meeting was arranged with ABATEL, a Swedish battery supplier, who provided the cells for our project. Although, the battery pack for the go-cart is finalized, major testing remains. At this point in time, it is difficult to estimate how well the cells will cope with the high current rates generated by the go-cart.

As stated in section *4.14 Extending the battery pack* and *4.34 Extending the BMU*, there is room for improvement in the project. The battery pack could be extended without major changes to the BMU and many different enhancements could be added to the BMU itself. Changing the microcontroller would allow further extensions of the SOC and balancing algorithm. For instance, a higher precision in measurements and calculations could be met by using floating point calculations. The impact of these improvements on the go-cart is unknown and further analysis is needed.

A balancing algorithm had to be implemented in this project, since no algorithms for large amount of cells exist. Some previous algorithms, such as the ones in the PowerPump balancers from Texas Instruments, can only manage a few cells. It would not be possible to implement active cell balancing for the go-cart with these algorithms. At the moment, it is not feasible to implement active balancing in EVs since the balancing currents are too low and the process would take too long. Even future improvements in the amount of current transferred during active balancing will not alone solve the problems associated with this balancing method. It is just as important to develop algorithms that can efficiently and accurately handle active balancing on a large scale. The algorithm used in this project is not efficient enough to be used in real EVs. Although the implemented algorithm could be optimized further for the go-cart, it is outside the scope of this thesis. Optimizing a general balancing algorithm, testing and analyzing it would be a thesis in its own right.

It has been stated throughout this thesis that balancing has benefits for the available capacity and the life-time of the battery. Since weaker cells drift when connected in series, it is reasonable to assume that balancing will improve the capacity of the pack. We were, however, unable to find research with sufficient data to support this assumption. The overall benefits of balancing, in terms of measureable values and comparisons of different techniques, have not been presented in any independent research. For example, there are no comparisons between an initial balancing of a battery pack and repetitive balancing throughout the life-time of a battery. The question remains as to how large the improvements of balancing really are.

Errors in prototype hardware are common and during the project some setbacks were caused by unknown hardware failures. For instance, there were discrepancies between data sheets and hardware. Some of the minor errors caused delays, while larger ones damaged the hardware which had to be replaced. As a result of the delays, there was not enough time to do more than basic testing of the system. Although the project was successful in developing a BMU and a battery pack with active balancing, a proper evaluation of the final product is still needed. Testing of the final battery pack and improvements of the go-cart will continue at QRTECH.

6. Conclusion

Battery systems are a complicated area in which many different engineering fields come together. During the project many different problems emerged, ranging from algorithms, programming and testing to the construction and implementation of electric circuits. Even though the broad compass of required skills was a limiting factor, we were able to complete a battery pack with a BMU for the prototype go-cart at QRTECH.

Due to the limitations mentioned in the discussion, it would not be possible to use the implemented BMU in a real electric car. Although this project focuses on EV implementations, today Li-Ion cells are used in many different portable devices. Some, such as computers and modern mobile phones, usually have processors and software that can control the cells without a large effort. There are also other portable devices, for instance power tools and medical devices, which are more limited when it comes to hardware and weight. These may need an efficient, light weight and cheap BMU for the battery pack. The use of a BMU, as implemented in this project, may be more appropriate in other kind of products than EVs.

In general, many difficulties remain to better the battery systems used in EVs. The accuracy and methods of measurements, as well as the active balancing currents and algorithms could all be improved. For instance, the SOC estimation methods presented in this thesis are inadequate and more research is needed to find a more optimal solution. Although the improvements of battery systems are important to illuminate, it is not the hardware or the software of the battery systems that limit the breakthrough of EVs into the commercial market. For an EV, the cost and capacity of the cells still remain as the most limiting factors.

Active balancing is a more desired balancing method for EVs, but the only feasible method at the moment is passive balancing. Given further refinements, it will be the preferred balancing method in the near future.

The $LiFePO_4$ battery technology used in this project has many benefits compared to the batteries in the hybrid EVs and the pure EVs of today. For instance, designing a battery pack of $LiFePO_4$ should result in a safer battery due to its more stable chemical properties. Exchanging a battery pack of NiMH cells, as used in the Toyota Prius hybrid EV, for a $LiFePO_4$ pack would decrease the amount of cells needed in series connections by almost two thirds. This would have positive effects on both the cost and weight of the battery pack. $LiFePO_4$ looks to be a promising battery technology for use in future EV´s.

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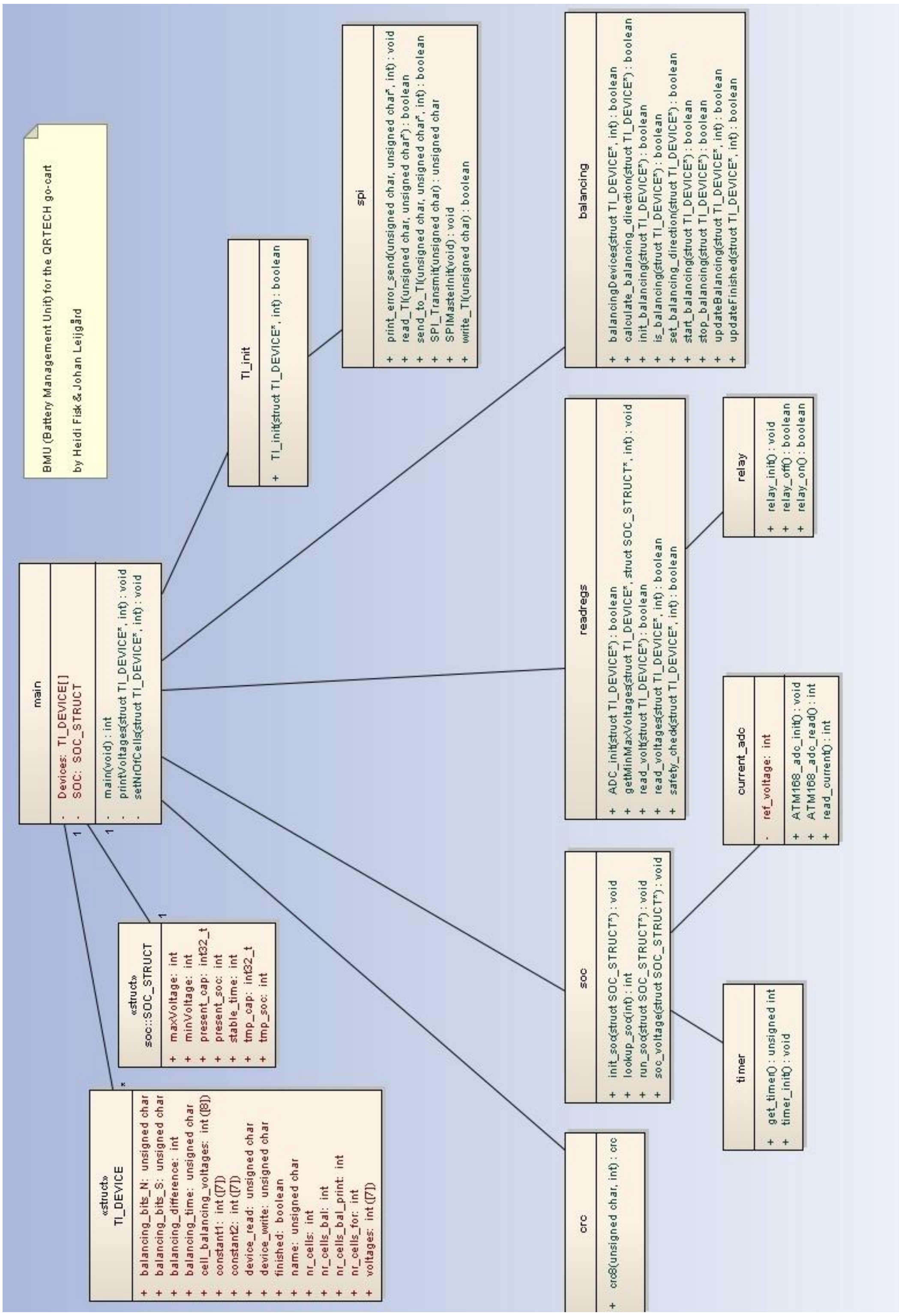
Appendix

A. UML description of the software

The UML model describes the main classes and functions of the software implemented in the BMU.



B. Specification of the $LiFePO_4$ cell

1. Scope

This specification is applied to the reference battery in this Specification and manufactured by Shenzhen Mottcell Battery Technology Co.,Ltd.

2. Type and Model : **Lifepo4 3.2V 20AH-2P**

3. Product Specification

Items			General Parameter	REMARKS
1	Capacity	Typical	20Ah	——
		Minimum	20Ah	——
2	Nominal Voltage		3.2V	——
3	Internal Resistance		< 10mΩ	——
4	Charge	Charge Method	CC/CV	——
		End Voltage	3.65V	——
		Standard current	≤10A	——
		Quick current	≤1.5C	
		Cut off current	0.5A	——
5	Discharge	Cut off Volt	2.0V	
		Const. current	≤10C	——
		Burst current	≤15C	
6	Size	Length	MAX135.0mm	——
		Width	MAX40.0mm	
		Height	MAX78mm	——
7	Weight		≈700.0g	——
8	Cycle Life		Higher than 70% of the Initial Capacities of the Cells	Carry out 2000 cycle Charging/Discharging in the below condition. • Charge: 0.5C to 3.65V then current down to 0.02C • Discharge:0.5 C to 2.0V • Rest Time between charge / discharge:30min. • Temperature:20±5℃
9	Self-Discharge		3% per month	Temperature：25±5℃
10. Working Temperature		Charge	0~45℃	——
		Discharge	-20-60℃	——
11.Storage Temperature		1 Month	-20-60℃	——
		3 Months	-20-45℃	——
		12 Months	-20-25℃	——
12. Air Pressure			86-106KPa	——
13. Humidity			45-75%RH	——

4. Technical Specification

4.1 Test Condition：

(1) Standard Charge：Charge at the temperature of（20±5）℃ with 0.2 C_5A，and the turn to C/V charge, current down to 0.01 C_5A。

(2) Standard Discharge：Discharge at temperature of 20±5℃with 0.2 C5A to cut off voltage

(3) Standard Test Environment：

temperature：25±2℃

Humidity：65±20%RH

Air Pressure：86kPa～106kPa。

5. Environment application test：

ITEMS		Test Method	Result
5.1	High temperature	Rest for 4hours at 70℃ after standard charge，discharge with 0.2C5A down to cut off voltage 2.0V. Then record discharge time.	≥240min
5.2	Low temperature	Rest for 4hours at -20℃ after standard charge，discharge with 0.2C5A down to cut off voltage 2.0V. Then record discharge time.	≥210min
5.3	Fixed heat and Humidity	Rest for 48hours at 40±2℃，and humidity of 93±2% after standard charge，discharge with 0.2C5A down to cut off voltage 2.0V. Then record discharge time.	No distort、No leakage ≥270min。
5.4	Extreme Temperature	Rest for 2hours at -20℃ then rest for another 2hours at 50℃ after standard charge. Do this test for 10 cycles.	No leakage No Fire

6. Safe Characteristic：

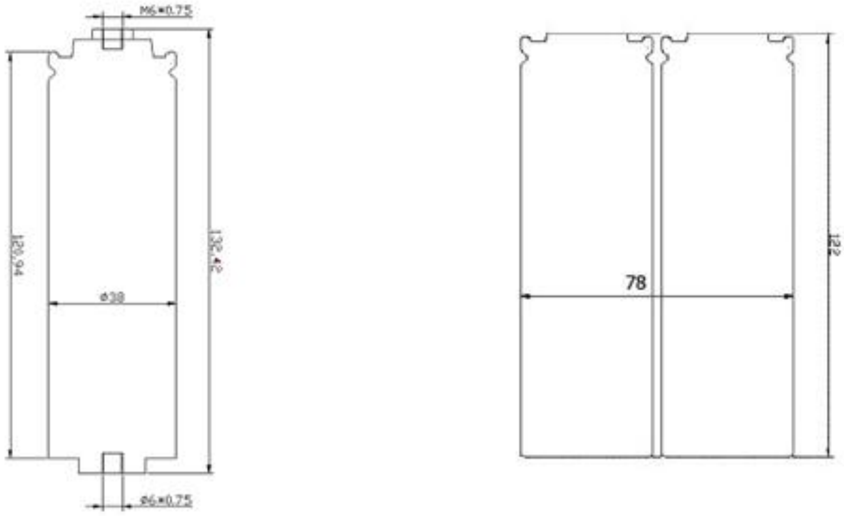
Test condition：The below experiment is required to carry on with strong ventilation system. All batteries must rest for 24 hours after standard charge before doing the experiment.

ITEMS		Test Method	Result
6.1	Over charge	Connect the Anode with the C/C and C/V Source at 20±5℃, fix the current at 3C5A，voltage at 10V. Then charge the battery with 3C5A until the battery voltage is up to 10V，current is closed to 0。Stop the test when the battery temperature is 10℃ lower than the peak.	No explosion No Fire
6.2	Force discharge	Discharge at 0.2C5A for 12.5hours at the temperature of 20 ±5℃	No explosion No Fire
6.3	Short Circuit	Short-circuit the battery with a wire with resistance lower than 50mΩ at the temperature of 20±5℃ for 6hours	No explosion No Fire
6.4	Extrusion	Put the battery between two iron boards at the temperature of 20±5℃，put the pressure of13kN to the boards.	No explosion No Fire
6.5	Heat resistance	Put the battery in the oven then raise the temperature up to 130℃at the speed of 5±1℃/min, keep for 0.5h。	No explosion No Fire

7. Storage

Battery should be stored in the clean, dry, ventilated room at the temperature of -5~35C , humidity less than 75%. Battery should be kept away from corrosive, heat and fire. Before storage, battery should contain about 50%~60% power of nominal capacity. In order to prevent over discharge, it's recommended to recharge the battery after 60 days storage.

8. Draft of battery



Shenzhen Mottcell Battery Technology Co.,Ltd

Model Number: 3.2V 20AH-2P
Data sheet number: SM-QS-HW-90022, VERSION: A/0 Date: 2010-3-1
Tel +86-755-2230-6827
Http://www.mottcell.com,
Email: mottLiFePO4@gmail.com

C. List of battery companies

A123
An American battery company
http://www.a123systems.com/

ABATEL
A Swedish battery supplier
http://www.abatel.com

Enertech
An American battery company within Enerdel
http://www.enertechint.com/

EIG Battery
A Korean and American battery company
http://www.eigbattery.com/

European Batteries
A European battery company with a factory in Finland
http://www.europeanbatteries.com/solutions/cells

Life Batt
An American battery supplier
http://www.lifebatt.com/cellspecs.html

Peak Battery
An American battery supplier
http://www.peakbattery.com/index.html