# Redesign of a Printed Circuit Board for a Battery Management System

A Master Thesis within Production Management

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Master Thesis in Production Management



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## Preface

The knowledge from working in the office of Knightec AB has been invaluable during the writing of this thesis. The guidance and knowledge from my supervisor Enric Ametller has made the project possible. A special thanks goes out to Viktor Åström and Mats Hansson for helping and instructing me in the ways of working with hardware design. Lastly I would also like to thank Bertil I Nilsson for his impeccable guidance throughout the thesis.

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## Abstract

The ever-increasing interest in electrical vehicles around the world creates a strong developing curve for demand for batteries in electrical vehicles. Meaning, the batteries needs to be able to function better and for a longer time without being destroyed in the process. At the same time the batteries also needs to be rechargeable to not unnecessarily pollute the environment. A battery management system ends up affecting all of this. The system uses analysing tools and specific electrical components to monitor, recharge, calculate, balance and control the battery's environment. All within the batteries safe operational area so their general life-time is prolonged.

Battery management systems consists of many electrical components, a market which becomes increasingly strained from the digitisation of society. This makes the choice of suppliers even more important. Not only to ensure future production but also to hold a certain level of cost, lead-time and technical compatibility.

**Title**
Redesign of a Printed Circuit Board for a Battery Management System

**Purpose**
The purpose of the thesis is to develop a new receiver printed circuit board for a battery management system. Which involves finding a replacement of the current integrated circuit which is out of stock, identifying a suitable supplier for the IC, calculating vital components on the printed circuit board and designing the layout and functionality.

**Methodology**
The thesis is based on different logistics models, interviews and circuit theory in order to establish a basis for further analysis.

**Research Questions**

1. How will the re-design affect the performance of the whole system?
2. Will the compatibility be a problem for communicating to the master board?
3. Who are the most fitting supplier for this specific project?

**Findings**

The supply chain for electrical components is a vulnerable area and affects businesses in many ways. To be able to have a way to pick suppliers in the huge market is impactful and have been shown to change the way of thinking when evaluating supply chains. PCB design and development is a way to further extract the value from the suppliers and the compatibility for specific company projects.

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**Keywords**

Battery Management System, Li-Ion Battery, Market Strategy, PCB Design, Supply Chain Management, Vehicle Electrification

# List of Definitions & Abbreviations

**BMS**
Battery Management System. A system handling and analysing batteries in it's optimal climate.

**ENNOID**
Manufacturer of the BMS currently in use at Knightec. And the providers of the reciever board LTC6811 which is currently unavailable.

**IC**
Integrated Circuit. This is the part of the PCB which is going to be replaced and re-designed in this project. The IC is an electrical component which is the main part of the PCB.

**LTC6811**
The current receiver IC in the BMS setup. It is presently out of stock worldwide and has not been available at the biggest resellers since 2020.

**PCB**
Printed Circuit Board. A board used to connect electronic components in a controlled fashion. A PCB is vital in almost every piece of technology today. (Keim, 2020)

## Contents

# 1 Introduction

In this chapter, the topic and background to the report is presented. Delimitations, purpose and research questions is also introduced here.

## 1.1 Background

### 1.1.1 BMS

Electrification in society is an ever-growing project. It is needed to help the modern world develop in to a future with clean and sustainable energy. But, with change comes challenges. Minerals in rechargeable batteries - such as lithium, cobalt and nickel - has suddenly become one of the most sought after minerals in the world. And the resources are finite (CME). The situation is even more complex than one might think. Since these materials are scattered around the globe some countries might use their overflow of minerals as a geo-political advantage. Other countries may be exploited for their natural resources and alter the landscape into a mining cluster. Therefore, measures are needed for batteries to be sustainable, rechargeable and recyclable. Thus, also creating sustainable life cycles. This thesis will focus on one of these measures; prolonging the lifetime of batteries, which involves sourcing a supplier solution and development of a PCB.

A Battery Management System (BMS) is an electronic circuit system that manages recharging of battery packs (I.E. multiple batteries coupled in series or parallel) or battery cells. The system manages the battery by not exceeding the batteries' boundaries within its operational area. Making the battery function for a longer time (Fowler and Tran). This makes the BMS an interesting area to develop and research for the purpose of prolonging battery life. The system consists of a micro controller which oversees the batteries during operation and gathers data regarding temperature, state of charge (SoC), current out of the batteries, total voltage, voltage per battery cell, cooling liquid, battery health and more. One of the most important data which the micro controller calculates is the SoC, which displays how much charge is left in each battery cell. This is important because if a single battery cell gets completely discharged the life-time of the whole battery will be affected. SoC data also provides the micro controller with how much longer the battery can perform before it needs to be charged or replaced. Meaning a control strategy may be implemented to further prolong the remaining capacity of the battery (Brush, Kate).

### 1.1.2 The Current Solution

The current BMS setup mainly involves a receiver board, gathering and analysing data and a master board, controlling the whole circuit and the receiver board. See figure 1.

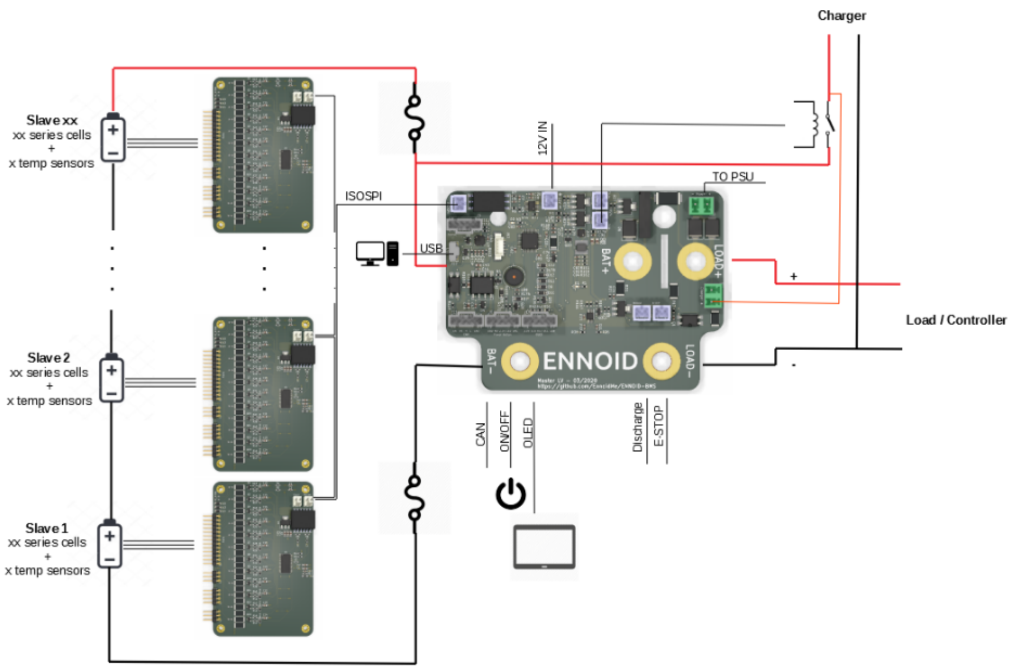


Figure 1: The receiver board(s) to the left and the master board to the right.

The receiver board is a battery stack monitor and is controlled by a LTC6811 IC. Since battery stack monitors are a vital part of battery management system engineering, ICs like the LTC6811 becomes immensely important. The PCB measures up to 12 series connected battery cells and use passive cell balancing (DigiKey). See figure 2 for a detailed schematic over the LTC6811 and figure 3 for an overview of a cell in the LTC6811. These cells may be identified in figure 2 as the green boxes.

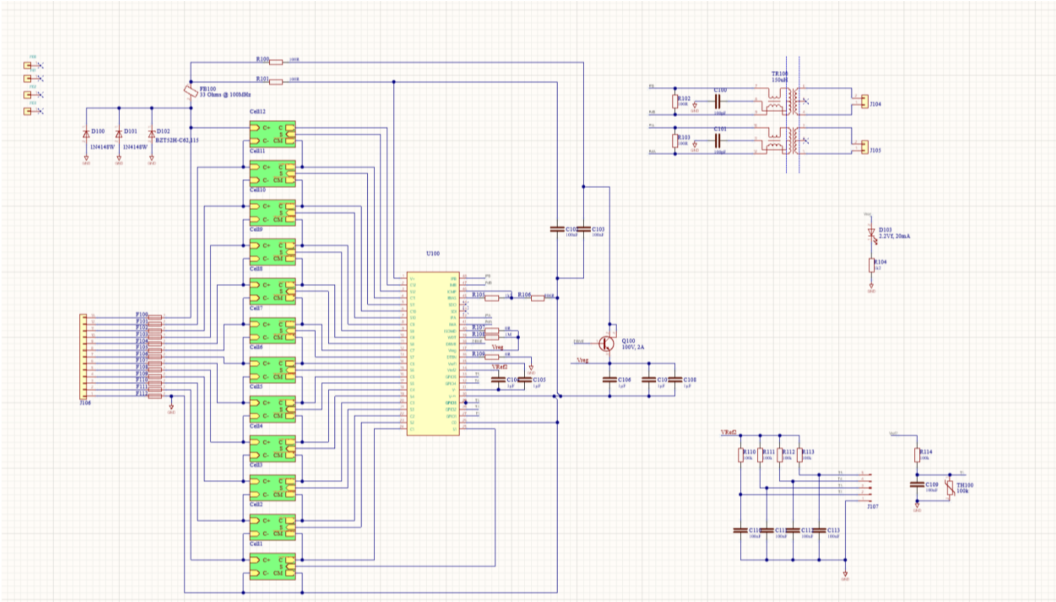

Figure 2: Schematic over the current receiver board with 12 cells and the LTC6811 IC.

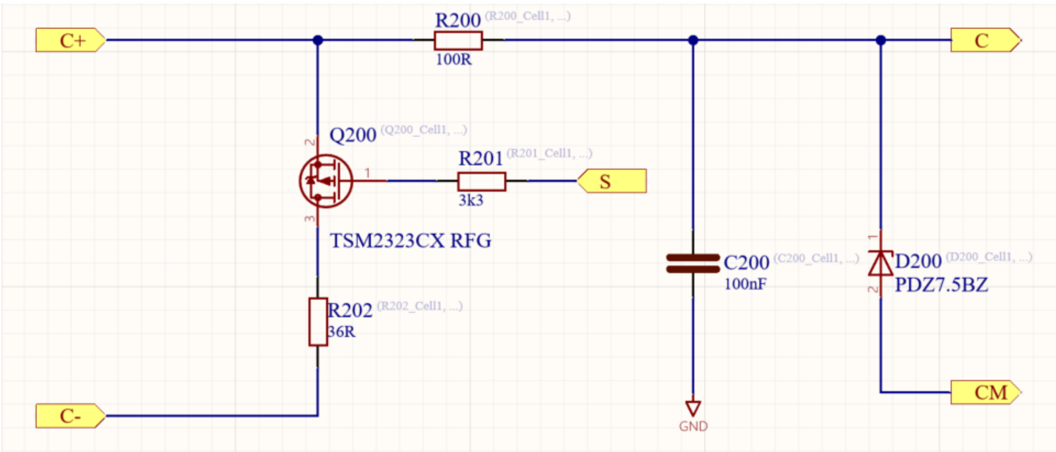


Figure 3: Schematic of one cell of the receiver board.

## 1.2 Problem Formulation

The ever-increasing interest in electrical vehicles around the world creates a strong developing curve for demand for batteries in electrical vehicles. Meaning, the batteries needs to be able to function better and for a longer time without being destroyed in the process. At the same time the batteries also needs to be rechargeable to not unnecessarily pollute the environment. A battery management system ends up affecting all of this. The system uses analysing tools and specific electrical components to monitor, recharge, calculate, balance and control the battery's environment. All within the batteries safe operational area so their general life-time is prolonged.

The case company of this master thesis, Knightec, see a potential in constructing a Battery Management System. But, because of a global shortage of the LTC6811 integrated circuit (IC) and for economic reasons they wanted to change the design of a similar and cheaper board so it may replace the LTC6811 in a battery management system.

Battery management systems consists of many electrical components, a market which becomes evermore strained from the digitisation of the society. This makes the sourcing even more important. Not only to ensure future production but also to hold a certain level of cost, lead-time and technical compatibility. If some great suppliers with reliant products can be identified that are compatible with the system it would greatly enhance the supplier picking pool and path new ways of thinking when constructing battery management systems.

## 1.3 Delimitations

Now, some delimitations of the thesis topic will be presented.

1. The circuit board which will be re-designed will be formed like a receiver board to the specific master board which ENNOID has created. The circuit board will therefore only work in a low voltage environment and have best compatibility with ENNOID's software.
2. The communication between the master board and receiver board may be done in many different ways. To limit the boundaries of the report and to keep focus on the main task will the report only treat isoSPI communication between the PCBs and other eventual components.
3. The market analysis will focus on only profoundly analyse 3-5 candidates from different suppliers. There are a lot of different options available and a lot of suppliers on the PCB market so some measures to slim down the selection needs to be done to give place to depth in the analysis. The PCB created in this thesis will only contain one IC, but to provide a more in-depth market analysis the assumption that many more of these PCBs are to be created, will be made.
4. The projec t intends not to print the newly design PCB within

the frame of this thesis so time may be focused on theory.

## 1.4 Purpose & Research Questions

The purpose of this thesis is to develop a new receiver PCB for a battery management system. This involves finding a replacement of the current IC which is out of stock, identifying a suitable supplier for the IC, calculating vital components on the PCB and designing the layout and functionality of the PCB. These following questions will be in focus in this thesis and will encompass the whole report.

1. How will the re-design affect the performance of the whole system?
2. Will the compatibility be a problem for communicating to the master board?
3. Who are the most fitting supplier for this specific project?

## 1.5 Structure of Thesis

To create a clear disposition that is easy to follow, the thesis has the following structure. It starts with an introduction and background to the topic, including delimitations, purpose and research questions. Next, the methodology surrounding the thesis is presented with the work process and tools used in the project. The next chapter contains the theory where important models, functions and general information, to be able to understand the result of the thesis, is presented. The following chapter introduces the results regarding the analysis and work that has been carried out. The results is later used and referenced in the analysis section where the result is discussed and elaborated. Lastly, the conclusions from the analysis are presented and a view on the future of the project is given.

# 2 Methodology

Chapter 2 will provide the work process and research approach used in the thesis.

## 2.1 Work Process

To be able to give the project a readable and understandable structure will Knightec be seen as the primary company analysed and discussed in this thesis. The potential suppliers will be seen as sub-case companies, revolving around the primary case.

Due to the fact that there are many potential candidates which can function in a BMS, but may not be able to live up to the technical requirements of the current BMS setup; a market analysis will be made over potential suppliers. The analysis will slim down quickly because of the strict technical requirements and will finish with a profound analysis of the top candidates. To gather data regarding technical requirements and preferences, interviews and discussions will be held to provide primary sources.

After the choice of replacement IC will the design work begin in the PCB designer Altium Designer. Altium Designer is a software made specifically for creating PCBs. It allows the user to create and customise their own circuit boards (Altium). Altium Designer (or any PCB designer software such as KiCad or Eagle) is a necessity when designing the new PCB that the new IC probably will require. Due to Altium Designer's great versatility and ease to learn was the software chosen as the preferred alternative for the project. Before producing a result from the software the thesis will contain a component analysis, calculating important values such as voltages, currents and impedances and lastly actually creating the board in Altium Designer. For verifying the component values, the circuit design program LTSpice will be used.

Finally, the PCB will go through some internal revisions to ensure safety and functionality when the scope of the project ends.

## 2.2 Research Approach

The paper "Guidelines for conducting and reporting case study research in software engineering" provides suitable research approaches to be able to gather data for this project (Höst and Runeson). Different research methodologies serve different purposes, which is why a research process needs to be distinguished for the thesis. The paper presents 4 different research methodologies.

1. Exploratory - finding out what is happening, seeking new insights and generating ideas and hypotheses for new research.
2. Descriptive - portraying a situation or phenomenon.
3. Explanatory - seeking an explanation of a situation or a problem, mostly but not necessary in the form of a causal relationship.
4. Improving - trying to improve a certain aspect of the studied phenomenon

Case studies were originally used with the exploratory mindset, aiming to primarily gather new insights in the case study. A descriptive way of working also have the same aim, if the generality of the situation or phenomenon is of secondary importance. An explanatory approach often involves testing and verification of existing theories. Lastly, the paper discusses the improving approach, which is mostly used in software development. The case study methodology is looking to improve a part of a system or a theory (Höst and Runeson).

To set up at plan for a case study the authors suggests to use the following points:

- Objective - what to achieve?
- The case - what is studied?
- Theory - frame of reference
- Research questions - what to know?
- Methods - how to collect data?
- Selection strategy - where to seek data?

With the points above in mind a general plan over the case study can be formed. The purpose of the thesis is to replace a part of a system and find a better replacement in regards of logistics aspects and system requirements. The goal to improve the supply chain cooperation and the BMS makes a case study with an improving approach suitable for this project. Where the case study plan consists of improving the BMS with a new supplier solution by the study of supply chain alternatives and circuit theory. Which is done by using the research questions presented in the previous section and the theory which will be presented in chapter 3. The data to use in the project will come from qualitative methods from know sources and theories (Höst and Runeson).

## 2.3 Research Strategy

The research strategy defines the ways of how to gain the necessary data for the project and clarifies the process for how the research will be conducted. Continuing on the paper from the last chapter the authors defines 3 major research methodologies which are related to case studies:

1. Surveys in form of an interview or a questionnaire.
2. Experiment, characterized by measuring effects from manipulating one variable of a system and analysing the result.
3. Action research, who's purpose is to influence or change some aspect of the focus of the research.

The case studies might be conducted in a quantitative or qualitative manner. The quantitative way of doing research focuses on gathering data from a deductive approach, involving quantifiable aspects such as numbers or other general results. A qualitative case study aims to collect data by theoretical methods and non-quantifiable results. Such as interviews, descriptions or images (Höst and Runeson).

For this thesis is the most suitable action above the usage of a survey in form of an interview to gather data. Since the BMS has many criteria that the new PCB and the supplier should fulfill. It is therefore reckoned that data from the primary source (I.E the case company) is needed to produce results for this project. Therefore, is a qualitative empirical study most fitting. But in a few cases, to get quantifiable results (customer service for example), a quantitative approach will be used. In this regard, interval scales will be used to provide more precision in the measurements. Which provides more flexibility in the analysis (Tracy).

## 2.4 Validity

Validity of a case study denotes the trustworthiness of the result and analyses the comprehension of any potential biased result in the project. There are different classifications of validity as seen below (Höst and Runeson).

- Construct validity
- Internal validity
- External validity
- Reliability

Construct validity reflects what is discussed in the report versus what is gathered from, for example, interviews. If the interviewee do not interpret the interview questions as the researcher does, then there might be validity flaws.

Internal validity is threatened if there is a risk that two investigated factor that affects each other is affected by a third factor that the researcher does not know about.

External validity is concerned with to what extent the results of the project is possible to generalise to other people. The aspect is important because scientific research should be able to produce generalised knowledge.

The reliability aspect reflects to what extent the research and data are dependent on the specific researcher. The result should be the same if another researcher conducted the same study.

All of the points above will be taken under consideration during the thesis, but cunstruct validity and reliability were identified as more important to ascertain in this case. To improve the reliability, peer reviewing will be conducted at the case company regarding the supply chain and the PCB design. To ascertain construct validity of the data gathering interview, the interview will be conducted with a person with great knowledge of the background of battery management systems and the project's case study (Höst and Runeson).

# 3 Theory & Related Work

In chapter 3 the theory behind the design of the new PCB is presented. This includes theory regarding components, general theory regarding PCB modelling and a market analysis for components.

## 3.1 Model for Market Analysis

It is of importance that digital components in any kind of electrical system is thoroughly scrutinised before purchase. Not only because of general reasons such as a value, size, cost and compatibility check. But also as research to see how long the component has been on the market and if its possible that the manufacturer of the component might cancel the production in near future. End-of-life products are not to be recommended to use in a new circuit, since the manufacturer has stopped the support and updates of the product. To avoid this happening to the PCB, a market analysis will be conducted over a few potential suppliers.

### 3.1.1 The Decision Model

Market uncertainty is related to the identification and evaluation of prospective suppliers. A way to further delve into the supplier issue is to extend the research of supplier markets. There are several means regarding how to evaluate different suppliers with regard to satisfy the buyers (Knighec's) different criteria. Therefore, the decision model will be of help when identifying purchasing uncertainties. See the model in figure 4 (Gadde and Wynstra 2017, p. 131-133).

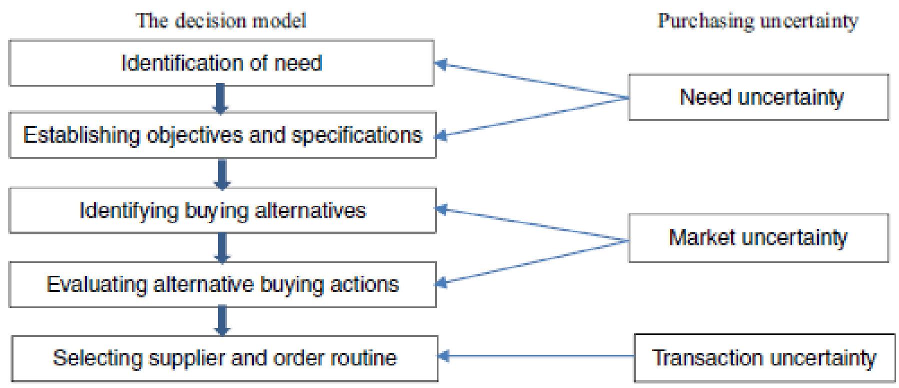


Figure 4: Uncertainties in the buying decision process (Gadde and Wynstra 2017, 131-133).

The authors of the model conclude that the factors in figure 4 is a good way to start when evaluating suppliers but the factors may need to be tweaked depending on the business and supplier need. They argue that by sticking to the same supplier over time, the buying firm might miss emerging supplier opportunities. Again, motivating why the market analysis is an important step before choosing a supplier and why its critical when purchasing electrical components. By relying on two or three suppliers the manufacturer will be protected in times of shortage by having alternative sources of supply. Furthermore, dependence on one source may lead to uncertainty whether the supplier can supply the goods in time. Many suppliers use Just In Time (JIT) as their inventory management method. Mainly, because they want to lower their storage cost for inventory, reduce overproduction and lower ongoing costs. The issue with JIT, though, is that the method is highly susceptible to disruptions in the supply chain (Sheldon, 2022). Meaning, any kind of disruption in the supply chain, such as, cargo vessels obstructing the Suez channel or the lack of raw materials will limit the ability for the supplier to fulfill the transaction.

Moreover, another reason to why evaluate current suppliers is to avoid supplier dependence. Which might lock the company into a specific solution of the supplier. By having at least one more supplier companies would easier avoid shortage issues.

### 3.1.2 The Impact of Purchasing Behaviour

The same author wrote in another scientific report, regarding impact of purchasing behaviour, that purchasing behaviour of the buying firm is more often formed and impacted by the first partners they have as suppliers. The supplier pool is also often large. Much larger than it might need to be, only because of the trial and error methodology that generally characterises a buyer-supplier relationship in a component based market like this. Later on, the pool of potential suppliers are slimmed down, though there might be new entrants, until a long-term solution is found (Dubois and Gadde 2021, p. 696).

Further on, the paper discusses that ambition to attain cost reduction and a sustainable low-cost strategy was one of the most important driver of change in the supplier base. Avoiding dependence on individual suppliers was also a huge driver for this change. The paper use a Swedish company operating in the vehicle market with focus on technical factors as an example for purchasing behaviour. A market where the companies has many similar challenges as the component market analysed in this thesis.

External factors may also adjust the buyer's purchasing behaviour. Such as dissatisfaction with the supplier in previous business cases or discontinuing components without providing a functioning replacement. Putting a product to an end-of-life state might happen at a supplier as they find other larger and more lucrative buyers. These buyers then provide different needs and cooperation requirements than the supplier's other business partners. Which regularly results in a focus shift and a different market strategy at the supplier (Dubois and Gadde 2021, p. 696).

## 3.2 Design Choices of the PCB

Below will the circuit theory and vital components in the PCB be presented and discussed.

According to Knightec, the capabilities which are listed below are crucial for the BMS to function with a new IC, see appendix 3. That information and the technical capabilities will here be explained. Some important circuit theory will also be covered.

- Passive cell balancing.
- Ability to measure at least 12 battery cells in series.
- Built-in isoSPI interface.
- 4-5 general purpose digital inputs.

### 3.2.1 Passive Cell Balancing

Even though battery cells are of the same kind with the same sizing and voltage they will still always be a little bit different from each other. This is because they all are made independently and the chemistry making the battery cells creates inherently different batteries. The batteries might still have different capacities, internal resistances and self-discharge rates, general ageing, etc. Resulting in a battery pack consisting of battery cells will have small differences between the batteries. The batteries will therefore differ in output voltage to the circuit. Even more important, the battery cells will discharge in different rates, which might affect the capacity of the whole battery pack since the battery cell with the lowest SoC determines the whole battery pack's SoC. Consequently, will a depleted battery cell effectively deplete the whole battery pack. This is because a weak battery cell will charge and discharge faster than higher capacity cells, therefore they become the limiting factor for the life cycle for one charge. Depleting one battery cell will result in a non-operative battery pack and the batteries might be destroyed (Nork, Scott).

To tackle the issue, balancing resistors might be used in the PCB's battery input. See figure 5. The purpose of these resistors is to dissipate a small amount of current from the battery cells as heat, while they charge. The outcome will be that the battery cells all have time to charge to their maximum SoC. These resistors are working passively when it is needed, therefore is the process called 'Passive Cell Balancing'. The method is cheap and easy to implement in the circuit. It doesn't improve the run-time of the system and it wastes electrical energy though. Making passive cell balancing resistors preferable when running low-cost projects. Passive cell balancing represents charge drainage from battery cells having too much charge and its counterpart, active cell balancing, doesn't dissipate energy but tries to move charges in between battery cells to conserve energy (Plett, 2015).

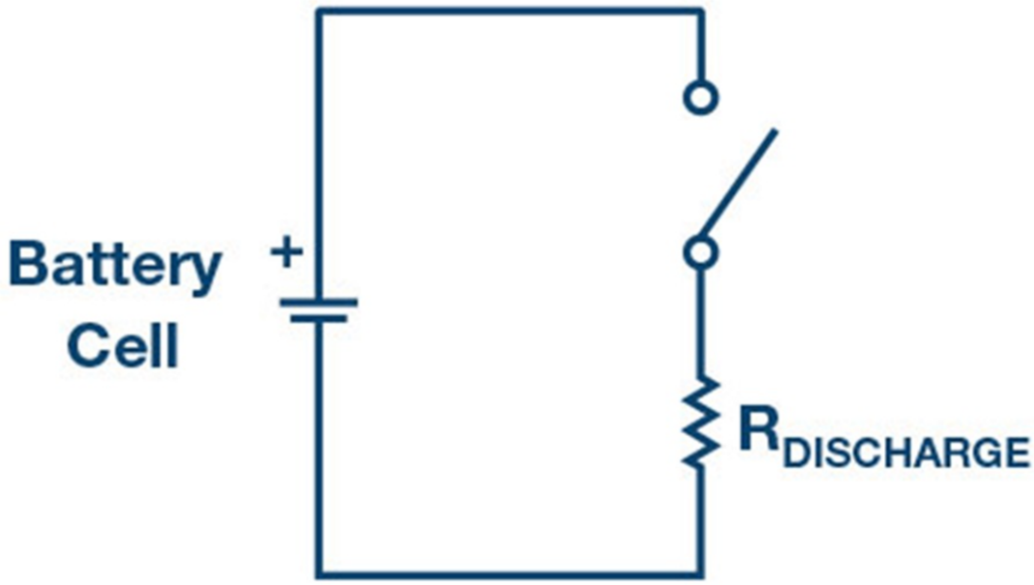


Figure 5: Passive cell balancing resistor and a battery cell.

### 3.2.2 Resistors & Dissipation

When sizing the passive balancing resistor it is important to know the typical battery imbalance and the allowable time for cell balancing. In most small battery applications it is reasonable for the balancing circuitry to be able to correct for a 5 % SoC error with every hour of balancing. In systems with very large batteries, it becomes difficult to use passive balancing to correct large SoC imbalances in short periods of time. But luckily this application is small so time won't be of issue.

To be able to easily dissipate energy and to not overheat the PCB. The balancing resistors might be larger than usual for a PCB in this general scale. To dissipate as much energy as possible and thus give the cells as much time to balance the SoC as possible, the resistors can be large in surface area. Since a larger surface area will provide a larger area for current to dissipate out of. Resistors with a sizing of 2512 (63mm x 32mm) would work fine, for example. The dissipated power would generally follow equation 1.

$$P_{dissipated} = U * I = R * I^2 \tag{1}$$

To be able to balance the batteries, theoretical assumptions are needed. As previously stated a standard assumption in Li-ion battery balancing theory is that the SoC error is approximately 5 % for every hour of battery cell balancing. Where the hours of balancing is the general time battery management systems, of this scale, use to completely recharge all battery cells. Which means that a battery with a capacity of 2 Ah has a total imbalance of 100 mAh, see equation 2 (Barsukov).

$$0.05 \cdot 2Ah = 100mAh \tag{2}$$

This means that using a 50 mA balancing current will balance the cells in 2h, see equation 3.

$$\frac{100mAh}{2h} = 50mA \tag{3}$$

The 2 equations above can be summarised into equation 4.

$$R_{Balancing} = \frac{V_{max}}{I_{Balancing}} \tag{4}$$

### 3.2.3 Li-ion Batteries

Lithium-ion batteries are a popular rechargeable battery which is used in many modern tools such as mobile phones and electric vehicles. They consist of one or more lithium-ion cells along a protective circuit board (Electrochemical Safety Research Institute, 2021). See figure 6 for more details.

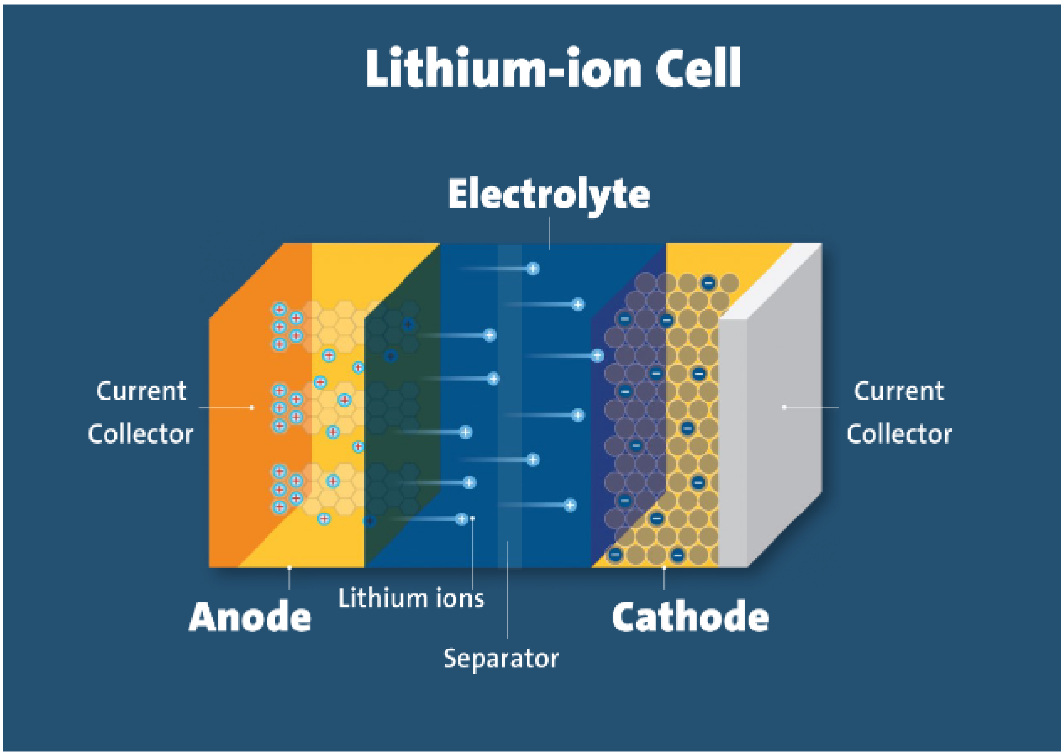


Figure 6: Li-ion battery cell.(Electrochemical Safety Research Institute, 2021)

### 3.2.4 isoSPI

isoSPI stands for isolated Serial Peripheral Interface Communication Protocol and acts as a communication link between sensors, actuators and the micro controller. The protocol facilitates data exchange between these devices and the central control unit. Furthermore, it also follows the master-receiver principle and is full duplex. isoSPI communication is ideal for usage with BMS since they require galvanic isolated communication due to their Li-ion batteries, which are partially explosive. The protocol also provides an easy way to implement daisy-chain connections, where one master controls multiple receivers (Brand). Figure 7 visualises how isoSPI can be configured for control over multiple receiver boards via a common master.

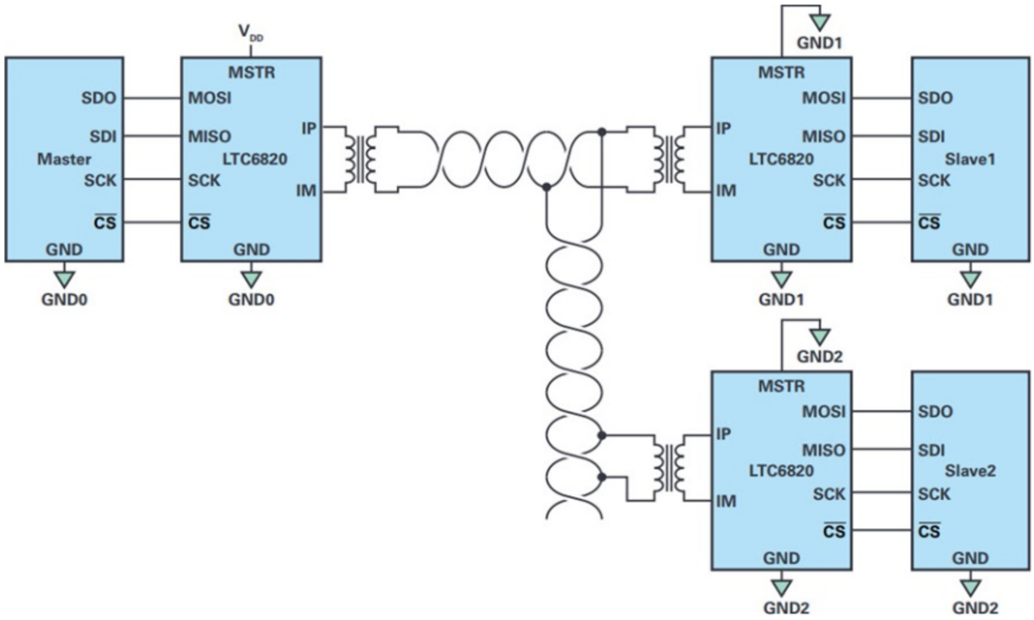


Figure 7: isoSPI connection between two receiver boards and a common master board (Brand).

### 3.2.5 Daisy-chain

Daisy-chaining is a way of propagating signals along a bus in which the devices are connected in series and the signal passed from one device to the next. Daisy-chaining is a great solution to implement if multiple receiver boards are going to be connected to the same master board. Otherwise the board layout of the system might become difficult because of the increase in hardware complexity (Maxim Integrated, 2006). In figure 8 a typical daisy-chain schematic for N devices is shown.

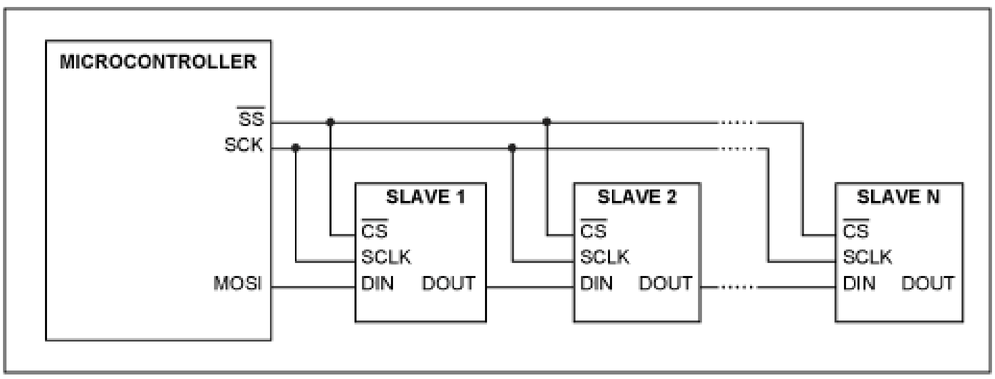


Figure 8: Daisy-chain configuration of N devices (Maxim Integrated, 2006).

### 3.2.6 Capacitors & Filters

Capacitors are one of the most common components found on PCBs. They work by temporarily holding electric charge and release it when power is needed elsewhere in the circuit. There is different kinds of capacitors. A ceramic capacitor features coating over ceramic discs. They store a smaller amount of charge but leaks less current. These kinds of capacitors may be used with higher frequencies than other capacitors and they yield high stability performance and low-loss in the circuit. Making them beneficial to use in circuits with emphasis on accurate results and measurements. Ceramic capacitors are also fail-safe components, suitable for harsh conditions, which is needed to protect battery cells. For example, a short in one of these capacitors would dissipate the charge in a closely connected battery cell instead of the cells burning up (Peterson, 2021).

A capacitor together with a resistor may form a capacitive low pass filter, which is widely used in PCBs to cut off high frequencies in the circuit and let through low frequencies. Furthermore, the filter does also reduce noise and electromagnetic interference (EMI) in the circuit which impacts the quality and functionality of the signals in the circuit and is therefore an important part of any PCB.

### 3.2.7 MOSFETs

MOSFETs are a type of field effect transistor (FET) and are used in PCBs as a controlling mechanism as they switch or amplify voltages in circuits by permitting or preventing the current flow between its source and drain.

Two kinds of MOSFETs are commonly used in PCBs, PMOS (p-channel MOSFET) and NMOS (n-channel MOSFET). Where the primary distinction between them is that a PMOS uses a P-type doped semiconductor as source and drain and N-type as the subrate. While NMOS use the opposite. The PMOS transistor forms an open circuit when it gets a non-negligable voltage and a closed circuit when it receives zero volts. The NMOS transistor works the same way but reversed. A PMOS is less prone to noise while a NMOS provide a smaller footprint than a PMOS for the same output current as a PMOS. The PMOS often makes a good high-side/high-power switch and the NMOS a good low-side/low-power switch (Elprocus). See figure 9 for an overview.

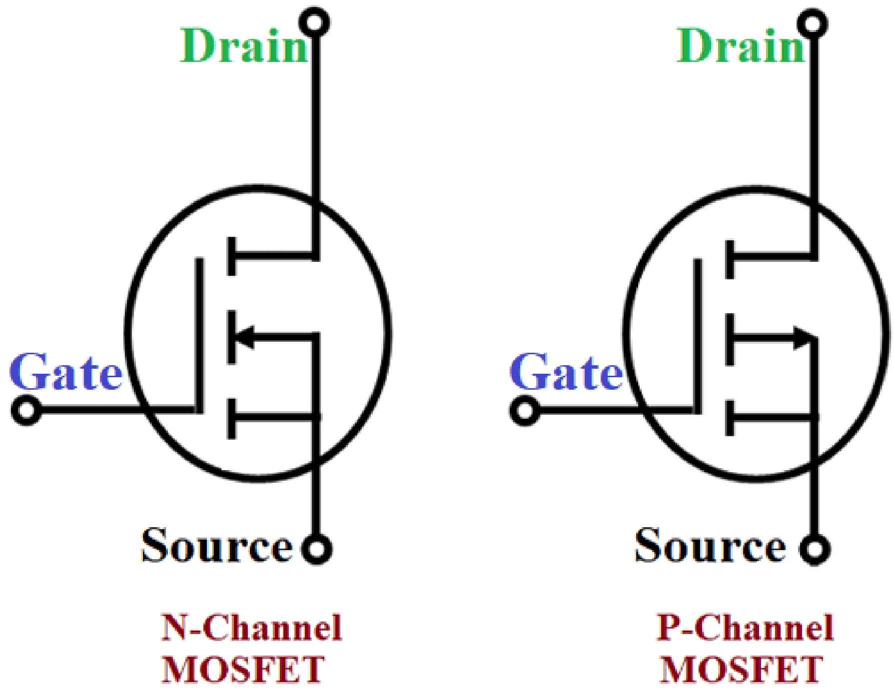


Figure 9: NMOS and PMOS MOSFETs (Cloudinary).

A mix of PMOS and NMOS transistors can be used to create a charge pump. A charge pump is a circuit block that generally consist of nothing but capacitors and transistors and work by carefully timing and controlling these transistors to exploit the charge transfer characteristics of capacitors. A charge pump can therefore increase or decrease a given input voltage to a desired level. They are commonly used if there is a large voltage potential in one part of a circuit that needs to be decreased before reaching small signal components. Another reason to use a charge pump circuit opposed to, for example, a switching regulator is that they do not need any inductance to function. Which means that a charge pump circuit will be cheaper and take less space then most other solutions. On the other hand tends charge pumps to be less efficient and have high levels of ripple and noise than other solutions. A great way to mimic a charge pump solution is to use a mix of PMOS and NMOS transistors (Hertz, 2022).

### 3.2.8 Zener Diodes

A Zener diode is a special type of diode designed to reliably allow current to flow in either forward or reverse direction. It works just as a normal diode but when a certain set reverse voltage, known as the Zener voltage, is reached the diode allows current to flow backwards. Zener diodes are manufactured with a great variety of Zener voltages and some are even variable.

The Zener diode is often used as a protecting piece for voltage spikes, because the voltage drop across the diode is constant. Making it a great component to have close to the voltage source. Since, its able to produce a stable output voltage to the rest of the circuit even if the output from a voltage source may be unstable at times. Because of the high voltage potential from the battery pack output into the circuit, the Zener diode should have a high breakdown voltage (Khan, 2015).

# 4 Empirical Findings

Chapter 4 will provide results regarding the market analysis and the resulting PCB. The replacement board had some fundamental criteria that needed to be fulfilled before they were further taken into consideration. They had to be able to measure at least up to 12 battery cells in series, built-in isoSPI interface, passive cell balancing and 4-5 general purpose digital inputs (for temperature inputs). Moreover, the ICs that cleared the mentioned criteria had to be further analysed regarding price, stock, delivery time and customer service. Therefore, was a market analysis conducted in this project to provide further depth to the report and get clarification regarding which IC would be a better fit for this specific system.

## 4.1 Market Analysis

The uncertainties that are presented in figure 4 have been applied to the market regarding IC's and further delved into. Resulting in the table 1 below. The most important factors where found to be: price, stock, standard lead time, number of cells, amount of general purpose inputs, order time and customer service. The technical demands helped narrow down the choice of IC's. The demands that needed to be fulfilled were the same ones presented in chapter 3.2 and additionally a well documented data sheet. All of the factors are further analysed in the discussion section. The data sheet that was used to provide the data in table 1 can be found under Appendices as appendix C.

To start to slim down the selection of potential IC suppliers, a first scouting was done. For this sorting process only the marketplace DigiKey was used. They have a great selection of components, ship world-wide and is Knighec's component market of choice. This would not slim down the selection much at all but it provided an easier way to structure and find potential suppliers, since the work only was on one web page and much knowledge regarding this market was to be found at Knightec. It was easy to find ICs that fitted several criteria, but hard to fit them all.

Table 1: Potential suppliers and technical factors as of October 2022. Data from DigiKey.com (DigiKey). *See Customer service data in 3.1.1

| Potential Suppliers | | | | |
|---|---|---|---|---|
| IC | LTC6811 (IC to replace) | L9963E-TR | ISL94212INZ | MAX14921ECS+T |
| Manufacturer | Analog Devices | STMicroelectronics | Renesas Electronics | Maxim Integrated |
| Price (kr/pcs) | 226 | 134 | 118 | 160 |
| Stock (pcs) | 0 | 10 | 311 | 25 |
| Standard lead time (weeks) | 90 | 52 | 18 | 28 |
| Cells (pcs) | 1-12 | 4-14 | 1-12 | 1-16 |
| General purpose inputs (pcs) | 5 | 9 | 4 | 3 |
| Order time (weeks) | Approx. 90 | Immediate shipping | Immediate shipping | Immediate shipping |
| Customer service* | – | OK | Great | Good |

### 4.1.1 Customer Service

To rate the customer service a simple grading scale from 1-5 was introduced to provide an easy way to visualise quantifiable results and to provide better precision in the measurements. In the grading scale 1 corresponded to "Terrible", 2 to "Bad", 3 to "OK", 4 to "Good and 5 to "Great". The grade of the customer service was a sum of the two most important factors that Knightec provided. Response time and availability. To test this, an inquiry to tell more about their product and how the compatibility would be with the current BMS setup was made through email and/or online chat with the respective suppliers.

The first potential supplier, STMicroelectronics, had good customer support on their webpage. Consisting of assisting online support and world-wide callable customer support. It took them 2 months to respond to the inquiry, though. Which is a bit too long in this case.

The second supplier, Renesas Electronics America Inc., had great online support. Answering to the inquiry after approximately one week. They provided useful information regarding the IC and its compatibility. They provided software drivers and the necessary micro controller values such as clocking speed etc. for the IC to function correctly with the BMS. They also shipped two free samples of the IC for testing.

The last supplier, Analog Devices Inc., had no callable support but they had a technical support chat on their web page. It took them a day to respond to the inquiry.

## 4.2 The Resulting PCB

In figure 10 can the resulting PCB be found and the chosen IC for the project, ISL94212 from Renesas Electronics America Inc. Why this IC was selected is further discussed in chapter 5. Figure 11 shows the PCB schematic, written in Altium.

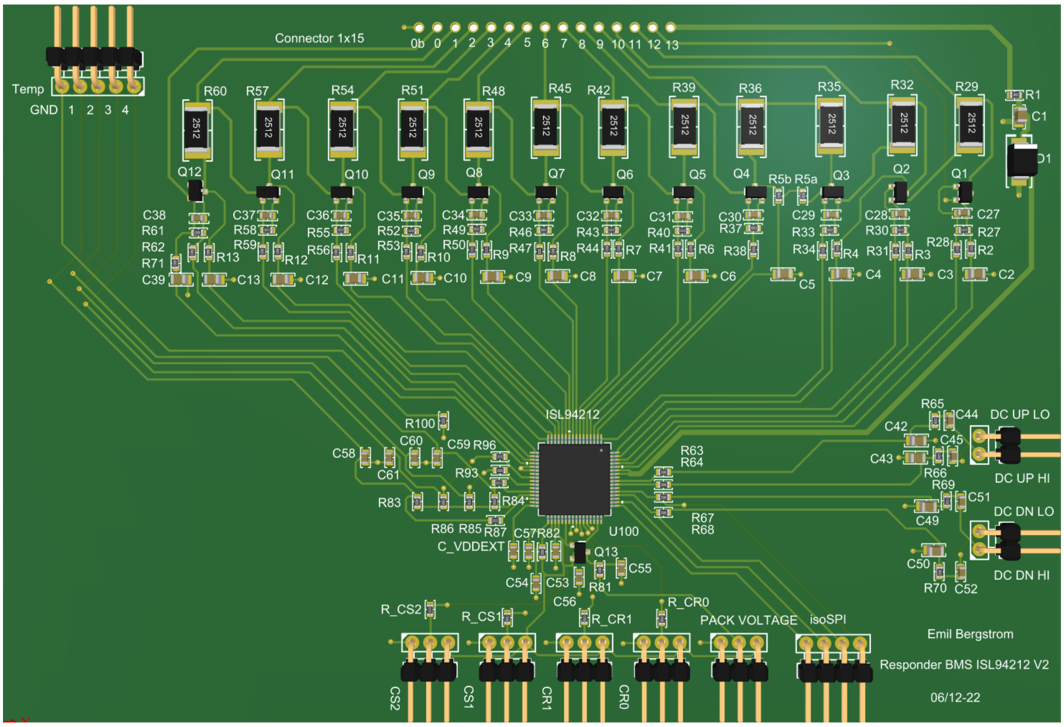


Figure 10: PCB in its full.

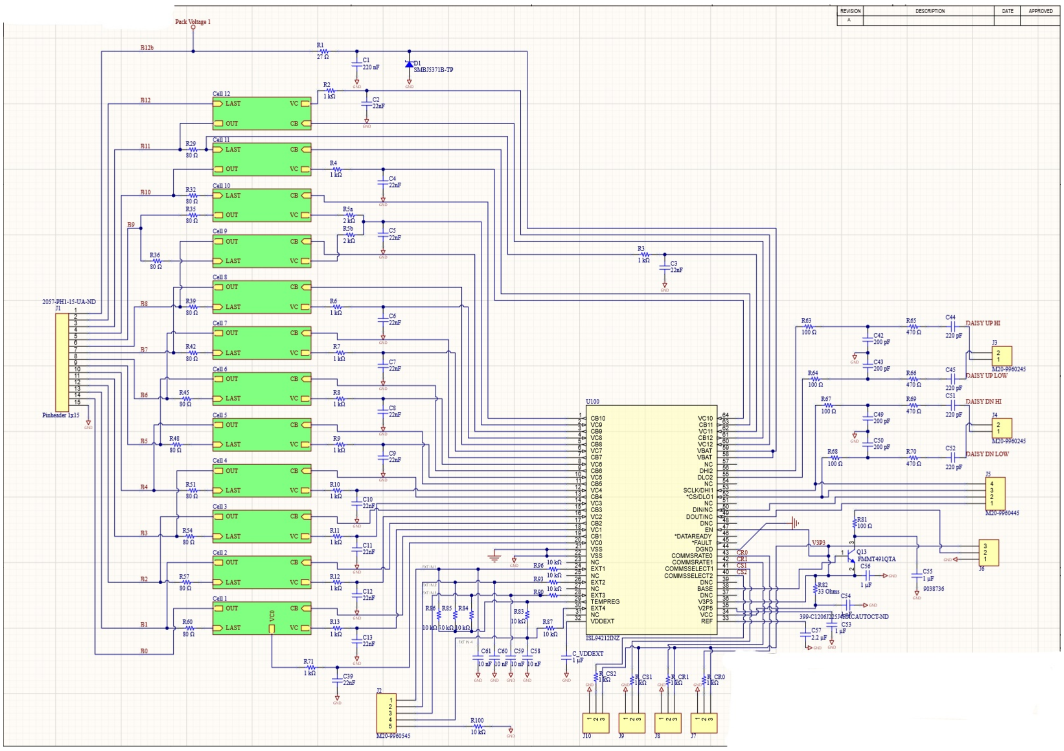

Figure 11: Schematic of the finished PCB.

The finished PCB is a simple two layer card with a top and a bottom layer. Starting from the left side of the PCB as seen in figure 12 at the card has a standard 2.54mm connection header. Where the temperature connection input is supposed to be coupled. This data then goes through some resistors and capacitors to protect the circuit from high current inputs and voltage transients. Continuing right in figure 12 the first cell balancing resistors, R60-R45, can be seen.

Furthermore, beneath the cell balancing resistors are the MOSFETs Q4-Q12. These are all the same NMOS transistors with basically the same connections to other components. Except at two components. The exceptions are at Q12 where there is an extra routing going through R71 and C39 to the IC. And in between Q3 and Q4 where R5a and R5b are located. Transistors Q1-Q3 are PMOS transistors. Beneath the MOSFETs are some more resistors, capacitors and RC-filters. This same structure goes on through the whole PCB.

At the right-most components in figure 13 there is a Zener diode, D1, which is coupled to the 1x15 connector header through C1 and R1. The trace is a bit thicker there as well. All components are grounded to the same net, which is done by a via with a hole size of 0.3mm and a diameter of 0.7mm.

Carrying on downwards, is the IC placed central on the board. Close around it are resistors with different values. Q13 is located below the IC and traces to the pack voltage connection header at the bottom of the PCB. The other connectors are for 'commsselect', which are left open if future use are wanted. The right-most connector is for the isoSPI communication to other boards. The two connector headers to the right are the communication for the daisy-chain (DC in figure 13) connection. They daisy-chain connectors also have some RC-filters and EMI protection.

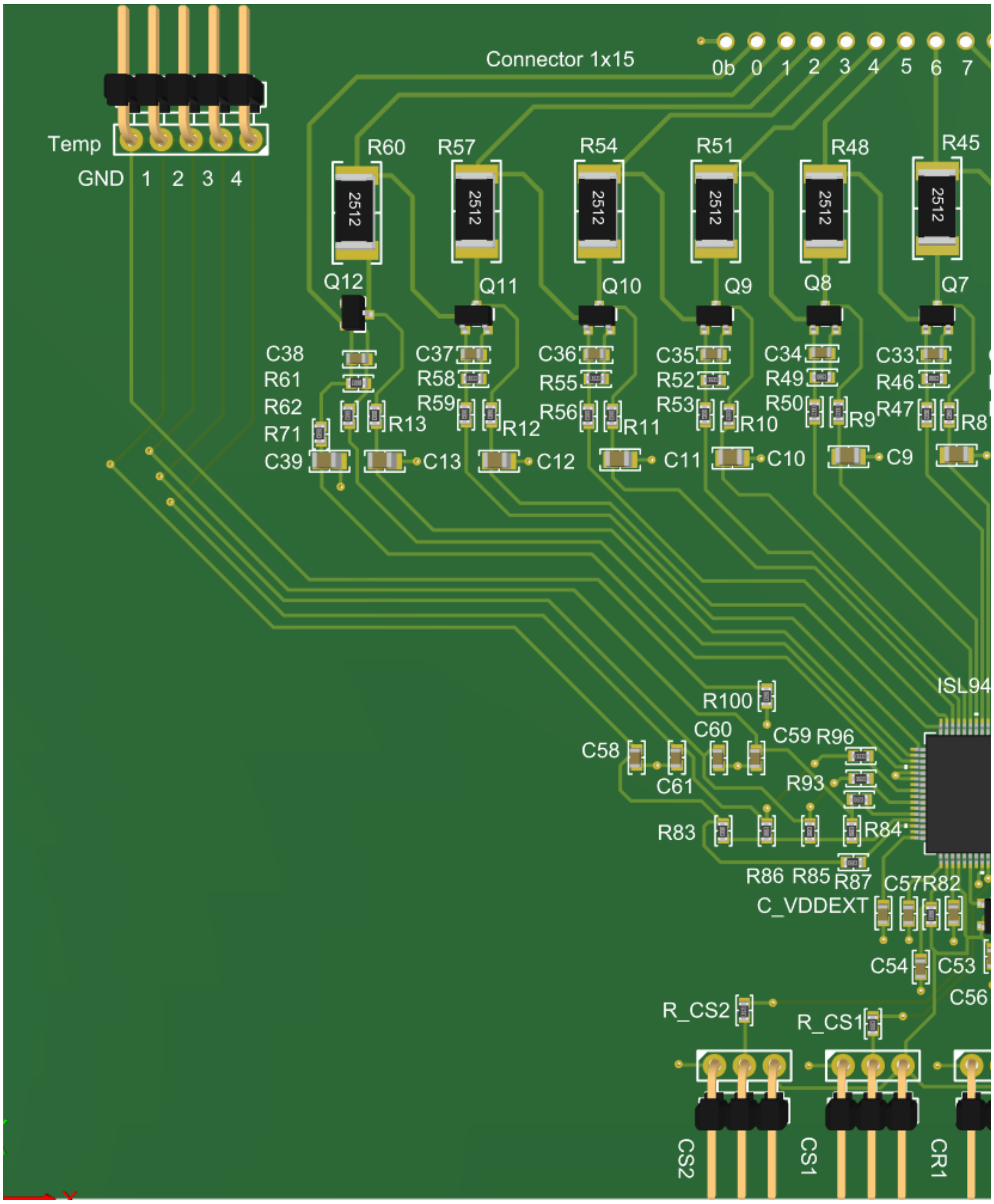


Figure 12: Left side of the PCB.

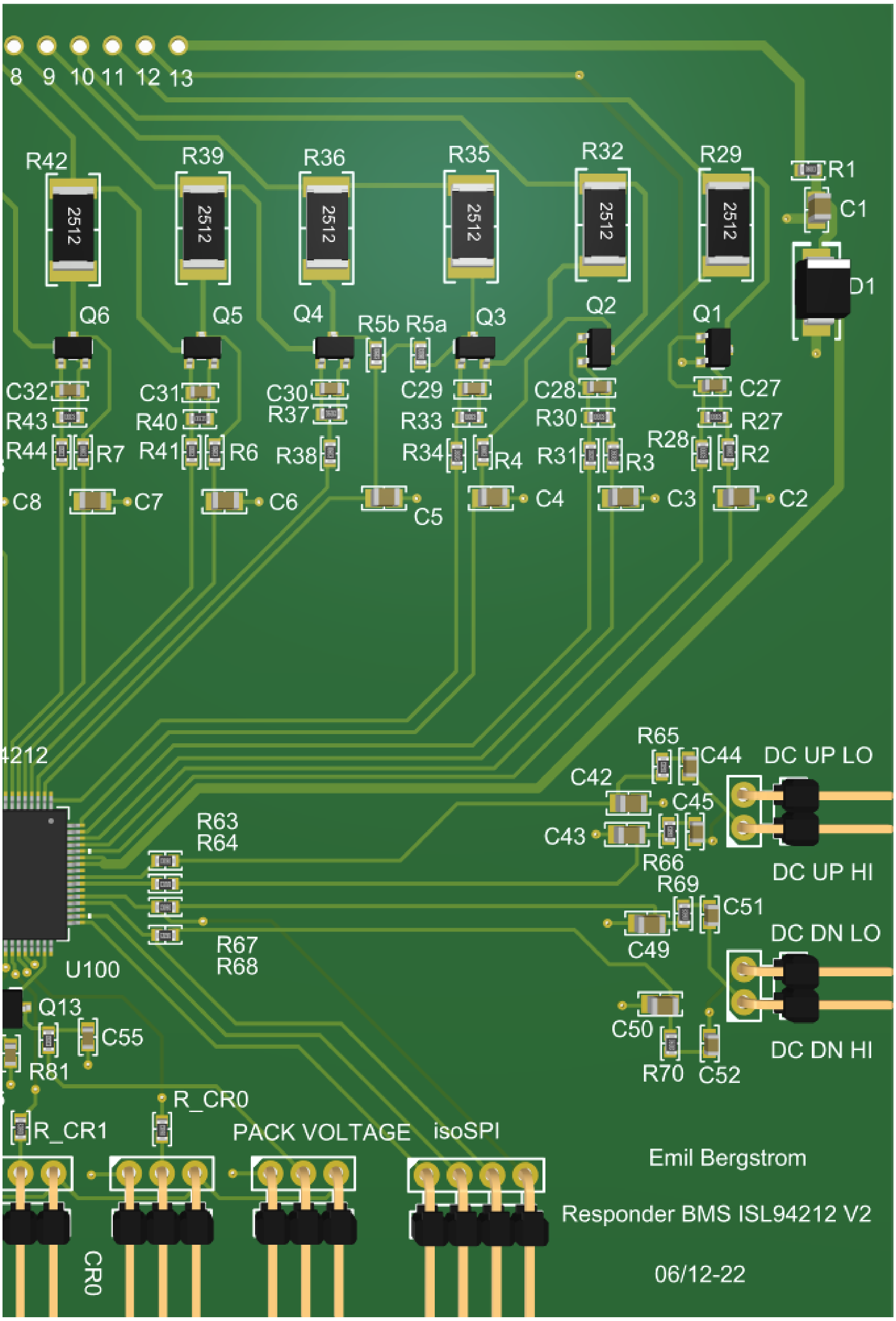


Figure 13: Right side of the PCB.

### 4.2.1 Passive Cell Balancing

As may be seen in appendix A does the batteries provide the circuit with 3,6V, with a capacity of 2000mAh. The maximum potential voltage charge of the battery is 4.2V. Which, for safety hazard reasons, is the voltage used in the calculations of the cell balancing resistors.

The resistors R29, R32, R35, R36, R42, R45, R48, R51, R54, R57 and R60 are the passive cell balancing resistors. In accordance with equation 5 and equation 6 they are all at 84 Ω, if the cell balancing is done in 2 h with a 5 % SoC error.

$$I_{Balancing} = \frac{0,05 * 2000mAh}{2h} \tag{5}$$

$$R_{Balancing} = \frac{V_{max}}{I_{Balancing}} = \frac{4.2}{50mA} = 84\Omega \tag{6}$$

The PCB supports up to 12 battery cells connected in series and the battery cells are all at 3.6V and thus the total potential at R29 becomes 3.6V $\cdot$ 12 = 43.2V. Though, this is only the general case and a the Li-ion battery cells used in this thesis, see appendix B, can have 4.2V charge at maximum depending on material and chemical compound. This makes the maximum potential 4.2V $\cdot$ 12 = 50.4V. The resistors dissipate a power of 23.3 W, according to equation 1 and 31.7 W at maximum summarised voltage from all cells. The current BMS setup only has eight batteries, which means a potential of 4.2V $\cdot$ 8 = 33.6V. See figure 14 for dissipated power and current simulation for 12 cells with 4.2V per cell. Some potential cases were simulated in LTSpice and are described in table 2 below.

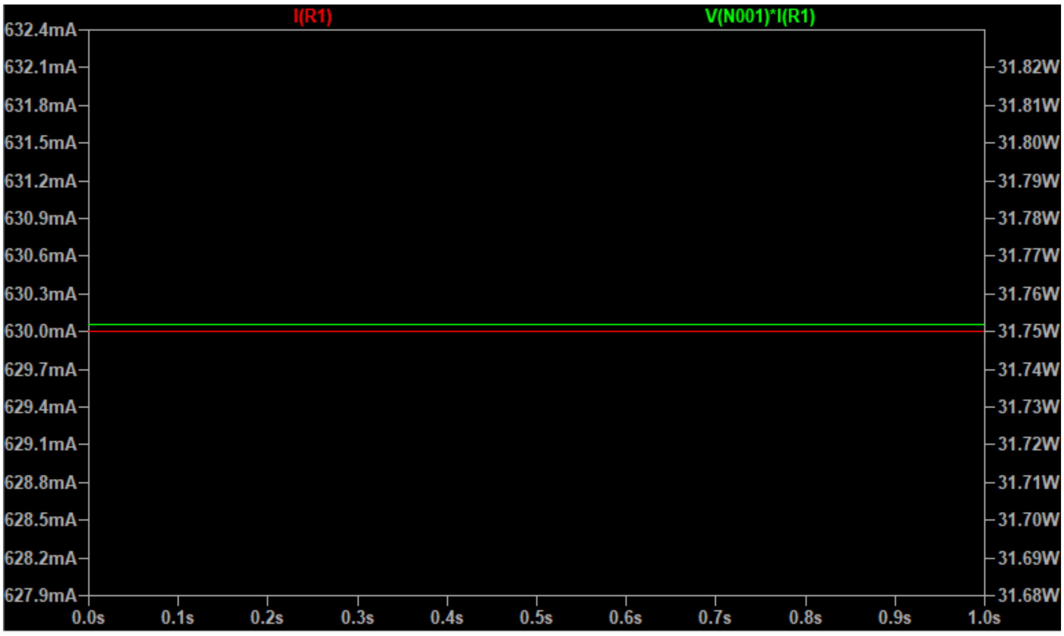


Figure 14: LTSpice simulation of dissipation from 12 cells with 4.2V each. Current on left y-axis, power on right y-axis and time on x-axis.

Table 2: Total dissipated power from battery cells.

| Dissipated Power from Passive Balancing Resistors | | | |
|---|---|---|---|
| Total Dissipated Power [W] | Voltage per cell [V] | Number of cells | Current [mA] |
| 31.7 | 4.2 | 12 | 630 |
| 23.3 | 3.6 | 12 | 540 |
| 14.1 | 4.2 | 8 | 420 |
| 10.4 | 3.6 | 8 | 360 |

It may be noted that all other components in the circuit are dissipating power as well, specifically the MOSFETs since there are many of them and since they have a large surface. This dissipation is only seen as positive from a overheating and fire hazard point of view. Additionally, the dissipation is less then the calculated dissipation above. Therefore will the calculation of the dissipation for those component be seen as abundant, but noteworthy.

# 5 Analysis

This chapter will focus on discussing the results of the market analysis and consider how well the components would function in the circuit.

## 5.1 Market Analysis

Using the model presented in figure 4 it becomes obvious that there isn't a need uncertainty. The PCB is well structured and the guidelines regarding the IC from Knightec are clear. An IC with the capabilities presented in chapter 3.2 is needed. Meaning identification of need and establishing objectives and specifications is done. The next step is identifying buying alternatives and evaluating alternative buying actions. These steps are vital for this project, meaning there is a market uncertainty. To be able to move past this uncertainty, suitable suppliers needs to be found. Which is presented in table 1. The suppliers were chosen based on their similarities to the original IC, LTC6811.

From the results chapter it is deducted that a vital quality of a supplier for electric components is the lead time. Since it has so much discrepancy relative to the other factors and because the lead time issue is the base of this thesis. Therefore, first and foremost, should the potential IC's be analysed from a lead time perspective. Other factors, that Knightec provided, with relatively large discrepancies and importance were stock and customer service. Surprisingly not making the cost one of the most important factors, since the cost didn't significantly vary between the candidates. The factor still differs between the suppliers though and might still be the deciding aspect in the choice of IC.

Continuing down the model, an evaluation of the alternative buying actions needed to be done. Which is discussed in the following section.

### 5.1.1 Evaluation of the Alternative Buying Actions

These evaluations was done in cooperation with Knightec and followed the question guide in appendix C. To interview and discuss the different alternatives with one of the supervisors of this thesis was identified as an easy and proper way go through with the evaluation. Since the person has the best knowledge in this precise matter while also representing Knightec's interests. It is important to still point out that the choice of the final supplier of the IC was done by the author of this thesis.

### L9963E-TR from STMicroelectronics

The IC L99963-TR was found to be a great replacement for the LTC6811 in theory. They had a great looking data sheet with much information and detailed data regarding how to typically create an application circuit for their IC. All cell connections were there and the circuitry looked good for the devices in the current BMS. Everything looked feasible to design and potentially solder. It looked like the supplier could provide the software drivers to program the micro controller as well, making the software part a bit easier in the future.

Customer service was a bit shaky, not responding to the inquiry in approximately 2 months. Might be a fluke or maybe the wrong method to get in touch with the customer support was used but that is not further analysed in this thesis. 2 months was a bit too much according to Knightec.

The biggest issue was the stock, there was only 10 components in stock when the evaluation was done and no saying if the product would have the same fate as the LTC6811 or if the company would have a restock soon.

### ISL94212INZ from Renesas Electronics America Inc

The circuit look great and had much of the same positive aspects as the previous IC. Circuitry looked similar and they suggested in the typical application circuit to use MOSFETs to control the cell balancing as well. In general, the typical application circuit looked good and feasible to use as a helping sketch when constructing the real PCB.

The customer service was the biggest surprise. They answered quickly and sent a free sample of the IC, which could be used in test applications while creating the PCB. The stock was superior in regards of the 3 ICs analysed.

**MAX14921ECS+T from Maxim Integrated**

The last IC looked great on paper but when diving into the data it was quickly concluded that the data sheet would make the circuit design unnecessarily hard. What made the IC harder to work with than the other circuits was that it did not have a typical application circuit in the data sheet. This made it hard to approximate how feasible it would be to use the IC as the replacement. Without a basis to create the application circuit in Altium Designer on, the circuit could be hard to create. The positives were that the IC could be used to monitor up to 16 battery cells in series. Making the BMS able to do more than before and creating a possibility to develop the BMS and its functions further. The general info and communication data looked good.

The stock level was fine, but not great. The IC only had support for 3 general purpose outputs out of the requested 4. But there were other outputs that could have been used.

Lastly, according to the Decision Model, is the selecting supplier and order routine step to prevent transaction uncertainty. This will be discussed below.

### 5.1.2 Selecting Supplier and Order Routine

With all information previously gathered and analysed the choice fell on the ISL94212 from Renesas Electronics America Inc. to be the IC which replaces the LTC6811 in the BMS. Mainly because the stock looked good with no signs of significantly declining anytime soon. The circuit did look really well in the data sheet and the appended typical application circuit would seemingly ease the design and component calculations a lot. The customer service was likewise good and free samples is a great way of promoting your product when doing test cases like this. Soldering test circuits to see how the IC worked in reality showed itself to be quite helpful and a good way to start on future work, see section 7.2 for more info.

## 5.2 BMS Design

To understand the final design of the PCB a design analysis will be performed, using figure 10 and its zoomed in versions, figure 12 and figure 13, as references. For easy access, figure 15 can be found below.

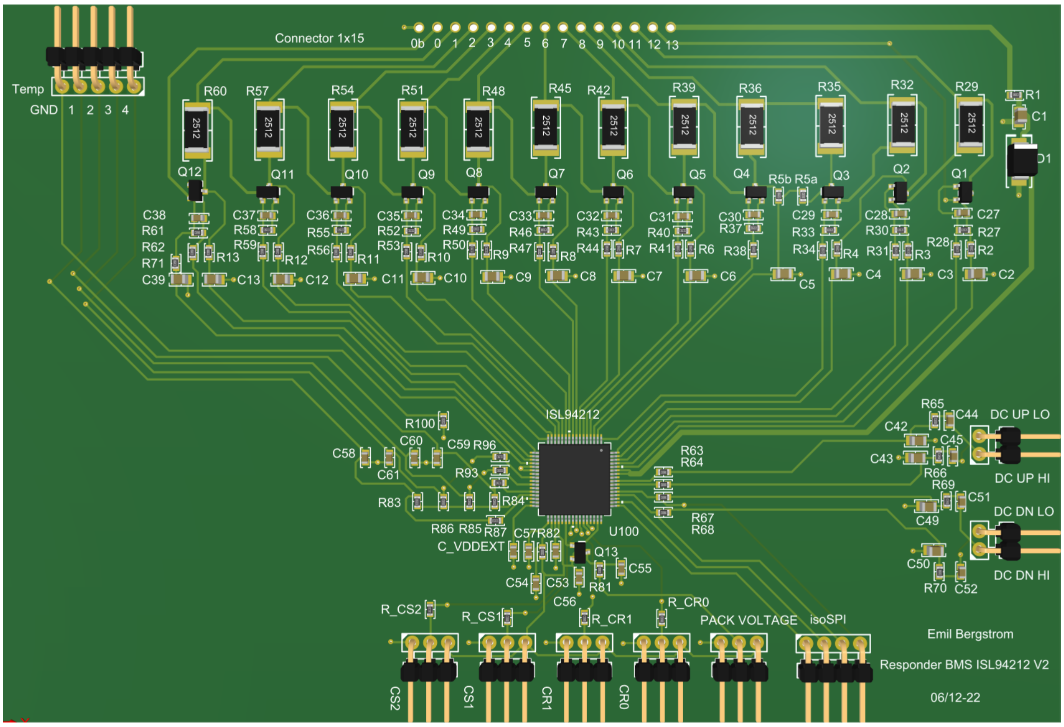


Figure 15: PCB in its full.

### 5.2.1 Cell Balancing

Firstly, the cell balancing resistors will be discussed. These are larger than the other resistors because of the dissipation criteria as previously mentioned. They have a capsule size of 2512, which is relatively large. The resistors are cooling the circuit while also making it possible for the battery cells, which are connected through the 1x15 connector, to charge equally much. They have been calculated to have a value of 84 Ωbut resistors with a value of 80 Ωwill be used because they are easier to find at suppliers and often cost less since 80 is a more generically used value than 84 for resistors.

Above the cell balancing resistors is the connector input for the battery cells. To be able to monitor the batteries and get calculable results, the signal from the battery input to the IC needs to be readable. By having resistors R1-R13, R71, C1-C13 and C39 structured as in 15 an input filter structure is formed. Which protects the input signal from the batteries from transients and electromagnetic interference. The components carry the loop currents produced by the electromagnetic interference, resulting in a less noisy signal. To efficiently make use of this, and to have a stable signal in the circuit as soon as possible, these components are placed close to the battery inputs. Creating an area between the mentioned components and the IC. This makes use of the whole board, sections the EMI and provides space for copper traces. This also creates space for the IC which is placed centrally on the board to ease routing and component placement.

As previously mentioned, the MOSFETs are a mix between PMOS and NMOS transistors. This specific arrangement is made so it would mitigate the need for a charge pump. The PMOS transistors are placed at those certain positions because they are connected to where the highest voltage potential will be in the circuit. As seen at the 1x15 connector the 0b pin is connected to ground, meaning the highest voltage will be at pin 13 and equalize between pin 0 and 12 because of this potential. With this in mind and the fact that P-channel MOSFETs makes good high-side switches and N-channel MOSFETS make good low-side switches, makes the placement of the MOSFETs quite clear. Additionally, P-channel MOSFETs are less prone to noise. Which is why they are used first in the cell chain; where there is most potential. The resistances R5a and R5b are serially connected between a PMOS and a NMOS so the high-side to low-side transition becomes smoother. All MOSFETs are controlled by the IC and the outputs from the IC is later controlled by the micro controller through communication tools. The current sources in the MOSFETs are turned on and off depending on the voltage in the battery cells and is an important part of the cell balancing function.

### 5.2.2 Protection

To the right in figure 13 is a Zener diode (D1) implemented. The diode is an important piece to have at this spot since it protects the circuit from voltage spikes, which does more impact where the voltage is higher in the circuit. It has the ability to produce a stable output voltage to the rest of the circuit even if the output from the battery pack is unstable at times. Because of the high voltage potential from the battery pack output into the circuit, the Zener diode have a high breakdown voltage. Because of the high voltage potential from the battery pack the copper tracing is thicker in this part of the circuit as well. The reason is to minimise the risk of the trace to melt because of the voltage.

Resistors such as R90, R93, R96 are used to ensure that no inactive pin in the IC will produce an unknown state of the pin (I.E. the resistors ensures no floating of the pin). This means the pin will remain in a known voltage state. All external in pins are connected to a 10kΩ.

A couple of 10nF capacitors (C27-C38) are included between the MOSFET gate and source terminals to protect against EMI effects. The capacitors provides a low impedance path to ground at high frequencies and prevents the MOSFET turning on in response to high frequency interference.

C1-C13 are ceramic capacitors, chosen because they are fail-safe components, suitable for harsh conditions. This is needed to protect the battery cells. A short in these capacitors would dissipate the charge in the battery cell if left uncorrected for an extended period of time, according to the data sheet. The same result would also be given by an open-mode capacitor, a switch would be needed for that case though. Making the circuit more expensive.

Furthermore, every power terminal in the IC is connected to the ground via a capacitor. Since, it needs noise protection which may affect the IC's performance, and the performance of other circuits, otherwise. The positive side of the capacitors is connected to the ground so the internal electric field, produced in the capacitor, is created. Otherwise would the positive charge have nowhere to go and the capacitor would be virtually useless.

### 5.2.3 Communication

The micro controller controls the ISL94212 via isoSPI communication in the PCB. This allows for isoSPI serial communication between several receiver PCBs or it may be configured as a stand-alone receiving device to the micro controller. For stand-alone connection see table 3.

Table 3: Communications Configurations.

| Comms Select 1 | Comms Select 2 | Comms Rate 0 | Comms Rate 1 | Communication Config. |
|---|---|---|---|---|
| 0 | 0 | SPI (Full Duplex) | Disabled | Standalone |
| 0 | 1 | SPI (Half Duplex) | Enabled | Daisy Chain, Master device setting |
| 1 | 0 | Daisy Chain | Disabled | Daisy Chain, Top device setting |
| 1 | 1 | Daisy Chain | Enabled | Daisy Chain, Middle device setting |

The connectors that table 3 shows can be seen in the bottom of figure 15. These connections refers to the different communication configurations in the table above. As seen in figure 16, CS1 stands for Comms Select 1, CR1 for Comms Rate 1 and so on. Lastly is the connection for the pack voltage which powers the circuit.

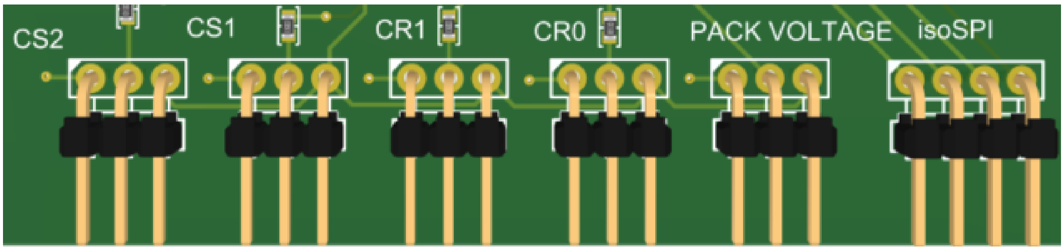


Figure 16: Communication configuration.

Finally, daisy-chain connections are implemented in accordance to the data sheet of the IC and the circuit can be complemented with additional hardware.

# 6 Conclusions

Chapter 7 contains recommendations for future work and the contribution to academy.

## 6.1 Result from Present Work

The result of this thesis is a custom solution for a receiver PCB in a BMS. The PCB works fine and looks good in theory. The system is scalable as daisy chaining provides ways to connect more devices and improve the performance of the system. Cell balancing resistors have been calculated and the addition of cell balancing MOSFETs have certainly increased the performance of the system. The chosen IC has many of the same technical functions as the previous IC had, making it easy to say that at least in theory the re-design has enhanced the performance of the whole system. Note that this is only in theory and the system may fail when testing the real hardware.

Testing will also involve checking the communication compatibility. As described before, the PCB is designed differently than previously and the IC is constructed from a different supplier. So there will most certainly be communication issues between the new PCB and the ENNOID master board. On the positive side is that the supplier provided info their data sheet (and on email) that the systems should be able to work together if the clocking speed of the PCB and the master board was synchronised. This means that the compatibility probably will be a problem when testing the BMS but there are measures that may be done.

The supplier issue has been solved through scrutinized analysis and theoretical bench-marking. Many details regarding technical functionalities, market structure, supplier management and purchasing uncertainties have been discussed in depth. Resulting in the chose of the ISL94212 from Renesas Electronics America Inc.

To summarise, trying to solve supply chain issues in the always more extensive and impressionable electrical component industry have been a interesting and time consuming task, but it has provided a great deal to this thesis and the BMS. The design process went great and the end product looks good. The theory needed to write this thesis was plenty since many different research areas were included but it has been an important basis for the creation of this broad and end-product-oriented project. All in all, the purpose of finding a suitable supplier and create a new PCB has been achieved.

## 6.2 Future Work

First and foremost the PCB needs to be verified, tested and reviewed. Which needs to be done by a design review in Altium Designer by a more senior Altium Designer developer. Secondly, a bill of material needs to be created and all components needs to be ordered, including the board. To decrease the total cost a bit, the components may be purchased separately and then soldered on at a later stage. The new PCB also needs to be tested in the whole BMS environment with the current 8 batteries and likewise with 12 batteries. Finally, the circuit needs to be tested with the current BMS setup, i.e. with the master board and the batteries and the voltages and currents in and out of components needs to be checked with a multi-meter.

Software also needs to be implemented in the future. There are currently no drivers to control the IC and the micro controller with. The supplier have provided some sample code though and their software team vouched that the open source software from ENNOID would work if the internal clocking was in the same phase as the one from the micro controller. This still needs to be verified and might provide some bumps on the future development.

Lastly, it is possible to implement additional functions such as a Vedder's Electronic Speed Controller (VESC) with the BMS. Which is an electric circuit that controls and regulates the speed of an electric motor. This would enhance the whole system since the electric motor get a signal from the VESC regarding how much to push the motor or how hard to brake, for example.

## 6.3 Contribution to Academy

The created PCB is only an experimental venture. It is hard to say if the project is a success or not before analysing and testing the hardware with the configured BMS environment. The project might not work at all with the master or the micro controller since there are some aspects which this thesis does not take in regard. Such as software compatibility between the PCB and the BMS. The supplier wrote that the IC should be working in with the current configuration, but it was important that the internal clock was in the same phase as the rest of the system. So the communication works. The thesis is likewise reliant on the open source software from ENNOID. If that, relatively new, software does not want to compile or has compatibility issues with the new board, a large problem might arise. Experience tells that nothing is always easy with high technology when it comes to new inventions in old systems.

On the brighter side, the thesis has great potential to show and illuminate new ways of working with supplier demands, end-of-life products and electrical system integration. The thesis describes a way of working with lead-time crisis' for integrated circuits and electrical components that can be the difference of survival or not for smaller projects, dependent on certain electrical components. This statement becomes even more meaningful and suggestive when seeing the catastrophe the pandemic of Covid-19 has had on the suppliers market. Visualising how fragile company's production capabilities are to delays in the supply chain. Furthermore, the project additionally shows a way of conducting requirement engineering and design while also taking market analysis and sourcing in consideration.

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# Appendices

# A Appendix: BMS Setup

The BMS that is used is provided by Ennoid-BMS and it consists of two boards, the main or master board and the slave board.

**Master-LV board:**
The following picture shows the Master-LV board.

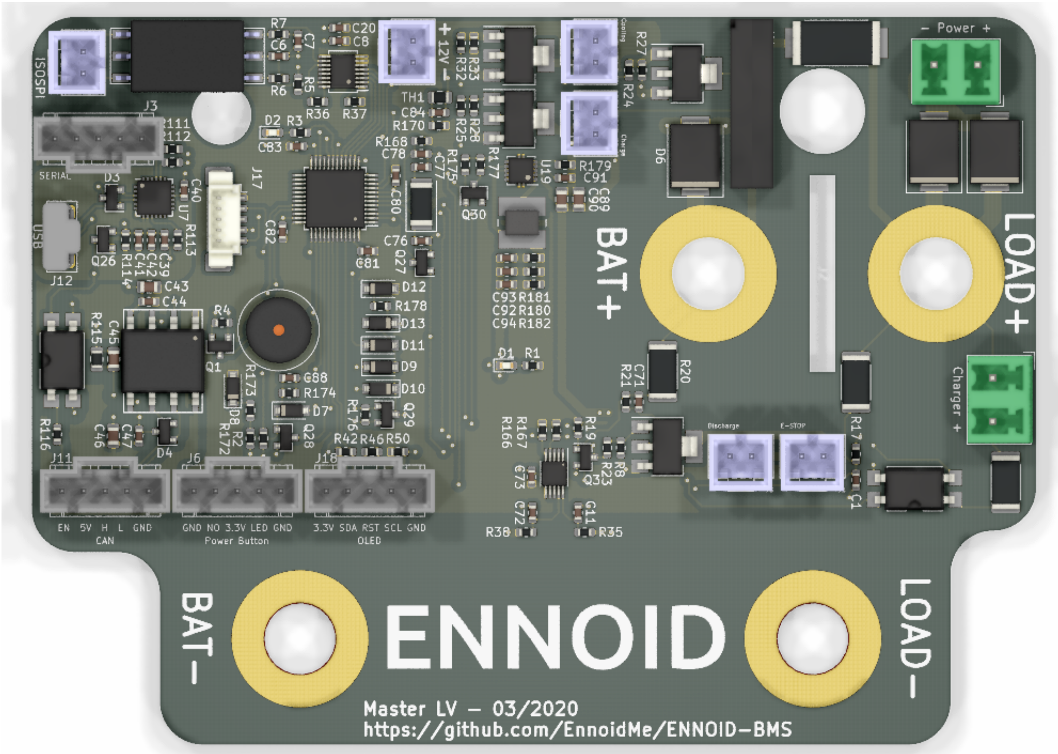


Figure 17: Master board of the BMS.

The main board has several connectors:
• LOAD+: Main current path to the positive side of the load.
• BAT+: Main current path to the positive side of the whole battery pack.
• LOAD-: Main current return path to the load.
• BAT-: Main current return path to the whole battery pack.
• 12V input: Connect a 12V power supply to this connector. Power supply needs power enough to supply the peak current when main contactor or other relays need to close, it should be around 3A.
• Discharge: This connector controls the main contactor (EVC500) which will connect of disconnect the battery pack to the load.
• E-STOP: This connector controls an emergency stop button in

case it is necessary, otherwise leave it shorted.
• Charge: This connector controls the relay that will open or close the circuit to the battery charger. If the BMS detect any dangerous parameter of the battery pack it will stop the charging process.
• Charger: This connector detects if the charger is on. If the voltage at this connector is higher than in the pack, it will automatically trigger the charger contactor.
• Cooling: This connector power on or off a cooling fan in case it is installed.
• ISOSPI: This connector connects to the first one of the slave boards.
• Button: This connector connects to the power button that will power on or off the BMS.
• OLED: This connector connects to an OLED display using I2C, the model of the display is SSD1306.
• CAN: This connector enables communication though CAN bus in order to monitor most of the parameters of the BMS.
• SERIAL: For communication between BMS and computer.
• USB: For communication between BMS and computer.

Receiver board (LTC6811-12S), the following figure shows how it looks:

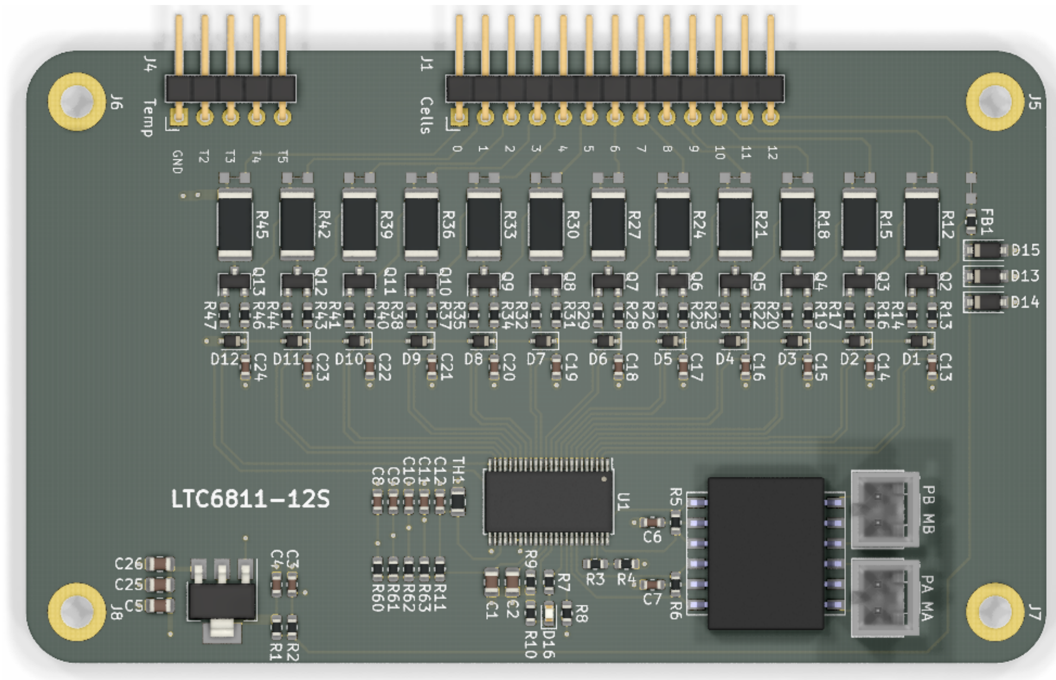


Figure 18: Receiver board of the BMS.

The connectors that feature the receiver board:

• PA-MA: Connect to the master board or to the previous slave board.
• PB-MB: Connect to the next slave board or leave unconnected if it is the last one.
• Cells: Connect to the positive terminal of each cell to monitor. It is in charge to monitor individual cells voltage and passive balancing them.
• Temp: Connect to each of the installed temperature sensors.

**Battery pack (8S1P):** The battery pack is conformed of an 8S1P configuration. The cells used in the pack are Samsung INR18650-20R. The nominal voltage of each cell is 3.6V which makes the nominal voltage of the pack to be 28.8V. The pack has a capacity of 2000mAh which is the same of each cell. For standard charge operation each cell requires 4.2V with a current of 1A, while 4A are required for a fast charging. If the whole pack is charged at once, it will require a total voltage of 33.6V. Although the power supply in the lab is cable of outputting at maximum voltage of 30V it will be considered enough for charging the battery pack, though it will never get fully charged. The following image shows the actual battery pack, that is prototyped at Knightec's lab:

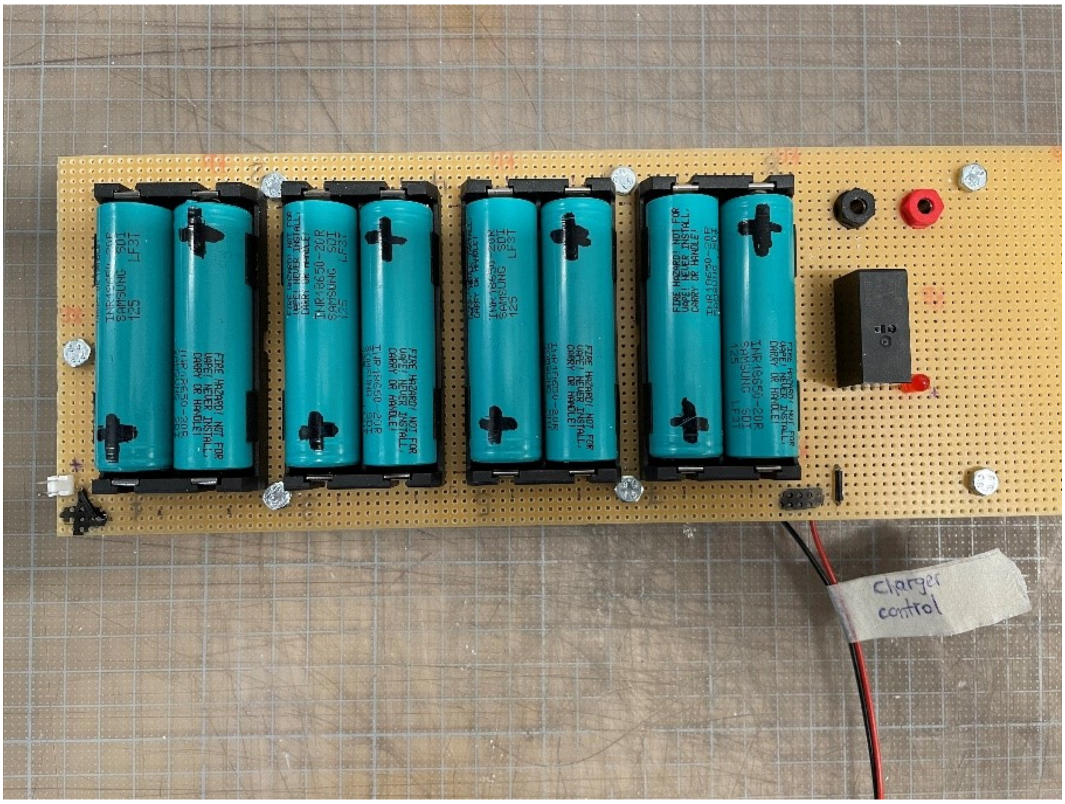


Figure 19: Battery cells.

On the top right of the image there are two banana female connectors that will connect to the battery charger/PSU. At the bottom right there appear a couple of cables that will connect to the “charger” output of the main board, those control the relay (black box at the right) that will connect and disconnect the charger when the conditions are met. Finally on the bottom left there is a white connector that connects the whole battery pack to the load, in other words, it has connection to the main positive and main negative wires from the battery pack. *In the photo there are missing the balancing cables that connect to the positive of each cell. They will be installed when the whole system is received and connected.

**The load:** The load is simulated in the form of a simple power resistor that will just dissipate energy as heat, it can be seen in the following image:

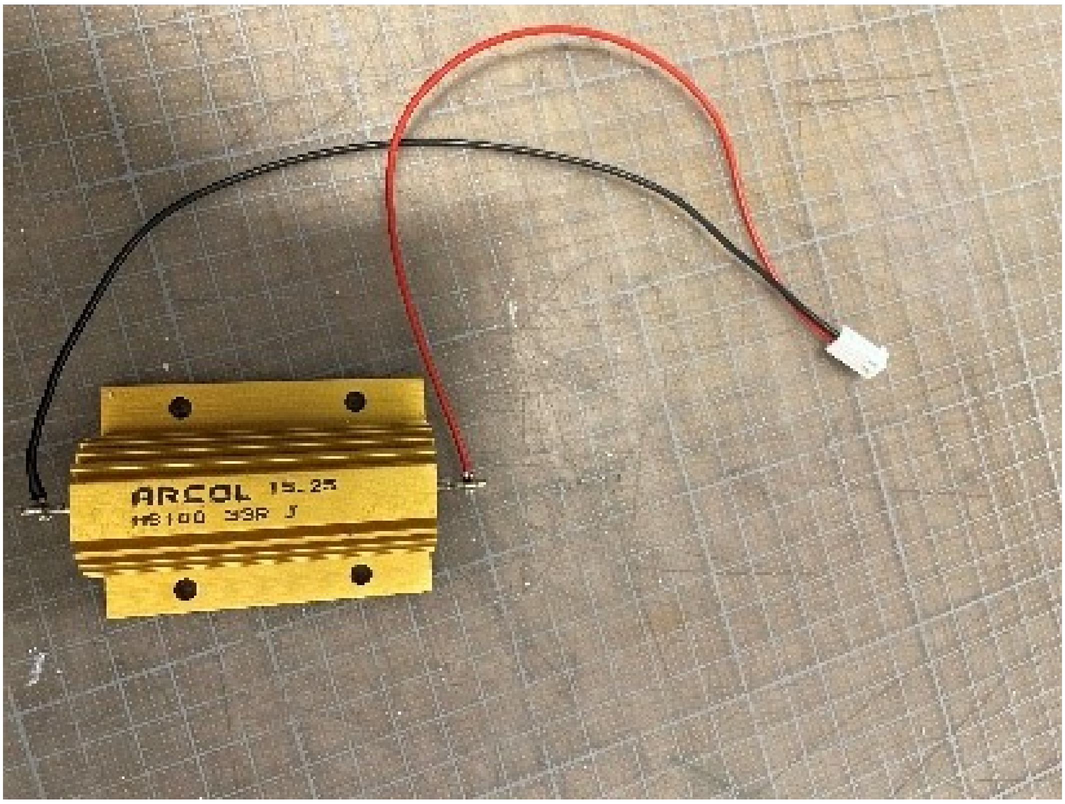


Figure 20: Power resistor.

It is a 33-ohm resistor, thus knowing the voltage of the whole battery pack we know that it will draw 0.87A of current, given that the battery has a capacity of 2000mAh, it will take around 2.3 hours to discharge the whole battery pack. ***Be aware of the amount of heat that it will dissipate, and that its surface may even get to 100 degrees, so take special precaution for that***.

**Connection of the whole BMS:** In order to connect the master board with the slaves and the battery pack the following picture will be used:

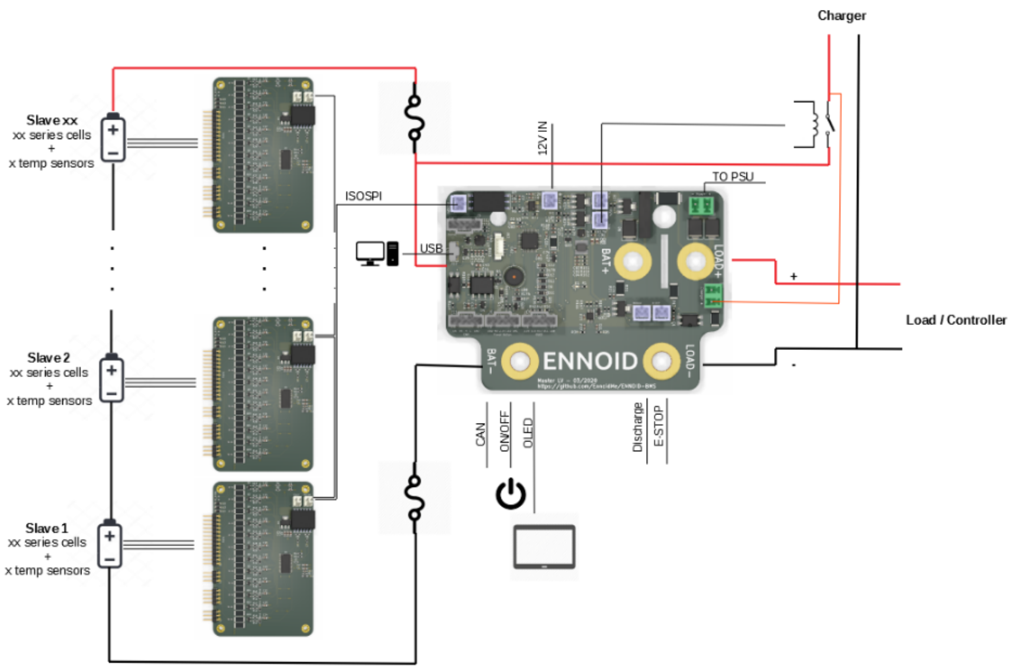


Figure 21: BMS.

At the right of the picture there is the Master-LV board, and the left of the picture there are the slave boards (LTC6811-12S), each of this board is cable of monitor 12 cells in series and 5 temperature sensors. The main contactor (EVC500) is connected directly (No cables are necessary) between the terminals LOAD+ and BAT+ where it fits perfectly. On the other hand, the main negative current path must run though the terminals BAT- and LOAD- in order to monitor the current going out of the battery. The solenoid that controls the main contactor is connected to the discharge connector.

The 12V power input is connected to a PSU with a fixed voltage of 12V and a fixed current of 3A. The charger used is a PSU configured as CC-CV (Constant Current-Constant Voltage) according to the battery pack that is used in the BMS. In this case it is an 8SP1 battery pack, thus a voltage of 8*4.2V = 33.6V must be provided. For the current 1A is necessary for standard charge or 4A for fast charge. The charger will be controlled by a relay (RS Components 476-808) that will open or close the charger circuit depending on the safety parameters of the battery, for example when a battery cell reaches the overcharge parameters the charger will be disconnected automatically. The coil output of the charger relay will be connected to the “charge” connector on the main board.

isoSPI will connect the main board with the first slave board to its “PA-MA” connector. This will enable the communication between master and slave. Charger detection input shall be checked with ENNOID for how to connect it properly. The OLED display and the power button will be connected to their respective sockets as it was described previously. They already come with the connectors wired.

**Connection of the battery pack:** From the above image, it can bee seen that the main positive and negative of the battery will connect respectively to the “BAT+” and “BAT-” connectors on the main board. One must take care that those cable may have to carry large amounts of current, and thus, they need to be dimensioned properly. Afterwards the balancing cables need to be connected from the “cells” connector to the positive side of each battery cell. Since the number of series cell is lower than the maximum capacity of cells that can monitor the IC, a special configuration needs to be followed, this can be seen in the following image:

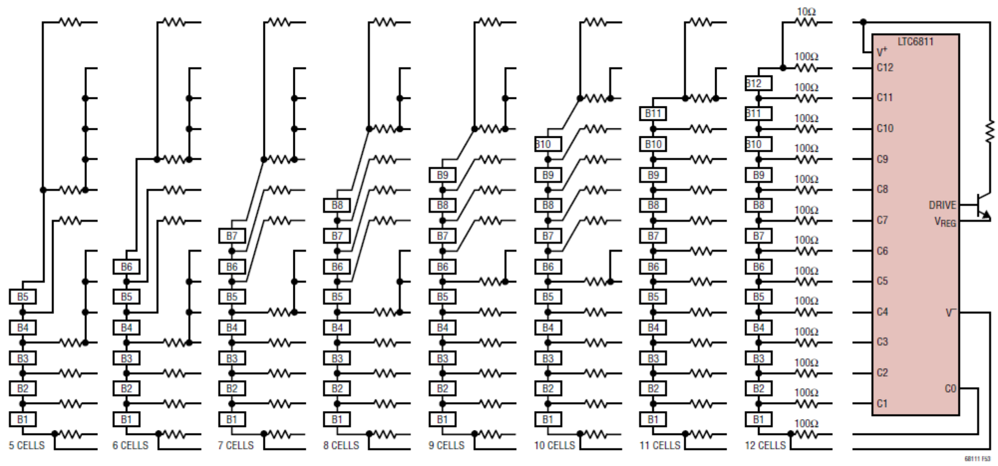


**Figure 53. Cell Connection Schemes for 5 to 12 Cells**

Figure 22: Special connection.

Please follow this connection to ensure a proper cell voltage monitoring. If further information is needed, please refer to the LTC6811 data sheet under the section: Using the LTC6811 With Fewer Than 12 Cells.

**Charging scheme:** Given that the batteries used are Lithium-ion, the charging procedure that is followed should be specific and controlled in order to maximize the life cycle of them. Standard charging should be chosen against fast charging for a longer cell live. For a standard charging scheme, 0.5C should be applied, which is equivalent to 1A, while the charging voltage is 4.2V per cell. These parameters should be adjusted to the PSU in order to achieve a CC/CV charging scheme. The following figure shows the typical current and voltage curves that happen during the charging process of a lithium cell:

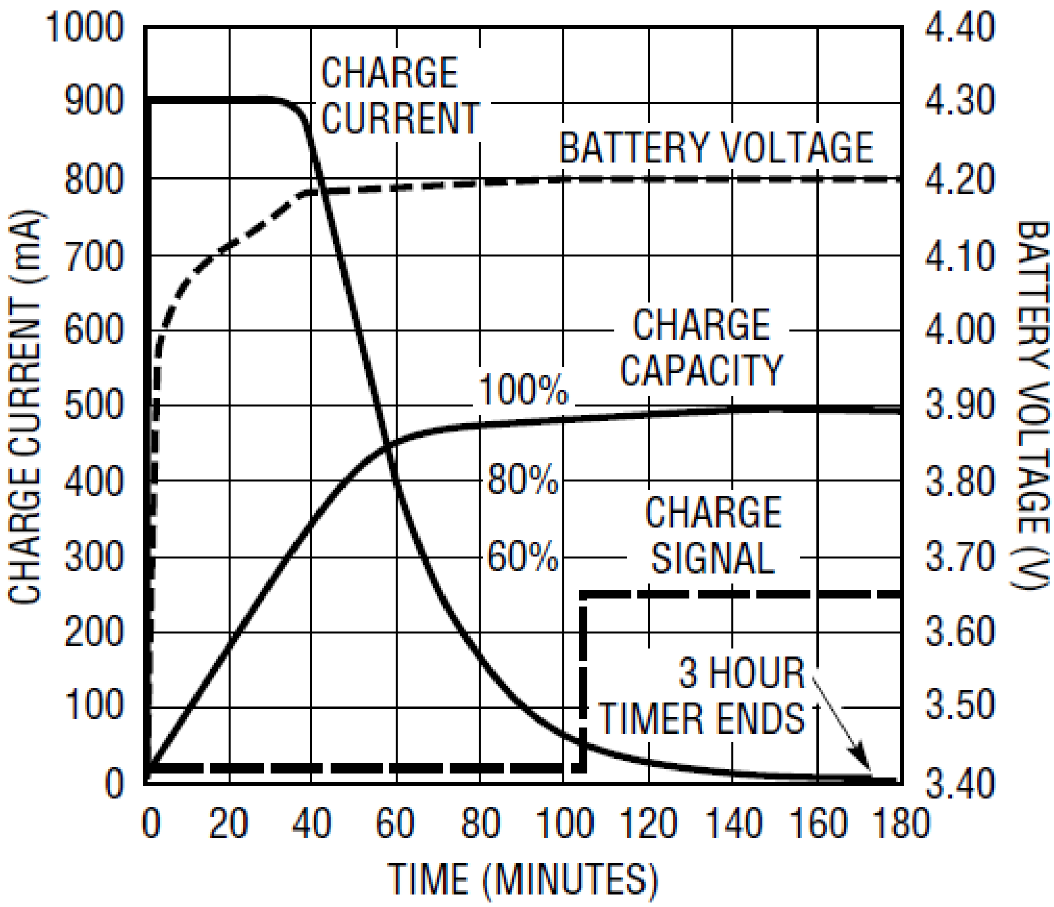


Figure 23: Charging process of lithium cell.

The charging scheme is divided in two parts, first part is the CC (constant current) part, where the battery gets charged almost to its 80% SOC. Here the current needs to be regulated by the charger or the PSU. Once the voltage has increased to almost 4.2V the current will start to drop and it will finish to charge the battery until its 100% SOC, this is the CV (constant voltage) phase. In order to know that the battery is fully charged, most of the fabricants recommend that when the charging current drops below 100mA the charging should be finished. In the case that the charging current of the charger cannot be accessed they recommend a charging time, in the case of our cells (Samsung INR18650-20R) it should be 3 hours for the standard charging scheme. Therefore, a socket switch timer should be installed in the PSU power socket that just turns off the PSU after the given amount of time. Longer charging time should not damage the battery as long as the rated voltage is controlled by the power supply, but they might degrade some of its specs, such as the capacity.

In summary, according to the 8S1P battery pack that has been described before a PSU adjusted with 33.6V and 1A should be connected for a duration of 3 hours for a correct charging scheme. Since the PSU can output a maximum of 30V, this will be the voltage chosen for charging the whole battery pack. The socket switch timer will be adjusted to 4 hours since the 3hours option is not available, it should be safe as well.

**Ennoid-BMS Tool**

Once all the hardware is set up, it is time to configure its software in accordance with the user defined parameters as well as the battery pack parameters. First, we connect the BMS with the computer using the USB cable, if the device is not recognized by the computer the driver for "silicon labs CP2104" shall be downloaded or updated. Next, the Ennoid-BMS Tool is used. To open it double click to the file ENNOID-BMS-ToolV5.02.exe which is found on the GUI folder. This window shall open the GUI.

Under the settings tab there are many parameters that shall be modified or adapted in accordance with the battery pack, other general parameters will be left in the default state until more test of the BMS have been done. By clicking to the question mark icon to the right of each parameter a brief explanation of itself will appear which is useful for understanding it's functionality. The more important parameters to set or tune are:

• General → pulse or power toggle button: Set to momentary in accordance with the button purchased.

• General → not used current threshold: Set to a lower current that the usual current consumption of the load, otherwise BMS

will shut down after the "not used timeout" has expired.
• Cell monitoring → cell monitor count: Number of slave boards connected.
• Cell management → cells in series: Specify according to the battery pack.
• Cell management → cells in parallel: Specify according to the battery pack.
• Cell management → battery capacity total: Multiply the capacity of one cell by the number of cells in parallel.
• Cell management → cell hard undervoltage: If any cell is discharged under this value the BMS will shut down.
• Cell management → cell hard overvoltage: If any cell is charged over this value the BMS will shut down.
• Cell management → cell soft undervoltage: If any cell is discharged under this value the BMS will open the main current path, meaning that the load will be disconnected.
• Cell management → cell soft overvoltage: If any cell is charged over this value the BMS will open the charger current input, meaning that the charger will be disconnected.
• Cell management → cell balance start voltage: If any cell is charged above this limit, and if there is a voltage higher than the cell balance difference threshold, the balancing circuit will start to balance. Once the parameters are set its time to upload the latest version of the Firmware for the product which is found at the Ennoid GitHub repository (https://github.com/EnnoidMe/ENNOID-BMS-Firmware), remember to swap to the branch that is currently being update by Ennoid. The latest version of the Firmware when this document was written was 5.2.

# B Appendix: Market Analysis Data Sheet

L9963E-TR from STMicroelectronics

**Price:** 134kr/qty, 123kr/10 qty.

**Stock:** 10 (Updates frequently) (21/10-22)
**Number of Cells:** 4-14
**Built-in isoSPI interface:** Intelligent diagnostic routine providing automatic failure validation. Redundant fault notification through both SPI Global Status Word (GSW) and dedicated FAULT line. Full ISO26262 compliant, ASIL-D systems ready.
**Passive cell balancing:** Yes. 200 mA passive internal balancing current for each cell in both normal and silent-balancing mode. Possibility of executing cyclic wake up measurements. Manual/Timed balancing, on multiple channels simultaneously; Internal/External balancing.
**Amount of general purpose inputs:** 9
**Order time:** Immediate shipping.
**Customer service:** Good customer support on their webpage, consisting of assisting online support and world-wide callable customer support. Responding within a month.
**Comments:** IC looks great on the data sheet. Circuitry looks good for the device we are using. Look at the primitive resistors and how much they are varying. Maybe the company can provide a software driver to program the micro controller and control the IC. Much work if to be done from scratch.

ISL94212INZ from Renesas Electronics America Inc.

**Price:** 121kr/qty, 109kr/10 qty.
**Stock:** 311 (21/10-22).
**Number of Cells:** 1-12
**Built-in isoSPI interface:** 2Mbps SPI
**Passive cell balancing:** Yes
**Amount of general purpose inputs:** 4
**Order time:** Immediate shipping.
**Customer service:** Great, got the shipped to me for free for testing before a possible purchase. Fast responses. Software driver available.

**Comments:** Circuitry looks similar, MOSFET that controls the balancing aswell. Typical application circuit looks good. Typical app circuit is well documented.

MAX14921ECS+T from Maxim Integrated

**Price:** 154kr/qty, 142kr/10qty
**Stock:** 25 (21/10-22)
**Number of Cells:** 1-16
**Built-in isoSPI interface:** Yes
**Passive cell balancing:** Yes
**Amount of general purpose inputs:** 3 for analog temperature inputs.
**Order time:** Immediate shipping.
**Customer service:** Had no callable support but they had a technical support chat on their web page. It took them a day to respond to the inquiry.
**Comments:** Poor data sheet and low amount of general purpose inputs.

# C Appendix: Interview Guide

## General Questions

1. Which are the most important technical capabilites for the IC?

They are:

- Passive cell balancing.
- Ability to measure at least 12 battery cells in series.
- Built-in isoSPI interface.
- 4-5 general purpose digital inputs.

## L9963E-TR from STMicroelectronics

1. Is the customer service approved/feasible for Knightec's standards? (Showing the graded customer service report)

   2 months is a stretch to be honest. This project is an internal project though so we have a longer time scale then in general but in 2 months you often forget about the project and that makes it harder to familiarise oneself in it again.

2. What are your take-aways after seeing the data sheet for the IC? How easy/hard would it be to replace the current IC with the information provided?

   Looks great on the data sheet. Should work in theory. All cell connections are there and the circuitry looks good for the devices we are using. Hopefully the company can provide software drivers to program the micro controller and the IC of we end up to chose them.

3. What do you say about the typical application circuit in the data sheet? Is it feasible to design?

   Yes.

4. Are the components in the typical application circuit feasible for me to solder?

   Yes.

5. How about the cost of the potential extra components in the typical application circuit? Feasible?

   Hard to say really, depends on the final design. But looks feasible.

6. How about the current stock? Comments?

   Very low stock, only 10 at the moment, they have a short order time, but this is still a red flag. We do not want to be in the same position of component shortage again.

**ISL94212INZ from Renesas Electronics America Inc**

1. Is the customer service approved/feasible for Knightec's standards? (Showing the graded customer service report)

   Seems great, nice to have free samples if you want to solder a test circuit.

2. What are your take-aways after seeing the data sheet for the IC? How easy/hard would it be to replace the current IC with the information provided?

   Circuitry looks similar, nice to have a MOSFET that controls the balancing as well. The typical application circuit looks good.

3. What do you say about the typical application circuit in the data sheet? Is it feasible to design?

   Yes.

4. Are the components in the typical application circuit feasible for me to solder?

   Yes.

5. How about the cost of the potential extra components in the typical application circuit? Feasible?

   Feasible.

6. How about the current stock? Comments?

   Good amount of stock.

**MAX14921ECS+T from Maxim Integrated**

1. Is the customer service approved/feasible for Knightec's standards? (Showing the graded customer service report)

   Any kind of customer support works, even chat, so its approved.

2. What are your take-aways after seeing the data sheet for the IC? How easy/hard would it be to replace the current IC with the information provided?

   data sheet looks worse than the other ones. There is no typical application circuit which makes the reassembling and design harder for you. Its still possible of course, the question is if you have time for this. Circuitry looks good and the general info looks good.

3. What do you say about the typical application circuit in the data sheet? Is it feasible to design?

   There is none. Still feasible but more work.

4. Are the components in the typical application circuit feasible for me to solder?

   No typical application circuit.

5. How about the cost of the potential extra components in the typical application circuit? Feasible?

   Feasible if you make your own application circuit from scratch.

6. How about the current stock? Comments?

   Ok stock, would be nice to have more.

7. What are your take-aways after seeing the data sheet for the IC? How easy/hard would it be to replace the current IC with the information provided?

   There is a great potential to have a bigger BMS test circuit made here since the IC supports up to 16 cells. All the communications and connections looks nice as well. The replacement would still be a more difficult task than the other ones since the data sheet does not provide a typical application circuit.

8. This IC has one fewer general purpose input (3 analog inputs instead of the preferred 4-5), would it still work?

   Looking in the data sheet we see that there also is a couple digital inputs which we might be able to use instead. So, yes, it probably would work but might create a hassle.