Development of a stretchable battery pack for textile integration

Kristof Pinnoo

Supervisors: Dr. ir. Thomas Vervust, Dr. ir. Frederick Bossuyt

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Electrical Engineering

Department of Electronics and Information Systems
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UNIVERSITEIT GENT

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Preface and acknowledgment

After four years of classes, exercise sessions, projects and lab sessions, it was finally time to start my final year. This one would be quite different, as it would include my master thesis. Spending most of my time on just one topic for an entire year would be quite a change. Selecting an interesting topic, a task at the end of my first Master-year, was the first challange and not an easy one. After gathering information about the content of several topics, one stoud out and was selected. Now I just had to wait until the new schoolyear to get started.

Working on this thesis was not always easy and I could not have done it without help. Therefore, I would like thank my supervisors, Frederick Bossuyt and Thomas Vervust, for all of their help. They provided me not only with plenty of technical assistance, but also with a lot of practical tips during this year. Their experience in stretchable electronics proved to be very valuable and I learned a lot from them.

Furthermore, I would like to thank everyone from the CMST research-group for the great work environment, you proved how easy it is to make the production of qualitative work into an enjoyable experience. I want to thank the ELIS department for the necessary materials and equipement. In particular, I want to thank Katrien Vanneste for placing all my orders, Bjorn Vandecasteele for helping me with all my assemblies, Jindrich Windels for the explanations of the equipment, Steven Van Put for the laserablation of the demonstrator and Bart Plovie for the proofreading.

Finally, I want to thank my parents, family and friends for their continuous support. In particular, I want to thank my girlfriend Laura. Thank you for the thorough proofreading and for supporting me as much as you did.

Ghent, 22 May 2015
Kristof Pinnoo

Development of a stretchable battery pack for textile integration

by Kristof Pinnoo
2014 - 2015

This paper is based on a thesis submitted in partial fulfillment of the requirements for the master's degree of electrical engineering at the university of Ghent in June 2015.

Faculty of Engineering and Architecture
Chairman: Prof. dr. ir. Rik Van de Walle
Department Electronics and Information Systems
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Summary
As the research in wearable electronics progresses, there is a growing need to integrate the entire circuit onto textile. While most circuits can already be integrated, no research has been done yet to investigate the possibility of integrating a battery (or when more are used: battery-pack) into the textile as well. This will allow wearable circuits to be used completely autonomously, without the need for any attached wires or cables. This thesis focuses on just that and aids the CMST reasearch-group in their projects on stretchable electronics. This text follows the order in which a designer of an integrated battery-pack will need certain information and production steps. An introduction to the subject and goals is given (chapter 1), followed by an study of the possibilities for energy storage in thin packages (chapter 2). As batteries can pose danger if faults occur, a protection circuit is needed (chapter 3). To assure the full capacity of a battery-pack can be used, balancing is added (chapter 4). Based on some example applications, a design methodology is given (chapter 5). As these batteries will need recharging, charging is reviewed (chapter 6). Considerations specific to stretchable and flexible circuits are explained (chapter 7), followed by the details of a demonstrator (chapter 8) built to demonstrate all the aspects of the design of a battery-pack. The text concludes with a summary and lists possible continuations on this work (chapter 9).

Keywords: Battery-pack, Balancing, Lithium-ion, Stretchable, Wearable Electronics

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***Abstract*—This article presents the results realized in a thesis submitted in partial fulfillment of the requirements for the masters degree of electrical engineering at the University of Ghent in June 2015. The goal is to investigate how a battery-pack can be integrated into textile. After investigating the key components and formulating a design methodology, a demonstrator is made to illustrate the functionality of such a battery-pack, along with a driver circuit to power a stretchable LED-matrix and a charging circuit.**

***Index Terms*—Battery-pack, Balancing, Lithium-ion, Stretchable, Wearable Electronics.**

I. Introduction

As electronics become smaller and more integrated, the next step is to integrate them into textile. Research to create textile-integrated electronics continually develops, but there is also a growing need for textile-integrated batteries. This will allow standalone applications, without any rigid parts attached. Many uses can be imagined, such as health monitoring, interactive clothing or fashion.

This thesis was performed at the CMST research-group [1] of the University of Ghent, where one of the six domains is stretchable microsystems.

First the different solutions for energy storage are investigated, followed by ways to protect the circuit against any type of fault that could occur.

II. Energy storage

Investigation shows that, for textile applications, two options are available to store energy. The first is lithium rechargeable batteries, which offer the largest energy density, but require protection against fault conditions. Because of this, they are inherently unsafe in abnormal operation. The second option is using supercapacitors, which offer a higher power density and are able to deliver larger current peaks to the application.

If the energy consumption of the circuit is really low, one could also opt for a non-rechargeable solution. Solid-state primary batteries, offer a safe solution with a high energy density. However, as they cannot be recharged and since replacement in textile is expensive and difficult, this is only useful in applications which they can power a long time.

A. Protection

As lithium batteries need protecting, a small circuit is added to each battery-cell (= primary protection). An IC, along with a few passive components, can sense over- and undervoltage conditions, overcurrent conditions and short-circuits. By controlling two FET-switches in the ground-connection path, the current flow can be blocked easily. A fuse is often added to protect against overcurrent conditions.

B. Balancing

When batteries are placed in parallel, they will balance themselves out automatically. If the voltage differences are large, they current that flows can be large. This should be avoided.

Series-connecting batteries is more critical: if cells are imbalanced, the protection circuitry will stop charging and discharging too soon, which will limit the effective capacity of the battery-pack. The cells can be balanced using passive balancing, where current is drained and dissipated from the cells with a higher charge. An alternative method in which no current is lost, is active balancing. In this case, current is redistributed over the cells, which can be done using capacitors, inductors or small DCDC convertors.

The IC that will facilitate this balancing often offers fault detections as well, but on the level of the entire battery-pack. This is called secondary protection.

It was demonstrated that selecting a good configuration of the cells is critical to maximize the reliability. Parallel connections are preferred over series connections.

III. Design methodology

Using a few simple steps, designers can quickly construct a battery-pack, suited for their application.

1) Calculate the required energy for the application, starting from the average current consumption, the supply voltage and the required operating time of the application.
2) Now the energy category can be determined. Applications requiring an energy storage of more than 5 Wh, will not be able to use a textile-integrated battery-pack without using a very large surface area.
3) Depending on the energy category and the required flexibility of the battery-pack, a battery-size category and the number of cells can be selected.

4) Next, the configuration of the cells can be determined, keeping in mind the implications with regard to balancing.
5) Depending on the configuration the maximum output current might not be sufficient to accomodate the maximum current consumption of the application. In that case, a new design or a change in configuration is required.

IV. Stretchable circuit

To integrate the battery onto textile, the circuit is produced on a flexible and stretchable substrate. Off-the-shelf components can be used on this substrate. They are placed on rigid islands, on which most of the routing is located as well. By interconnecting these rigid islands with meander interconnects, stretchability is assured.

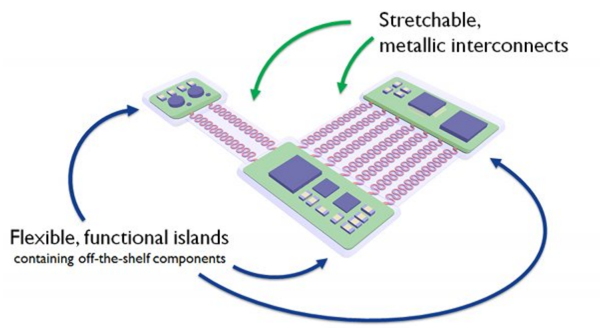


Fig. 1: Stretchable interconnects

The circuit is designed on a FCB (flexible circuit board), consisting of 50µm of polyimide and 18µm of copper. This is then attached to a rigid carrier using tape. The copper patterns are etched, after which the components are mounted. This allows the circuit to be tested. After confirming that all the components of the circuit function as desired, the islands and interconnects are patterned using laser-ablation. The polyimide, which supports the interconnect and islands, increases the reliability of the circuit [2].

The next production step is to laminate the top of the circuit with a thermoplastic polymer. After removing the carrier, this is also performed at the bottom of the circuit. The module can then be punched out.

Reheating this lamination once again allows the attachment onto textile.

V. Demonstrator

To demonstrate and test some of the findings of this thesis, a demonstrator was made. It was designed to power a LED-matrix consisting of 12 strings of 3 RGB-LEDs in series, where each color of each LED consumed 5mA.

Using a single color at any given time, this demonstrator, consisting of 8 200mAh flexible rechargeable batteries, could power this matrix for more than 5h.

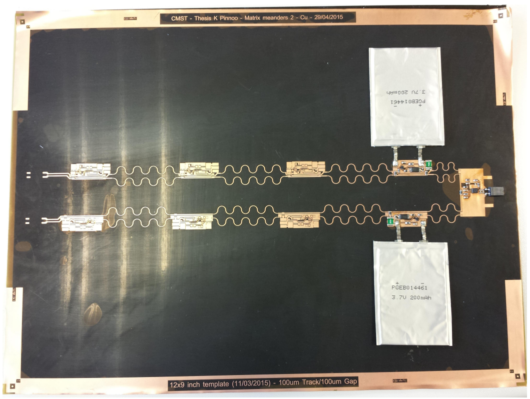


Fig. 2: Demonstrator

This demonstrator is accompanied by a LED-driver and a charge circuit, allowing the demonstrator to be charged from a USB port. It allows charging of the entire demonstrator (dual cell charging), or just one of the 2 rows (single cell charging).

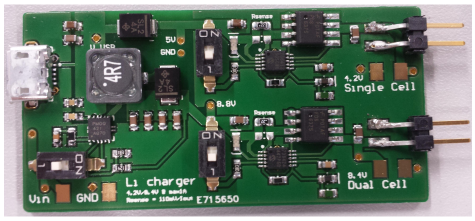


Fig. 3: Charger

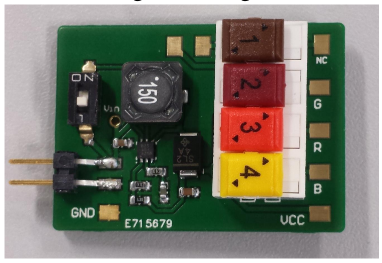


Fig. 4: LED-driver

VI. Conclusion

After investigation, the options to store energy on a substrate, suitable for textile integration, protection circuits were reviewed, as well as balancing techniques. Flexible Li-ion polymer batteries proved to be the best option with regards to energy-density and supercapacitors when a high power-density is required. This information was combined into a demonstrator, made on a FCB.

References

[1] Centre for microsystems technology. http://www.cmst.be/index.html.
[2] Thomas Vervust. *Stretchable and washable electronics for embedding in textiles*. PhD thesis, Universiteit Gent, 2012 - 2013.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Today, electronics in all shapes and sizes help us in almost all aspect of daily life. Sometimes unnoticed, they are everywhere. Advancements in manufacturing, processing, reduction in component-size and new materials allowed electronics to become more powerful, yet also lighter and smaller. Discrete circuits evolved into integrated circuits, which allowed the functionality to increase. As circuits became smaller, electronics also came to be integrated into everyday objects like cellphones, cars, household appliances and domotics. As there was no reason to stop there, electronics became integrated in portable devices as well, leading to a new sector: wearable electronics.

Figure 1.1: Wearable electronics: smartwatch and smartglasses

1.1 Wearable electronics

Wearable electronics, such as the smartwatches, smart glasses, virtual reality headsets and fitness bands, are a growing market. To allow further integration and to optimize the use of all available space, flexible substrates can be used instead of rigid PCB materials. Wearable electronics can also be integrated into our clothing, which is called e-textiles, smart textiles or intelligent clothing. They can contain sensors, actuators, antennas, interconnections and processing units and can have many functions: health-monitoring, motion-detection, movement-monitoring or fashion. These circuits are integrated on stretchable substrates, which allows them to move along with the body and makes them comfortable to wear.

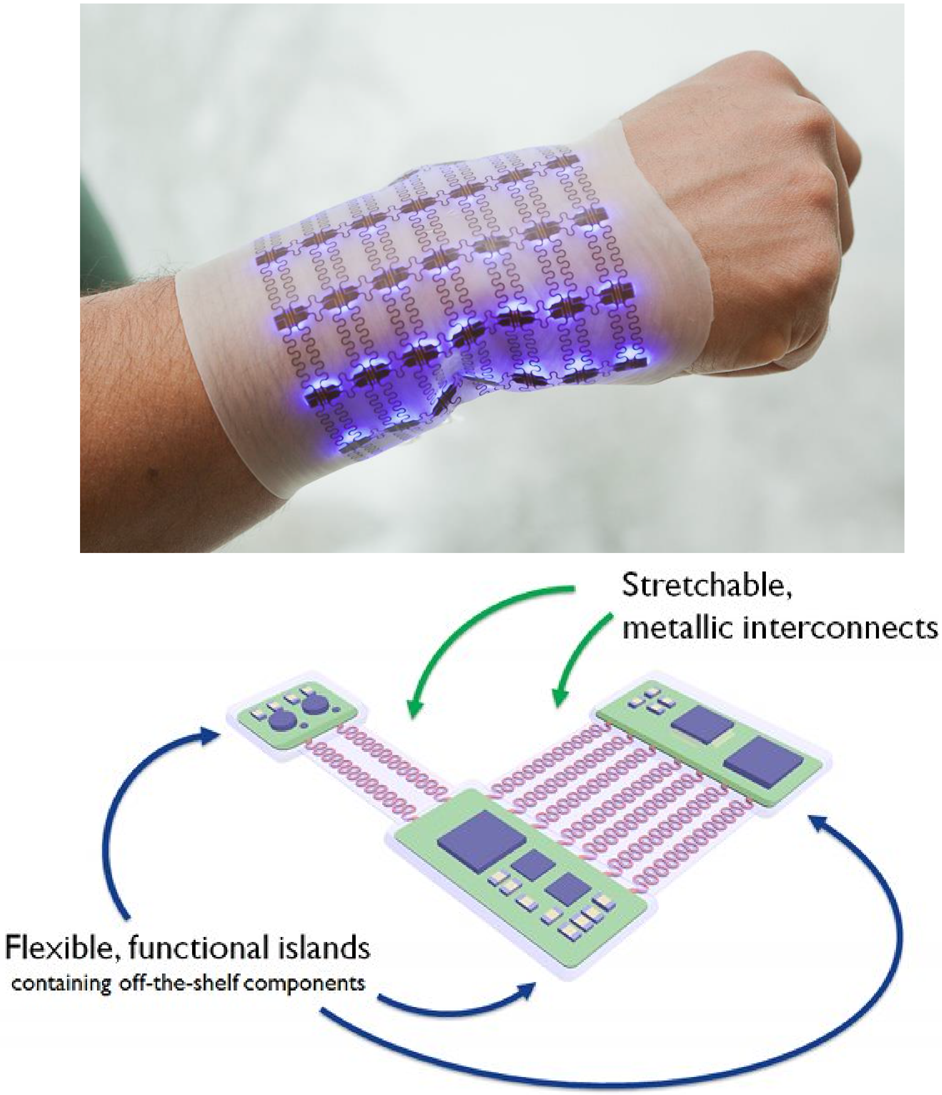


Figure 1.2: Stretchable textile-integrated circuit: picture (top), principle (bottom) [1]

1.2 Goals

As currently textile-integrated electronics still use rigid batteries, research on this topic is paramount. This thesis focuses on investigating how such a circuit can be powered using a flexible and stretchable battery-pack. Using ultra-thin flexible batteries on a stretchable substrate, which can be laminated onto textile, a battery-pack is constructed.

1.3 Thesis overview

There are several options when the goal is to store electrical energy. When the system to do this is to be made flexible, stretchable and ready to be integrated into textile, options are limited. The next chapter investigates these options. A short review of all types of electrical energy storage are given, indicating why some forms can be used for portable applications and why others cannot. To guarantee that the batteries will be safe during use and not cause harm to the user, all faults that could occur are discussed along with how they can be prevented (chapter 3). Depending on the configuration of the batteries in the pack, additional circuitry is required to optimize the effective available capacity of the battery-pack (chapter 4). To aid future designers of such battery-packs, a quick guide consisting of just a few simple steps is constructed (chapter 5). Next, the advised charging method for batteries is discussed (chapter 6). Since the goal is to integrate the battery-pack into textile, the circuit has to be made on a flexible and stretchable substrate. The design-process to do this is discussed, along with the implications of a stretchable circuit on the circuitry itself (chapter 7). To demonstrate the discussed techniques, a demonstrator is made. This contains not only the battery-pack, but also a charge circuit and LED-driver to power a LED-matrix (chapter 8).

Chapter 2

Electrical Energy storage

When designing a battery pack, the first step is to select a battery. A lot of batteries are available on the market today. They can be categorised by their chemistry, size, electrical or mechanical characteristics, and much more. Since most properties of batteries are dependent on the chemistry used to store energy, this criterion is used to characterise the different types of batteries.

However, apart from batteries, there are some less obvious options for electrical energy storage. Therefore, we will also take a look at supercapacitors and fuel cells.

2.1 Battery types

A battery (which can consists of in series or in parallel connected cells) has a cathode (more commonly known as the positive terminal), generating electrons and ions which travel to the anode (negative terminal). This is the case for a primary cell. In the case of a rechargable or secondary battery, this can also happen in the other direction. The anode and cathode are the electrodes of the cell. The electrons pass through the external circuit providing the necessary current. The ions travel inside the cell, through the electrolyte separating the two electrodes. This electrolyte is usually a liquid solution containing a salt which is dissolved in a certain solvent. At both electrodes, a metal is present to allow the electrons to travel from the electrodes to the external circuit. These metals are commonly referred to as the current collectors. The chemical reaction which occurs in the cell has a certain energy, which determines the cell voltage. In figure 2.1, the operating principle of a secondary battery is shown. [2–4]

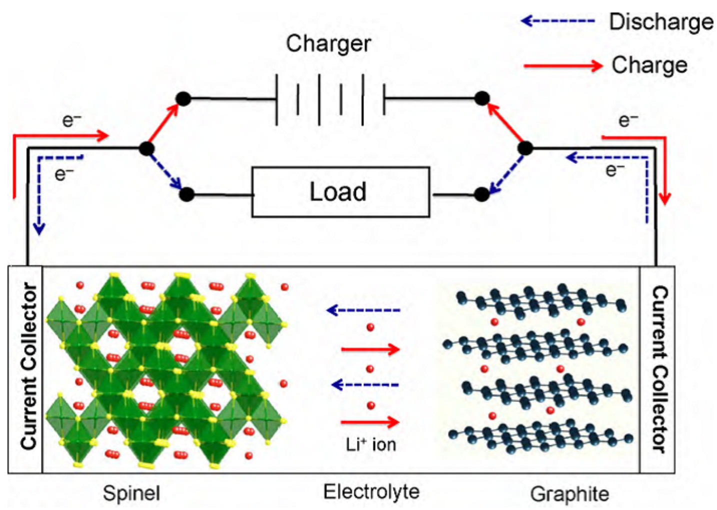


Figure 2.1: Battery operating principle in charge and discharge mode [2]

The capacity of a battery determines how much energy can be stored and is expressed in mAh. As can be seen from the unit, this tells us nothing about the voltage, only the current; it is therefore not the same as the energy capacity. However, the energy capacity can easily be calculated using equation 2.1. From this, the maximum power (equation 2.2) that the battery can deliver can be computed.

$$\textbf{Battery energy:} \qquad E[\text{mWh}] = \mathit{capacity}[\text{mAh}] \times V_{nominal}[\text{V}] \tag{2.1}$$

$$\textbf{Battery power:} \qquad P[\text{mW}] = \frac{E[\text{mWh}]}{\mathit{time}[\text{h}]} \tag{2.2}$$

2.1.1 Primary batteries

Primary batteries are not rechargeable, meaning their chemical reaction is not reversible. Once the energy that they store has been depleted, the battery has no further use. Early on, they were easy to produce and therefore cheap, which provided a good market for consumer-applications. The popular **zinc-carbon** batteries were replaced over time by the more expensive, but longer-lasting and safer **alkaline** batteries. Over time, rechargeable batteries became cheaper and took over the lion's share of the market. In developing countries, wind-up, solar-powered and rechargeable batteries undermined the market for primary batteries. In China, one of the fastest growing markets for batteries, locally produced alkaline batteries dominate the market. [5]

Apart from zinc-carbon and alkaline batteries, some other primary batteries are worth mentioning: **primary lithium batteries**, **silver-oxide batteries**, **mercury-oxide batteries** and **other zinc-based batteries**. Each type has its specific advantages and disadvantages, linking them each with a certain type of application.

The low self-discharge of primary batteries makes them the best option if long storage is needed, and a single lifecycle is adequate. Although attempts were made to prolong the lifetime of alkaline primary batteries, this was not very successful, due to the declining capacity with the number of cycles. Rechargeable alkaline batteries also exist, but they still only offer about 20 cycles, especially when they are fully discharged [6]. However, the chemical reaction of secondary batteries is easily reversible, allowing them to be recharged numerous times.

2.1.2 Secondary batteries

Secondary batteries are more expensive and have a higher self-discharge, but they offer the possibility to be recharged. Even though this also requires tools to recharge the batteries, this type of battery quickly became more succesful then primary batteries. The cost of the (re)chargers and the higher cost of the batteries themselves is outweighted by the energy the batteries offer the consumer over their total lifetime.

The three most used types are **Lead-acid**, **Ni-Cd** (nickel-cadmium), **Ni-MH** (Nickel-metal hybrid) and **lithium** batteries. Lead-acid batteries are heavy, but are the most economical option for larger power applications. The nickel-based batteries offer a more stable voltage during operation than lithium batteries, eliminating the need for a convertor to achieve a stable supply voltage, but also work at a lower voltage. Their nominal voltage approximates 1.25V, whereas lithium batteries have a nominal voltage of about 3.7V. For this reason, it is necessary to place more batteries in series in order to achieve the same voltage. Nickel-based batteries also show a memory effect: if shallow charge/discharge cycles are followed by a deep discharge, the operating voltage lowers, reducing the capacity. Moreover, nickel-based batteries do not come in very thin form factors, where lithium-ion batteries do. Using a gel electrolyte, often based on a polymer, thickness can, to a great extent, be reduced. This, combined with the large energy density of lithium batteries, forms the main reason lithium batteries are currently the best option when it comes to rechargeable energy storage in textile applications. [7–9]

2.1.3 Solid-state batteries

As quite a lot of batteries are not inherently safe, one could use solid-state batteries. Here, the electrolyte is not a liquid, but a solid. For this reason, they are also called dry batteries. Currently, solid-state batteries are primary batteries and usually have a pouch-cell shape, making them suited for wearable applications. Because of their safer nature, drilling holes, cutting off parts, as well as many other forms of abuse, do not damage the battery itself. Even when damaged, the remaining parts of the battery remain functional. Zinc-carbon and zinc-air batteries were the first dry batteries, but other chemistries, such as lithium, also offer dry batteries. These batteries are sometimes printed, which allows cheap mass-production. Because solid-state batteries are a recent development, most companies are still in the researching phase. Apart from primary batteries, secondary printed batteries also exist, but they are not yet on the market [10].

2.2 Lithium batteries

Compared to older types of rechargeable batteries, lithium batteries offer many advantages, such as: a higher energy-density, both in terms of weight and volume, a longer cycle life, due to the lack of the detrimental memory-effect, and a higher power output, as a result of the larger voltage. For these reasons, lithium batteries quickly became the most widely used rechargeable battery in consumer electronics and hybrid electric vehicles [11].

The anode consists of graphite, the cathode is a lithium-metal-oxide like $LiMO_2$ or $LiCoO_2$. Both are complex composites of the active material, (polymeric) binders and conductive dilutents like carbon black. Reactions of the electrodes with the electrolyte solution (a lithium salt) make lithium batteries so dangerous. In normal operation, a protective film is developed at this boundary, but any of the faults discussed in the following chapter can stop the forming of this film. As a result, the electrolyte continues to oxidize, leading to damage to the cell.

Research on lithium batteries led to newer compositions of the electrodes. Tin- and silicon-based metal alloys, titanium oxide or $Li_4Ti_5O_{12}$ at the anode and lithium manganese alloys like $LiMn_2O_4$ or lithium iron phosphate at the cathode are just some of the developments. Most of these developments use these new (compositions of) materials to achieve a higher power and energy density or to improve the safety of the battery.

2.2.1 Lithium-ion polymer battery

To reduce the risk of spills of the electrolyte, polymer films can be used. In a first type, the polymer forms a separator between the electrodes and the electrolyte. The electrolyte, consisting of salts and liquid solvents, is trapped in between the two polymer separator films. In the second type of polymer films, the polymer is part of the electrolyte. Although inactive, it is used to store the salts and solvents in its pores. Hybrid forms of these polymer films, in the form of electrolyte-gels also exist [12]. There are a number of hard-to-reach constraints on these films, such as: chemical and electrochemical stability, mechanical strength to be able to handle the mechanical stresses during fabrication and high porosity to allow ion-flow through the conductive electrolyte. For these reasons, such lithium polymer batteries (for short: LiPo, Li-poly or LIP) were not really succesful for consumer electronics [13].

Although confusing, these same names are also used for a more recent type of battery. It then means a polymer casing is used, rather than a polymer electrolyte. This polymer casing allows more shapes and thinner packages, like the popular pouch-shaped batteries. These batteries are thin, flexible and lightweight. Most of the commercially available lithium batteries are of this type. The name-convention is not very clear: in radio-controlled applications LiPo remains the most popular term, while in most other sectors the term Li-ion is used. The most general term is a combination of both: a lithium-ion polymer battery. Due to the lack of a clear name-convention and the unwillingness of the manifacturers to specify the compositions of the electrodes and electrolyte, selecting a lithium battery can be confusing.

2.2.2 Battery terminals

Batteries have two terminals: one positive and one negative. However, some commercially available lithium batteries have a third terminal, often denoted 'T'. Inside the battery pack an NTC (negative temperature coefficient resistor) is attached to the negative terminal of the battery-pack. This terminal can be used by an external circuit to check for (unacceptable) increases in temperature. Its presence shows that a protection circuit is present inside the package of the battery. Because space consumption is one of the critical parameters in textile applications, it is best to opt for a battery that does not have such (or any) protection circuit build in, and design this yourself (see section 7.1.1). This allows the designer to create a protection-circuit that is adapted to its application in size, shape, functionality and position. Keeping the size of the circuits small is necessary to obtain a high level of flexibility.

2.3 Battery specifications

2.3.1 Self-discharge

A battery that is stored will slowly deplete its charge over time. The temperature at which the battery is stored, the discharge-rate, as well as the degree of deep discharge, all influence this self-discharge rate. A deep discharge means that the battery was more depleted than advised. The self-discharge rate is the largest at the beginning of storage and slowly decreases as the battery is stored longer. The self-discharge rate is higher if the battery contains more charge during storage, if the battery is stored at higher storage temperatures or if the battery has experienced more deep discharges. However, even a fully discharged battery might still slowly discharge, making the charge cycle more critical. When the battery voltage is lowered too much, a preconditioning phase is needed before normal charging. This is a low constant-current charge, allowing the battery to increase its voltage slowly to a safe threshold, after which normal charging can occur. Lithium batteries have a lower self-discharge rate than other rechargeable batteries, but still discharge approximately 10% in three months. A higher charge during storage and a higher storage temperature also deteriorate the capacity of the battery. If the battery is stored correctly, this capacity drop is about 4% a year. For these reasons it is advised to store batteries at a low charge and in low-temperature environments [14–16].

2.3.2 Battery capacity and C-rate

Each battery has a certain capacity, which is expressed in [mAh]. Since its main function is to power a certain application, the capacity of a battery is its main property and will determine how much batteries the battery-pack should contain. As demonstrated in equation 2.1, the energy a battery can store is this capacity multiplied by its nominal voltage. For this reason, only batteries with the same chemistry should be compared by looking at the capacity, since the nominal voltage depends on the chemistry of a battery. Even then, batteries from the same chemistry might have a slightly different nominal voltage.

Over time, this capacity fades. This means the battery can not be charged as much as in the beginning of its life-cycle. Capacity fade is mostly determined by the age of the battery and the cycle count. Improper storage at elevated temperatures, or at full charge, increase this capacity fade. During charging, Li-ions travel to the anode, which travel back during discharging. However, a small fraction of ions remain at the anode, forming a solid electrolyte interface (SEI). This layer grows as the battery cycles and decreases the interaction with the ions and the anode. At the cathode a similar layer, called electrolyte oxidation, develops when the battery has high voltages at high temperatures. These two layers form the main causes of capacity fading. Coulombic efficiency, which is the ratio between the amount of charge that is introduced during charging and the amount of charge that is depleted during discharging, measures both changes. Newer lithium batteries offer electrolyte additives which improve coulombic efficiency and decrease capacity fading.

Even if the battery should not last a long time, selecting a battery with a high capacity might be wise. Maximum charge and discharge currents are expressed in terms of C-rate.

$$[\text{C-rate}] = \frac{\text{capacity[mAh]}}{1\text{h}}$$

To illustrate: a charge rate of 2C for a battery with a capacity of 200mAh, means a current of 400mA. This is equivalent to saying the battery charges or discharges fully in a half an hour. And a charge rate of C/5, or a current of 40mA, implies a full (dis)charge in 5 hours. When the application demands a high maximum current, the capacity should be taken into account to assure the battery-pack can handle this current.

2.3.3 Cycle life

Since the capacity of batteries will fade over time, batteries can only be used a limited number of times. Storing the battery properly does not damage the battery much, but going through charge and discharge cycles does. Placing a number on the amount of cycles a battery can go through is difficult, as the number of cycles will depend on the type of battery, the properties of the cycles, temperature, humidity, resting time and much more. Fully charging or discharging a lithium battery is not healthy for the battery, so it is best to only partially charge and discharge the battery. If less charge is introduced and depleted, this cycle will be less harmful for the battery and will introduce a smaller capacity fade.

2.3.4 Safety concerns

Over- or undervoltage and overcurrent in a lithium battery can lead to melting of the lithium. Current lithium batteries use lithium ions and are safer than the old lithium metallic ones. However, it remains important to protect the battery. Faults can cause a violent reaction: it causes fire, toxic fumes and even explosions. This is inherent to the chemistry of the lithium. Other batteries can exhibit dangers in some of these cases, but are usually safer. Due to the high energy-density of lithium batteries, as well as the possibility to create more shapes and sizes, they remain the most popular rechargeable battery, even in textile applications. Provided they are adequately protected, lithium batteries are even safer than other battery chemistries, which often lack a protection circuit [17]. As the protection circuit might fail during testing, the battery should always be placed in a safety-bag when it is charging. This bag is reinforced with fiberglass and absorbs any explosion that could occur.

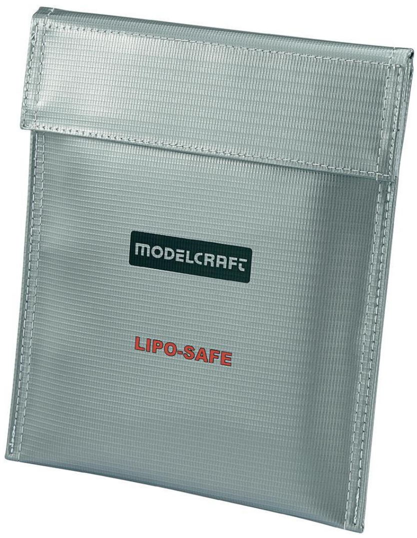


Figure 2.2: Safety-bag, used for safe storage and for charging of lithium batteries

2.3.5 Ultra-thin battery comparison

In tables 2.1 and 2.2, a selection of the currently available rechargeable and non-rechargeable batteries is given. This includes only ultra-thin batteries, with a thickness under 2 mm, leads inclusive. This slimness is a necessity in textile integrated applications. The lithium batteries are somewhat flexible, the button-cells are not, but they are also smaller. It is clear from this table that the smaller batteries not only have a lower energy capacity, but also a lower energy density. They are so small that the size and weight of the packaging plays a role in these densities.

Table 2.1: Ultra-thin rechargeable batteries: (thickness, incl. leads, under 2mm): lithium batteries (top), button-cells (bottom)

Brand	**Model**	**Capacity** [µAh]	**Height** [mm]	**Width** [mm]	**Thickness** [mm]	$\mathbf{T_{min}}$ [°C]	$\mathbf{T_{max}}$ [°C]	$\mathbf{V_{nominal}}$ [V]	**Weight** [mg]	$\mathbf{E_{grav}}$ [Wh/kg]	$\mathbf{E_{vol}}$ [Wh/L]
Cymbet	CBC012 SMT	12	5.0	5.0	0.9	-40	70	3.8	6	7.6	2.03
Cymbet	CBC050 SMT	50	8.1	8.1	1.0	-40	70	3.8	36	5.3	2.90
STMicro-el.	EFL700A39	700	25.7	25.7	0.2	-20	60	3.9	200	13.7	20.7
I.P.S.	MEC225	130	12.7	12.7	0.17	-40	85	3.9	125	4.1	18.5
I.P.S.	MEC220-S	300	25.4	12.7	0.17	-40	85	3.9	255	4.6	21.3
I.P.S.	MEC201-S	700	25.4	25.4	0.17	-40	85	3.9	490	5.6	24.9
I.P.S.	MEC202-S	1700	25.4	50.8	0.17	-40	85	3.9	975	6.8	30.2
G.E.B.	GEB014128	40000	29.0	42.0	1.1	-20	60	3.7	1800	82.2	110.5
G.E.B.	GEB088120	50000	20.0	81.0	0.8	-20	60	3.7	1800	102.8	142.8
G.E.B.	GEB084364	60000	65.0	44.0	0.8	-20	60	3.7	2300	96.5	97.0
G.E.B.	GEB084253	65000	53.0	42.0	0.8	-20	60	3.7	2300	104.6	135.1
G.E.B.	GEB085046	80000	46.0	50.0	0.8	-20	60	3.7	2600	113.9	160.9
G.E.B.	GEB104461	180000	61.0	44.5	1.0	-20	60	3.7	5000	133.2	245.4
G.E.B.	PGEB014461	200000	44.0	60.0	1.0	-20	60	3.7	6000	123.3	280.3
Seiko Instr.	MS412FE	1000	4.8	4.8	1.6	-20	60	3.1	70	44.3	112.1
Seiko Instr.	MS412GE	2000	4.8	4.8	1.7	-20	60	3.1	80	77.5	224.3
Seiko Instr.	MS614E	2300	6.8	6.8	1.8	-20	60	3.3	170	44.7	117.3
Seiko Instr.	MS614SE	3400	6.8	6.8	1.8	-20	60	3.1	170	62.0	162.8
Maxell	ML2016	25000	20.0	20.0	1.9	-20	60	3.0	1800	41.7	117.2

Table 2.2: Ultra-thin NON-rechargeable batteries: (thickness, incl. leads, under 2mm): solid-state batteries (top), other thin batteries (bottom)

Brand	**Model**	**Capacity** [µAh]	**Height** [mm]	**Width** [mm]	**Thickness** [mm]	$\mathbf{T_{min}}$ [°C]	$\mathbf{T_{max}}$ [°C]	$\mathbf{V_{nominal}}$ [V]	**Weight** [mg]	$\mathbf{E_{grav}}$ [Wh/kg]	$\mathbf{E_{vol}}$ [Wh/L]
Solicore	SF-2529-10	10000	25.8	29.0	0.45	-10	60	3.0	300	100	89.3
Solicore	SF-2529-14	14000	25.8	29.0	0.45	-10	60	3.0	300	140	125
Solicroe	SF-4823-25	25000	48.8	23.0	0.45	-10	60	3.0	600	125	148.6
Enfucell	REG1.5V	10000	60.0	42.0	0.7	-35	50	3.0	1400	21.4	17.0
Enfucell	Mini1.5V	18000	36.0	46.0	0.7	-35	50	1.5	900	30.0	23.3
Enfucell	REG3.0V	90000	60.0	72.0	0.7	-35	50	1.5	2900	46.6	44.6
BlueSpark	110-ST	30000	55.3	47.6	0.75	-30	65	1.5	-	-	22.8
BlueSpark	111-ST	54000	78.7	47.6	0.75	-30	65	1.5	-	-	28.8
BlueSpark	107-UT	10000	63.0	26.0	0.5	-30	65	1.5	-	-	18.3
BlueSpark	103-UT	10000	40.0	30.0	0.5	-30	65	1.5	-	-	25
BlueSpark	101-UT	20000	55.0	47.0	0.5	-30	65	1.5	-	-	23.2
BlueSpark	104-UT	37000	79.0	47.0	0.5	-30	65	1.5	-	-	29.9
BlueSpark	113-UT	5000	30.0	80.0	0.5	-30	65	3.0	-	-	12.5
UltraLife	CP064243	135000	53.5	49.0	0.6	-40	60	3.0	2600	155.8	257.5

2.4 Supercapacitors

When two conductors (electrodes) are placed in an electrolyte solution and a power source is added, there is a charge separation at the interfaces between the electrodes and the electrolyte, creating a voltage difference between both electrodes. When the power source is removed, the voltage difference remains and electrical energy is stored.

The mechanism to store energy is different from the one used in batteries. In batteries, apart from the travelling electrons, positively charged particles (the ions) also travel from one electrode to the other. In other words, energy in a battery is chemical energy, which is converted into electrical energy during discharge. Capacitors store electrical charge on the interface between the electrodes and the electrolyte, storing energy electrically. The fact that both mechanisms work in a fundamentally different way means that some properties are different, although both options store energy and can be used as a power source. Capacitors, for example, allow fast charging and discharging, have a high reliability and generally have a much larger number of charge-discharge cycles (in the order of hundreds of thousands) and a larger temperature range than batteries. However, they can store less energy than batteries [3].

Table 2.3: Comparison between a capacitor, a supercapacitor and a battery

Parameter	Capacitor	Supercapacitor	Battery
Discharge time	$10^{-6} - 10^{-3}$s	$1 - 3$s	$0.3 - 3$h
Charge time	$10^{-6} - 10^{-3}$s	$1 - 3$s	$1 - 5$h
Energy density [Wh/kg]	< 0.1	$1 - 10$	$20 - 100$
Power density [W/kg]	< 10000	10000	$50 - 200$
Charge/Discharge efficiency	~ 1	~ 0.9	$0.7 - 0.9$
Cycle life	infinite	> 500000	$50 - 2000$

Conventional (often ceramic) and electrolytic capacitors cannot store a lot of energy, this in contrast to electrochemical capacitors, also known as super- or ultracapacitors. Two types of electrochemical capacitors exist: electric double layer capacitors (EDLC's) and pseudocapacitors. Their larger capacity is due to thinner dielectrics and high surface area electrodes [18].

Electric double layer capacitors have carbon-based electrodes, which prevent recombination of the ions from the electrolyte, creating a Helmholtz double layer at the interface between the electrolyte and the electrodes. Charges are stored electrostatically instead of electrochemically, so higher cycling is possible. Psuedocapacitors, however, store charge electrochemically (Faradaically), by transfering charge between the electrodes and the electrolyte. While they offer a smaller amount of cycles compared to EDLC's, they achieve greater capacitances and energy densities. The electrodes consist of polymers or metal oxides.

Apart from EDLC's and pseudocapacitors, a third type of supercapacitors can also be distinguished: hybrid capacitors. These simply combine the properties of EDLC's and pseudocapacitors, by using asymetric electrodes. This way, they combine the advantages of both types [3], [18]. In this type of supercapacitor, polarity is critical, as asymetric electrodes are used. However, even in other types of supercapacitors, polarity should be respected as reverse-charging will lower the capacity. More exotic types of supercapacitors are being researched and developed, some even specifically for use in textile applications. Examples are dynamically stretchable supercapacitors [19] and ultra-thin twistable supercapacitors [20].

2.4.1 Energy and power

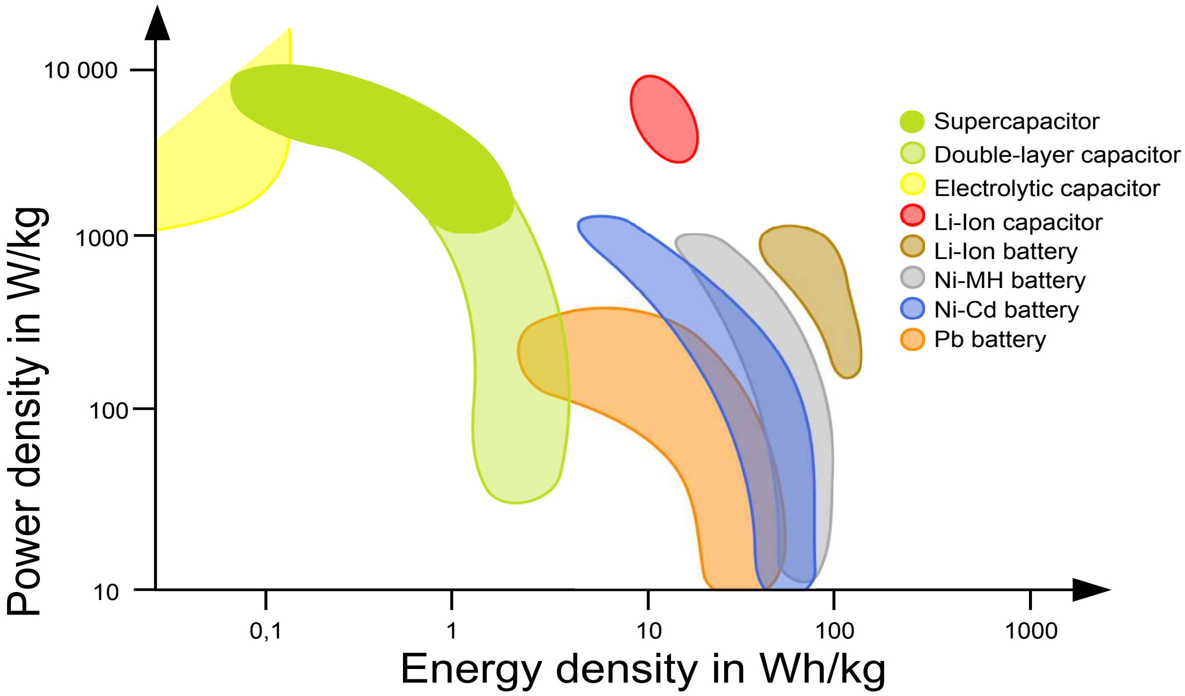


Figure 2.3: Ragone-chart: capacitors, supercapacitors and rechargeable batteries [21]

Although initially developed to compare different batteries, a Ragone-chart, such as the one given in figure 2.3, allows us to compare all sorts of electrical energy devices. It shows the specific (normalised in term of weight) power and energy density of all electrical energy storage solutions. The energy a capacitor can store is calculated using equation 2.3, from which the power can be derived (equation 2.4). To do this, we keep in mind that: [J] = [Ws].

$$\textbf{Supercap energy:} \qquad E[\text{J}] = \frac{C[\text{F}] \times V^2[\text{V}^2]}{2} \tag{2.3}$$

$$E[\text{mWh}] = \frac{E[\text{J}] \times 1000\ [\frac{\text{mW}}{\text{W}}]}{3600\ [\frac{\text{s}}{\text{h}}]} = \frac{C[\text{F}] \times V^2[\text{V}^2]}{7.2}$$

$$\textbf{Supercap power:} \qquad P[\text{mW}] = \frac{E[\text{J}]}{1000 \times \text{total time[s]}} = \frac{C[\text{F}] \times V^2[\text{V}^2]}{2000 \times \text{total time[s]}} \tag{2.4}$$

$$\textbf{Supercap maximum power [22]:} \qquad P_{max}[\text{W}] = \frac{V^2[\text{V}^2]}{4 \times R_i[\Omega]} \tag{2.5}$$

If we compare this with the formula we derived for the energy of a battery (equation 2.1), we see that the energy can easily be compared by converting the units.

However, comparing the power a battery and a supercapacitor can deliver is not straightforward. The power given in equation 2.4 is the power that the supercapacitor will deliver at the beginning of the discharge cycle, assuming constant current is drawn. We need to keep in mind that when the capacitor is discharging, its voltage will drop to 0. For this reason, most circuits will need a DCDC-convertor to be able to produce a stable power supply voltage to power the circuit. In order to be able to have a constant current and voltage (and hence a constant power) at the output of the convertor, the supercapacitor will also have to deliver a constant power. The different behaviour in terms of voltages of supercapacitors and batteries is shown in figure 2.4.

2.4.2 Constant power

In figure 2.5, a simulation is made to show the voltage, current and power drawn from a supercap, in case a constant power is drawn from it. A supercap of 1F with a nominal voltage of 1V is used in this simulation. The current and power have a negative sign because the supercapacitor is delivering energy to the circuit. We use the definition of power (2.6) and current through a capacitor (2.7) to calculate the voltage, current and power.

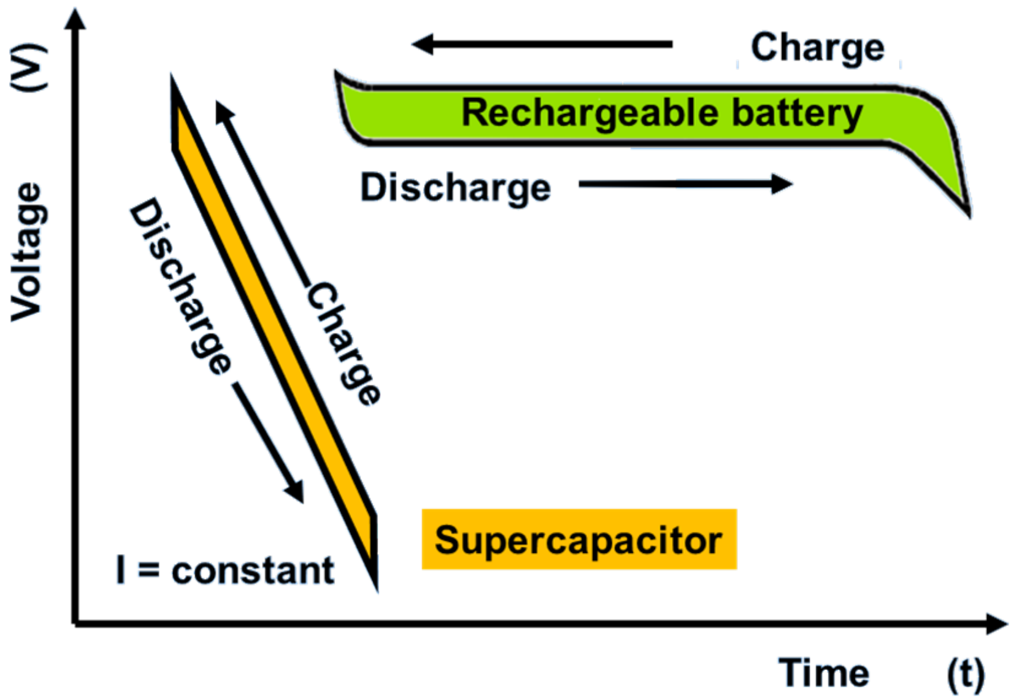


Figure 2.4: Comparison of voltages of supercap and battery during charge and discharge cyles [23]

$$\textbf{Definition 'power':} \qquad P = V(t) \times I(t) \tag{2.6}$$

$$\textbf{Definition 'current through capacitor' [18]:} \qquad I = -C \times \frac{dV(t)}{dt} \tag{2.7}$$

$$\Leftrightarrow P = constant = -C \times V(t) \times \frac{dV(t)}{dt}$$

$$\Rightarrow \qquad V(t) = V_{nom} \times \sqrt{1 - \frac{t}{\text{total time}}} \tag{2.8}$$

$$\text{and} \qquad I(t) = -\frac{C \times V_{nom}}{2 \times \text{total time} \times \sqrt{1 - \frac{t}{\text{total time}}}} \tag{2.9}$$

$$\text{and} \qquad P = -\frac{V_{nom}^2 \times C}{2 * \text{total time}} \tag{2.10}$$

In formula (2.10), time is expressed in seconds. If the application has an average power consumption in the order of 10mW, a supercapacitor can last a few minutes at most. This shows that supercapacitors will only be useful for circuits that have a low average power consumption or circuits that do not need to be powered for long periods (without recharging).

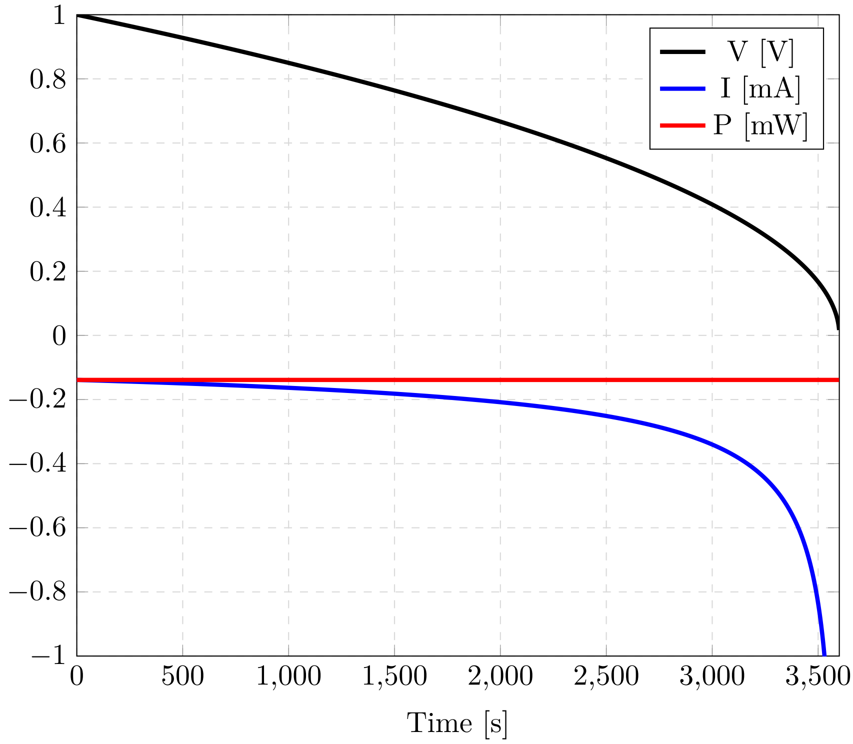


Figure 2.5: Simulation of supercapacitor ($C = 1\text{F}$) delivering constant power, normalised to V_{nom} (See equations: 2.8, 2.9 and 2.10)

2.4.3 Internal resistance and ESR

The most basic model of a supercapacitor is an ideal capacitor in series with a resistor. This resistor consists of a DC and AC part. Although often confused, the AC part is called internal resistance (R_i) and the DC part is called the Equivalent Series Resistance (ESR). The movement of ions at the electrodes causes this internal resistance. This R_i causes a voltage-drop when a charged supercapacitor is connected to a circuit, after which normal discharge occurs. It also determines the maximum current (and hence power) peaks the capacitor can handle, as can be seen from equation 2.5. These current peaks are usually still larger than in batteries. A good capacitor has a low ESR, and this is also the case with supercapacitors. However, unlike regular capacitors, R_i is usually larger than ESR in supercapacitors. Nonetheless, this internal resistance is often called the ESR.

When measuring R_i, which is a relatively low resistance, a 4-wire measurement, also called Kelvin measurement, should be used. This should be done in DC regime and not in AC regime, as is usually done with capacitors to measure ESR. In a traditional 2-wire measurement, the resistance-meter divides the voltage it senses at its inputs by the current through the resistor it has to measure. However, in that case, the resistance of the wires is also measured.

When using a 4-wire measurement the meter uses 4 connections: 2 to put a current through the resistor and 2 to measure the voltage across the resistor. Since the voltage-meter has a high input-impedance, not much current passes through these leads and the measured voltage is much closer to the actual voltage across the resistor. This way, the resistance of the leads is compensated [24]. Using this method, table 2.4 indicates the dependence of ESR on the level of charge on the capacitor. Here the EDLC supercapacitor DSK-614 of Elna is used [25], which has a rated ESR of 200Ω.

Table 2.4: ESR of supercap Elna

$\mathbf{V_{capacitor}}$ [V]	**Measured ESR** [Ω]
2.075	122
3.050	170
3.175	174

2.4.4 When to use supercapacitors

Although supercapacitors offer a lower energy density than lithium batteries, they can deliver higher power peaks. For this reason, they can also be placed in parallel with a battery. This way, the battery-pack will also be able to deliver (short) power peaks when necessary. Nevertheless, it is of critical importance to make sure the nominal voltage of these supercapacitors is higher than that of the battery by placing enough of them in series.

2.5 Fuel cells

The chemical reaction in a fuel cell is similar to that of a battery. The main difference is that in a fuel cell, the reactants are stored externally, in gas or liquid form. While a battery needs to be recharged, a fuel cell will produce electrical energy as long as fuel is available. They also produce waste, which is also stored externally [26].

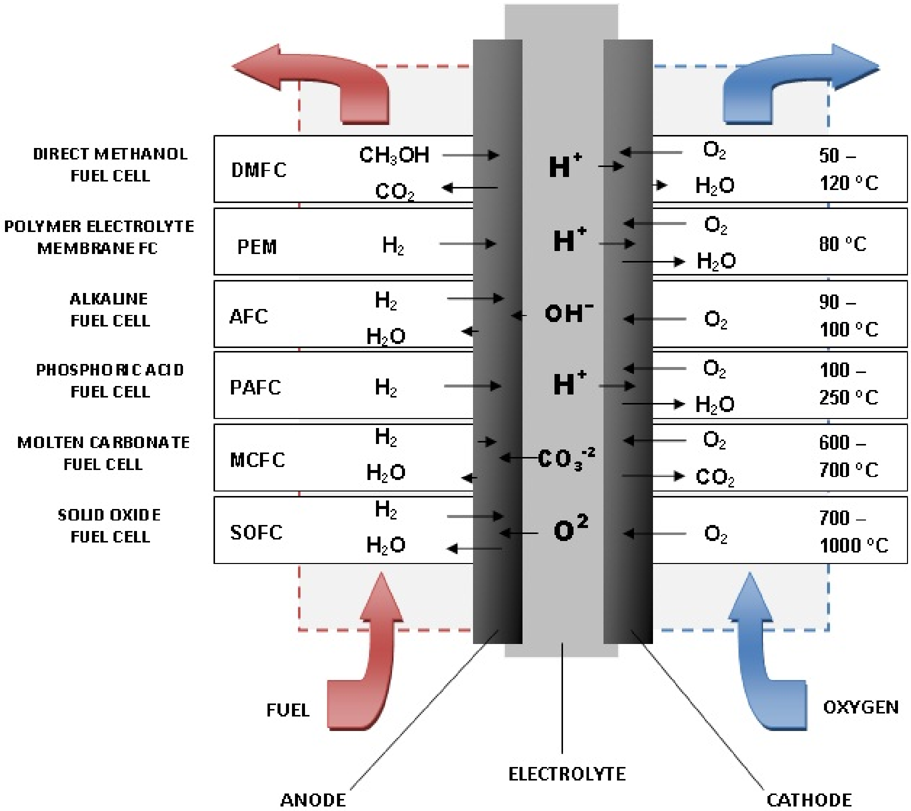


Figure 2.6: Operation of different types of fuel cells [27]

Fuel cells offer some advantages over batteries. Firstly, they have a longer lifetime and service life than most batteries. Secondly, they are more ecological to produce and are safer to work with. They also have a lower self-discharge. Their energy density in terms of volume and weight is also an advantage, although the weight and volume of their support systems should also be taken into account. These support systems consist of their fuel cannisters, connectors and waste collection systems. Finally, they are relatively low cost.

Their disadvantages range from a lower energy-conversion efficiency ($25 - 35\%$ compared to $> 80\%$ in batteries) to the simple fact that they need seperate fuel supplies, since the energy source (=fuel) and the energy convertor (=fuel cell) are stored seperately.

Although they are sometimes used in portable and low-power applications [28–30], integration into textile is not feasible. Even fuel cell-battery hybrids are possible, but the fuel

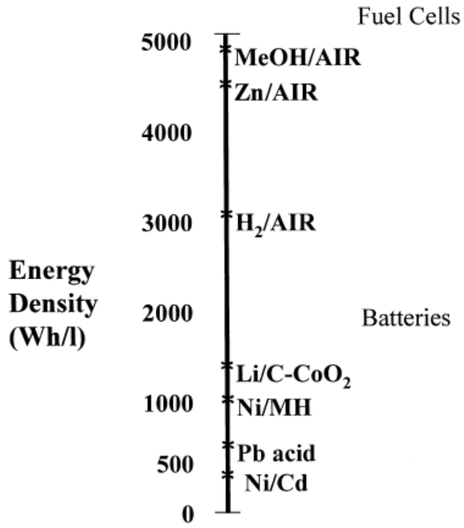


Figure 2.7: Theoretical energy densities [28]

cells and cannisters are hard to miniaturise. This makes them a viable option for portable applications ($< 200W$), and, to some extent, even for wearable applications ($< 20W$), but not for textile integration.

Chapter 3

Battery protection techniques

When electrical equipment is to be sold, several safety standards have to be adhered to, depending on the type of product. They ensure that the product does not pose any risk to its users and provide a low warranty return. In the case of a battery, some faults might occur, which cause an unwanted reaction from the battery. Since this reaction can destroy the circuitry attached to it, and even pose a danger to the user, a battery needs protection. Batteries can be sold with a protection circuit already integrated into the package, or in their raw form, with only basic packaging. For textile integration, the battery-pack needs to be as thin as possibl, so as not to hinder the user. For this reason, most batteries that will be considered will not have an integrated protection circuit and will need an external protection circuit. In a battery-pack, each battery might become faulty, so each battery will need seperate protection. To provide adequate protection, most battery packs incorporate 2 levels of protection. The first one is used to protect each cell seperately (primary protection), the second is a global protection of the entire battery pack (secondary protection) [31].

3.1 Overcurrent protection

All batteries have a current rating. This can be further devided into a maximum current during charging, a maximum current during discharging and a maximum pulse current (which can only last a few seconds). An overcurrent can also be the result of a short in the circuit. The protection circuitry should be equipped to protect the battery against damage from this type of fault condition.

A basic protection technique that will be used is a fuse. The principle is quite basic: it consists of a low resistance component placed in series with the rest of the circuit. However, once the current flowing through it reaches a certain point, the fuse blocks that current, thus providing overcurrent-protection for the circuit in which it is incorporated. [32]

Two types exist: fuses and PTC resistors, both of which can be used as mentioned above.

A fuse is not selfresettable, meaning that it has to be replaced once the fuse has to block current. In case of overcurrent, the wire inside is heated to its melting point, blocking all current, which provides excellent protection. Nonetheless, the use is limited to applications where this event is so rare that the replacement-costs (considering it can be replaced) are acceptable.

A more recent method consists of using PTC (positive temperature coëfficiënt) resistors, often polymer based. These are resistors with a very low resistance in normal operation, just like a fuse, but that raise their resistance when their temperature rises as a result of an overcurrent. This means that a certain amount can still pass through, but it will reset itself (its impendance lowers again) when the current drops, as long as it is not destroyed due to too much overcurrent. If PTC resistors are used for this purpose, they are often called 'resettable fuses'. For protection circuits, like the ones used in this thesis, PTC resistors are preferable, because a large current is usually temporary, and PTC's reset once the problem has passed. Fuses have the advantage that they can handle larger voltages, current and temperatures, but this is not necessary for an integrated battery pack. [33]

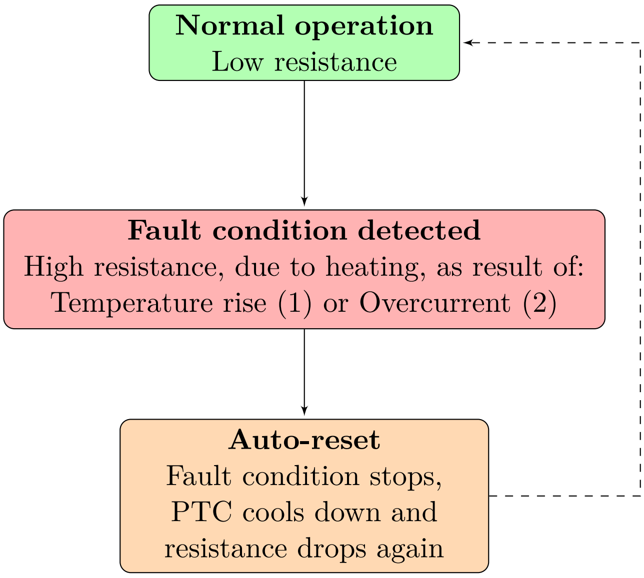


Figure 3.1: Modes of a resettable fuse

PTC resistors respond slowly. The higher the current that passes through them, the faster they will heat up and increase their resistance. For this reason, they can only be used to limit the current that lasts at least several seconds. To properly react to short-duration current pulses, overcurrent protection is also needed in the protection IC.

Of course, the placement of the fuse is critical for a proper use of its functionality. In most cases, it is placed at the input of the circuit, so it stops the current flow for the entire circuit.

3.2 Temperature ranges

Each battery also has specifications regarding temperature. Due to the fact that fuses and PTC resistors sense rising temperatures (usually as a result of overcurrent), they also protect the circuit by limiting the current when the temperature rises too much, thus decreasing the chance of damage to the battery. However, even when no current flows, the battery can still get damaged. Temperature ranges are specified during operation (charging or discharging) and during storage. Extreme temperatures can deplete the battery.

3.3 Over- and undervoltage protection

When charging or discharging a battery, the voltage will not remain constant. During discharge, the voltage will drop slowly. Starting with a short but steeper decline from the battery charging cut-off voltage, the decline-rate decreases for the largest part of its discharge, after which the decline gets steeper again until it reaches the discharge cut-off voltage. These cut-off voltage are specific to a certain battery. For most lithium batteries, these voltages lie around 3V and 4.2V. During a charge cycle we see the same, but in opposite direction. Also noteworthy is the fact that, while it is the responsibility of the charger to charge until the charge cut-off voltage is reached, it is wise to implement this feature in the protection circuit as well. Because the application, which acts as the load of the battery, will rarely implement protection against overdischarge, overdischarge protection is always required in the protection circuit.

Since the voltage is almost constant for the largest part of a (dis)charge operation, the battery has a third type of specified voltage: the nominal voltage. This is the voltage in the middle of its operating range. When calculating power and energy capacities, it is this voltage that is used in the calculations.

As the charge and discharge cut-off voltages are the rated voltages for normal operation, each battery will also have specified overcharge and overdischarge detection voltages. In case the voltage rises above the overcharge threshold, the protection circuit will cut off the current to the battery. As soon as the voltage drops below the overcharge release voltage, current can flow again. The same happens in case of a voltage that gets too low: at the overdischarge detection voltage, the battery should stop discharging and normal operation can resume when the battery voltage rises above the overdischarge release voltage. The detection and release voltages are not the same, this to make sure that the battery can rest a while after entering a fault condition. This also prevents the battery from oscillating between a fault condition and normal operation.

The values of these voltages are always specific for a certain battery and should always be checked. In table 3.1, average values are given to give the designer some idea of the values of these voltages.

Table 3.1: Example of battery voltages

Specification	**Value**
Charge cut-off voltage	4.20 V
Discharge cut-off voltage	2.75 V
Nominal voltage	3.70 V
Overcharge detection voltage	4.25 V
Overcharge release voltage	4.05 V
Overdischarge detection voltage	2.50 V
Overdischarge release voltage	3.00 V

3.4 Protection IC

To provide the primary protection, each battery gets a protection circuit. The outputs of this circuit are given in figure 3.2.

Although both PACK- and BAT- are considered ground connections, they are not shorted. Two enhancement-type FET's are placed in between, with connected drains, as is shown in figure 3.3. These can be used to stop the current flow in a certain direction, thus acting as switches. In normal operation, where the transistors are in the ON state and allow current to flow, high voltages are applied to the gates of the NMOS transistors. As soon as a fault condition is detected, the gate-voltages COUT or DOUT are driven low by the IC, so that no current can pass through the transistor in that direction.

An equivalent circuit is possible with two enhancement-type PMOS transistors which are placed between PACK+ and BAT+. Which option should be used is determined by the proterties of the output-pins of the chosen protection IC. Since the full current applied to the circuit will flow through these MOSFET's, enough heat dissipation should be possible. For this reason, power MOSFET's are preferable. Moreover, MOSFET's with a low on-resistance are preferred, to minimize losses. In that regard NMOS are better than PMOS, as they usually have a lower on-resistance. A depletion-type NMOS transistor is a third type of power MOSFET, but none of the reviewed IC's used this type of transistors. Here, a 0V V_{gs} places the transistor in the ON state. They are turned OFF by applying a negative V_{gs}. BJT transistors need a base current in the ON state and are therefore less suited as power- and switch-transistors as a result of their higher power consumption (which also causes more heat-dissipation) [34].

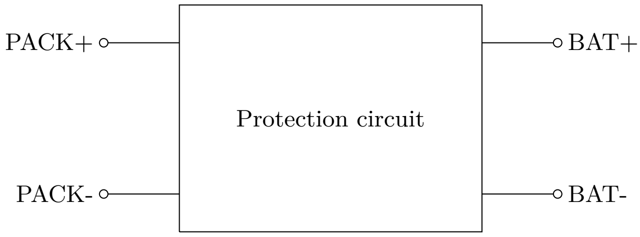


Figure 3.2: Protection circuit

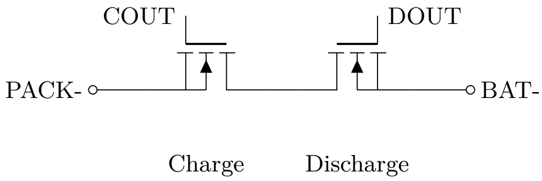


Figure 3.3: Using NFETs to control current flow in both directions

In table 3.2, the different fault conditions are given, along with how they are detected and which voltage is altered to turn one of the FET's off. Here, V- is a pin on the IC, which is connected to PACK- through a sense-resistor.

Table 3.2: Battery fault detections

Fault	**Abbrev.**	**Detection by**	**Controlled pin**
Overcharge (V)	OVP	BAT+ is too high	COUT
Overdischarge (V)	UVP	BAT+ is too low	DOUT
Charge overcurrent (I)	OCC	V- rises with respect to BAT-	COUT
Discharge overcurrent (I)	OCD	V- rises with respect to BAT-	DOUT
Short circuit	SCC	V- rises with respect to BAT-	DOUT

3.4.1 Zero-voltage charging

When a battery is depleted, it is not advised to start CCCV charging (see section 6.1). The charger can then implement preconditioning or even trickle charging. However, the protection IC might open the FET-switches as an undervoltage condition is detected. If the IC implements zero-voltage charging, it will allow charging, even if an undervoltage condition occurs.

3.4.2 Battery authentication and fuel gauging

On some IC's, other additional options are also available. A first one is authentication, which checks if an acceptable battery was attached. For this to work, the load or host checks the data received from the battery-pack to see if it matches any of its preprogrammed acceptable battery packs. This is done to assure no battery is attached that might damage the load, or be damaged by the load. This means that restrictions can be placed on battery-voltage, size/package, maximum current etc. However, most of the time only one specific battery-model is accepted by the host. Since textile integrated circuits need to be kept small, such a authentication check is not advisable. It complicates the design of the battery and load and in most cases, the designer will make both items. It is therefore the designer's responsibility to use an acceptable battery to power the circuit. Moreover, this communication increases the amount of meanders required between the battery and load, which reduces flexibility. IC's that implement this communication will also have a larger power consumption. Moreover, since this power needs to come from the battery, it will reduce the lifetime of the battery.

A second additional option is fuel gauging. Coulomb-counting allows the IC to estimate the amount of energy that is still available in the battery. This technique is usually not very accurate and regular recalibrations have to compensate for variations in temperature and (dis)charge speed. To use this information, additional meanders are needed. This type of monitoring also increases power consumption.

Authentication and fuel gauging might be necessary in some applications, but in textile applications, it is preferable to reduce the surface that is used and the number of interconnecting meanders. Moreover, this protection IC uses the battery it is attached to as its power source and is therefore always powered on, even when it is not attached to a load. This means that an IC with low power consumption should be selected. For these reasons, most textile applications should use IC's that do not have these features.

3.4.3 Component selection

In table 3.3, currently available single cell protection IC's are compared. In this thesis the BQ29701 of Texas Instruments is used [35] (attached to the 200 mAh PGEB014461 battery), since it offers all the forms of protection, without authentication and fuel gauging, while at the same time limiting the number of components around the IC and the total required area. The schematic is given in figure 3.4. Two high-impedance resistors are added between the gates and sources of the MOSFET's to deplete the charges in the gate-source capacitance. Also, in the connection to PACK+, a PTC fuse is added for additional overcurrent protection. To sense the battery-voltage a RC filter is used to filter out noise and to make sure that, even during sharp negative transients, the device still functions. From the BQ29700-series, the BQ29701 is selected, because it has the specified over- and undervoltage thresholds.

Since textile integration is required, all components need to be SMD to provide flexibility. To save space, passive components of the size 0603 [1608] are used. For the MOSFETs, a package is chosen which offers dual NMOS transistors (2 transistors in a single package). The TSSOP-8 package is preferred over the SOIC-8 for its lower height and lower board area.

Even smaller packages exist, but they do not offer the required current and voltage ratings.

Table 3.3: Battery-protection ICs

Brand	**IC**	**OVP**	**UVP**	**OCC**	**OCD**	**SCC**	**FG**	**Auth**	**#comp.**	**#pins**
Maxim Int.	DS2762*	x	x	x	x	x	x		15	16
Maxim Int.	DS2764*	x	x	x	x	x	x		16	16
Maxim Int.	DS2784*	x	x	x	x	x	x	x	13	14
Texas Instr.	2946xy	x							6	6
Texas Instr.	2970x	x	x	x	x	x			5	6
On Semic.	LC0511x	x	x	x	x				5	6
On Semic.	LC0513x	x	x	x	x				6	6
On Semic.	NCx261	x							2	5
Ricoh	R540yz	x	x	x	x	x			5	5
Ricoh	R547yN	x	x	x	x	x			5	5
Ricoh	R548yz	x	x	x	x	x			6	6
Seiko	S82xy**	x	x	x	x	x			5	6
STMicroEl.	STC31xy†	x	x				x		7	8
STMicroEl.	GG25L†	x	x	x	x		x		9	10
FreeScale	MM912*	x	x	x	x	x	x	x	19	48

*Also provide data communication

**Models S8230A and S8250A also add external discharge control, adding 1 component

†Fault conditions are communicated via I^2C communication. External control of (dis)charge-FETs is needed.

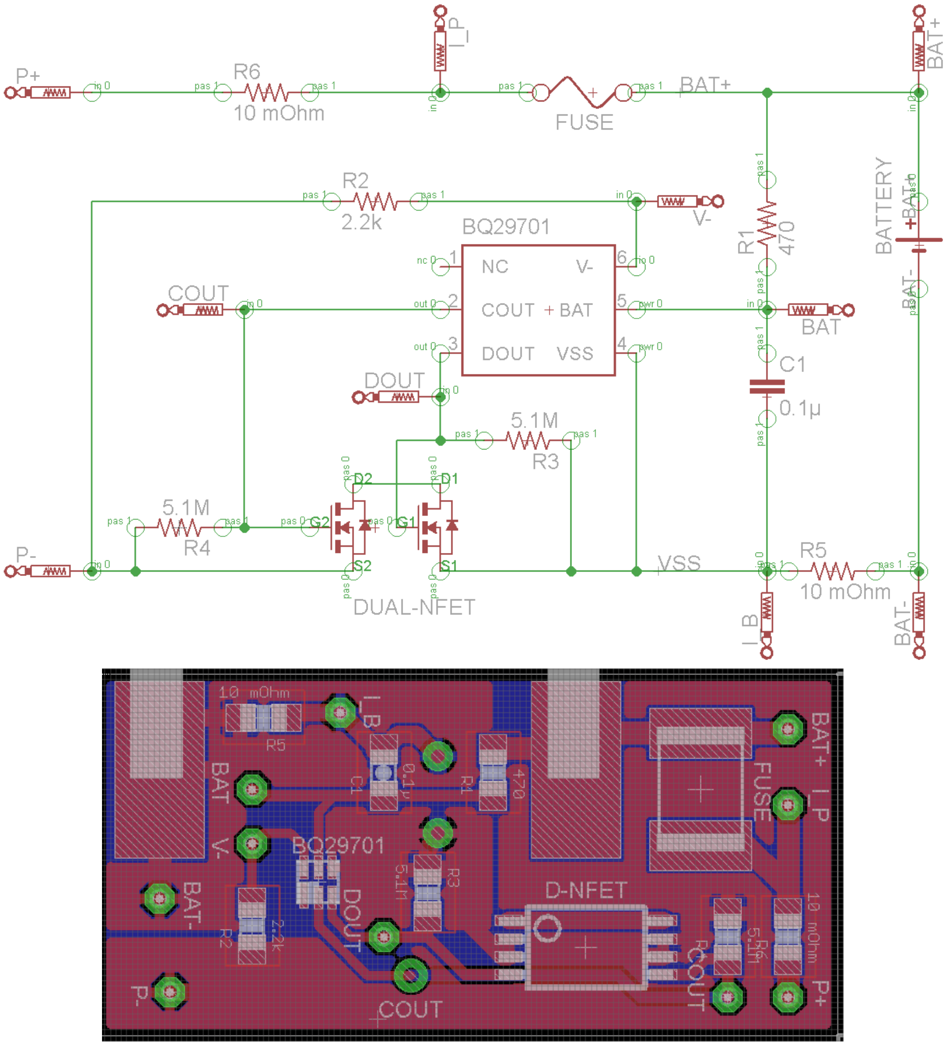


Figure 3.4: Battery protection circuit, basic on BQ29700 [35]

3.5 Protection test-circuit

A test-circuit is made to test the proposed protection circuit for the 200 mAh PGEB014461 battery [36]. Additional vias are added to the design to allow measurements of the voltages at those points (see figure 3.4). By measuring the voltages at the COUT and DOUT pins and applying voltages between VSS and VBAT and between VSS and V-, all fault conditions can be simulated.

In table 3.4, all measured parameters are given. Since the battery specifications are the ones that should be met, the error is calculated with regard to these specifications. All errors are small, so it is concluded that the protection circuit works as expected. The overcurrent thresholds are sized according to the maximum short-duration current of 2.7A, which corresponds to a measured voltage of 130mV between the V- and VSS pins. Note that this also implies that, when the two 'ground' connections (PACK- and BAT-) are attached to two ground planes, these planes cannot be decoupled, as this would not allow a voltage difference between V- and VSS to occur in AC regime. The maximum long-duration current is 1C for charging, and 2C for discharging. In this case, the PTC fuse will limit the current.

Table 3.4: Measurements of the parameters of the protection circuit

Fault	**[unit]**	**Spec. battery**	**Spec. IC**	**Measured value**	**Error** [mV]
OVP	[V]	4.275	4.280	4.291	16
$OVP_{release}$	[V]	4.175	4.180	4.187	13
UVP	[V]	2.300	2.300	2.288	12
$UVP_{release}$	[V]	2.400	2.400	2.389	11
I_{normal}	[µA]		4	6	
OCD	[mV]	130	125	124	6
OCC	[mV]	130	100	102	28

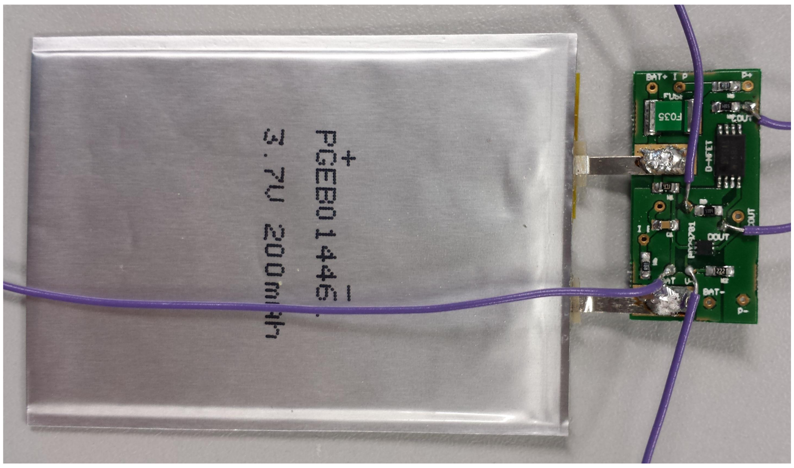


Figure 3.5: Test-PCB for protection circuit, with battery attached

Then, the battery is attached, and two charge and discharge-cycles are tested. This can be seen in figure 3.6. Discharging is stopped when the battery voltage reaches 2.7V. The datasheet of the battery advises to discharge to 3V, but this is the battery-voltage after resting. When a load is attached, the battery-voltage quickly drops, and it rises again when the load is removed. This voltage difference depends on the state-of-charge (SoC) and the amount of current that was drawn from the battery (larger voltage differences occur at low SoC and/or when more current is drawn). For the C/2 cycle, the voltage after detaching the load rose to 3.54V and for the C/5 cycle, the voltage rose to 3.38V. This indicates the dependence on the drawn current. The dependence on the state of charge is tested by interrupting the discharge cycle and checking settling voltages. During the C/2 cycle, an interruption at a battery voltage of 3.48V was made and the voltage after settling was 3.78V. This is a voltage difference of 0.3V, whereas the voltage difference at the end of the charge cycle was 0.68V.

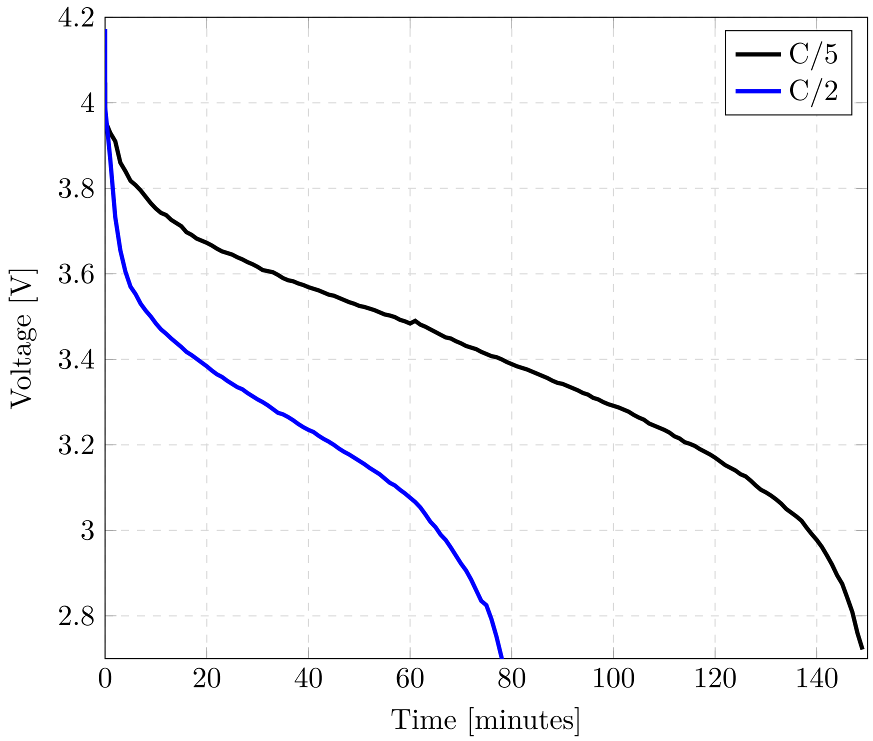


Figure 3.6: Discharge cycles

We see that the voltage drops faster when more current is drawn from the battery, as expected. Drawing more current means the remaining capacity of the battery drops faster. As the voltage is proportional to the remaining capacity, this also drops faster. Looking at the duration of the discharge, we can calculate the capacity that was drawn from the battery.

$$\text{Used capacity [mAh]} = \frac{\text{Discharge duration [min]} \times \text{(average) current [mA]}}{60\ [\frac{\text{mins}}{\text{h}}]} \tag{3.1}$$

This is 100 mAh for the cycle at C/5 and 130 mAh for the cycle at C/2. This is lower than the specification of 200 mAh, which is due to several reasons. Firstly, the battery was not new, so its capacity might have decreased over time. Secondly, the specified capacity of a battery is measured in optimal conditions and its effective capacity is usually lower. Thirdly, the battery was not fully charged. Although we see that the battery voltage is close to its rated fully-charged voltage of 4.2V, this voltage was not fully reached. (Once again, this specified voltage is after a period of resting.) The charger is responsible for charging to 4.2V (CV), followed by a constant current (CC) charge, until the current that the battery draws is below a current limit. In most cases, a limit of C/10 is sufficient, but a different limit can be determined by the charge circuit. If the battery is detached from the charger before that limit is reached, as was the case in these tests, it is simply not fully charged.

3.6 Protection against ESD sparks

Apart from reversed connection, the battery pack should also be protected against ESD sparks from direct connection or airgap sparks. To do this, spark gaps can be added between the pack-connections in the copper layer. It is best not to add a soldermask on these gaps, as this would increase the voltage breakdown. Adding a capacitor with short and wide connections between these terminals also helps. A shunt capacitor can also be placed across the control FET's in the protection circuit, as they lie in the high-current trace. [37]

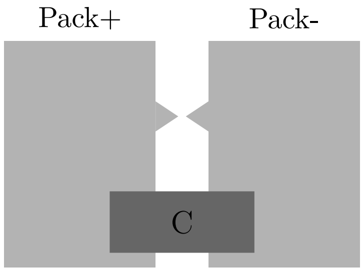


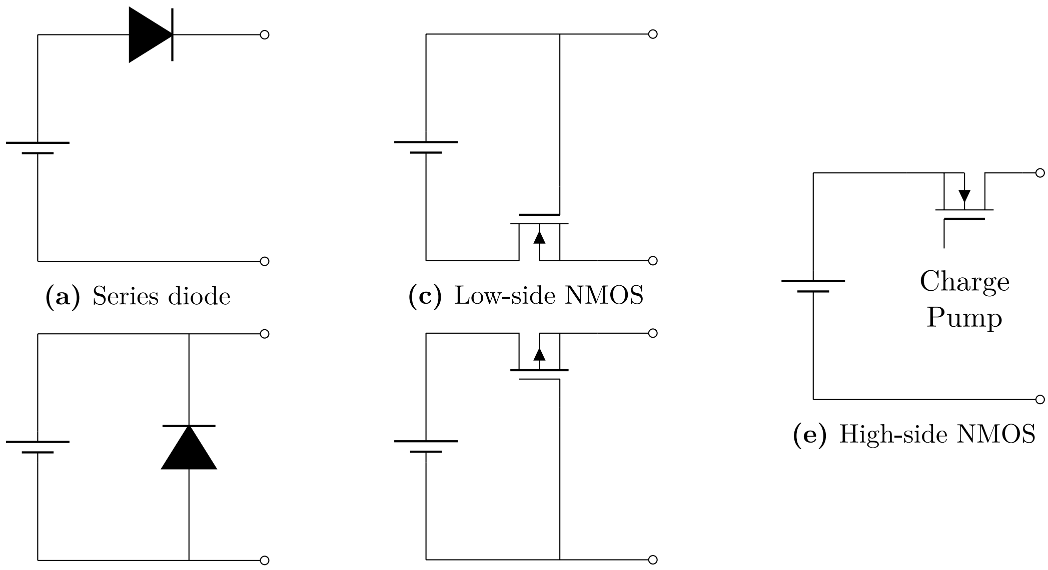
Figure 3.7: ESD protection at terminals: sparkgap (top) and bypass capacitor (bottom)

3.7 Protection against reversed connection

Connecting a battery or battery-pack the wrong way can be detrimental, both for the battery and for the circuit to which it is attached. This is the case in both charging and discharging modes. The most simple solution can be used when a connector is employed. By simply selecting a asymmetrical connector and connecting the wrong way is not possible anymore. However, in portable applications, such a connector might use too much space. So, apart from this mechanical solution, an electrical solution is also needed.

The easiest electrical solutions consist of diodes. A diode in series with the battery will allow current to flow in only one direction. This is either the direction the current will flow in during charging, or the direction during discharging, depending on the orientation of the diode. For this reason, a correct placement is critical. This can be on the charge- and application- circuit, or can be integrated in the battery-pack itself. The disadvantages are that the diode has to handle the full current and there is a forward voltage drop across the diode, which even depends slightly on the current. When a battery with a high output impedance is used, a shunt diode can also be used. [38]

This can be improved by replacing the diode with a transistor. A BJT transistor will consume base current, so a MOSFET is better suited, similar to the switches in the protection circuit (see section 3.4). A NMOS as a low-side switch offers a lower ON-resistance, but might cause a small voltage drop, called 'ground level shift'. This can be solved by using a high-side PMOS switch, which will have a higher ON-resistance, or by using a high-side NMOS. The disadvantage of this high-side NMOS is that, in normal operation, a positive V_{gs} is needed. So, the gate should be driven with a higher voltage than the battery voltage, which is usually the highest voltage in the circuit (the power supply) [38].



(a) Series diode **(b)** Shunt diode **(c)** Low-side NMOS **(d)** High-side PMOS **(e)** High-side NMOS

Figure 3.8: Reverse protection options

3.8 Absence of primary protection

In same applications, space might be a critical design parameter. Especially when using smaller batteries, the (relative) area used for protecting each battery can become substantial. The batteries might still be protected by the secondary protection, protecting the entire battery pack. In that case, it is possible to leave out primary protection. Looking at the dangers this poses, carefull consideration is needed to ensure the battery-pack is still safe to handle.

Current consumption might be limited by proper use of a charger (during charging) and the maximum current consumption of the application (during discharging). However, this only ensures that no overcurrent will occur during normal operation. Shorts that are introduced by improper handling of the battery pack will still pose a real danger. Since batteries, especially Li-ion batteries, are inherently dangerous, adding a protection circuit to each battery is always advisable.

Chapter 4

Balancing techniques

In most applications, the battery-pack will consist of more than one cell. The maximum output power of a battery-pack is the output power of a single cell multiplied with the number of cells. However, the degree in which this offered either as a high voltage or as a high current depends on the configuration. After examining the effects of connecting several cells in series and in parallel, the implications this has on the circuitry will be explained.

4.1 Parallel connection

Basic knowledge of electronics is enough to predict the behaviour of cells connected in parallel. The voltage will remain the same, but the maximum current will be equal to the sum of the current through all the cells. Placing several voltage sources with a different voltage in parallel is dangerous, which also applies to batteries. In a parallel connection, the overall voltage should be the same across each cell. If cells of different charge are placed in parallel, the cells with a larger charge will 'bleed' in the cells with a lower charge. This is called mismatch. If the battery gets enough settling time, mismatch due to cells connected in parallel will automatically resolve. During bleeding, the higher charged cell will push current to the lower charged cell. However, this can be a large current, which is proportional to the difference in charge, and this large current can damage the cells. Therefore, large mismatches should be avoided.

If all cells are completely identical, all cells will carry the same current. When one or more of the cells are damaged, the others will divide the current. Three things need to kept in mind if one of the cells in the parallel connection is damaged:

- If a damaged cell does not work anymore, the rest of the pack will still work. However, if this damage causes a short, this not the case anymore. Replacement of the damaged cell will then be necessary.

- Since the other cells in parallel will now carry all the current, each of them will carry a larger current than before. If the pack was used near its maximum current-rating, this will cause an overcurrent in the remaining cells. However, this is not a problem, if the pack is used well below its current-rating.
- The capacity of the total parallel connection is now lower. If this parallel connection is a part of a series connection, the capacity of entire pack goes down. The total capacity is then equal to the capacity of the parallel connection with the lowest amount of correctly functioning cells.

To conclude, as long as the difference in charge between cells connected in parallel is small, they will balance each other by bleeding. This means no balancing circuitry is needed if only parallel connections are present in the battery-pack.

4.2 Series connection

Placing cells in series might seem similar to placing them in parallel, except for the fact that no bleeding and automatic balancing will occur. The overall voltage will be equal to the sum of all individual voltages and the current will remain the same of a single cell. However, series connections are more complicated.

One of the cells in a pack might have a larger charge (so a larger voltage, call this cell 'L'), and one might have a smaller charge (so a lower voltage, call this cell 'S') than the other cells (see figure 4.1). When charging, the protection circuit of cell 'L', will stop the charging process sooner than the other cells. A charger that checks all cells in series seperately, will even stop charging completely, since an overvoltage is detected in one of the cells. At this point, the other cells will not have reached a full charge yet. Something similar will occur when discharging, because of the presence of cell 'S'. Undervoltage will be detected and discharging will stop, although the other cells still have charge left. The batteries will deteriorate differently: whereas cell 'L' will experience charges to its maximum, cell 'S' will be deeply discharged and the other cells will be somewhere in between. This assymetry will further increase the difference in charge (or voltage) between the batteries. As a result, the total effective voltage range in which the batteries operate will decrease, reducing the effective capacity of the battery-pack [39]. Moreover, more charge/discharge cycles will be required which reduces the battery lifetime. Such a charge imbalance will always be present, since differences in chemical and electrical characteristics are inevitable.

To make sure all cells have an (almost) identical charge, balancing of the cells is needed. This can happen in two ways: passive balancing (dissipative) or active balancing (non-dissipative) [40]. Passive balancing dissipates charges from the cells with a higher charge than the others in order to maintain an equal charge on all the cells. It means power is

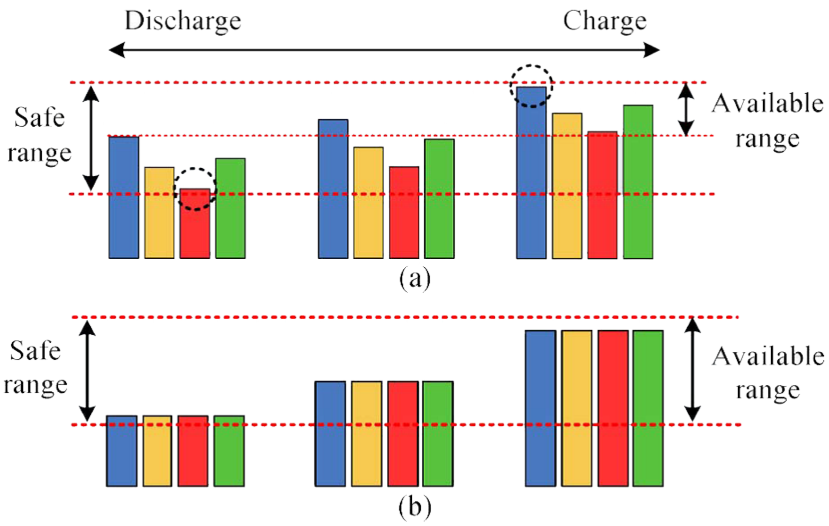


Figure 4.1: Decrease of available voltage range due to difference in charge between batteries in series [39]

wasted during balancing. Active balancing always uses active components (this will usually also mean more components are required) and is therefore consuming energy, even when no balancing is needed. This causes heat dissipation, which is a problem in textile applications, but luckily, this power consumption is low. In textile applications, this higher number of components will be the most important parameter, as it will increase the area required for the balancing circuit, reducing flexibility. Active balancing does not waste excess charge on the cells with a larger charge. It redistributes this charge over the other cells, as illustrated in figure 4.2.

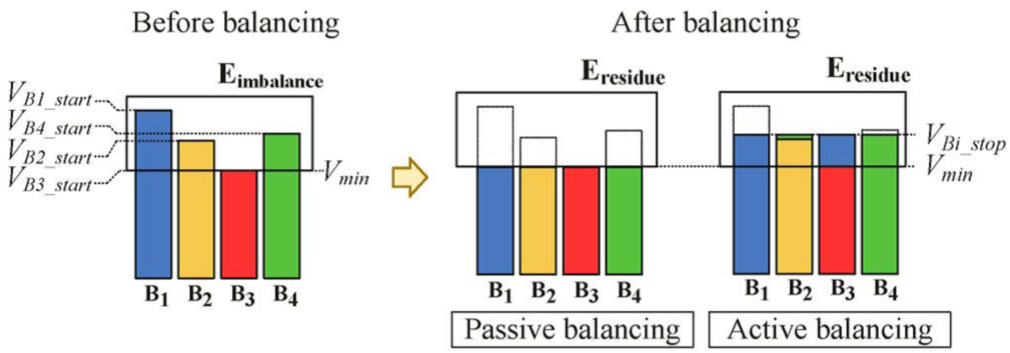


Figure 4.2: Benefit of active balancing over passive balancing [39]

Three different algorithms can be used to passively or actively balance the cells [41, 42]:

- Voltage based (active and passive): This is the simplest solution. It balances as soon as a voltage difference is detected. As the voltage curve in the middle of a battery's operating range is almost flat, this algorithm does not guarantee accurate balancing.

- Final voltage based (active and passive): Similar to voltage based balancing, but now balancing happens only at the end of the charge cycle. Using a larger current for balancing, balacing time is reduced and accuracy is improved.
- SOC history based (active only): Continous monitoring of state-of-charge (SoC) and comparing with the SoC history of each cell, this provides the most accurate balancing, while keeping the balancing current low. However, this also implies that the balancing circuit will be more complex and more power consuming. This type of balancing is often called battery redistribution and is sometimes considered as a third balancing technique, apart form active and passive balancing.

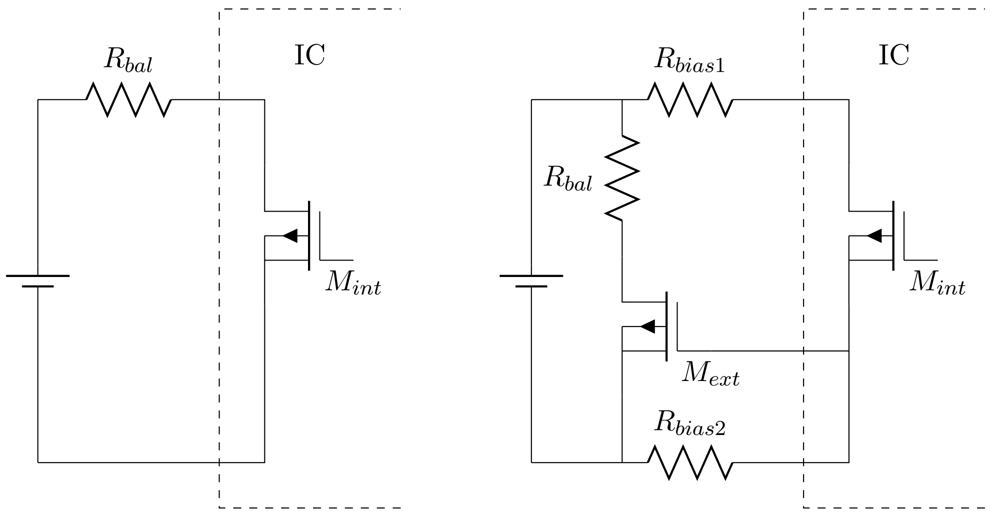
Apart from differences in initial charge, cells may also be unbalanced by a difference in leakage current, a difference in internal reistance and a difference in capacity [41]. When balancing is used, the voltages and hence the charges of all the cells remain balanced. Balancing can happen continuously or during charging only, in which case it is usually mounted on the charge circuit and not on the battery-pack, so as to save space. By balancing during charging, differences in leakage currents do not cause voltage difference at the end of the charge cycle, as long as balancing can happen fast enough. By doing this continuously, imbalance due to difference in leakage current is also compensated. Differences in the capacity of each cell, however, cannot be equalized that easily. Only active balancing will ensure that the total capacity of the battery-pack is equal to the sum of the capacities of all the cells. Passive balancing will limit the total capacity to the capacity of the cell with the lowest capacity multiplied with the number of cells [42, 43].

4.2.1 Passive balancing

For passive balancing, the simplest and most commonly used configuration consists of a resistor and a MOSFET switch parallel to each cell. By controlling this switch, current passes through the resistors, slowly removing excess charge from that cell. A balancing IC will be needed to control the switches. In most cases, these switches are integrated in the IC itself, saving a lot of space. As Li-ion cells usually have a low self-discharge rate, which keeps the imbalance low, the low currents of internal passive balancing are adequate [42]. If larger balancing currents are required, external circuitry is needed for balancing. Passive balancing is also called dissipative balancing or bypass balancing.

Figure 4.3 shows how the components in passive balancing are connected. For internal balancing, only one component is added: a resistor (see figure 4.3a). The resistor R_{bal} is required to limit the balancing current. Balancing is enabled by pulling the gate of M_{int} high.

When a larger balancing current is needed, the internal MOSFET should not be used. As it is integrated in the IC, not enough heat dissipation is available. Luckily, the same IC can



(a) Internal balancing

(b) External balancing, allowing higher balancing currents

Figure 4.3: Passive balancing

be used to employ external balancing, where the balancing current passes through an external MOSFET, which allows a better heat dissipation. When the gate of the internal MOSFET is pulled high and M_{int} conducts, a current runs through R_{bias1} and R_{bias2}. This results in a voltage across R_{bias2}, which pulls the gate of M_{ext} high. Now the balancing current runs through R_{bal} and M_{ext} [44].

The disadvantage of this technique of external balancing is that neighbouring cells cannot dissipate simultaneously. The low bias resistor R_{bias2} will function as the high bias resistor $R_{bias1'}$ of the cell below. When both M_{int} are driven high, no net current will flow through this resistor, so no voltage is created across it and the top cell will not balance. Luckily this is not a big problem in practice, since currents are higher when using external balancing, so balancing is faster and the cells can balance one after the other [44].

4.2.2 Active balancing

It is clear from figure 4.2, that active balancing offers an advantage over passive balancing, as no charge is dissipated and the total capacity of the cells remains available in the battery-pack. However, it is used less in portable applications, because it is more space-consuming [42]. Active balancing, also called non-dissipative balancing or charge redistribution balancing, can happen in three ways:

- Cell-to-battery: excess charge is removed from the cell and redistributed over the entire battery
- Battery-to-cell: charge is removed from the battery to charge a single cell

- Cell-to-cell: charge is redistributed from one of the cells to the other cells (usually neighbouring cells only), also called bidirectional balancing

Three common techniques exist to perform active balancing:

The first is the switched capacitor (SC) technique, also called charge shuttling [45]. Switches are used to charge capacitors, by connecting them in parallel with the cells. By changing the states of the switches, each capacitor can be placed in parallel with its neighbouring cells. This way, charge is transferred to neighbouring cells (cell-to-cell). If a capacitor is added with connections to the upper and lower cells, the result is a chain or ring structure. An additional capacitor can be placed across the entire battery-pack (double-tiered switched capacitor or DTSC) to allow charge to be depleted from the entire pack (battery-to-cell). Similarly, this can be used to discharge a cell, and charge the entire pack (cell-to-battery) [39]. Since charge can only travel to neighbouring cells (or to the entire battery-pack), redistribution of charge might be slow. This can be sped up by adding even more capacitors, attached to different cells (multi-tiered switched capacitor or MTSC). Depending on the number of cells in series, a compromise should be made between a reasonable time to balance and a low number of capacitors. If many cells are placed in series, the number of both switches and capacitors can be reduced by using a single capacitor (SSC) or dividing by the series-string into modules (modularized switched capacitor or MSC).

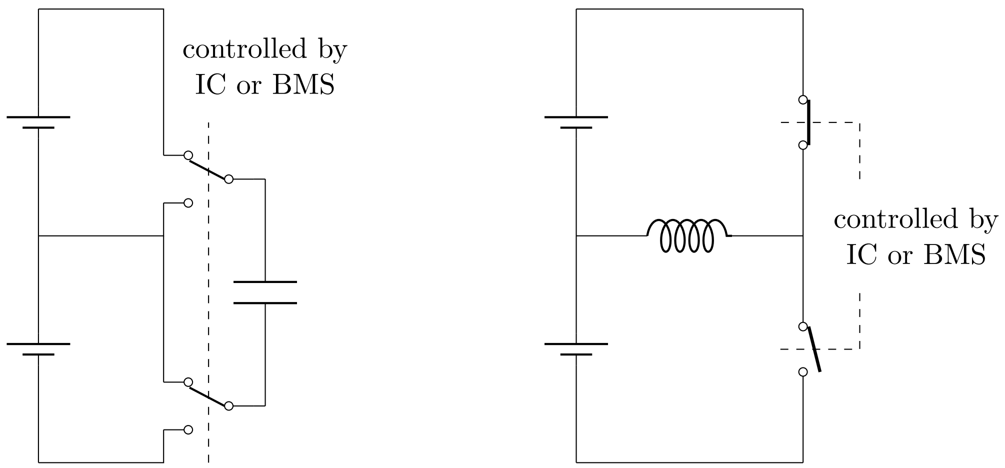
The second technique is similar, but uses inductors to temporarily store charge, instead of capacitors. This is also called charge shuttling or power pumping. Often capacitors are placed in parallel with the cells to smooth the charge transfer. As this increases the number of components, it is used in applications containing a lot of cells.

The third technique uses small DCDC-convertors to redistribute charge. These type of balancers also contain inductors [46].

Apart from the three techniques described above, many more active balancing techniques exist. However, they are less common and require more components [47]. Therefore, they are not suited for textile integration.

4.2.3 Battery management system

Both active and passive balancing can be controlled by a battery management system (BMS). This is a circuit that adds several features to the battery pack. It often provides monitoring of all the cells, it will keep a history and will control the balancing circuit. By keeping a history of all the data during charging, discharging, storage and balancing, it can monitor state-of-charge (SoC) of all the cells, but also state-of-health (SoH) of all the cells, as well as of the entire pack. This sytem will also offer data-communication options. As this system needs more components and more space, it is less suitable for portable applications.



(a) Balancing using capacitors (SC) **(b)** Balancing using inductors

Figure 4.4: Active balancing

4.2.4 Other considerations of series connections

Although chargers might have a built-in secondary protection, this is not reliable when no protection or balancing circuit is present in a battery-pack with series connected cells. The over- and undervoltage thresholds are equal to the thresholds of a single cell, multiplied by the number of cells in series. As the voltages across each cell might differ if no balancing is present, a cell can pass its threshold long before the threshold of the entire series string is passed, at which point charging will stop. Therefore, primary protection is required to check each cell seperately, especially when no balancing is present.

An additional important disadvantage of series connection is that the entire string cannot be used if one cell in the string does not work anymore, as the current has to travel through all the cells.

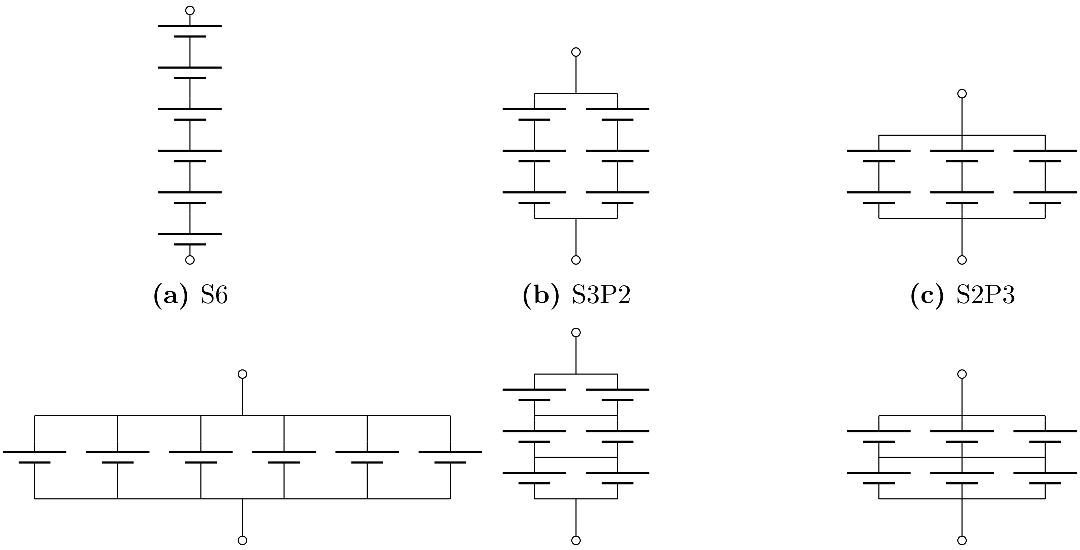
As series connections usually employ balancing, it is important to select a proper placement of this circuit. If the connections to each part of the series-string (which can consist of several cells in parallel) are different, the voltage drop across those connections might be as well. Therefore the balancing circuit should be placed at equal distances of each part of the string. The balancing circuit can be placed on the battery-pack itself, or on the charger. If space consumption is a critical design-parameter, it is best to place it on the charger, otherwise it should be placed on the battery-pack. Balancing can then happen continuously, which offers a longer time to correct the imbalance, and offers balancing even during storage or discharging.

4.3 Combining series and parallel

By using series and parallel connections together, even more cells can be combined. At the start of a design process, the total required energy capacity is determined. After having selected the model of battery that will be used, the minimum number of cells is fixed. Now, the designer should consider in which configuration to place these cells. It is clear that, for all configurations, each row, as well as each column, should contain the same amount of cells. To assure that the cells react as identically as possible, identical cells should be used. It is best not to mix different models of batteries, or cells of a different age. If possible, making sure the cells all come from the same batch is advised.

Using a simplistic example based on [48], the dependence of the reliability on the configuration is shown. In this example following assumptions are implied:

- The number of cells in each configuration is the same, leading to an equal power output for each configuration. However, depending on the voltages and currents required by the application, some configurations will require a convertor. It is assumed that this conversion is perfect.
- All cells are assumed to be identical, with the same probability of getting damaged. Their degradation, as well as their age, is identical.
- This example consists of 6 cells. They can be placed in 6 configurations. The cells can be placed with 3 in series and 2 in parallel, or 2 in series and 3 in parallel. In each of these cases, a parallel connection of cells in series is possible. This is called series-parallel or in short: SxPy, where x is the number of cells in series and y the number of cells in parallel. One could also use a series connection of cells in parallel, called parallel-series or PySx, with x and y defined as before. Apart from those four configurations, all cells can also be placed in series or in parallel, called Sx and Py respectively. These configurations are illustrated in figure 4.5.



(a) S6 **(b)** S3P2 **(c)** S2P3

(d) P6 **(e)** P2S3 **(f)** P3S2

Figure 4.5: Different configurations of series and parallel connected batteries

Figure 4.6 shows the probability that the pack will stop functioning, where p is the probability of a damaged cell. This chance of malfunctioning is shown in equations 4.3, 4.4, 4.5 and 4.6, based on equations 4.1 and 4.2.

Probability of failure:

Series connection: $$(1-p)^x \tag{4.1}$$

Parallel connection: $$(1-p^y) \tag{4.2}$$

Probability that the battery will still function:

Series-parallel (SxPy): $$(1-(1-p).^x)^y \tag{4.3}$$

Parallel-series (PySx): $$1-(1-p^y)^x \tag{4.4}$$

Series only (Sx): $$1-(1-p)^x \tag{4.5}$$

Parallel only (Py): $$1-(1-p^y) \tag{4.6}$$

Several conclusions can be drawn from figure 4.6. Firstly, we see that the more cells are placed in parallel, the less likely it is that the entire pack becomes non-functional. Secondly, parallel-series connections perform better than series-parallel connections. Although the same number of cells are placed in parallel and series, the extra connections that can be seen in figures 4.5e and 4.5f, compared to figures 4.5c and 4.5b, improve the reliability considerably. Thirdly, using more cells, all of which are connected in parallel, is more reliable than when a larger single cell battery would be used, considering all p-values. However, in most cases p will be low, in which case all configurations perform better than the single cell alternative, apart from the all-series configuration. This also leads to the following conclusion: when it comes to reliability, replacing a battery or cell with more, though smaller, cells will increase the reliability of the battery-pack. This also means more protection and balancing circuitry will be required. However, it will increase flexibility, as more surface area will be used for interconnecting the cells.

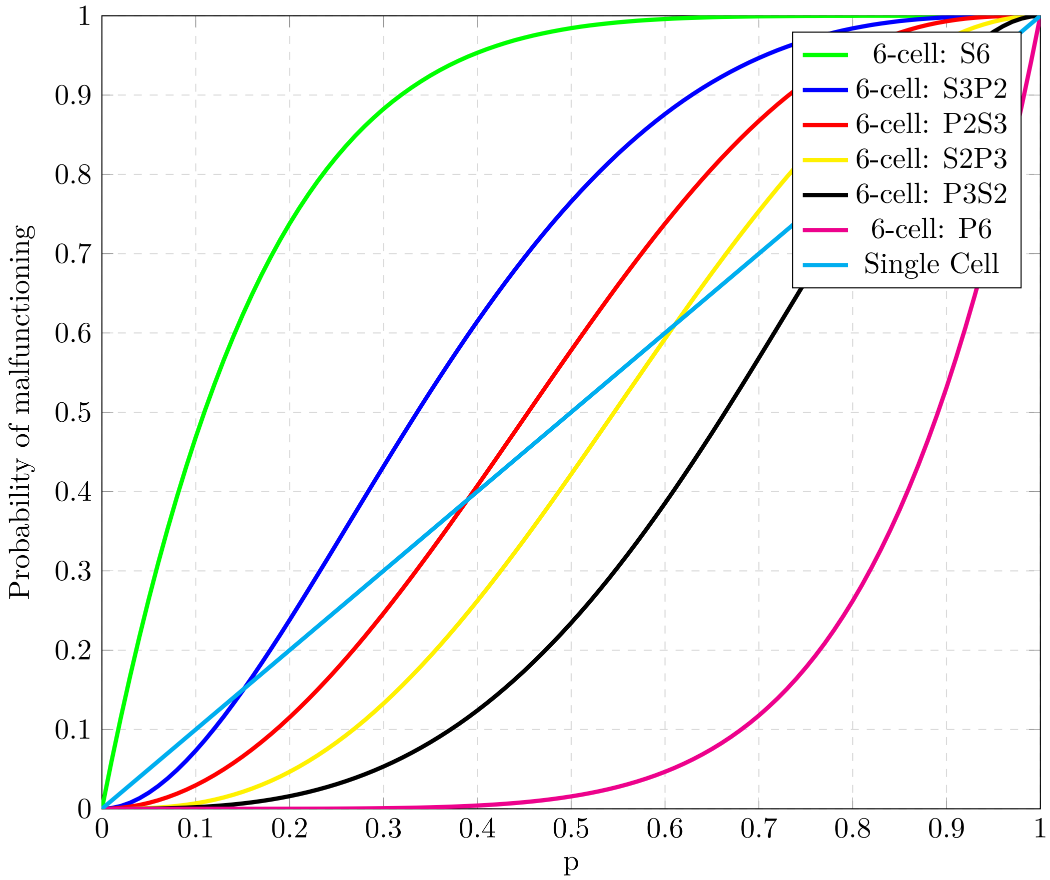


Figure 4.6: Probability of malfunction in a battery pack, as a function of p=probability of a malfunctioning cell, for 6 configurations of a 6-cell battery and for a single cell battery

It is of course wise to keep two things in mind. Firstly, an energy loss will occur when the voltage has to be boosted to a larger voltage to power a circuit. Secondly, depending on the configuration, a balancing circuit will have to be constructed. Not all balancing tchniques are available for all configurations. For example, most balancers balance two cells or more than four cells. Balancing circuits to balance three cells in series are rare.

4.4 Balancing supercaps

As supercapacitors are used as batteries, they also need balancing. Deterioration of the supercapacitors is not that much of a problem, except for when they are recharged very frequently. Some supercapacitors will need the balancing circuit as secondary protection, but balancing will also ensure that the complete energy-storage capacity is used.

To test the principle of balancing, three test-PCB's were made. The details on these circuits are given in table 4.1 and pictures are provided in figure 4.7.

Table 4.1: Details of the three test-PCBs for balancing

	Model + Brand	**Cap./cell**	**# Supercaps**	**Configuration**	**Total cap.**
PCB 1	DSK-614 of Elna	0.2 F	10	5P2S	0.5 F
PCB 2	HS130F of CapXX	2.4 F	2	2S	1.2 F
PCB 3	HS130F of CapXX	2.4 F	4	2P2S	2.4 F

After having charged these cells, it became clear that the balancing IC that was used, LTC3225 of Linear Technology, was not adequate. It only provided balanced charging, by dividing the input current between the cells in series, according to their respective voltages. This is a type of balancing not described above, as it is only advised to use this in supercapacitor-circuits.

Due to the limited energy-storage capabilities of these supercapacitors, charging is very fast and can happen within one minute. However, these supercapacitors showed a high level of self-discharge. This could be the result of the connection to the balanced charging circuit, even when the supercapacitors were not charging, which added a loss-mechanism.

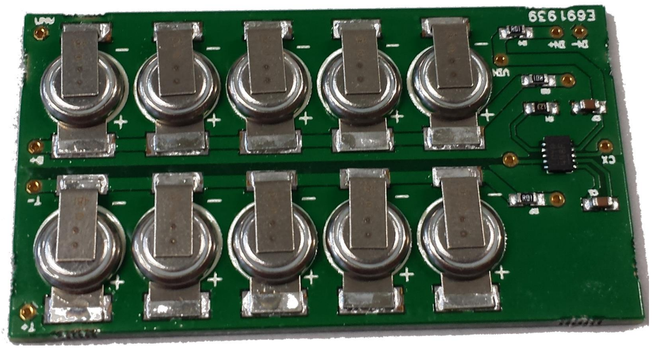
4.5 Conclusions

To conclude, the following main items should be kept in mind. Firstly, placing batteries in parallel will lead to automatic balancing. As long as the number of cells is not too large and the difference in voltages is not too large either, a small current can bleed between the cells, to keep the overall voltage across each cell equal.

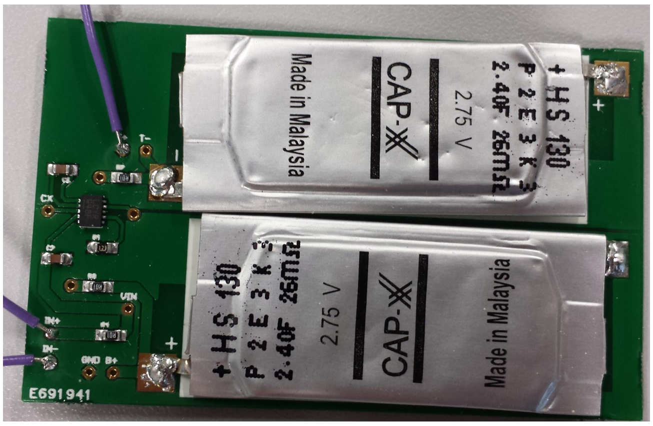
Secondly, placing cells in series poses more problems. Here, cell balancing is needed to assure each cell is charged and discharged equally. Imbalance would deteriorate some cells faster than others, lowering the lifetime of the entire battery-pack. Balancing can happen by using passive techniques, removing excess charge, or by active techniques, redistributing the charges. While active balancing maximizes the capacity of the battery-pack, it is both more complex and more space-consuming, making it less suited for portable applications. As long as only small imbalances occur, passive balancing is adequate.

Thirdly, when the number of cells is fixed, it is preferred to use parallel connections of cells over series connections. The total energy capacity remains the same, but this increases the reliability of the battery pack.

Finally, is best to always use batteries that are as similar as possible: the same type, model, capacity, age, voltage and charge. This ensures that all batteries will deteriorate equally, and they will therefore deteriorate the slowest.



(a) Test-PCB 1



(b) Test-PCB 2

(c) Test-PCB 3

Figure 4.7: Test-PCBs for balancing

Chapter 5

Design methodology

When a battery pack is designed, the battery has to be selected first. The next step is to add protection and balancing circuits. During this process, we need to take charging into account and factor in that everything should be integratable into textile. In this chapter, we review some example applications, to find out which configurations should be considered for a certain application. This leads to a decision tree, which will help a designer to quickly select the optimal configuration.

Firstly, we will look at some examples. For each application, a battery type and the amount of batteries that will be needed are selected. Here, only two batteries are considered. This is the small EFL700a39 of STMicroelectronics, which has a capacity of 700µAh, and the large PGEB014661 of General Electronics Battery, with a capacity of 200mAh. Since the capacity of a battery will decay over time and the actual capacity might therefore be lower than the specified capacity, an efficiency factor of 75% is applied [49]. The capacity (expressed in [mAh]) should also be converted into an energy capacity (expressed in [mWh]), since not all batteries have the same nominal voltage and we need to make a correct comparison. Moreover, not all circuits will have the same power supply voltage, so we need to compare power usage of the different example-applications. The efficiency of a possible DCDC-convertor is not taken into account in this first step. The need for such a convertor will depend on the configuration of the battery-pack.

This results in the following energy capacities:

$$\textbf{(A):}\ \text{PGEB014661: } 200\text{mAh}, 3.7V \rightarrow 555\text{mWh} \tag{5.1}$$

$$\textbf{(B):}\ \text{EFL700a39: } 700\mu\text{Ah}, 3.9V \rightarrow 2.05\text{mWh} \tag{5.2}$$

First, some examples demanding a high power are examined. This is the case when a LED-matrix is used (applications 1-3). Next, two circuits demanding less power are reviewed (applications 4-5).

5.1 Example applications

5.1.1 Application 1: LED-matrix CMST

This application consists of 12 parallel strings of 3 RGB LED's each (in series), and is a part of the SSC-project [1]. Each color of each LED consumes up to 5mA. This means that the maximum consumed power is 180mA $\times$ 12V = **2.16**W. We could, for example, power this circuit for about 1 h, by using **4(A)**.

5.1.2 Application 2: large LED-matrix

This large application contains 80 colums by 45 rows of RGB LED's, consuming 1mA/color /LED, is a part of ongoing research at CMST Ghent. This gives us a maximum power consumption of 43.2W. Even when using the large batteries, no less than 78(A) would be needed, which is not suitable for textile integration since the required surface area would simply be too large. However, in normal operation, these columns are scanned, so only one row of LED's is turned on at any given time. By scanning quickly enough, this is not visible to the naked eye and one would get the impression that all LED's are continuously emitting light. If such scanning is employed and only 1 out of the 80 columns is on at any given time, only **0.54**W of power is consumed. This means that just **1(A)** can power this matrix for 1 h.

5.1.3 Application 3: LED-driver for 16 LED's with communication

The maximum output current this driver [50] can deliver to the LED-matrix is 120mA. When data-communication is employed, the driver itself also consumes a maximum of 30mA. Assuming this circuit is working at the highest rated power supply voltage of 5.5V, we get a power consumption of **0.825**W. So, **1(A)** can power this driver for about 40 min.

When the power supply voltage is below 3.6V, the maximum output current drops to 60mA. In this case, **1(A)** can provide power for 103 min, and **10(B)** would be able to last for about 4 min.

5.1.4 Application 4: Accelerometer

An accelerometer is a good example of a simple sensor-circuit, consuming only a limited amount of power. Here, the ADXL343 is used as the basis of the calculation [51]. This accelerometer uses 30 to 150µA when on and 0.1µA when off. Considering one measurement is done per second, we get an average current of 1.6µA. At a voltage of 2.5V, we get a power consumption of **4**µW. Using **1(A)**, it can last about 15 years and **1(B)** would last 21 days.

[1] Self Sensing Composites project (SSC), funded by the Flemish Agency for Innovation by Science and Technology (IWT) – through the program for Strategic Basic Research (SBO) under grant agreement nr 120024

5.1.5 Application 5: Sensor tag

This sensor tag (model CC2541 of Texas Instruments [52]) is a small development kit, containing a PCB with a Bluetooth chip, along with a DCDCconvertor, different connectors and most types of sensors. It contains a humidity sensor, an accelerometer, a gyroscope, a digital barometric sensor, a magnetometer and an infrared temperature sensor. Taking one measurement per second, as well as communicating this data to another Bluetooth device, a power of about **50**mW is consumed, which means **1(A)** lasts about 10h and **10(B)** about 24min.

5.2 Design guide

After examining several applications, the following step-by-step design guide, illustrated in the following figures and tables, reviews each step. This guide will allow a designer to quickly design a battery-pack for textile integration, suited for his/her application.

Step 1. Calculate the required energy for the application

Before a battery can be selected, it is necessary to know what the requirements of the applications are. As voltages and current can be converted if needed, the most important parameter is the required energy (note that is not the same as the required power!). A convertor is often needed anyway: battery-voltage is dependent on its charge and most circuits need a stable, fixed, supply voltage. The battery does not only need to be able to power the circuit by supplying enough current and voltage, it also has to last long enough. Some application have to be powered for only a few minutes or hours, others have to last days or even months. Start with the average current consumption. Take into account the different power modes of the IC's, the time required for communication and the rate at which sensors need to perform measurements. (See figure 5.1)

Step 2. Determine the energy category

Based on the example applications described above, one of four categories of energy consumption are distinguished. (See figure 5.1)

Step 3. Select the battery size category

Depending on the energy category and required flexibility, a battery category and the amount of cells can be selected (see table 5.1). Table 5.2 then gives the average values of the specifications for all three categories of batteries. Once a size is chosen, a specific battery can be selected. To find the exact number of cells that are needed, use following formula:

$$\#cells = \frac{\text{Required energy capacity}}{\text{Battery's energy capacity}} \tag{5.3}$$

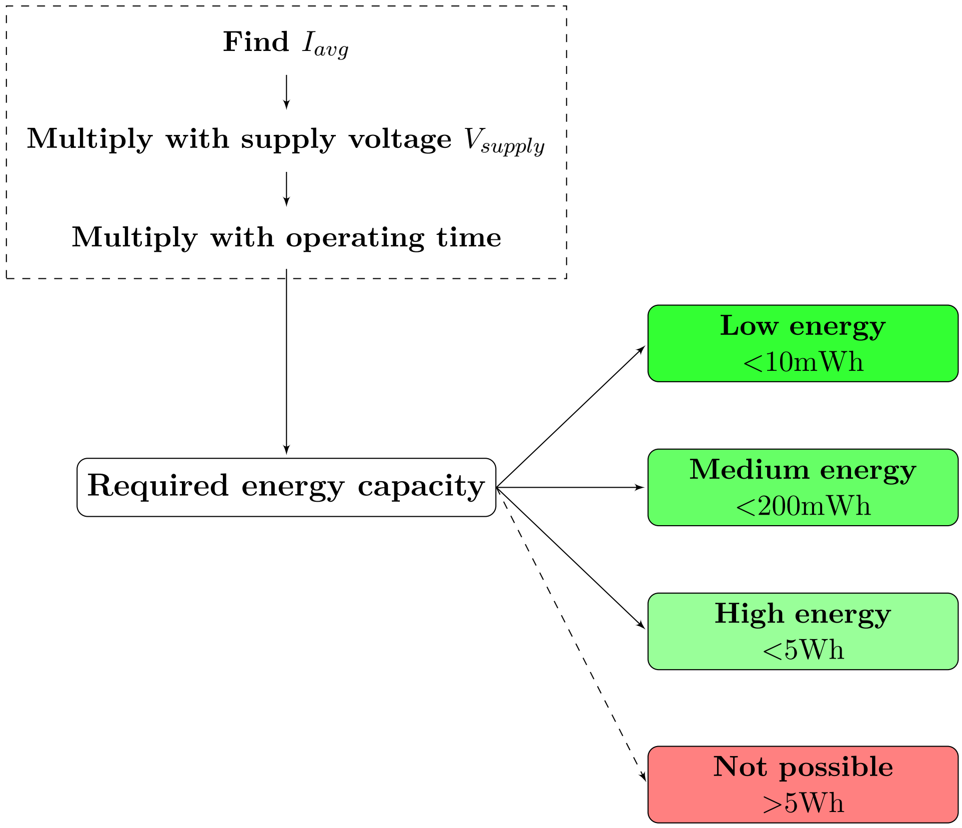


Figure 5.1: Calculating the required energy (step 1, dotted) and determining energy category (step 2)

Table 5.1: Selecting the battery size category (step 3)

	Limited flexibility	**Large flexibility**
Low energy	one M	several S
Medium energy	one L or several M	many S
High energy	several L	many M

* 'Several' is about 4 and 'Many' is in the order of 10

Table 5.2: Battery category specifications (step 3)

	Size	**Capacity**	**Energy capacity**	$\mathbf{E_{grav}}$ [Wh/kg]	$\mathbf{E_{vol}}$ [Wh/L]	$\mathbf{E_{surf}}$ [mW/h]
S	5×5 cm^2	10-200 mAh	30-800 mWh	100	200	200
M	2.5×2.5 cm^2	5 mAh	4 mWh	5	20	80
L	0.5×0.5 cm^2	100 µAh	200 µWh	-	2	2

Step 4. Determine the cell-configuration

Depending on the number of cells, a configuration needs to be selected. Take into account that if a series connection is used, balancing will be necessary. Also, if possible, use a number of cells in series that offers a voltage close to the required supply voltage, as this will offer a better convertor efficiency. A practical limit on the number of cells in parallel is about 5-10. Keep in mind that each series string and each parallel connection has to contain the same number of cells.

Step 5. Check the maximum current rating

We need to make sure the battery pack will be able to handle the maximum current peaks the circuit will draw. Especially when the operating time is short, this might not be the case. Look in the datasheet for the maximum discharge current (and convert from C-rate to current if needed) and multiply with the number of cells in parallel to get the maximum discharge current of the pack. Remember that if a convertor will be used, this conversion of current should be kept in mind. If the maximum peak current of the application circuit is higher than the maximum discharge current of the pack, the configuration should change to have more cells in parallel. This can be achieved by reducing the number of cells in series (and keeping the same number of cells) or by increasing the total number of cells. In some cases, it might even be necessary to select a different model of battery.

Chapter 6

Charge Circuit

As this thesis focusses on a battery pack and not on the development of a charger, only the key take-aways of charging are discussed. Supercapacitors are charged using the same method as Li-ion batteries, so this chapter will focus on the latter.

6.1 Constant-current constant-voltage (CCCV)

Lithium batteries are charged using the CCCV (constant-current, constant-voltage) method, as illustrated in figure 6.1. The first phase (called fast charge) uses a constant current to raise the voltage of the battery to the maximum specified voltage, which is 4.2V most of the time. This current is specified by the charger and is often regulated by a low-ohmic resistor. In this phase, most of the charge is transferred. Then, the second phase starts (called taper charge or one of its many synonyms), in which the voltage is kept constant and the current will drop. When the battery reaches a certain termination current (expressed in absolute or relative value) charging stops.

A battery can be depleted by discharging, self-discharging or both and its voltage might be below the advised voltage to start charging. To avoid damaging the battery by rushing in the large current that is used during the fast charge phase, a preconditioning phase is entered before fast charging if needed. This is also a constant current phase, but one where the current is lower. If the battery voltage is really low, an even lower constant current phase can be added before the preconditioning phase, which is always linear.

Three types of chargers exist, each of which uses the CCCV method, but in a different way. Switch-mode chargers require more space and are more complex, but the power dissipation is limited, yielding a higher efficiency. Linear chargers however, are far simpler and more popular for space-limited portable applications, but have a larger power dissipation. Pulse chargers use a transistor as a switch, which is turned on during the CC phase. This same transistor is pulsed on and off during the CV phase. They consume as little space as linear

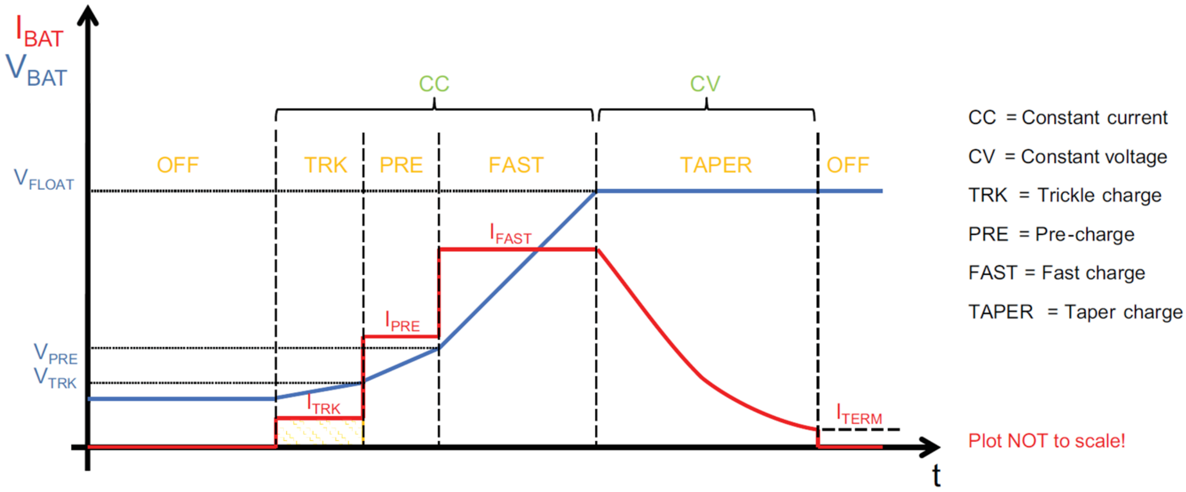


Figure 6.1: Charge cycle of a Li-ion battery [53]. Note that the actual voltage will rise log-like instead of linear during CC phase.

chargers, but have a lower power dissipation. They require a current-limited input source and just like a switch-mode charger, they introduce switching noise, which needs to be filtered out [54].

Note that the power dissipation in a linear charger is the largest at the beginning of the constant-current phase. A large current is used, while the voltage difference between the input source of the charge circuit and the battery voltage is also large. If an input source with a current limiter is used, this dissipation can be reduced. By setting the current limit of the source below the charging current, the source will lower its voltage to just above the battery voltage. The voltage difference is now minimal and the power dissipation is greatly reduced. This technique is called quasi-pulse charging and uses the advantage of pulse charging, but by using a linear charger [55].

6.2 Charging: when and how

Rechargeable batteries can be recharged when depleted or when there is still charge left. In most chemistries of rechargeable batteries, other than lithium, this plays a large role, as recharging a battery which still contains charge will deteriorate the battery. Luckily, lithium batteries can handle this. As long as deep discharging is avoided, the difference between a full charge and several partial charges is minimal.

To charge safely, the batteries should be warmed up to room temperature before charging. It is best to charge slowly, meaning at a low current. A maximal current rate of 0.5 to 1C is adequate. Charging slowly also assures that the battery is fully charged at the end, as fast charging might stop the charging too soon.

Chapter 7

Stretchable Circuits

For wearable applications, a rigid PCB (printed circuit board) is not suitable. A flexible variant has to be used. While in regular rigid PCB's, the rigid FR4 is used, a flexible circuit board uses a flexible substrate. This allows the circuit to be bend either once (bendable or formed flex) or continiously (dynamic flex). Apart from formed flex and dynamic flex, a third type of flexible circuits exists: stretchable circuits. For wearable applications, this stretchability is an absolute necessity.

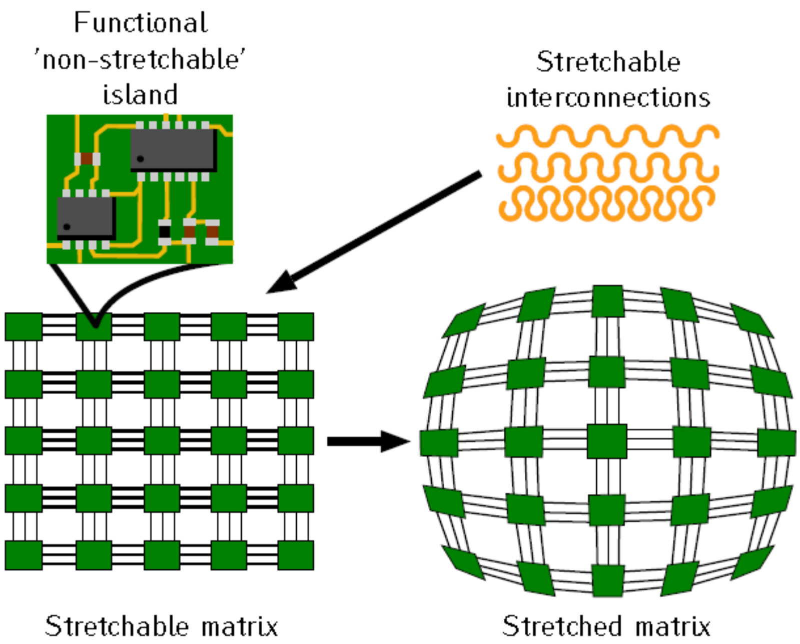


Figure 7.1: SMI-technology [56]

7.1 Stretchable Mouled Interconnect technology

To reach this stretchability, while at the same time allowing the use of off-the-shelf components in the fabricated circuits, the circuits consist of stiff islands and stretchable interconnects. This technology is called Stretchable Molded Interconnect (SMI) technology, as depicted in figure 7.1. The stiff islands contain the components, along with most of the routing. They are interconnected with stretchable structures.

7.1.1 Rigid islands

The rigid islands consist of interconnected copper pads, similar to that on a PCB, supported by polyimide. This polyimide provides more rigidity to assure that almost all strain, when stretching is applied, is provided by the interconnects. On these copper pads, the components can be soldered using standard soldering techniques. This allows the use of off-the-shelf components in the design. If the flexible substrate is still too flexible, a FR4-stiffener can be added for additional support. Creating small islands leads to a higher level of flexibility.

7.1.2 Stretchable interconnects

Different materials can be used to produce interconnects. The three best options are conductive polymers, nanotechnology-based materials and metallic conductors [57]. The first option does not provide the same conductivity as metallic conductors. The second option does have a larger conductivity, but is at the moment very expensive. Metallic conductors offer the highest conductivity and the lowest cost, but are intrinsically not stretchable. However, this can be solved by correctly shaping the interconnects. This also keeps the conductivity constant [58].

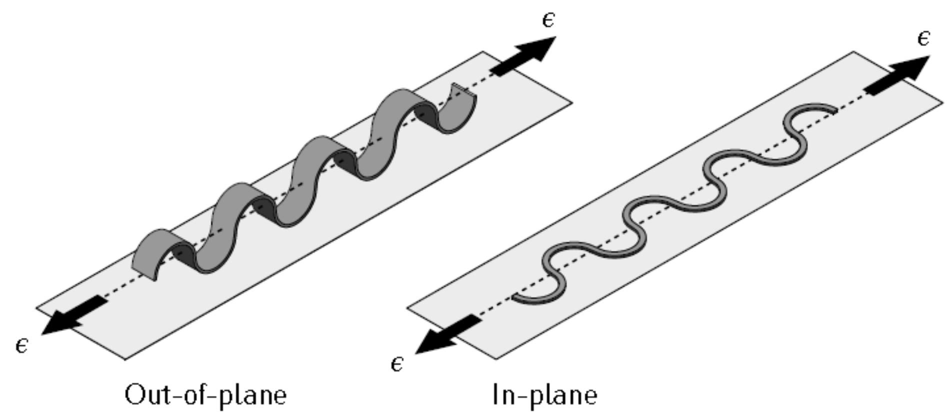


Figure 7.2: Out-of-plane and in-plane design of stretchable interconnects [56]

There are two options to provide stretchability in metallic conductors [59]. A first one is to have an out-of-plane stretchability, as shown in figure 7.3. In this process, the interconnects are placed on a temporary wafer. A stretched elastic is applied, which bonds with the conducting interconnects. Both are peeled off the temporary carrier and the interconnects form waves, due to the release of tension that was in the elastic. Similar techniques in which the conductor is placed directly on an already stretched substrate, after which the tension is released, also exist [60]. The disadvantage of these techniques in the case of more complex interconnection-structures is obvious: in both cases, the stresses that are introduced when removing the tension in the stretchable substrate are also applied to the rigid islands.

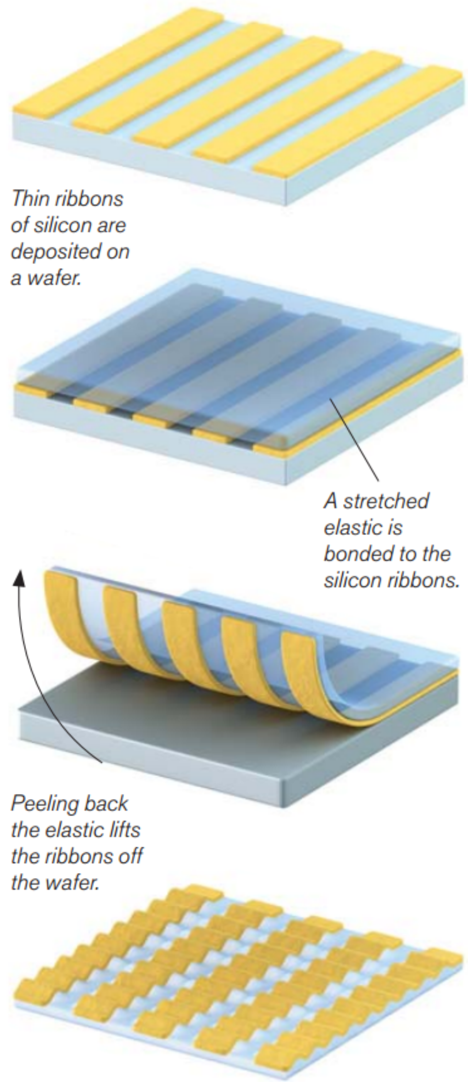


Figure 7.3: Out-of-plane stretchable interconnects [61]

A second possibility is to have in-plane meanders (see figure 7.2). This is much easier to produce than out-of-plane solutions. Both the rigid islands and the interconnects can be made together, without introducing stresses to the islands in quiescent state. A second advantage is that these interconnections are produced in the same way as the tracks on the rigid islands, thus reducing cost. These meanders can either have a horseshoe shape or zigzag shape [62].

Zigzag meanders allow very fine pitch interconnects, but the stresses focus on the sharp edges. Using a Finite Element Method (FEM), researchers at CMST have shown that the optimal shape for stress distribution was a horseshoe shape [63].

These horseshoe-shapes have only 3 parameters: the width (w) of the meanders, the radius (r) and the angle (α). The ratio r/w is important, as it is one of the determinants of the reliability. Selecting this ratio at about 10 allows for a good reliability and offers the best reliability if a simple transition (without tapering) is used. The highest reliability can be achieved when the meanders are aligned in the direction they are stretched in and the starting angle of the meanders at the rigid islands in 90°. [64, 65].

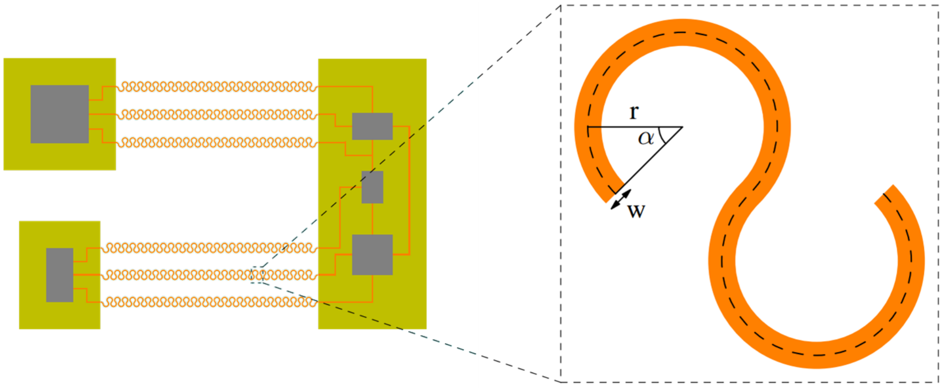
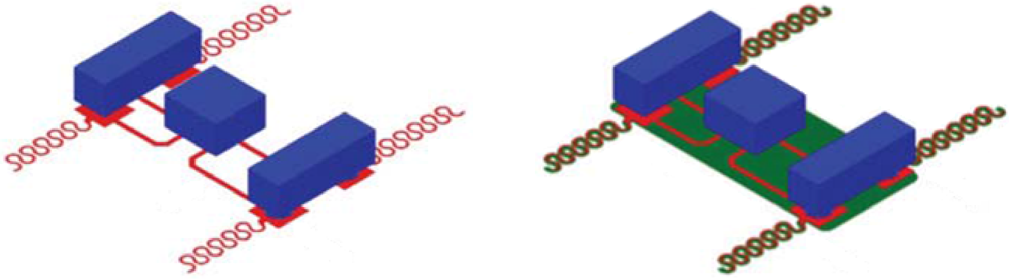


Figure 7.4: Meander parameters in horseshoe-shaped in-plane stretchable interconnects [66]

To strengthen the interconnects, they are also supported by polyimide. This increases the reliability, as it forms an intermediate layer between the rigid copper and the flexible PDMS in which it will be encapsulated. The main failure mechanisms are accumulation of plastic strain in the copper interconnects and delamination of the interconnects.



(a) Without polyimide support **(b)** With polyimide support

Figure 7.5: Stretchable electronics, without (a) and with (b) polyimide support [59]

7.2 Production Steps

To produce a circuit using SMI technology, three phases are used:

1. Production of the circuit
2. Encapsulation to create a stretchable module
3. Integration into textile

During the first phase, the circuit was designed on a flexible circuit board (FCB) that is attached to a rigid carrier using adhesive (see figure 7.6). This FCB consists of 50 µm flexible polyimide and 18 µm copper. In case a thermoset encapsulation is used, this adhesive is a wax, as it is resistant to the production steps. However, in the case of a thermoplastic encapsulation, a tape is used, as wax limits the molding temperature. The copper is etched and the polyimide is patterned using laser-ablation. Optionally, a solder mask can be applied. Finally, all the components are placed and soldered.

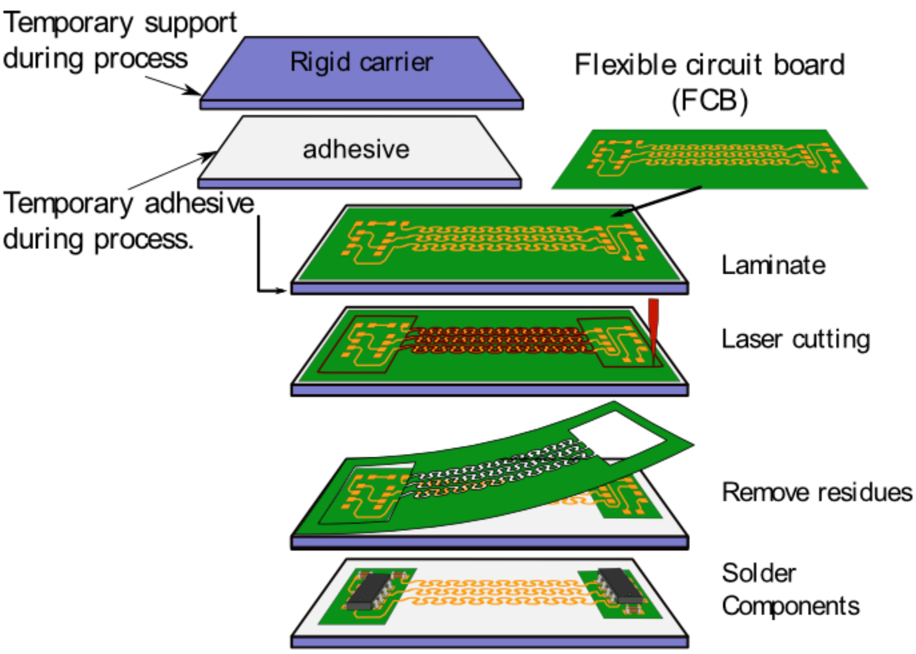


Figure 7.6: SMI, phase 1: Production of the circuit [56]

In the second phase, the circuit is encapsulated. This can be done either by injection molding with a thermoset polymer like PDMS (see figure 7.7) or by lamination with a thermoplastic polymer (see figure 7.8).

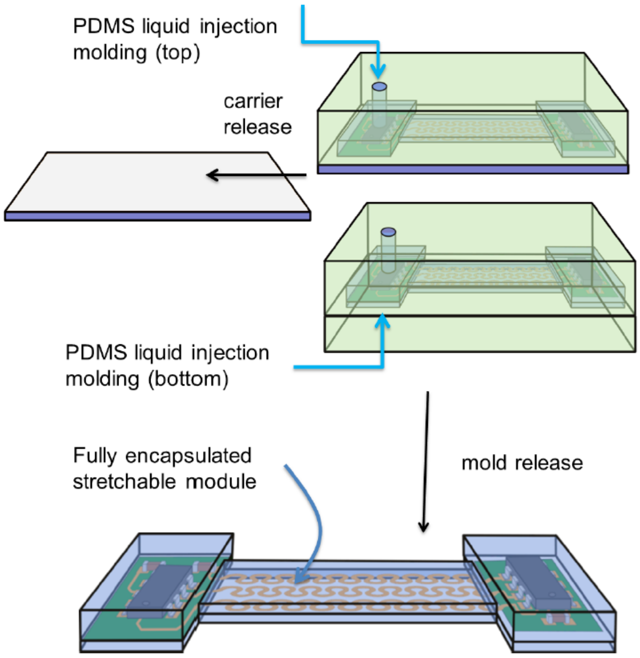


Figure 7.7: SMI, phase 2: Encapsulation in the case of PDMS [67]

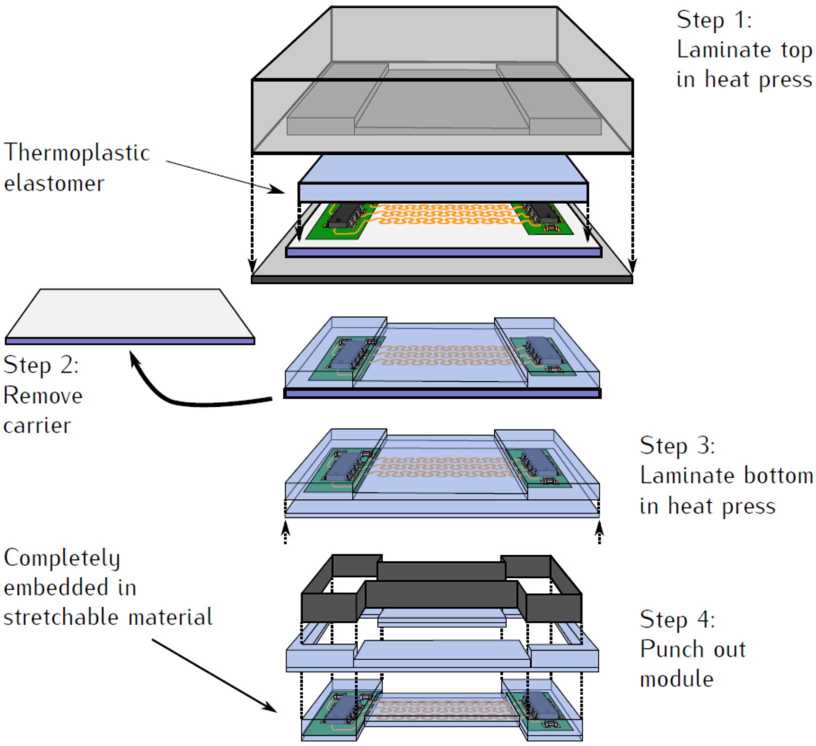
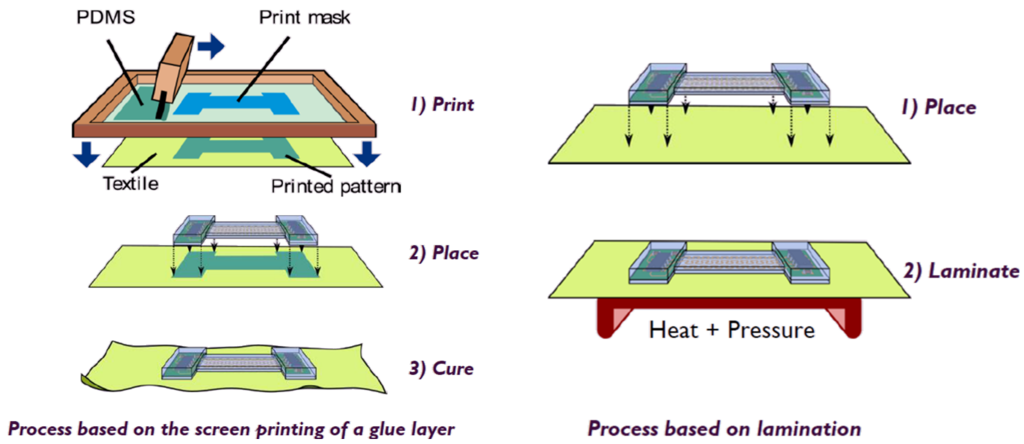


Figure 7.8: SMI, phase 2: Encapsulation in the case of thermoplast [56]

The third phase consists of curing or laminating the stretchable module onto textile, depending on the encapsulation material (see figure 7.9).



(a) Encapsulation PDMS **(b)** Encapsulation of thermoplastics

Figure 7.9: SMI, phase 3: Attaching to textile [1]

7.3 Lamination

All the production steps are suited for off-the-shelf components. Soldering can happen manually or in the reflow-oven. However, a test run is advisable so as to make sure that the battery can handle the lamination process, as the used temperatures are quite high. This test is done with the battery PGEB014661. The datasheet indicates that this battery can survive temperatures of up to 150°C, but does not specify if the battery will also work after this. Two batteries of this model, one fully charged and one half charged, are laminated with Krystalflex429, a type of poly-urethane (PU) with an approximate thickness of 600µm. Usually, lamination is performed between 2 presses, but given the small area of these batteries and the minimum pressure of the lamination equipment, no pressure is used. This means that heat is only applied from the bottom and heat is distributed slowlier, as air is present between all the layers. The layer-stack is built up as shown in figure 7.10.

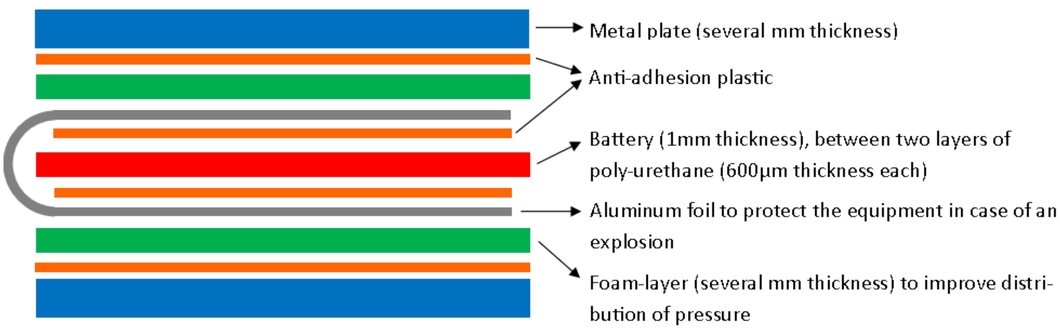
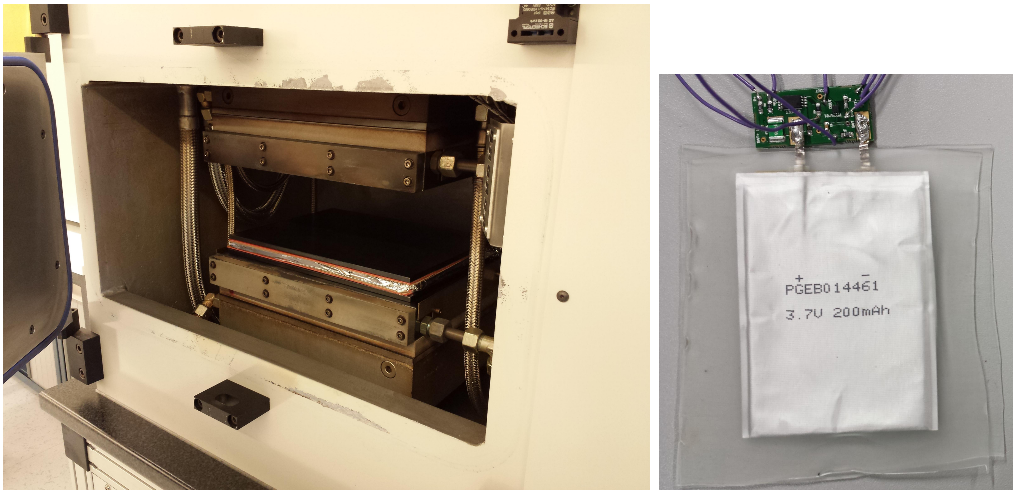


Figure 7.10: Layer stack of the lamination process



(a) Lamination process **(b)** Laminated battery attached to protection circuit

Figure 7.11: Testing of the lamination process on the battery

The batteries are laminated twice. The first lamination consist of heating for 4 minutes from 50°C to 90°C, keeping the heat at 90°C for 2 minutes and then cooling for 4 minutes to 50°C. As the PU showed too little adhesion, a second lamination was performed. This time, the process consisted of 6 minutes heating, 4 mintues holding and 6 minutes cooling, but now to a temperature of 110°C. The voltage and thickness before and after lamination is measured, see table 7.1. The thickness of the PU after lamination was 560 µm for a single layer and 1160 µm for a double layer.

Table 7.1: Lamination Test

	Fully charged battery	**Half-charged battery**
Before lamination		
Voltage [V] ± 1mV	4.152	3.763
Thickness [µm] ± 5 µm	940 - 960	975 - 1200
After lamination		
Voltage [V] ± 1mV	4.149	3.764
Thickness [µm] ± 5 µm	2130 - 2225	2140 - 2270

The table shows that the voltage, and hence the charge, on the battery hardly changed. Not one thickness, but a range of thicknesses is measured, indicating that the pouch-shaped battery did not have an even thickness. As no pressure was used, the electrolyte which caused this uneven distribution was not redistributed during lamination.

7.4 Component selection

On the flexible substrate used in the demonstrator, no soldermask is applied. This means that all copper on a flex substrate is exposed. This poses some practical restrictions, which is less of an issue when working with regular PCB's. Firstly, the solder that is applied can disperse more easily from the solder pad. Secondly, the tracks are not covered, so it is easier to introduce a short when soldering. This is a valid argument for opting for large components. However, in order to allow a flexible substrate to actually be flexible and stretchable, we need to make sure the rigid islands remain as small and as thin as possible. Selecting smaller components and increasing the component density makes the rigid islands smaller and lengthens the size of the stretchable meanders. It is therefore important to keep the components as small as possible, while making sure the clearances are still large enough to avoid shortcircuiting or problems during assembly.

7.5 Routing on one-layer substrates

Because flexible circuits are often one-layer circuits, so as to simplify production, as is the case for production in the UGent cleanroom, some considerations need to be kept in mind. To avoid short-circuits, tracks (which might be a part of a power plane) underneath components are to be kept to to a minimum.

When two traces (one of which can be a part of a power plane) have to cross each other, and this can not changed by routing differently, jumpers have to be used. These are 0Ω resistors that come in the same packages. One of the traces is attached to both ends of the jumper, the other runs underneath the jumper. When the trace running underneath the jumper is a high-current trace, a larger package is used to make sure the width can be wide enough, this without ignoring the necessary clearances.

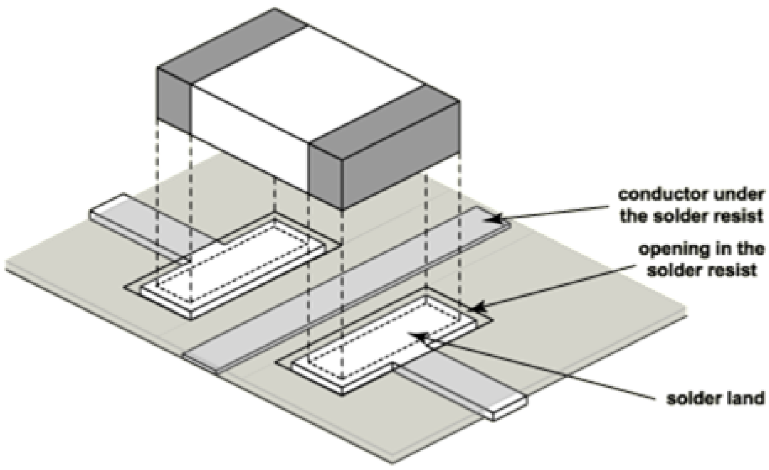


Figure 7.12: Using a jumper to allow crossing of tracks in a one-layer circuit

Chapter 8

Demonstrator

After having reviewed all the components a battery pack for textile applications can consist of, a demonstrator is made. Many applications are possible, but a single case is chosen to demonstrate the considerations that are relevant for such a battery pack. The chosen application is the high-power ledmatrix from CMST (see section 5.1.1).

Consisting of 12 strings of 3 RGB-LEDs ($\frac{5mA}{\text{color}\times\text{LED}}$), the total power consumption is:

$$I_{max} = \frac{5mA}{\text{color} \times \text{string}} \times 3 \text{ colors} \times 12 \text{ strings} = 180mA$$

$$V_{supply} = \frac{4V}{\text{LED in series}} \times \frac{3 \text{ LEDs in series}}{\text{string}} = 12V$$

$$P_{max} = I_{max} \times V_{supply} = 2.16W$$

Firstly, we need to calculate how much cells will be required. Since the supply voltage is 12V, a single cell battery pack offers only 4.2V and a dual cell battery pack offers only 8.4V, a DCDC stepup-convertor is needed in the drive circuit for the LED's. The efficiency of this convertor is assumed to be 90% and the effective capacity of the batteries is assumed to be 75% of the specified capacity, as was done in chapter 5. When the efficiency of components in the charge circuit is lower than 100%, more power is consumed from the charge source (USB, wall-adapter or other DC source). However, this does not change the amount of time the battery pack will be able to power this LED matrix. For this reason, these efficiencies are not taken into account.

Two cases are considered: the case where all colors are used simultaneous (on all LEDs) and the case where a single color shines (on all LEDs). It is further assumed that all LEDs are powered constantly. This means no PWM signal is used and maximum power usage occurs. The total power consumption can be reduced greatly by using PWM. For example, switching between the 12 strings, so only one string is turned on at any given moment, would decrease the power consumption (thus increasing operating time) by a factor of 12. When this is done quickly enough, the switching is not visible and it is still perceived as a matrix where all LEDs are on all the time.

To create our battery-pack, we go over the design steps discussed in section 5.2. The required power is 2.16W. Powering this circuit for 2h, this yields a required energy capacity of 4.32Wh. This puts us in the high energy category. Limiting the number of cells by sacrificing some stretchability, several large batteries are required. Each PGEB014461 battery has a capacity of 555mWh, so 8 cells are required, which are placed in a 4P2S configuration. Given the discharge current-rating of 2C, the maximum current output is 1.6A, which is more than enough to power this circuit with a maximum consumption of 180mA. By placing 2 cells in series, balancing can be demonstrated.

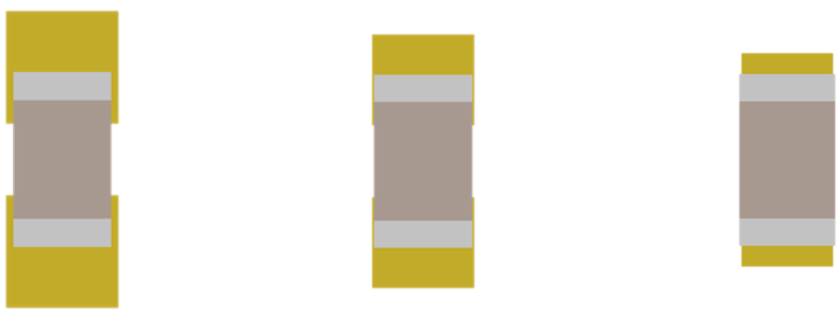
In table 8.1, the time that the demonstrator can power the LED-matrix is shown. Using 8 batteries, the battery pack can provide power for quite some time, even in the case all colors are used.

Table 8.1: Amount of time that the demonstrator can power the LED-matrix

	1 Battery	**4 Batteries**	**8 Batteries**
All colors (white)	13.9min	55.5min	1h 51min
One color	41.6min	2h 46.5min	5h 33min

8.1 Flexible circuit

In the demonstrator, components of the package 0603 [1608] are used. Smaller components are not used (except for one low-power led), since it would increase the chances of shorting the pads/tracks when soldering. Pads for SMD-components can be L (least environment), N (nominal environment) and M (most environment). Since space-reduction is important, one could opt for L-pads, but as no soldermask is used on this flex, N-pads are used.



(a) SMD M **(b)** SMD N **(c)** SMD L

Figure 8.1: SMD footprint sizes [68]

8.1.1 Design Rules

In tables 8.2 and 8.3, the track sizes and clearances that are used are given. For high-current traces, a wide connection is used to reduce the resistance and hence the voltage drop caused by that trace. Shorter connections have a smaller width to allow easier routing. This is needed, since we work with a one-layer substrate, which means that crossing connections need jumpers (see section 7.5) and we want to keep the amount of jumpers as low as possible. This is better for the reliability (less chance of accidental shorts caused by soldering and less components that can detach from the substrate), reduces the total required surface and reduces the total cost. Traces (often a part of a power plane) running underneath components (in between the solderpads), are even smaller. This is done to keep them far enough away from the solderpads, to reduce chances of causing a short when soldering. Using a smaller width is allowed since these traces are always very short. The connections to the battery are somewhere in between. They have to be large enough to reduce their parasitic resistance and small enough so as not to conduct too much heat to the power plane when soldering.

Table 8.2: Design rules: Track sizes

Parameter	**High/Low I**	**Value** [mm]
Tracks (battery connection)	High	0.8
Tracks (passing under components)	High	0.35
Tracks (other, short)	High	0.6
Tracks (other, long)	High	1.2
Tracks (passing under components)	Low	0.25
Tracks (to power planes)	Low	0.3
Tracks (other)	Low	0.2
Meanders	High	0.35

Table 8.3: Design rules: clearances

Parameter	**Value** [mm]
Clearance (power plane - power plane)	0.2
Clearance (power plane - track)	0.25
Clearance (power plane - solder pads)	0.25
Clearance (track - track)	0.15
Clearance (track - solder pads)	0.25
Clearance (solder pad - solder pad)	0.25

The maximum current the battery-pack can handle is 0.8A in charge mode and 1.6A in discharge mode. It was not possible to design the meanders to be able to handle this current. This would lead to meanders with a width of 1.2mm, and a radius of about 1.2cm, which is too large for stretchable applications. A USB port, which will be used for charging, can only handle 0.5A, so this entire pack is designed to that specification. The width of meanders should then be larger than 230µm for a 10° temperature rise. This can be calculated by using equation 8.1, based on the IPC-2221 specification. To decrease the voltage drop across the meanders, this width is slightly increased to 350µm. This already causes a resistance of 42.6 mΩ, or a maximum voltage-drop of 21.3mV, across the meanders between neighbouring cells.

$$W_{min} = 645.16 \times \frac{\sqrt[0.725]{\frac{0.5A}{0.048 \times (10°C)^{0.44}}}}{17\mu m \text{ thickness}} = 0.23\mu m \tag{8.1}$$

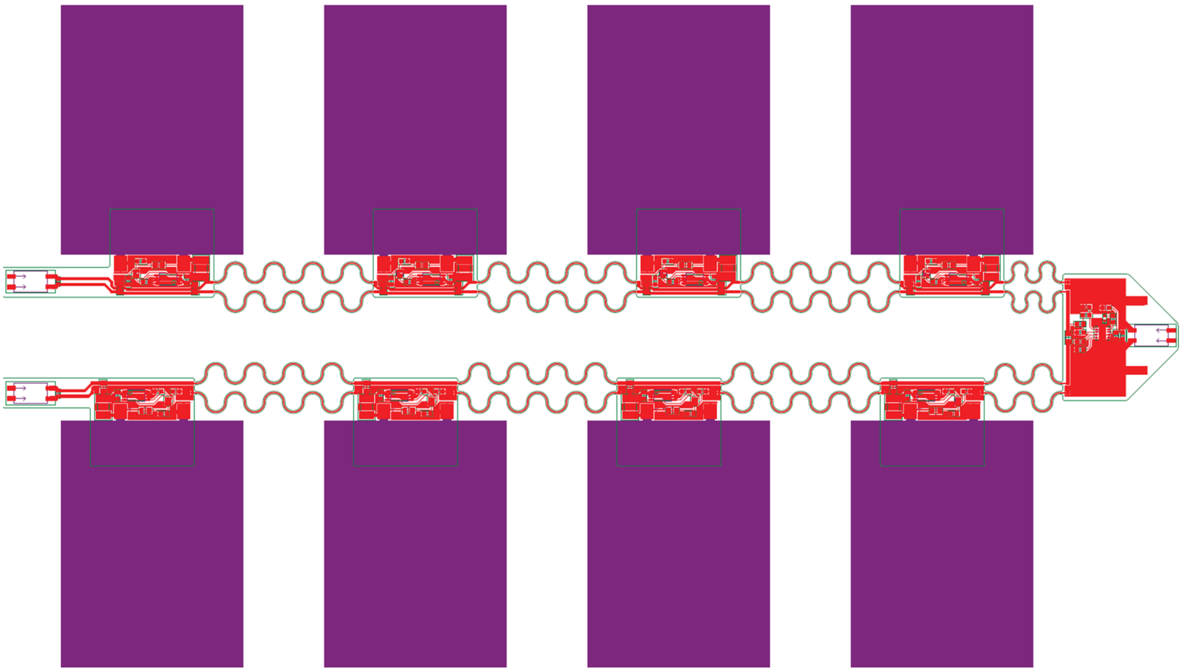
8.1.2 Battery-matrix

The battery-pack matrix consists of 2 strings of 4 batteries in parallel. Each battery has a seperate protection circuit. A balancing circuit is placed on the flexible demonstrator to provide continuous balancing.

In figure 8.2, the design of the battery-pack matrix is shown. In purple, the batteries are shown, each one connected to its protection circuit (copper tracks and ground-planes are shown in red). On the right-hand side, each row (=parallel connection) is connected to the balancing circuit. Plugging in the connector on that side allows the use of all the cells (dual cell). If the connectors on the left-hand side are used, the top and bottom row can be used seperately, each forming a single cell. In green, the outline of the supporting polyimide is shown. This partially runs under the batteries, so as not to introduce a weak spot at the edge of the battery.

The protection circuit is the same one as was used in the first test circuit. However, some changes are needed to make sure we can produce this circuit on flex. This means that it has to be adapted to a one-layer circuit. Reducing the contact pads of the battery provides more freedom for placing and routing all components. Smaller traces and clearances also offer more freedom. In tables 8.2 and 8.3, the design rules that are used are given. Using these smaller track sizes and clearances, it was possible to produce a one-layer protection circuit, without the use of jumpers.

To connect all the protection circuits, which are placed in parallel, symmetric connection pads are used, which makes it easier to add the meanders. One connection (C-) can be attached to one of the power planes. The other connection also runs across the length of the protection circuit. For this reason, a jumper is needed. The protection circuits at the TOP need two jumpers. These jumpers are of the 0805 [2012] package, to allow a trace running underneath the jumper that is wide enough.



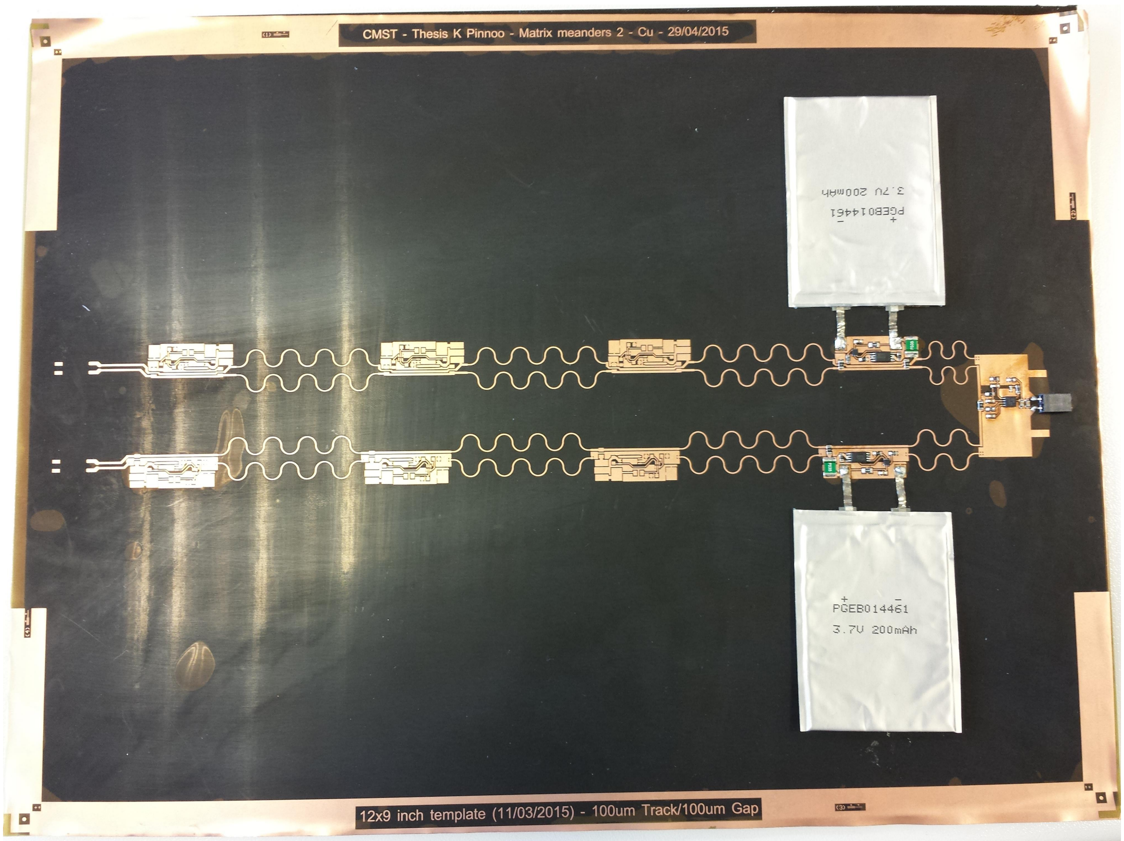


Figure 8.2: Demonstrator: battery-pack matrix, board design (top) and picture (bottom)

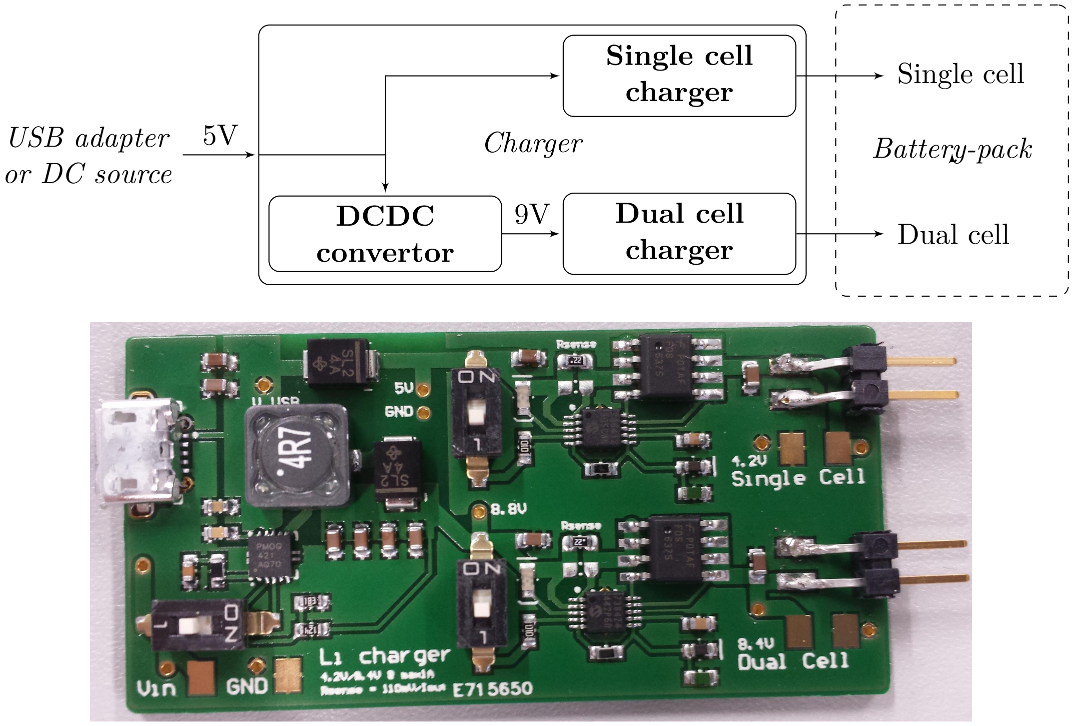


Figure 8.3: Demonstrator: charge circuit, diagram (top) and picture (bottom)

The balancing circuit consists of the BQ29209 of Texas Instruments [69], which provides continuous passive balancing. A small very-low-power LED indicates fault conditions.

8.1.3 Meander interconnects

Given the large width of the meanders, there is not much freedom for selecting the radius, as a compromise between total area and stretchability fixes the space between the batteries. By selecting a radius of 2.375mm, which yields a ratio r/w of 6.8, all the protection circuits are interconnected. The radius of the meander connecting the bottom cells with the balancing circuit is slightly smaller: 2.275mm. At the top cells, this connection was not possible using a 0° horseshoe-meander. In order to achieve more than 1 meander a radius of 1.8mm, a width of 300µm and an angle of 22° are used. This lower width is allowed due to the short distance.

8.1.4 Decoupling

At the input of the demonstrator, a decoupling capacitor is placed. This will form an open circuit for DC and a short for AC signals. The capacitors are placed between the 2 power connections and will make sure no AC signal travels to the rest of the circuit. For this reason, they are placed as close as possible to the outside connections of the demonstrator. This is needed because power circuits, or in this case the charge circuit, often introduce noise. It also reduces ripples on the power supply voltage that the charger might cause. This can

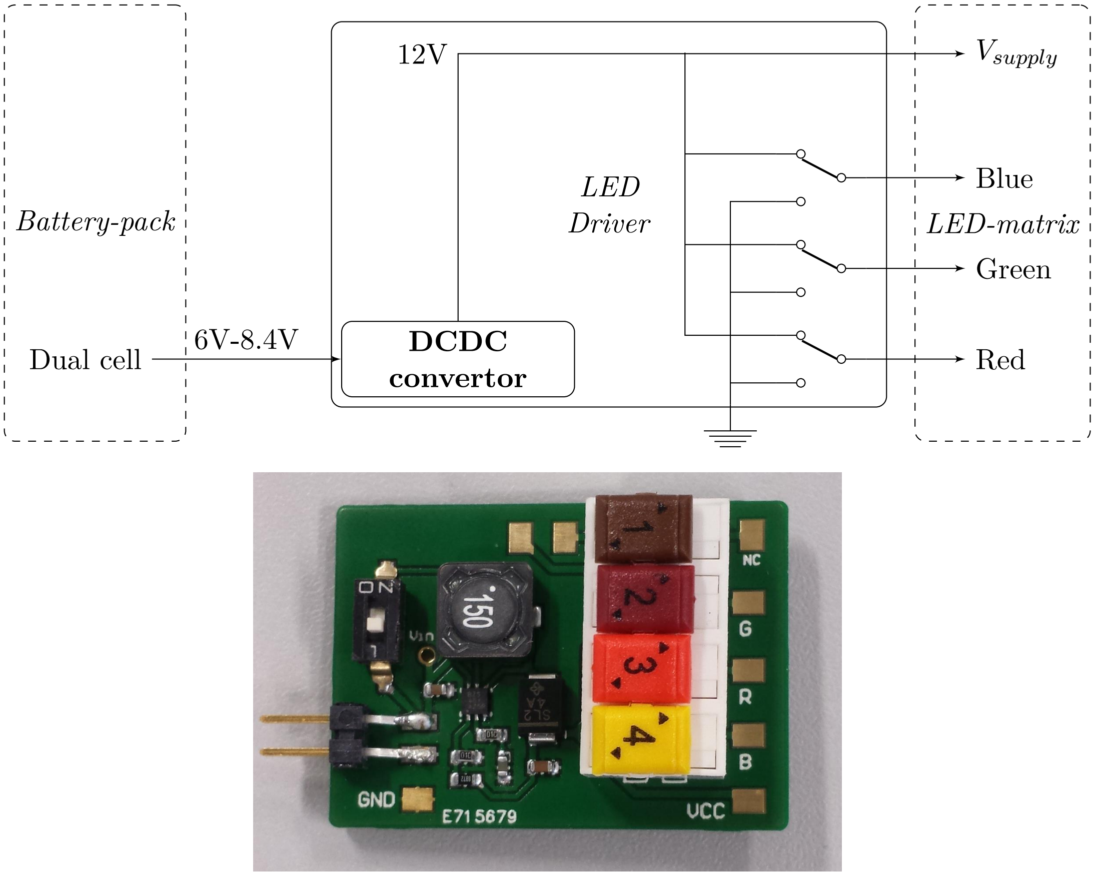


Figure 8.4: Demonstrator: LED-driver circuit, diagram (top) and picture (bottom)

happen when the current consumption changes abruptly (in case of changing power modes of the attached IC's for example) and the power supply can not adapt quickly enough. This capacitor will also reduce the effect of ESD on the circuit. Decoupling capacitors are also used at the power supply connection of integrated circuits. It bypasses high frequency noise to the ground plane, which also explains its synonym: bypass capacitor. At the IC of the protection circuit, this is also done, but in the form of a RC filter. Since it sees the battery it is attached to as its 'power supply', the battery itself will also help smoothing out any ripples.

8.2 Charger and LED-driver

Next to the flexible battery-pack, a charge circuit is made to be able to charge the matrix from a USB port or any other DC source with a voltage of about 5V. It consists of a charger for single cell (one cell in series) and a charger for dual cell (two cells in series), which requires a DCDC-convertor. To be able to power the LED-matrix, a simple driver was also constructed to power the LED's. Schematics and board design are placed in the appendix, while figures 8.3 and 8.4 give the diagrams and pictures of these circuits.

8.3 Production and Measurements

Most parts of the production of the battery-pack is done as described in section 7.2. One key difference is the order of the production steps. The regular procedure consists of laser cutting, after which the components are placed and soldered. This ensures adequate adhesion to the substrate during the laser ablation and makes sure no deformation occurs, which might lead to incorrect cutting. To be able to test the circuit sooner, the components were soldered on first. Then the circuit is tested, after which the batteries were detached, and the laser ablation took place.

8.3.1 Component placement

To keep the components in their place, solder paste is added and the components are placed. Then, the FCB is placed in the reflow oven. Due to the vapors of oil in this reflowoven, the FCB detaches from the carrier. Peeling the FCB off and cleaning it, as well as the carrier, allows a reattachment. However, as shown in figure 8.2, the adhesion is lost at the corners and air-bubbles form. This is due to the fact that the FCB cannot be firmly pressed onto the carrier, as the components are already placed.

The large components, specifically the batteries and connectors, can now be soldered by hand. Since the delivery of the batteries posed problems, only 2 batteries are used in this demonstrator, although it was designed to feature 8 batteries. By placing them in series, as shown in figure 8.2, all the key components of the battery-pack can still be demonstrated: a protection circuit at the bottom as well as the top are used, the balancing circuit will ensure balancing and the external charge circuit, as well as the LED-driver, can still function properly. The maximum current output is still enough to power the LED-matrix, although the maximum operating time will now be limited.

8.3.2 Testing of the battery-pack

Now that all components are placed, the circuit is tested, starting with the protection circuit. In table 8.4, the measured values are given for the protection circuits. Although the values are not as close to the expected value as with the rigid test-circuit (see section 3.5), the values are still more than acceptable and show adequate protection is present.

Table 8.4: Measurements of the protection circuit of the battery-pack

Fault	**[unit]**	**Spec. battery**	**Spec. IC**	**Measured (top)**	**Measured (bottom)**
OVP	[V]	4.275	4.280	4.32	4.29
$OVP_{release}$	[V]	4.175	4.180	4.23	4.24
UVP	[V]	2.300	2.300	2.35	2.29
$UVP_{release}$	[V]	2.400	2.400	2.41	2.38

Due to the difficulty of the setup used during testing (shown in figure 9.1), which is a result of the lack of testpads, the accuracy of this measurement is lower than the test of the test-circuit (see table 3.4).

The balancing circuit is tested by placing the 2 batteries on the FCB while they have a different voltage. Over the R_{CB} (for details on the circuit: see the appendix), a voltage of 825mV is measured and the current through this resistor slowly depletes the battery with the highest charge. After several minutes, the voltage over the top battery dropped from 3.875V to 3.860V while the voltage over the bottom battery dropped from 3.411V to 3.409V. This last voltage-difference indicates a slight energy-loss due to the balancing.

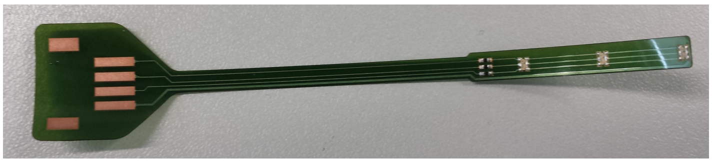


Figure 8.5: Single string-variant of the LED-matrix

Using the constructed battery-pack and the LED-driver, a single string-variant (see figure 8.5) of the LED-matrix which will be used as the application circuit for this demonstrator, is powered. The DCDC-convertor offers the required 12V and all lights can be switched as expected. Connecting the LED-string directly to a DC voltage source shows that a DCDC-convertor is not strictly needed. The lights still work in the entire voltage range of this dual cell battery-pack ($6V \rightarrow 8.4V$). However, at lower voltages the lights (especially blue and green) burn very faintly.

The charger is tested using a DC-source, instead of the USB connection to avoid damages in the case a problem occurs. The DCDC-convertor in this circuit offers a voltage of 9.5 V, which powers the dual cell charger. This charger uses CCCV charging to 8.4V. A LED is present to indicate charge status. If the LED is on, the battery is charging, and it is off when no charging occurs. After attaching the charger to the battery-pack, the LED flashes. This was not expected: flashing should only occur when an invalid temperature is measured or when a safety timer is expired. Measuring the voltage at the temperature sensing pin, we confirm that no invalid temperature is sensed by the IC. Luckily, another unexpected behaviour is found: even though the LED flashes, in which case the IC should not charge, it does charge, though only in the periods the LED is on. This means the charge circuit does charge the battery-pack, though at half the speed (as the flashing has a dutycycle of 1/2).

8.3.3 Lasering and Lamination

After removing the batteries and the connector, the FCB is lasered. Next, the batteries and connector are reattached and the circuit is laminated. To allow the laminator to reach the desired lamination-temperature of 110° C as described in section 7.3, the warm-up and cool-down time are increased. Now, the heating lasts 10 minutes, after which the temperature is kept constant for 4 minutes and then the circuit is cooled down for another 10 minutes. As shown in figure 7.8, the FCB should be laminated twice: first a layer is laminated on top, then, this layer, along with the FCB, is peeled from the carrier. Now, the bottom can also be laminated. This process is first performed on a circuit without components attached, then on a circuit with components.

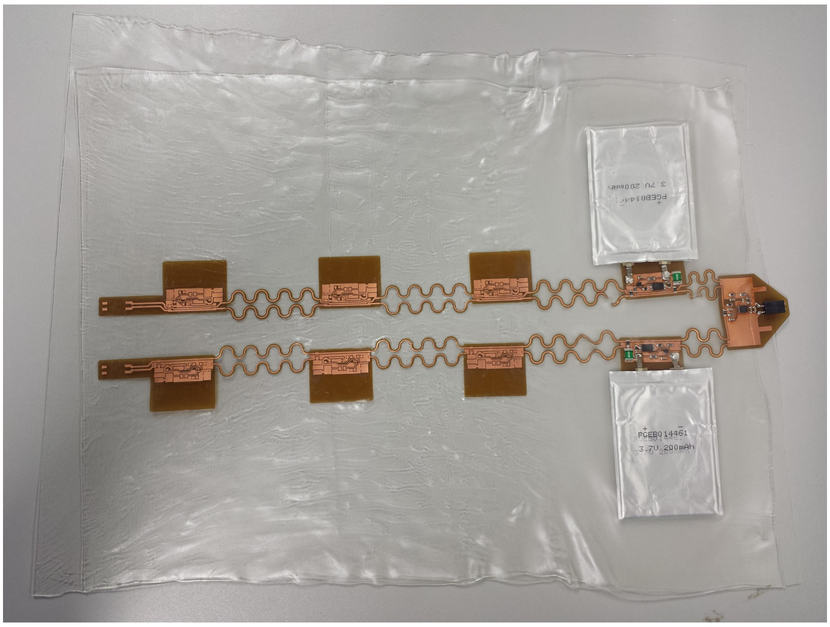


Figure 8.6: The demonstrator after laser-ablation and lamination

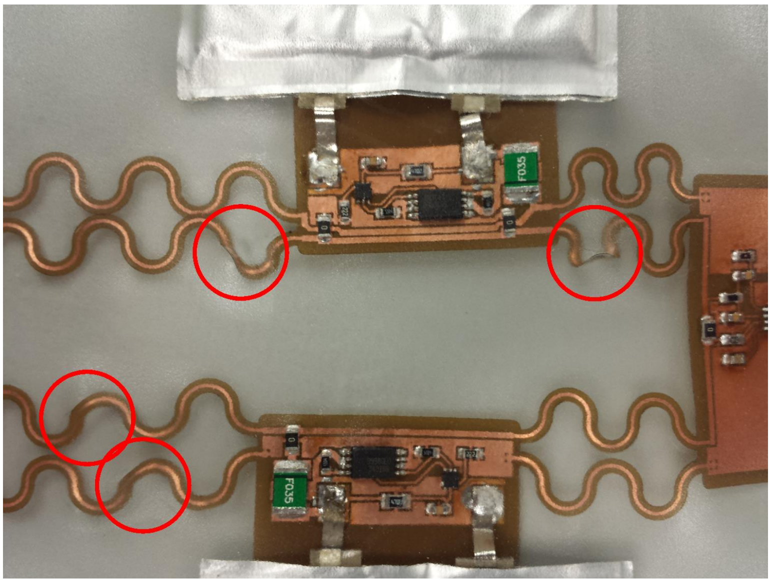


Figure 8.7: A closer look on the demonstrator; problem areas circled in red

It is clear from figures 8.6 and 8.7 that this lamination did not go perfectly. Due to the differences in thickness between the FCB, the components and the batteries, the polyurethane was not fully attached to the circuit during the first lamination step. Moreover, the layer stack was not stable, causing a slight shift of the circuit. Due to this, a slight air gap is present between the lamination layers. This could be solved by using a higher temperature to increase the flowing of the polyurethane, and by using a rubber encompassing the entire circuit, but with holes where the batteries are placed to account for the differences in thickness.

Despite the deformations, the circuit functions correctly, as shown in figure 8.8, making it suitable for stretchable and textile applications.

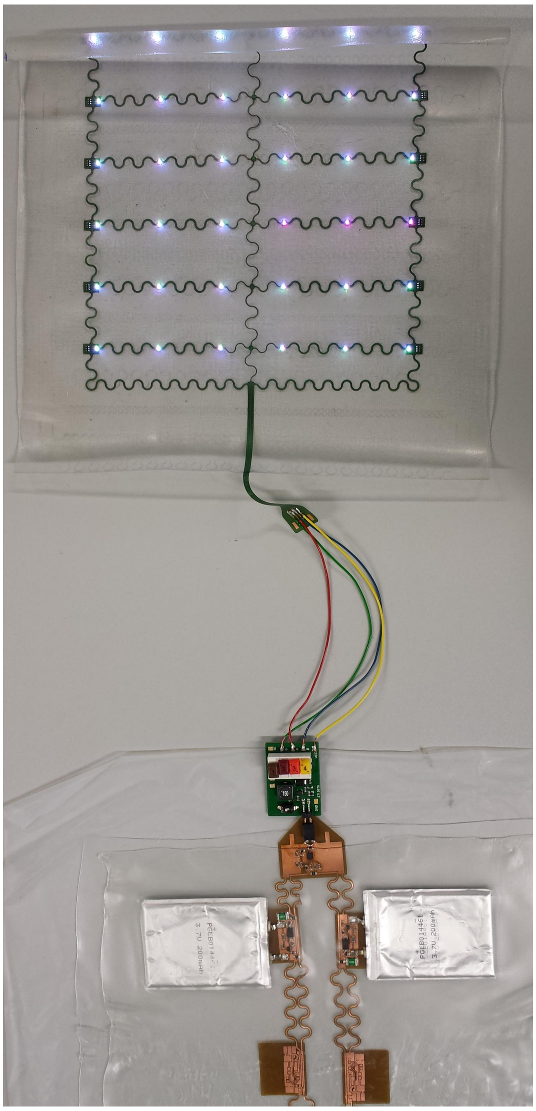


Figure 8.8: Demonstrator of the stretchable battery-pack, attached to the LED-driver and LED-matrix

Chapter 9

Conclusion and Future Work

9.1 Conclusion

After examining the different ways to store energy, two options stood out as suitable to be used in textile applications: ultra-thin lithium batteries and supercapacitors. While capacitors can handle larger current peaks, leading to a larger power density, lithium batteries offer a far larger energy density. While for most applications batteries will be the optimal solution, requiring less recharges, they require more protection.

Lithium batteries need protection against many fault-conditions. Luckily, simple primary (=attached to each cell) protection circuits exist. Depending on the configuration, balancing will be added, which guarantees equal charge on all cells and often also provides secondary (= on the level of the entire battery-pack) protection.

A design methodology was described, offering designers a quick guide to estimate the type and amount of batteries needed for their application, followed by a description on the advised method of charging.

Next, the principles of stretchable circuits and their production were described. While many production steps are similar to that of regular rigid-PCB design, some considerations are needed as this battery-pack needs be flexible. This includes meander-shaped routing between rigid islands and one-layer routing.

After having discussed all techniques for the design of a battery-pack for textile integration, such a battery-pack was constructed as a demonstrator. This was accompanied by a charge-circuit, to allow charging via USB connection, and a LED-driver. This LED-driver formed the bridge between the battery-pack and the LED-matrix it was designed to power. Despite problems with during the lamination process, this demonstrator functioned properly and was able to power the LED-matrix succesfully (see figure 8.8). This battery-pack can easily be integrated onto textile, as proposed.

9.2 Future Work

While the demonstrator worked as designed, some improvements are still possible. These are discussed here, along with some possible future research-topics.

Due to problems with the delivery of the batteries used in the demonstrator, no testing was done on the full demonstrator, containing all 8 cells. Entire charge and discharge cycles on the demonstrator containing all cells, along with further testing on the balancing could still be performed. To aid the testing of the protection circuits, more pads could be added, as testing if they work as expected was difficult in the current board-layout (see figure 9.1).

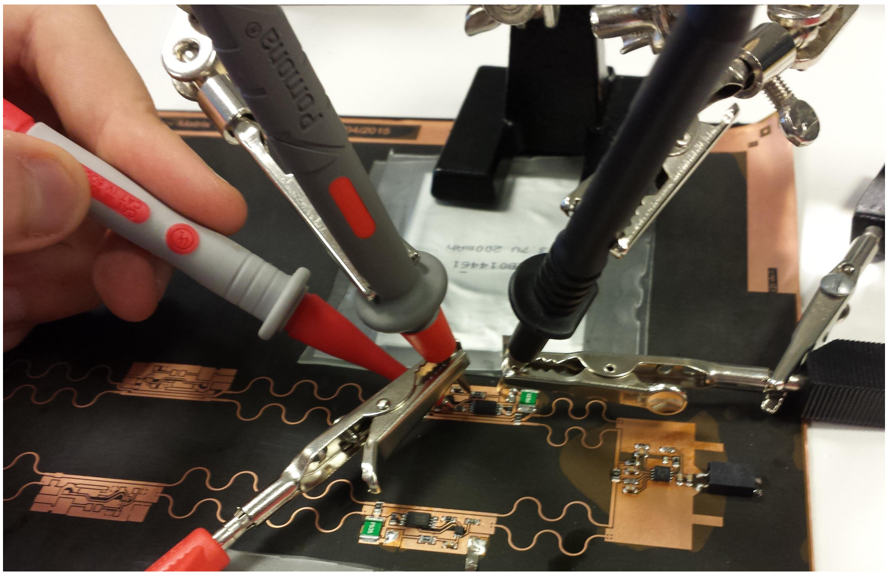


Figure 9.1: Lack of test-pads on the battery-pack resulted in difficult testing

Further experimenting with lamination materials and processes could produce better adhesion of the circuits to the lamination material. As attachment to textile was not examined, this forms a basis for future work as well.

While the protection circuit was designed to protect each cell against most faults, little protection against ESD was present: only filter-capacitors were added. ESD protection could be improved by adding spark gaps at the input of the circuit.

The meanders could not be sized sufficiently to allow the batteries to draw or deliver their maximum current, as this would have led to meanders with a width and radius that was too large and hence unreliable. Further research might investigate alternate ways to provide this wider routing. This could be done in the form of several meanders, connected in parallel.

To increase the maximum power output of the batteries, supercaps could be added in parallel with each cell to handle current peaks.

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Appendix: Schematics and board designs

On following pages the schematics sheets and board designs of the demonstrator are given. First the schematics and board design of the battery-pack matrix are given, in following order:

- Battery-pack matrix: toplevel sheet
- Battery-pack matrix: protection circuit of cells at the top
- Battery-pack matrix: protection circuit of cells at the bottom
- Battery-pack matrix: balancing circuit
- Battery-pack matrix: board design

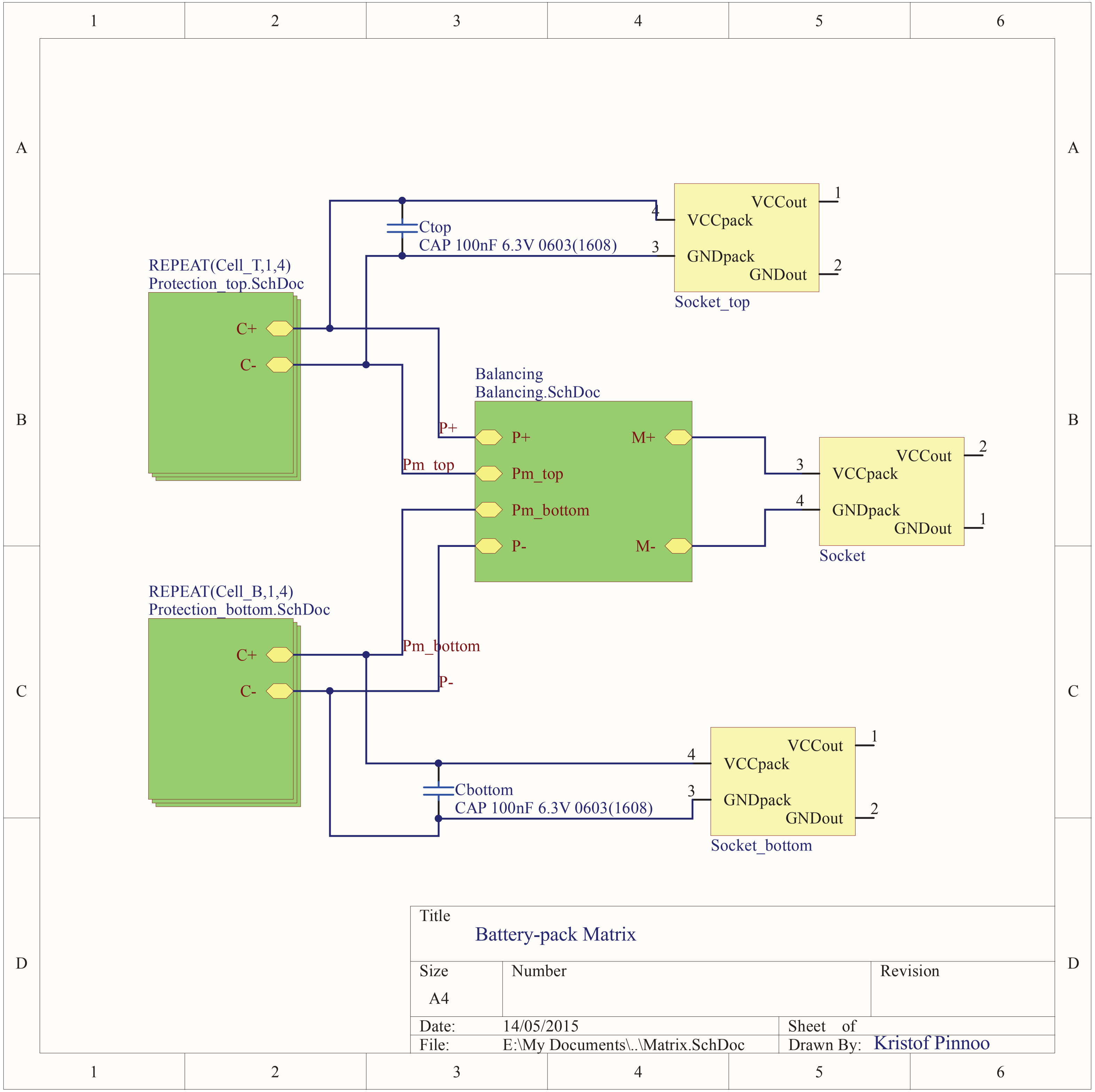
This is followed by the schematics and board design of the charge circuit:

- Charger: toplevel sheet
- Charger: Single cell charge circuit
- Charger: Double cell charge circuit
- Charger: DCDC convertor circuit
- Charger: board design

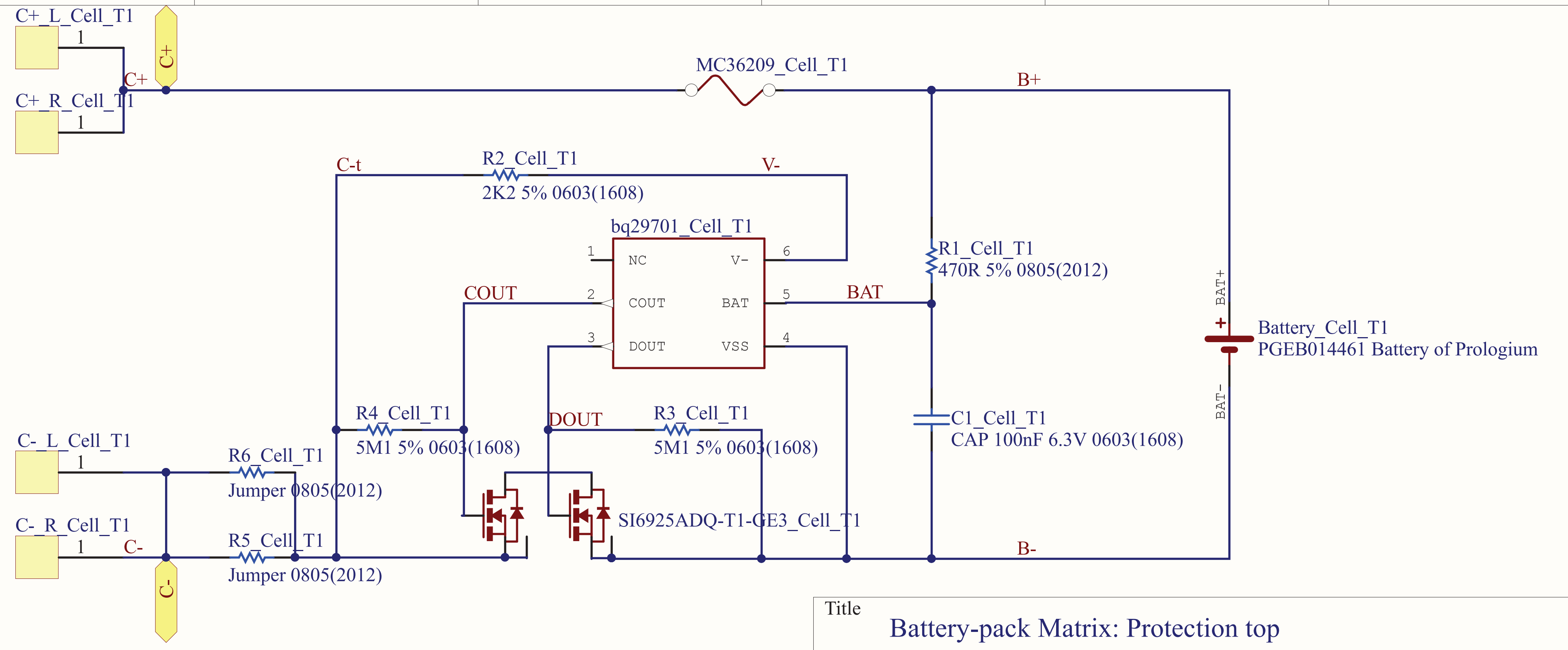
Finally the schematics and board design of the LED driver are given:

- LED-driver: toplevel sheet
- LED-driver: DCDC convertor circuit
- LED-driver: board design

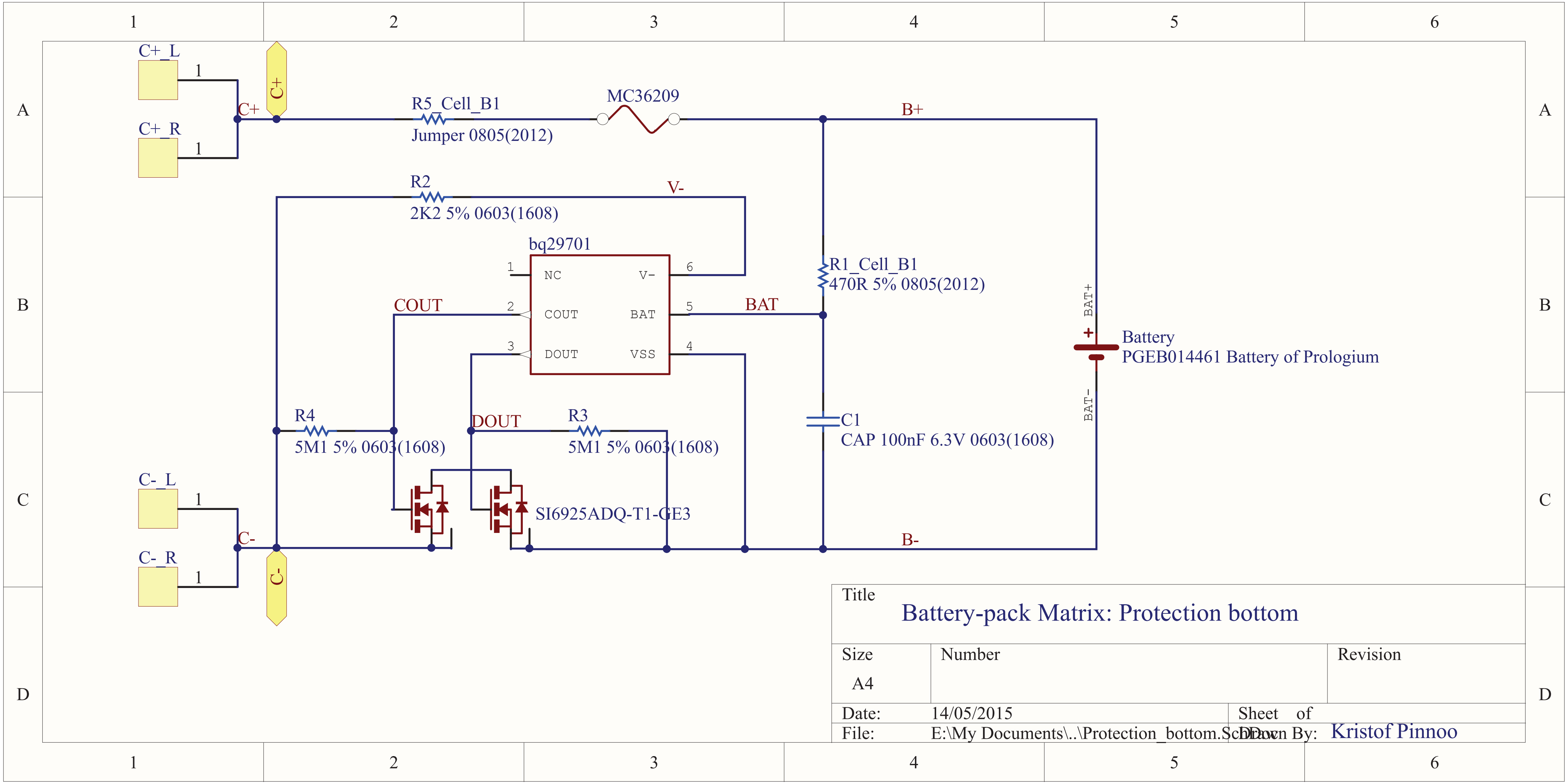
All the board-designs are shown on a scale of 1:1.



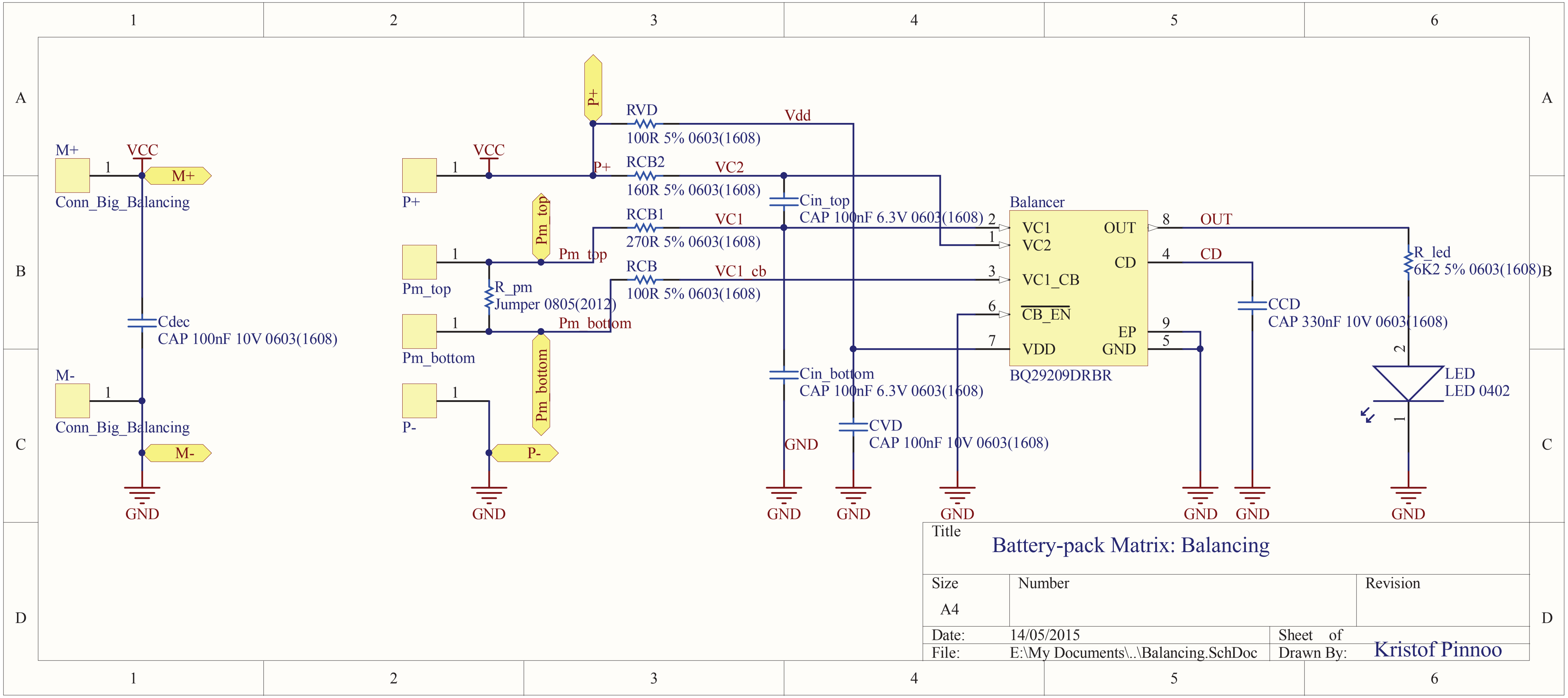
REPEAT(Cell_T,1,4)
Protection_top.SchDoc
C+
C-
Ctop
CAP 100nF 6.3V 0603(1608)
VCCout
VCCpack
GNDpack
GNDout
Socket_top
Balancing
Balancing.SchDoc
P+
Pm_top
Pm_bottom
P-
M+
M-
VCCout
VCCpack
GNDpack
GNDout
Socket
REPEAT(Cell_B,1,4)
Protection_bottom.SchDoc
C+
C-
Pm_bottom
P-
Cbottom
CAP 100nF 6.3V 0603(1608)
VCCout
VCCpack
GNDpack
GNDout
Socket_bottom
Title
Battery-pack Matrix
Size
A4
Number
Revision
Date: 14/05/2015
Sheet of
File: E:\My Documents\..\Matrix.SchDoc
Drawn By: Kristof Pinnoo

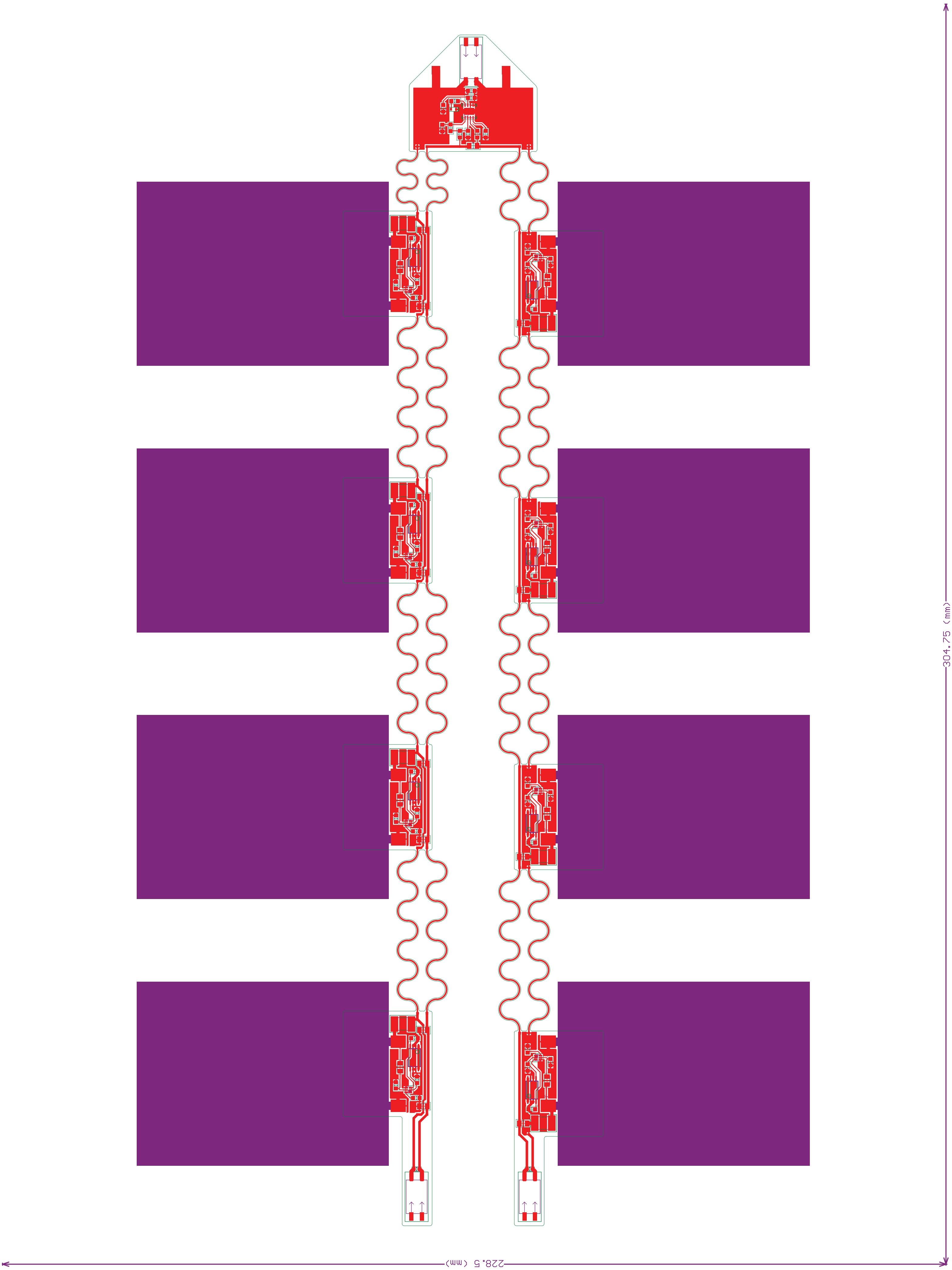


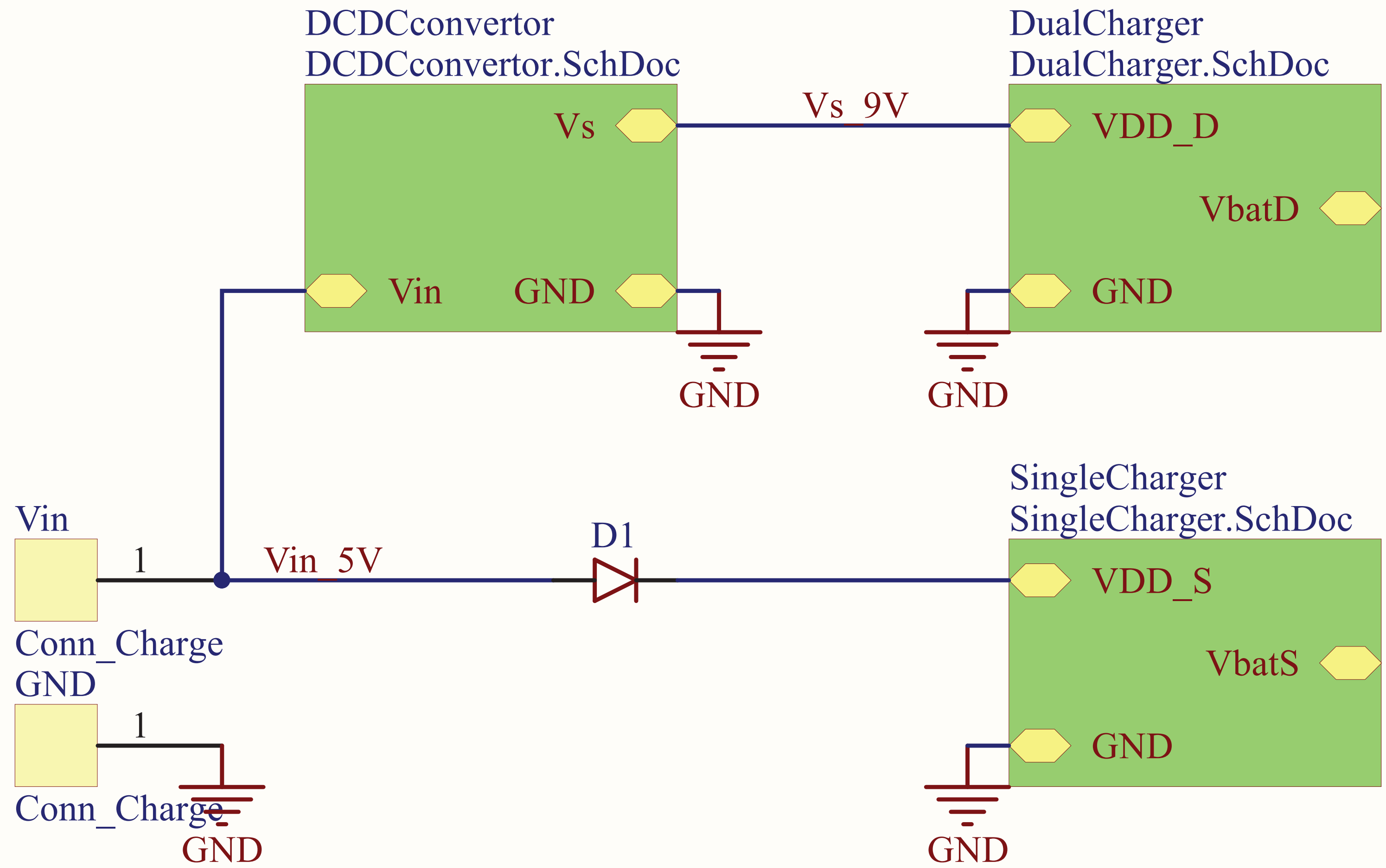
Title	Battery-pack Matrix: Protection top		
Size A4	Number		Revision
Date:	14/05/2015	Sheet of	
File:	E:\My Documents\..\Protection_top.SchDoc	Drawn By:	Kristof Pinnoo



C+_L
C+_R
C-_L
C-_R
C+
C-
R5_Cell_B1
Jumper 0805(2012)
MC36209
B+
R2
2K2 5% 0603(1608)
V-
bq29701
NC
COUT
DOUT
V-
BAT
VSS
COUT
BAT
R1_Cell_B1
470R 5% 0805(2012)
BAT+
BAT-
Battery
PGEB014461 Battery of Prologium
R4
5M1 5% 0603(1608)
DOUT
R3
5M1 5% 0603(1608)
C1
CAP 100nF 6.3V 0603(1608)
SI6925ADQ-T1-GE3
B-
Title
Battery-pack Matrix: Protection bottom
Size
A4
Number
Revision
Date: 14/05/2015
Sheet of
File: E:\My Documents\..\Protection_bottom.SchDoc
Drawn By: Kristof Pinnoo


M+
VCC
M+
Conn_Big_Balancing
Cdec
CAP 100nF 10V 0603(1608)
M-
Conn_Big_Balancing
M-
GND
P+
VCC
P+
RVD
100R 5% 0603(1608)
Vdd
RCB2
160R 5% 0603(1608)
VC2
Cin_top
CAP 100nF 6.3V 0603(1608)
RCB1
270R 5% 0603(1608)
VC1
Pm_top
Pm_top
Pm_top
R_pm
Jumper 0805(2012)
RCB
100R 5% 0603(1608)
VC1_cb
Pm_bottom
Pm_bottom
Pm_bottom
P-
P-
GND
Cin_bottom
CAP 100nF 6.3V 0603(1608)
CVD
CAP 100nF 10V 0603(1608)
GND
Balancer
VC1
VC2
VC1_CB
CB_EN
VDD
OUT
CD
EP
GND
BQ29209DRBR
OUT
CD
CCD
CAP 330nF 10V 0603(1608)
R_led
6K2 5% 0603(1608)
LED
LED 0402
GND
Title
Battery-pack Matrix: Balancing
Size
A4
Number
Revision
Date: 14/05/2015
Sheet of
File: E:\My Documents\..\Balancing.SchDoc
Drawn By: Kristof Pinnoo


304.75 (mm)
228.5 (mm)



Title	Charger		
Size A4	Number		Revision
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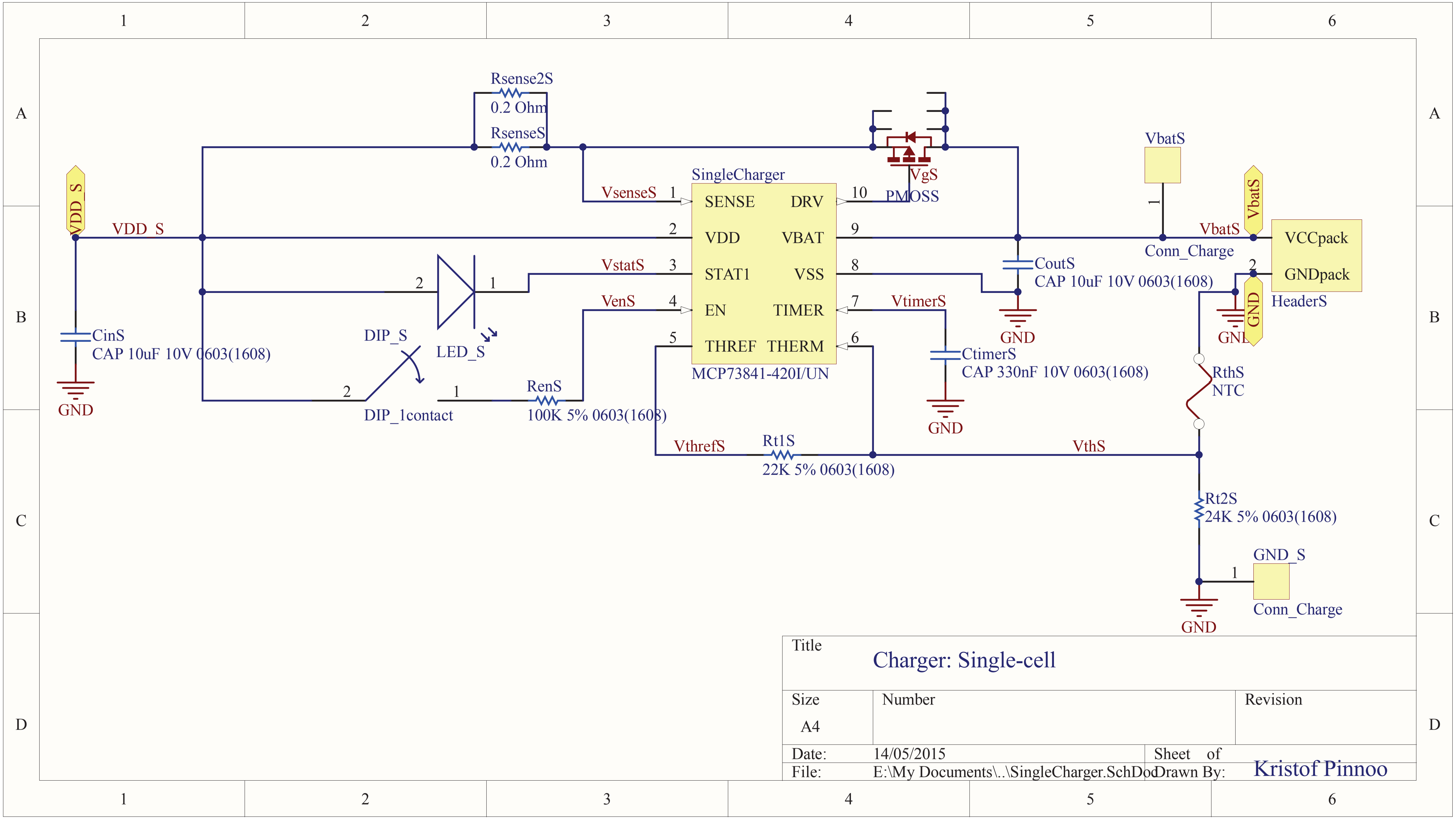
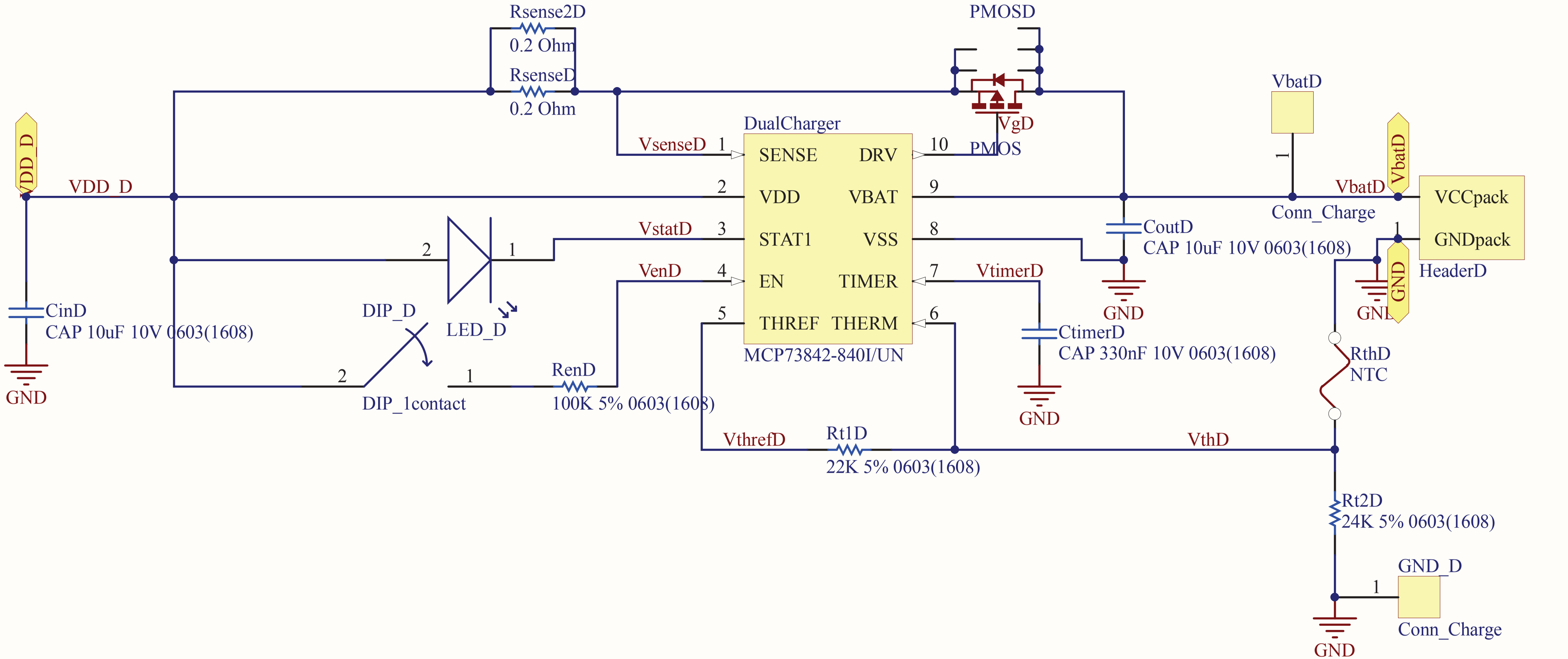
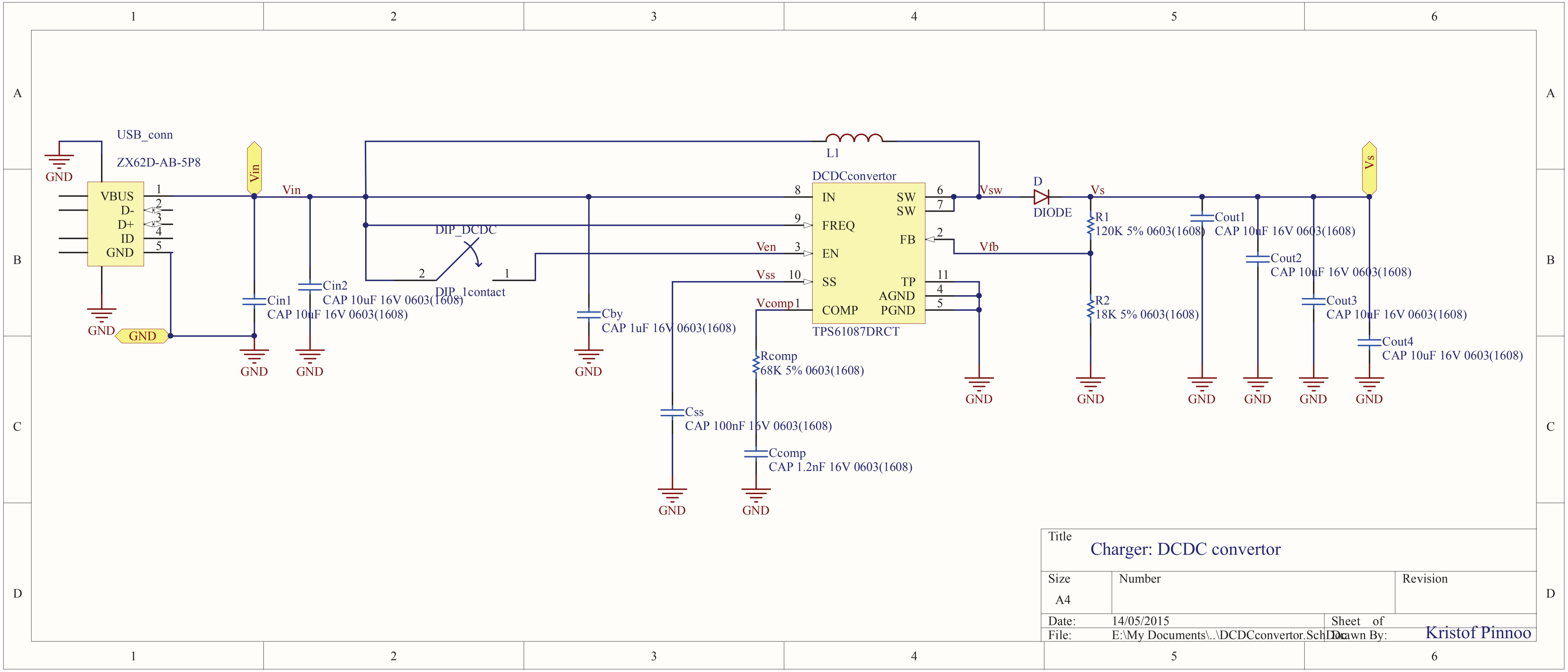


Rsense2S 0.2 Ohm
RsenseS 0.2 Ohm
VDD_S
VDD_S
CinS CAP 10uF 10V 0603(1608)
GND
DIP_S
DIP_1contact
LED_S
RenS 100K 5% 0603(1608)
SingleCharger
VsenseS
VstatS
VenS
SENSE
VDD
STAT1
EN
THREF
DRV
VBAT
VSS
TIMER
THERM
MCP73841-420I/UN
VgS
PMOSS
VtimerS
CtimerS CAP 330nF 10V 0603(1608)
CoutS CAP 10uF 10V 0603(1608)
VthrefS
Rt1S 22K 5% 0603(1608)
VthS
VbatS
Conn_Charge
VbatS
VbatS
VCCpack
GNDpack
HeaderS
GND
RthS NTC
Rt2S 24K 5% 0603(1608)
GND_S
Conn_Charge
Title
Charger: Single-cell
Size
A4
Number
Revision
Date: 14/05/2015
Sheet of
File: E:\My Documents\..\SingleCharger.SchDoc
Drawn By: Kristof Pinnoo



Title	Charger: Double-cell		
Size	Number		Revision
A4			
Date:	14/05/2015	Sheet of	
File:	E:\My Documents\..\DualCharger.SchDoc	Drawn By:	Kristof Pinnoo


USB_conn
ZX62D-AB-5P8
VBUS
D-
D+
ID
GND
Vin
Cin1
CAP 10uF 16V 0603(1608)
Cin2
CAP 10uF 16V 0603(1608)
DIP_DCDC
DIP_1contact
L1
Cby
CAP 1uF 16V 0603(1608)
Ven
Vss
Vcomp
DCDCconvertor
IN
FREQ
EN
SS
COMP
SW
FB
TP
AGND
PGND
TPS61087DRCT
Rcomp
68K 5% 0603(1608)
Css
CAP 100nF 16V 0603(1608)
Ccomp
CAP 1.2nF 16V 0603(1608)
Vsw
D
DIODE
Vs
Vfb
R1
120K 5% 0603(1608)
R2
18K 5% 0603(1608)
Cout1
CAP 10uF 16V 0603(1608)
Cout2
CAP 10uF 16V 0603(1608)
Cout3
CAP 10uF 16V 0603(1608)
Cout4
CAP 10uF 16V 0603(1608)
GND
Title
Charger: DCDC convertor
Size
A4
Number
Revision
Date: 14/05/2015
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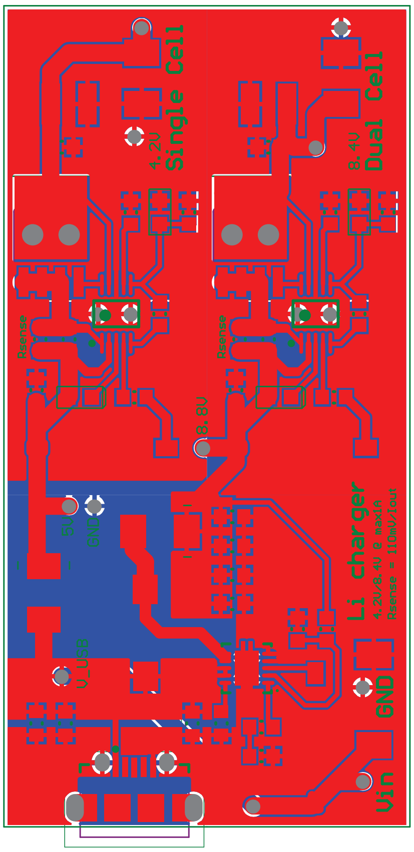
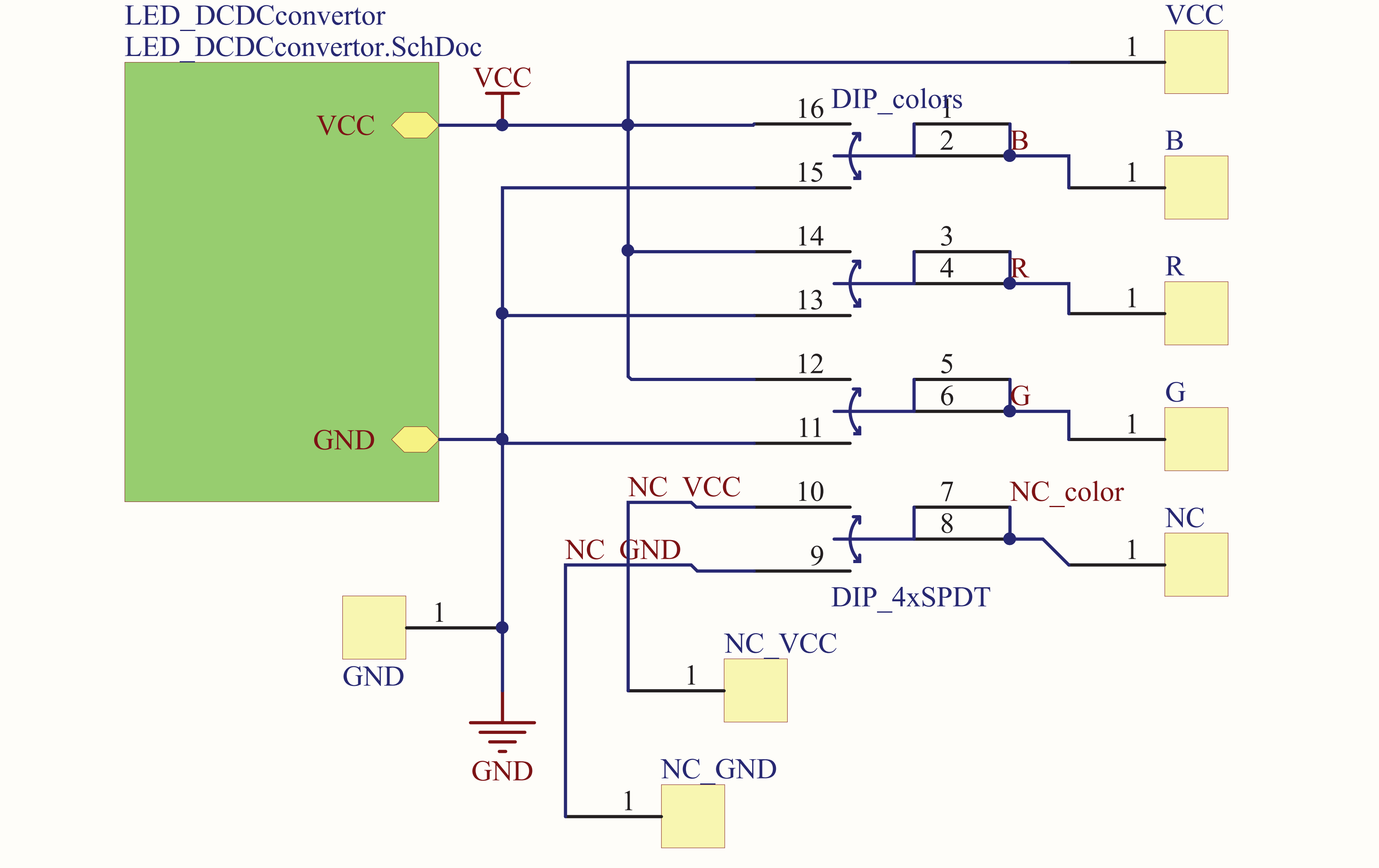
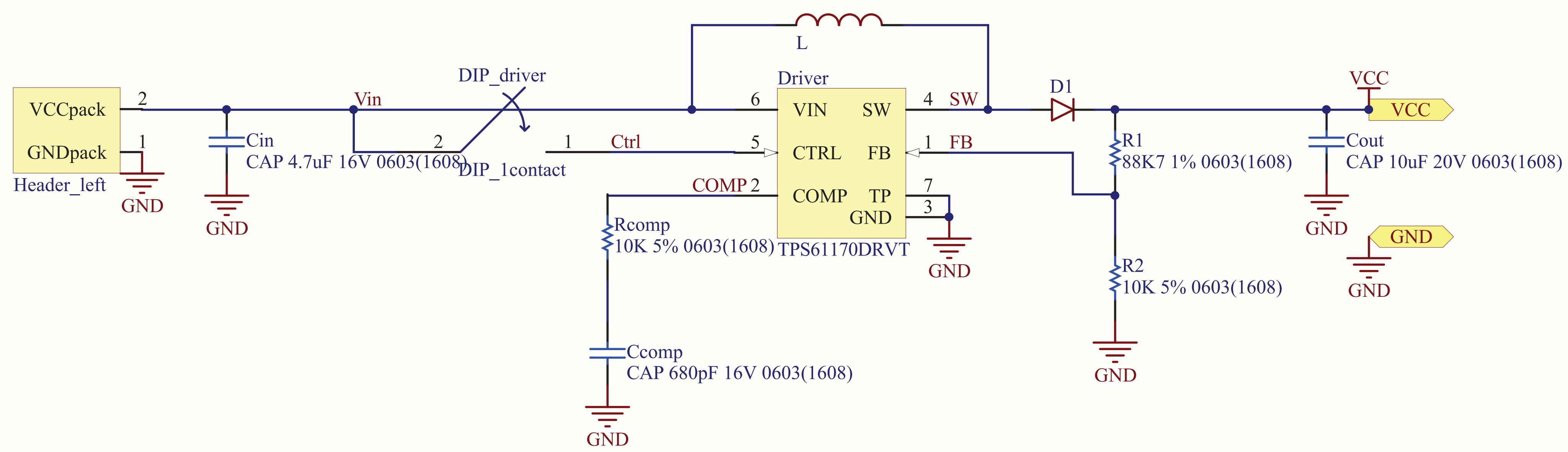
Drawn By: Kristof Pinnoo


Single Cell
4.2V
Dual Cell
8.4V
Li charger
GND
Vin



Title	LED-driver	
Size A4	Number	Revision
Date: 14/05/2015		Sheet of
File: E:\My Documents\..\LEDdriver.SchDoc		Drawn By: Kristof Pinnoo



Title	LED-driver: DCDC convertor	
Size: A4	Number	Revision
Date: 14/05/2015		Sheet of
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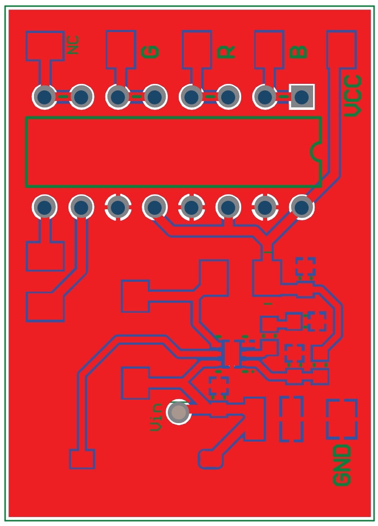

NC
G
R
B
VCC
Vin
GND