DELFT UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering, Mathematics and Computer Sience

BACHELOR END PROJECT

# Design of an Energy Management System for usage in the 'DISQ' portable fitness device

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# Preface

This report is the bachelor thesis that was written in the scope of the bachelor end project ‘Frictionless Resistance’. In the scope of ten weeks, we as group of six Electrical Engineering undergraduate students worked on the design of a system and development of a prototype. We learned a lot from this process, and while we faced severe challenges, we are happy with the results. Before we introduce the topic of our thesis, we would like to thank the persons that helped us in the design and writing process:

**Erik Driessen** for his help and guidance with the design and building of the prototype and his enthusiasm about the new product development.
**Henk Polinder** for the feedback he provided on our progress, design considerations, and thesis using his experience in academic research and report writing
**Xuezhou Wang** for the feedback that he provided and his daily supervision.
**Joris Koeners** for the practical advice that he gave and assistance with assembly and soldering of the prototype
**Luc Does, Floris Drijver, Tong Dong Qiu** and **Niels van der Veen** for their participation in the project, the fun time we had and the good collaboration between the different teams.

# Abstract

In this thesis the design of a frictionless resistance system with a speed independent mechanical resistance is presented, this system is meant for the portable fitness device "DISQ". The goal of this device is to provide a mobile exercise similar to an exercise with weights but with more flexibility. The goal of the change from the current friction braking version to the one discussed in this thesis is to minimise wear on the device and to ease the user's interaction with the device.

This is accomplished by implementing the frictionless resistance with a rheostatic braking system which is controlled to provide the speed independent mechanical resistance. The control circuitry is fed by a battery system which is recharged through combining the rheostatic braking system with a small regenerative braking system.

The system described in this document shows that the a frictionless resistance for a portable fitness device can be obtained through rheostatic braking and that it's also feasible to harvest energy from this process for powering the control system. The implementation discussed in this document is not yet sufficiently small and cheap for a commercially viable fitness device. It does however show that this method of implementing it can work and with further development a version can be made that is sufficiently small and cheap.

# Contents

# Chapter 1 | Introduction & Problem Definition

## 1.1 Introduction

In the last few decades, fitness has become a popular way of effective and diverse body workout. One disadvantage of fitness however is that it is bound to a single place, unlike sports such as running or cycling that can be exercised everywhere. A second disadvantage is that fitness devices are rather large and take up a lot of space. The 'DISQ' portable fitness device presents a solution to this problem (See figure 1.1). It is a device that can be worn around the waist, and has two discs with a cord that can be extended. By first adjusting the knob on the device and pulling the rope during the workout, the user can do workouts at various mechanical resistances. When the knob is tightened, the pressure on the braking disc is increased, resulting in a larger braking force and a higher mechanical resistance to the end user. In this way the DISQ adds resistance to the movements of the user. The DISQ suffers from some problems however: because there is a lot of friction in the braking mechanism of the current DISQ, the product wears out quick. Secondly, it is hard to control the braking force precisely by turning the knob. Finally, the mechanical resistance has no ways of providing feedback to the end user about the force or power that was delivered during the workout.

In this day and age more and more devices are implemented electrically for a variety of reasons. Given the known room for improvement on the current DISQ, the company DISQ set out an assignment for the development of a prototype for a newer version of the DISQ, that could solve the issues listed above. Currently, the DISQ uses a mechanical friction-based braking system. In this project an electric frictionless replacement for this mechanical brake was designed to help decrease wear, allow the user to more accurately choose the mechanical resistance and to provide the user with feedback on their performance. The prototype that was designed in the scope of this assignment converts the mechanical energy from the DISQ into eletric energy using a generator. The energy generated is partly used for storage, and partially dissipated. The system has a user interface that provides feedback to the user about the workout and enables the user to adjust the resistance of the DISQ. An overview of the system is shown in figure 1.2. The design of the prototype was divided into three different systems: 1) The Generator system, that converts the mechanical energy using a generator, 2) the Energy Management System, that stores and dissipates the generated electric power, and 3) the User Interface, that controls the other systems and provides user feedback via Bluetooth. Each of these subsystems was designed separately. This thesis describes the design of the Energy Management System. The considerations for this type this approach to an improved version of the DISQ can be found in 2.

## 1.2 Statement of the Problem

The energy management system has multiple responsibilities. It must be able to present an adjustable load to the generator, it must store a part of the energy generated and it must provide a constant voltage output for the user interface system. These three parts can, for the most part, be designed separately. The problem statement for this thesis will be formulated as follows:

**PROBLEM STATEMENT**

*An Energy Management System must be designed, that is able to present a variable load to the Generator System, of which the current is governed by the User Interface. The Energy Management System must be able to store enough energy from the Generator System to power the User Interface, and generate a stable supply for he User Interface. The energy that can not be stored, must be dissipated in some other way.*

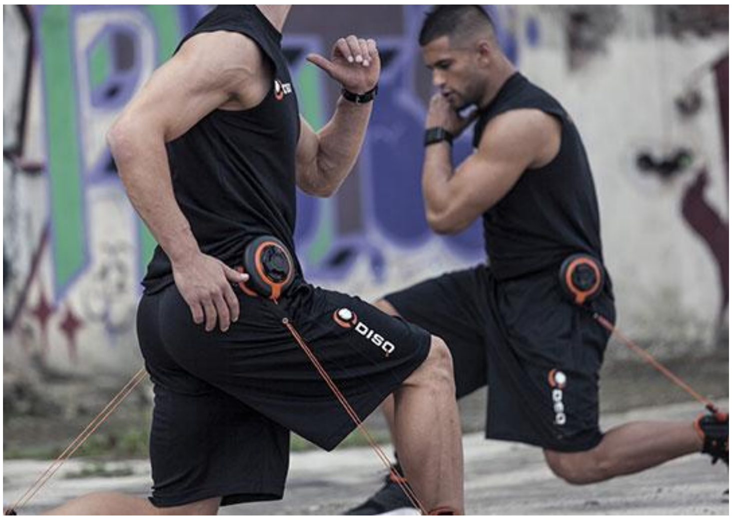


Figure 1.1: The 'DISQ' portable fitness device uses a mechanical braking disc to add extra resistance to all kind of workouts.

The requirements that are set out in the problem statement will be quantified in the next section.

## 1.3 Programme of Requirements

In this section the requirements for the product will be set. This product is a new version of the "DISQ" fitness apparatus with a frictionless resistance, this is a system meant to enable more flexibility in training locations. In specific the design of the energy management system is discussed in this thesis. In the following subsections the requirements for the complete system will be discussed first and where applicable the specific requirements for the energy management system will be discussed afterwards.

**Critical Requirements** There are a few requirements that are of main importance in the design of the Energy Management Systems. Because of their importance for the design process, they are marked as critical requirements. The critical requirements for our design are **REQ3.4**, **REQ3.7** and **REQ3.14**.

### 1.3.1 Requirements from the Intended Use

**REQ1.1** A mechanical resistance has to be applied when the cord is extended

**REQ1.2** The mechanical resistance must be adjustable by the user

**REQ1.3** The mechanical resistance should preferably be independent of the speed of the extension

**REQ1.4** The system should function without a connection to an external power supply during operation

**REQ1.5** The system should preferably never require connection to an external power supply

**REQ1.6** The system should provide the user with feedback on his performance using a Bluetooth connection

**REQ1.7** The user accessible parts of the casting should not reach harmful temperatures

**REQ1.8** The system has to be at most twice as large as the current DISQ

**REQ1.9** The system should not weigh more than 1kg

**REQ1.10** The system should not emit any noise which a user would find annoying

**REQ1.11** The system should not expose the user to harmful voltage levels

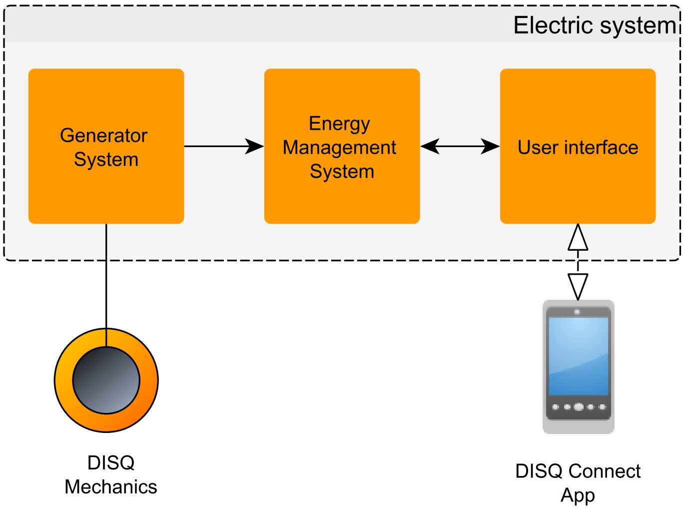


Figure 1.2: An overview of the electric system that was developed. The figure shows the three systems, and how they interact with the mechanics of the DISQ and the DISQ Connect App. The design of the Energy Management System, as well as the general design choices, are described in this thesis.

### 1.3.2 Ecological Requirements

**REQ2.1** All components used in the device should comply with Dutch RoHS standards

### 1.3.3 Requirements for the Designed System

#### Usage Characteristics

**REQ3.1** The system should function at cord extension speeds up to $2,5m/s$

**REQ3.2** The system should be able to provide a resistance of up to $100N$ at a speed of $1,5m/s$

**REQ3.3** The system should be able to start providing feedback to the user within the first 10 seconds of an exercise

**REQ3.4** [CRITICAL REQUIREMENT] The system should be able to maintain the Bluetooth-connection to the smartphone for at least 5 minutes after the end of an exercise

**REQ3.5** The system should remain functioning (pass all the requirements set in this programme of requirements) up to at least two years after purchase.

**REQ3.6** The time it takes to start a work out should not be increased by more than 10 seconds compared to that needed for the current versions of the DISQ

**REQ3.7** [CRITICAL REQUIREMENT] The mechanical resistance of the braking system in the DISQ should be as low as possible.

**REQ3.8** The system should remain functioning (pass all the requirements set in this programme of requirements) for the following usage scenarios:

(a) A 30 minute exercise at 45W power input to the system

(b) A ten minute workout at 90W power input to the system

Because of the way the electrical generation system and the user interface system are implemented these requirements can be translated into the following extra requirements specific to the energy management subsystem:

**REQ3.9** The energy management system should be able to continue functioning at voltages up to 40V

**REQ3.10** For input voltages between 5V and 30V, the system should be able to sink at least 6A from the electrical engein erm

The energy management system should be able to extract at least 6A peak from the electrical generation subsystem at an input voltage between 5V and 30V

**REQ3.11** The energy storage subsystem should be able to charge the energy storage with input voltages between atleast 5V and 30V

**REQ3.12** The energy management system should be able to provide a constant DC voltage of 3.6V to the user interface system within at most 10 seconds of the start of an exercise

**REQ3.13** The energy management system should be able to provide this 3.6V voltage with a load current of 100$mA$ constantly during the exercise and for at least 5 minutes after the end of an exercise.

**REQ3.14** [CRITICAL REQUIREMENT] The energy management system should be able to handle the full system input power as described in **REQ3.8**.

**Production and Operation Requirements**

**REQ4.1** The user should not need to perform any extra actions compared to the current version of the DISQ to start using it on first use

**Recycling**

**REQ5.1** Any components containing dangerous substances should be easily separable from the rest of the device

### 1.3.4 Commercial Requirements

**REQ6.1** The manufacturing costs of the device should not be higher than €250 when producing more than 1000

## 1.4 Thesis Layout

In this chapter, the problem statement was given together with the requirements for the system. Next, the main choices for a general method of implementing the frictionless resistance will be discussed in chapter 2. The overview for the implemented system will be given in section 3.1 together with an in-depth look at the subsystems that make up the energy management system in the rest of chapter 3. In chapter 4 the circuits for each previously mentioned subsystem will be designed. Then, in chapter 5 the testing of the physical circuit will be discussed and compared to the simulations, possible further development will also be discussed. The conclusion of this thesis can be found in chapter 6. In the appendix, some extensive calculations of certain parts of the system can be found, as well as an overview of the ethical considerations for this project.

# Chapter 2 | General System Choices

In this section, different methods will be compared that provide a mechanical resistance. The requirements on the maximum speed and force that the device and the resistance mechanism mus support can be found in section 1.3. The most important aspects of different resistance techniques are the precision with which the resistance can be controlled, the possibility of harvesting power (or need for an external power source) and the total size of the system.

## 2.1 Eddy Current Braking

Eddy current braking is a method that uses a spinning disk in a magnetic field. Due to flux changes on the surface of the disk, a circular current is induced on the disk. This current is called an Eddy current. This current generates heat in the disk, and generates an opposing magnetic field, generating a drag force on the disk. Since the calculations of eddy currents and forces involved with eddy current are severely complex, numerical calculations of eddy currents have been done. Figure 2.1 shows the power dissipation for a 38 cm disk with 10A 300-turn electromagnets[1]. Another study generates a braking force of approximately 50 N on a 7 cm wide rail, at a speed of 0.6 m/s and with a field of 0.4 T [2]. It is shown that the braking torque increases when disk speed, disk dimensions, disk conductivity and applied magnetic field are increased, and decreases with increase of the air gap[3],[4]. Eddy currents have been used as braking mechanisms for trains [5]. Because a higher rotational speed of the disk results in a higher flux change, the drag force on the disk is dependent on the disk speed. If a mechanical resistance that is independent of speed is desired, the flux change on the disk needs to be controlled. This van be achieved by two different methods: either by using permanent magnets and regulating the distance between the disk and the magnets, or by using electromagnets and control of the current and thus the generated magnetic field. A disadvantage of using electromagnets is that to generate a magnetic field of comparable strength as permanent magnets, high currents are needed.

## 2.2 Regenerative and Rheostatic Braking

Dynamic braking uses an electric motor as a generator to provide mechanical resistance. When the generated energy is used to power a device or when it is stored, i.e. the generated energy is used in a useful way, this is called *regenerative braking*. When the generated is dissipated directly using a load, this is called rheostatic braking. Dynamic braking, and especially regenerative braking, is a technique that is widely used in the automotive industry and a topic of active research. An electric generator can be modelled as a voltage source with a series resistance, and the induced voltage varies linearly with the speed of the rotor. The torque that the generator exerts is determined by the current flowing through the generator. By controlling the load of the generator, the current can be controlled, and thus the braking torque. When a purely resistive load is connected to the generator, the braking current and torque increase linearly with speed, because the voltage increases linearly with speed. This means that the braking force can only be independent of speed when the load is controlled. A drawback of this implementation is that DC motors are relatively expensive. Most DC motors operate at rotational speeds that are much higher than that of the DISQ, so probably a gearbox will be needed, which would further increase production costs and weight.

## 2.3 Braking Using Electrorheological Fluids

Electro-rheological fluids (ER fluids) change in viscosity when an external electric field is applied. If fins are attached to the rotating disk, increased viscosity will increase the effort required to move the disk through the fluid. Because the friction is not concentrated on a single point, heat dissipation is

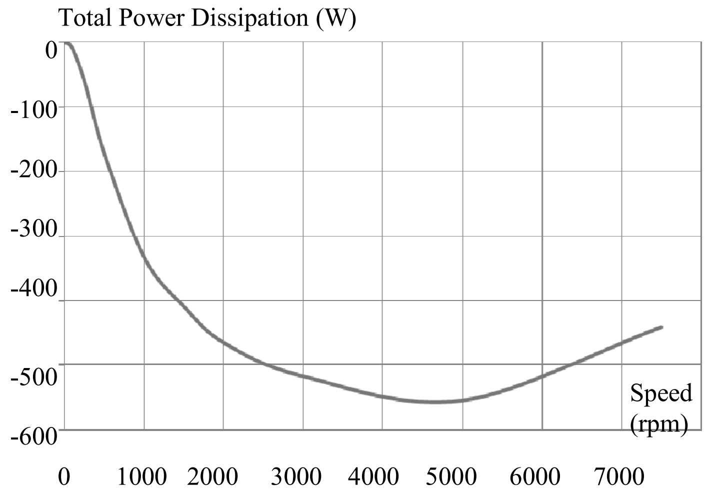


Figure 2.1: The disipated power as a function of a 38 cm disk with 10A electromagenets as a function of the radial frequency. The figure was taken from [1].

equally spread over the fluid. An extra requirement on the DISQ would be that it needs to be leakproof, to prevent the fluid from leaking out. Electrorheological fluids require a high potential of up to 3-4 kV/mm to work[6][7], which is near the breakdown voltage of air. A prototype of a disk brake using electrorheological fluids showed that with a 2.5kV source a braking torque of 8 Nm can be realised[8].

## 2.4 Electrically Controlled Mechanical Brakes

Braking using mechanical friction is the most simple and fastest method of delivering mechanical resistance. The advantage of mechanical braking is that high braking forces can be achieved with few components, which results in low costs and weight. Mechanical brakes have the advantage that the frictional force, and thus the generated braking force is independent of the speed of the braking disk. The frictional force is described by $F = \mu \cdot F_N$ with $\mu$ the rolling friction coefficient and $F_N$ the normal force, that is, the force that pushes the two braking parts together. To control the braking force, the normal force must be adjusted. This can be done mechanically using a knob or a spring. In order to control this force electrically, a motor or actuator would be needed. A disadvantage is that the braking parts wear out relatively fast due to the high friction.

## 2.5 Comparison

When comparing the different techniques, the only method that allows energy harvesting is regenerative braking. With energy harvesting and an energy storage system, the system can operate without an external power supply, and **REQ1.4** can be met. For eddy current braking and ER-fluid braking, high voltages or currents are needed, which would quickly deplete an external supply such as a battery. Mechanical braking is an effective braking method, but since **REQ3.7** requires the design to have as low mechanical friction as possible, this is not a desirable option. This leads to the conclusion that dynamic braking in this case is the solution with the least disadvantages, and the advantage that is the only system of the possibilities described in this chapter that allows for energy harvesting, and hence this method is chosen for the design. The system needs to be able to handle a maximum input power of 90W, and a maximum input energy of 45Wh as described in **REQ3.14**. Since there are no systems currently available that are able to store this full amount of energy, as is further explained in 3.4, but it is still desirable to have a control system that provides feedback to the end user and can control the mechanical resistance, it was decided to implement a combination of rheostatic and regenerative braking. A full system overview is shown in the next chapter in section 3.1.

# Chapter 3 | Qualitative Design

In this chapter, all qualitative design choices will be made. This means that different technologies are compared, and a choice for a technology is made based on its advantages and disadvantages. The energy dissipation system, the control system for the energy dissipation system and the energy storage system will be designed. In the next chapter, each subsystem will be further designed in this same order, and design choices on the specific components and component values will be made.

## 3.1 System Overview

### 3.1.1 Total System Overview

This chapter includes the comparison and selection of different techniques for energy storage and dissipation used in the subsystem by qualitative analysis. Before the subsystems are specified in the rest of the chapter, an overview of the total system is provided in this subsection, and the input and output requirements for the output system are shown.

An overview of the complete system is shown in figure 3.1, with the subsystem highlighted in the darker color. The system is divided as follows:

1. The first subsystem is the energy generation system. The energy generation system consist of a three-phase brushless DC motor, and a gearbox. The motor has a nominal voltage of 24 volts and a gearbox ratio of 1:12, with a nominal speed of 3190 RPM. Design considerations on motor and gearbox selection can be found in the other bachelor thesis of this project [9].
2. The second subsystem is the subsystem that is described in this thesis. It controls the load of the first subsystem, stores energy and supplies power to the last subsystem.
3. The third subsystem is responsible for the overall control. This subsystem consist of a PIC18F4550 microcontroller and a RN42XV Bluetooth module, both fabricated by Microchip. The microcontroller measures the output voltage and current of the generator, and adjusts the load in the energy management system accordingly. The Bluetooth module is used to control and obtain feedback from the total system externally. A PC application is developed to control the system and to analyse data from the workout. Further details about the controller can be found in [10].

### 3.1.2 Energy Management Subsystem

The energy management subsystem is itself composed of different separable parts, as can be seen in figure 3.1. The rectifier converts the three-phase AC input voltage of the generator into a smoothed DC voltage. This DC voltage is fed to both the energy dissipation system and the battery management system. The battery management system circuitry converts the DC voltage to the voltage level of the battery and charges the battery. At the maximum charging current the power delivered to the battery is approximately 2W. The battery charges a lithium-ion battery, which in turn powers the control circuitry. Because the control circuitry operates at a different voltage level as the battery voltage, and because the battery voltage is dependent on the state of charge, a DC/DC converter is used to deliver a stable output voltage to the control system. For more information the reader is referred to the paper on the control system of this project [10]. The energy dissipation circuit consist of a MOSFET and a combination of resistance. The resistance consist of multiple resistors, so that the heat dissipated in the resistance can be spread over a large area. The MOSFET is switched using a PWM signal. By controlling the duty cycle of the PWM signal, the average current through the inductor and thus the torque that the generator exerts can be controlled.

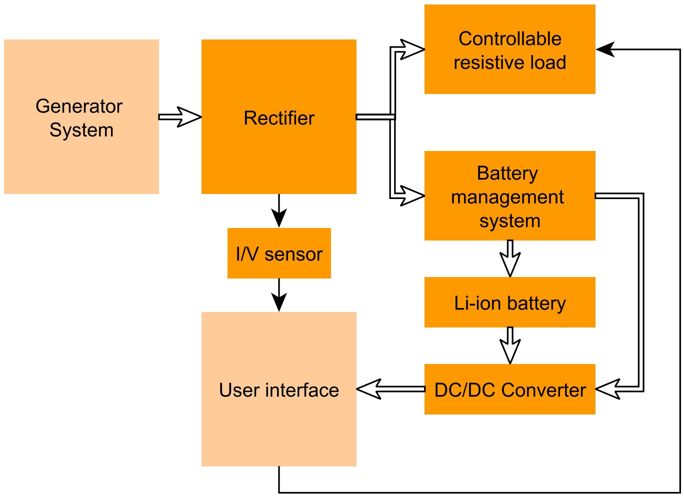


Figure 3.1: The overview of the total system. The subsystem that is designed in this thesis, along with its subsystems, are highlighted in the darker color.

## 3.2 Energy Dissipation System

One of the primary goals of the complete system is for it to act as an adjustable mechanical resistance, which will be done through a generator. To adjust the mechanical resistance the user experiences from the generator the amount energy extracted from the generator must be adjustable, which means that it must be possible to adjust the electrical load to the generator. Because all the energy extracted from the user will be electrical energy this system faces a very rare challenge; an excess of electrical energy. As the requirements state the system needs to be able to handle $90W$ input for the heaviest workouts **REQ3.14**, this is quite a substantial amount of power and in this section multiple methods for handling it will be discussed.
First the relevant requirements for this subsystem will be reiterated, then the possibility of storing all generated energy will be examined, afterwards dissipation through EM radiation will be discussed and then dissipation through a resistive load is examined. Finally a comparison between these methods will be made in which the one that will be implemented is selected.

### 3.2.1 Requirements

The system will need to be able to handle both large peak power for short durations and a smaller average power over longer durations, specific values were laid out in the programme of requirements. The system needs to be able to handle the extreme cases laid out in the requirements of $45W$ for 30 minutes, 90W for 10 minutes as specified in requirement **REQ3.14** and 180W peak power as specified in requirement **REQ3.10**.

### 3.2.2 Storage

A logical choice to look at first is storing this excess energy. This could be in an extra internal battery or external batteries. As a first look at charging external batteries the most logical choice is phone batteries, most users will have one so why not? Well there are are 3 good reasons: Firstly the batteries in phones generally charge with a maximum of around 3W, in our application we need to be able to handle 90W so this is insufficient by far, which means another temporary storage would be needed for this. Another big problem is that some of the larger phone batteries can still only store about 15Wh, which isn't enough for the longer workouts. Lastly it always need to be possible to store the energy we generate, with a phone battery we can't discharge the battery when we want to make room for our extra energy so this can't be

made sure.
Well if phone batteries aren't the solution possibly some extra internal storage is, however this faces some large problems as well, the requirements laid out previously for peak power and total energy to be stored during a full workout generally require too large batteries or supercapacitors. As is seen in section 3.4.1 to store 22,5Wh in a supercapacitor you would need atleast somewhere around 5kg of material, which would be unacceptable due to requirement **REQ1.9**. This means that a purely supercapacitor based approach won't work, however the battery approach doesn't provide a much better picture, generally the charge rates of batteries are lower than the discharge rates. A fairly generous maximum acceptable weight for the battery might be 200g to be able to stay under the 1kg maximum for the complete system, this would mean a power density of around $1w/g$ is needed, which is near the absolute maximum available for commercially available lithium-ion batteries[11]. These batteries are generally very expensive and wouldn't be reasonable with requirement **REQ6.1** on total cost.
The standard solution to this type of problem is a hybrid system of supercapacitors and batteries, where the high power density of capacitors is used to temporarily store the energy from the moment of large peak power and the batteries high energy density is used for main storage. This would introduce extra costs due to manufacturing a more complex system and the final result would not add too much to the functionality of the product. Only a relatively small energy storage is required to be able to power the user interface systems and any extra stored energy will still need to be dissipated in other ways, so why even store it? This would only be required if it's not possible to dissipate the energy fast enough, this will be examined in the next section.

### 3.2.3 EM Radiation

Another possible method of dissipating electrical energy is EM radiation. This method is possibly a strange one but it allows us to directly remove energy from our system without being dependant on the surroundings or a certain maximum storage capacity as is the case for thermal dissipation. The main problem however is the way this EM radiation affects the surroundings and the efficiency of this generation, if the generation is very inefficient it would basically be a worse version of resistive dissipation via heat.
There are many devices available for generation of EM radiation in the visible spectrum, which might make this method seem interesting, however the newest LEDS still convert around 50% of their energy to heat[12][13]. This would mean 45W heat generation, so even this method would require some consideration for the heat dissipation, which invalidates the whole purpose of using light for energy dissipation. Another possibility are natrium lamps, however these are simply too large and expensive. In general any light frequencies won't work. Outside of that the only possibility is going to the far larger wavelengths where antenna's can be reasonably made. Here high efficiencies are possible, however this is also a very strongly regulated spectrum and fairly complicated circuitry is required.

### 3.2.4 Resistive Load

A normal resistive load converts electric energy to heat with $P = I^2 * R = V^2/R$. A large advantage of using a resistive load is the ease of controlling the current drawn from the motor, which is desirable because this directly corresponds to the amount of mechanical resistance experienced by the user, with $I = V/R$ it immediately follows that either controlling the resistance value or the voltage means controlling the current. This also leads to the possibility of controlling the current in such a way that it becomes independent of the speed at which the user extends the cord as is mentioned in optional requirement **REQ1.3**.
There are many methods for controlling either the voltage over a load resistance or the (effective) resistance itself, however the basic principle of using the resistive load doesn't change. All methods change the amount of current drawn for a certain input voltage, in this way acting like a controllable resistance to the input. The methods are generally quite simple, for example the options range from using arrays of transistors in series with resistors to allow directly choosing certain resistance values, using a transistor

in series with a resistor and varying the duty cycle of PWM signal to the resistor to control the effective resistance or using a PWM controlled DC/DC converter to control the voltage over a resistor. Of these methods the PWM methods are generally preferable due to needing fewer components, fewer control signals and not having the possible resistance values be quantized.
The main possible problem with this method is the heat generation, following from requirement **REQ3.14** this would mean the total device needs to stay within safe temperature ranges when 90W is converted directly to heat in the system. Even if the thermal capacity of the system would be large enough to do this without any problems this the system would also need to handle 45W for half an hour. While this might seem like a pretty steep requirement for a portable device it's actually already know for sure that this isn't a problem, this is because the current mechanical DISQ must already dissipate the same amount of energy as heat. It's actually easier to do for this version because the locations of the power resistors can be freely chosen, allowing a more effective use of the surface area of the DISQ for heat dissipation.

### 3.2.5 Comparison

In general it seems that direct dissipation via resistive loads is the best option. The circuitry for doing this is simple and the generated heat can be dissipated well enough to not cause discomfort to the user while the other choices have large downsides. Storage of all energy would require too large supercapacitors, too large batteries or a smaller but complex combination of both, while still requiring another dissipation method for the inevitable dissipation, in this way only avoiding a larger peak temperature. And the EM radiation methods are generally too expensive and run into too many regulations because of the requirement of radiating nearly 100W. Because of this a resistive load will be used in the system. The specific implementation of this load will be discussed later in section 4.1.

## 3.3 Energy Dissipation Control

In this section the top level design will be discussed of a control system for keeping the torque the user experiences speed independent as stated in requirement **REQ1.3**. This will be done through controlling a resistive load as decided in section 3.2, the control will be done with a PID control scheme due to the ease of implementation.
This control is needed because the voltage a motor generates when mechanical power is applied to it depends directly on the speed of the movement. If the electrical resistance is kept constant this means the current also varies in the same way the voltage does and this directly relates to the torque experienced by a user. To enable constant torque the goal is thus to keep the current constant. This goal is not actually feasible, because then the load needs to have an infinite resistance range, this is because when a user starts extending the cord the speed will always be 0 and then go up gradually. To make sure the user experiences constant torque during the whole extension this would mean that even at a speed infinitely close to $0m/s$ the current should be constant, at this speed the voltage also is infinitely close to $0V$ which means the load needs to become infinitely close to 0Ω.
First a set of requirements will be determined for this subsystem, then the choice of implementing the control in an analog or digital circuit will be examined, afterwards the method of generating the current sense signal to enable feedback will be discussed and then the type of output signal will be considered.

### 3.3.1 Requirements

As mentioned previously the control system should control the load in such a way that it's speed independent or a constant torque. This directly translates into being able to control the current independently from the speed, which is controlling it independently from the voltage. This requirement will be further specified as follows: For input voltages from $5V$ to $60V$ the control system should be able to keep the average current over a time of 0,1s constant at any value between $0A$ and $6A$ with a maximum deviation of $\pm 0,1A$. This must be achieved by varying the duty cycle of a PWM signal for use in switching the resistive load.

### 3.3.2 Analog or Digital Control Generation

In designing the control system one of the first choices will be whether the control signal generation happens in an analog circuit or digitally. Normally digital control provides many advantages due to the ease of changing the behaviour of the circuit through software and easy interfacing with other elements of the system or providing feedback to the user. However this is already being implemented by the group creating the user interface system and in this thesis a separate analog solution will be discussed, this is mostly meant as a possibility if the MCU is deemed undesirable for a final product or if the delay requirements for a control system are too strict for the used MCU.

### 3.3.3 Current Sensing

The goal of this circuit is to control the current drawn from the motor. To do this reliably the system requires information about the current. The easiest way of doing this is converting the current to voltage information through a resistor and then using that voltage as the input to the control generation. The design can make use of the known value of the main power dissipation resistor to do this, however that would ignore the load the battery charging system represents. Instead a shunt resistor will be place in the current path to measure the current extracted from the motor. The precise circuit for readout will be discussed in section 4.2.1.

### 3.3.4 Output Signal Form

The output signal can be provided in various forms. The control could possibly be incorporated directly in the amplitude of an output, in a set of digital signals or in the duty cycle of a PWM signal. These different methods will now be discussed and compared.

#### Amplitude Output

Providing the output as an analog amplitude output is likely the easiest to generate. A likely implementation of the control system is that of a PID controller, which can be created with an error amplifier with integrators, differentiators and normal amplifiers feeding to a summing amplifier, where the output will be an analog signal with the control encoded in the amplitude of the signal. While this generation is easy it cannot be used directly, the easy methods of creating an electrically controllable resistance involve various methods of switching, which are generally implemented with transistors. So this means that the output signal of the control systems needs to have quantised amplitudes, methods of doing this will be discussed next.

#### Analog to Digital Conversion

A possibility for enabling controlling switches is taking the analog output of the previous option and using an analog to digital converter (ADC) to convert this to a vector of digital outputs. A downside of this method is the large number of different signals required for a large range of control settings.
If the voltage were constant, the requirement of $0,1A$ maximum deviation and a range of $0A$ to $6A$ would require 30 settings, resulting in a 5 bit vector at least. Adding the varying voltage, which can be as low as 5V and as high as 30V, extra settings are required. The amount can be determined by noting that the settings available for 30V are sufficient for all the lower current settings for a voltage of $30V\frac{5,8A}{6A} = 29V$ but the lowest resistance of 5Ω is not enough to come close enough to 6A at 29V, so add a setting for $4,83\Omega$. By adding a resistance setting for every $100\% * (1 - \frac{5,8A}{6A}) = 3,33\%$ lower voltage makes sure the required precision in current settings can always be reached. So find the amount of settings x so that $V_{max}(\frac{5,8}{6})^x < V_{min}$.
For $V_{max} = 30V$ and $V_{min} = 5V$ means an extra 53 settings are needed or 83 in total, which means atleast a 7 bit vector. This number of signal lines would take up more space and more components. However it might be a good method depending on the used implementation of the resistive network.

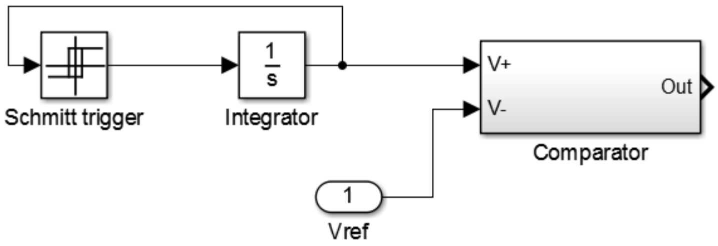


Figure 3.2: Abstract block level schematic for PWM generation

**PWM Generation**

Another possibility is a PWM output, where the basic idea is producing a square wave where the percentage of the time that the amplitude is high, called the duty cycle D, can be controlled. For the analog system there is a pretty clear choice for PWM generation. In abstract form the blocks required for PWM generation are shown in figure 3.2 with an Schmitt trigger and an integrator for generating a sawtooth signal and a comparator with the sawtooth signal and a reference signal as inputs, where the output is the comparator high supply when the reference input is higher than the sawtooth and it's the low comparator supply otherwise. Controlling the reference signal here thus determines the duty cycle, in this way the rest of the control system will take a voltage representing the sensed current as input and it will output a voltage reference for this comparator.

**Comparison**

In general output signals with quantised levels which can be directly used for switching are preferable. Of these the PWM generation would be preferred due to the smaller amount circuitry needed to generate it and having the control signal be just 1 line instead of 7. However the precise choice between PWM and ADC mainly depends on the chosen implementation of the controllable electrical resistance, which will be discussed in 4.1.

### 3.3.5 Summary

As was seen most parts of the system are pretty straightforward, with the exception of the output signal type where the preference is PWM but this depends on the implementation of he controllable electric resistance used, for now however PWM will be assumed.
With the parts that make up the control subsystem now decided the complete system will be as shown in figure 3.3. This shows a feedback loop consisting of a current measurement circuit measuring the current through the load, this is provide to the PID controller together with a reference signal, the PID controller will then create a reference voltage for the PWM generation, the duty cycle of this PWM generation is directly controlled by the reference. Now the duty cycle of this PWM signal controls the effective resistance of the controllable electric resistance, thus controlling the current drawn.

## 3.4 Energy Storage System

### 3.4.1 Energy Storage Method

For our design, a lightweight energy storage system is needed. The energy system must be able to supply enough electrical energy to power the microcontroller. When it comes to electrical energy storage systems, there are unfortunately not a lot of options. The most widely used for energy storage systems are batteries and supercapacitors, which can store the electric energy either in an electric field or chemically. Another way of storing electric energy could be by using inductors. The main disadvantage of using inductors is that storing energy in an inductor requires a continuous current to flow through the inductor.

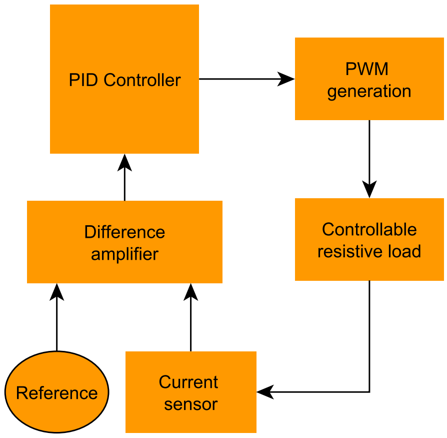


Figure 3.3: Abstract block level schematic for complete control system

Supercapacitors are mostly used for short time energy storage, while batteries can store more energy and keep the energy stored for a longer time. Because the weight is very limited as described in **REQ1.9**, and most of the weight will be due to the motor and aluminium casing parts, the energy storage part should contribute very little to the overall weight. The requirement for the total weight of the storage system is set to 50g.

### Batteries

**Comparison of battery types** Because lithium is a very light-weight material, and offers a high nominal cell voltage, lithium-ion batteries offer a high energy density in comparison to conventional batteries and offer a higher specific energy and specific power than Ni-Cd, NiMH or Pb-Acid batteries, as shown in the Ragone chart in figure 3.4 that was taken from the paper "Powering MEMS portable devices" [11]. Another advantage of lithium-ion batteries over Ni-Cd and NiMH batteries is that the lithium-ion batteries do not suffer from the so-called 'memory effect'. Due to this effect, nickel based batteries loose capacity if the batteries are not fully discharged before being recharged. This effect is highly disadvantageous in the current design situation, since the battery will be charged and discharged for short periods repeatedly during a workout. Due to the low specific energy of lead-acid batteries, and the memory effect of the nickel based batteries, the lithium-ion battery is the battery type that is most suited for this design.

**Lithium-ion batteries** Lithium-ions provide the advantage of a high energy capacity. It was found that lithium-ion batteries currently on the market that meet the requirements on size and weight have capacities of around 1-2 Ah, and energy densities of over 100 Wh/kg have been reached [14, 15]. This gives the advantage that the system can be powered for a long time, even when not being charged. Another advantage of lithium-ion batteries is their low leakage current of around 3% per month [16], which allows the energy to be stored for a prolonged period of time with neglectable losses. Lithium-ion batteries have a significant higher cost than conventional batteries, such as nickel or lead-based batteries. Lithium is a rare metal, which makes the batteries more expensive. While decreasing rapidly, production costs of most lithium-ion batteries are often still at around $500/kWh, with market prices of around 2-3 times this production cost. A second disadvantage of lithium-ion batteries compared to other battery technologies is the cycle lifetime. The capacity of lithium-ion batteries decreases with up to 40% after 300-500 full charge cycles[17, 18, 19]. Considering that most capacity fade occurs due to irreversible reactions that occur when the battery is fully depleted or overcharged, and that the battery will almost never be fully discharged in the usage scenario of the DISQ, it is expected that the capacity fade will have less effect than when the battery would be fully discharged. The charging of Lithium-ion batteries is a tedious task, and must be done carefully to ensure efficient charging, and to prevent overcharging the

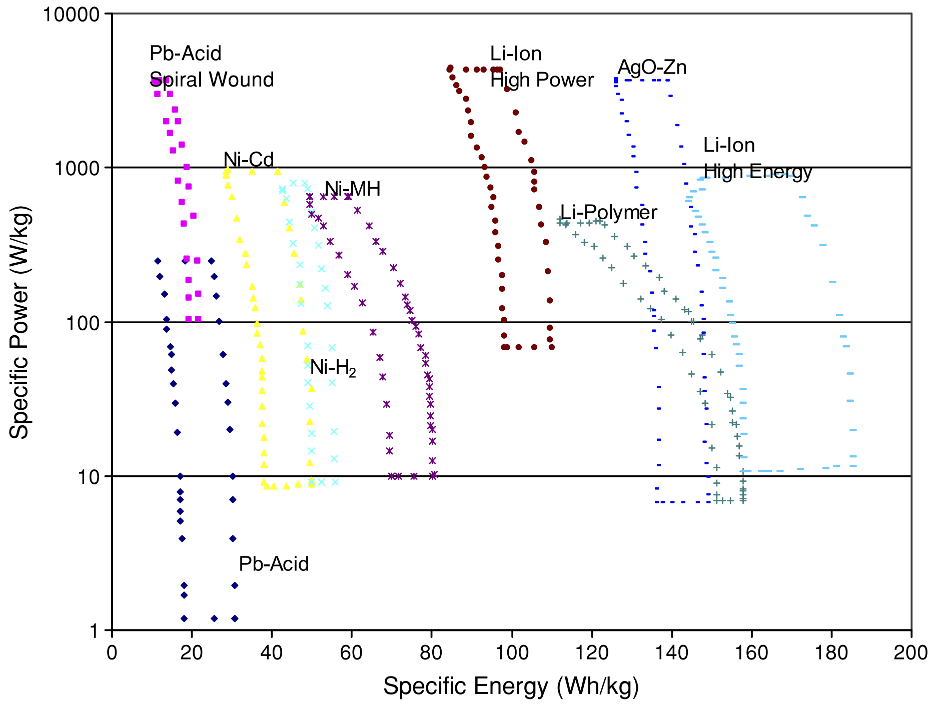


Figure 3.4: A comparison of the specific energy and specific power of different battery types. The figure was taken from the paper "*Powering MEMS portable devices – a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems*"[11]

battery. Even though the Lithium-ion batteries do not suffer from the memory effect that was mentioned in the paragraph on different battery types, they still require some control system that estimates the state of charge and charges the battery accordingly. More information is found in section 4.3.4.

**Supercapacitor**

Supercapacitors are capacitors that use cathodes with very small charge separation or electrochemical pseudocapacitance. The latter technique is based on the principle of Faradaic charge transfer to generate capacity by transferring electrons between the electrode and the electrolyte[20]. This method is a combination of chemical storage and electric field storage. It is said that supercapacitors bridge the gap between conventional capacitors and batteries, because they have a much higher power density than batteries, and a higher energy density than conventional capacitors [15]. Supercapacitors typically have a capacitance range from 1F for smaller capacitors up to a few hundred farad for larger capacitors. The advantage of the supercapacitor is that it can be directly charged by a current source. Because of their high power density, they can be charged really fast, and a large amount of input power could be used for charging when the supercapacitor is not fully charged yet. Typical energy densities are around 5 Wh/kg for commercially available supercapacitors. Supercapacitors have higher costs than conventional batteries, because of the advanced techniques used in production and because of the higher energy capacitance. The costs for energy are approximately $20/Wh with current technologies[21]. Supercapacitors have a very high lifetime, when they are stored at the right temperature. At room temperature supercapacitors typically have a lifetime of up to 10,000 cycles. The lifetime of the supercapacitors quickly decreases when the temperature rises above 65-85 degrees Celsius for most supercapacitors. [22]. This means that it is important to take the maximum operating temperature into account when using supercapacitors as storage units. The applied voltage also has a significant influence on the lifetime. This means that if the supercapacitor is used for long-term energy storage, meeting **REQ3.5**, the lifetime requirement of two years, might become difficult. Another disadvantage is that larger supercapacitors have cell voltage of around 2.7 Volts, and would thus not be able to power the electronics directly.

| | Specific energy | Pricing | Lifetime |
|---|---|---|---|
| **Supercapacitors** | 5 Wh/kg | 20 $/kg | 10 000 cycles |
| **Lithium-ion batteries** | >100 Wh/kg | 0.50 $/kg | 200-500 cycles |

Table 3.1: An indication for the specific energy, pricing and lifetime that can be achieved with current technoglogies.

#### Comparison

An overview of the specifications of supercapacitors and lithium-ion batteries is shown in table 3.1. Albeit larger than the specific energy of conventional capacitors, the specific energy of supercapacitors is roughly 10-20 times smaller than that of lithium-ion batteries of comparable size. It could be possible to design a energy storage system that powers the device for a sufficient time period to meet the requirements on the energy storage system, but the supercapacitor will be quickly depleted afterwards. The energy required to power the control system for one minute is approximately 21.6 J or 6mWh at 3.6V and with a 100mA load. Given the estimates for the specific energy as stated above, a supercapacitor of 50g with should be able to store about 250 mWh, and a Lithium-ion battery of the same weight approximately 2 to 5 Wh. Both devices would be able to power the device long enough to meet **REQ3.4**, but the battery would keep the device powered much longer. The main strength of supercapacitors is their high power density. Lithium-ion batteries on the other hand are cheaper and, as stated before, have a higher energy density. Since the electronics of the user interface (microcontroller and Bluetooth module) are a relatively stable and low-power load, and the main focus for the design of the energy storage system is minimizing weight and costs, it was decided to use a lithium-ion battery in favour of a supercapacitor. While the choice for a battery makes the charging of the energy system more difficult, the advantages of the lithium-ion battery still outweigh that of the supercapacitor. Further considerations on the choice of a specific commercially available battery that meets the requirements set on the energy storage system can be found in section 4.3.1.

### 3.4.2 Conversion

Another design choice that must be made is the usage of AC or DC for the power conversion. The generated power by the generator is three phase AC, while the energy management system involving the battery and the control system requires a DC input voltage. This means that somewhere along the way the AC power signal must be converted to DC by rectification. The rectification will be described in section 3.4.3. The amplitude of the output voltage of the generator is determined by the speed of the generator. To regulate the amplitude of the rectified DC voltage, there are three options for the design: regulating the amplitude before the AC/DC conversion, regulating the amplitude after AC/DC conversion or regulating it during the AC/DC conversion.

The first option, AC/AC conversion, is a widely used and efficient method to convert AC signals. The most common method for AC conversion is using a (variable) transformer. Transformers are passive components that allow for conversion with high efficiency. Although AC transformers are simple, robust and efficient, their disadvantage is that they are only mechanically adjustable, since the transformer is a passive component. A second drawback is the high weight of the transformer due to the coils and iron core.

The second option, DC/DC conversion, uses transistor switches to regulate the current that flows from the source, and uses capacitors and coils as short-term energy storage devices to generate a DC voltage at the output. DC/DC converters are complex circuits, that require an external PWM-signal to regulate the switching duty cycle can thus the conversion rate of the converter. The main advantages of DC/DC converters is that the conversion ratio is electrically adjustable. DC/DC converters have a relatively high efficiency.

The third option, voltage regulation during AC/DC conversion, uses transistor switches in a similar configuration to a rectifier to both turn the AC input into a DC output and to regulate the amplitude of this

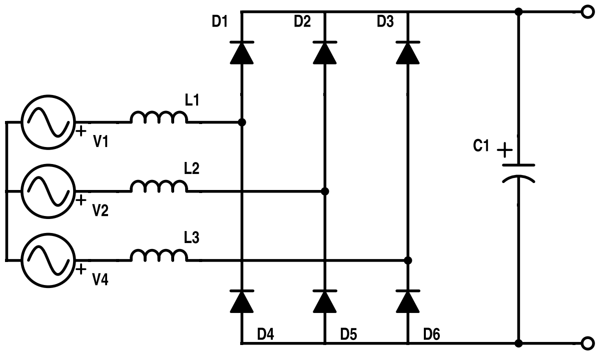


Figure 3.5: The three-phase passive rectifier with a smoothing capacitor at the output.

output. This method requires a complex control circuit and the only possible advantages are improved efficiency for the rectification (which isn't useful due to the energy dissipating nature of our complete system) and possibly fewer require components due to combining two subsystems.

Because of the high weight and low adjustability of transformers, and the complexity of AC/DC conversion it was decided to use DC/DC conversion to generate the appropriate DC level for the energy management system.

### 3.4.3 Rectification

The generator provides a 3-phase voltage. To convert this voltage to a DC voltage for the energy management system, a rectifier is needed. To fully convert the AC voltage, a full bridge rectifier is needed. Because rectifiers use diodes, and diodes always have a forward voltage drop over the diode, a diode-based diode bridge is bound to have losses. By using MOSFETS that are switched at the right frequency and with the right timing, this problem can be avoided, since the on-resistance of power MOSFETS is typically in the order of milliohms. This would result in a voltage drop over the MOSFET that is way lower than that of a diode. An active MOSFET rectifier requires a separate control system that measures the state of the generator or detects when the MOSFETs must be switched by looking at the generator output. in the current design, the efficiency of the converter is of less importance, since most of the power is dissipated and converted to heat anyway in the energy dissipation system. This means that as long as the diodes have an appropriate current rating, the losses in the rectifier are not problematic. Since an active rectifier requires MOSFETs instead of diodes, and a seperate control system, it was decided to use a passive rectifier instead. A schematic view of the passive three-phase rectifier is shown in figure 3.5. The full bridge three-phase rectifier converts the AC signal from the generator into a rectified DC voltage at the output. Because the output is a sum of the rectified sinusoidal phases, the output is a DC voltage with a voltage ripple. The capacitor that is placed parallel to the output of the rectifier reduces the ripple voltage of the output. Another effect that needs to be taken into account, is that the inductances in the generator requires the current to be continuous. Because the energy dissipation system consists of a resistive load that is switched on and off during at a high frequency, the capacitors need to be able to handle the current that the generator supplies during the off-time of the MOSFETs of the dissipation system. A calculation for the size of the capacitor is found in section 4.3.2.

## 3.5 Combining Different Subsystems

Now that the qualitative design choices have been made for the subsystems of the Energy Management System, a few considerations on how the subsystems can be combined are to be made. The overview and coordination of the different subsystems is shown in the system overview in figure 3.1. In this section the design choices that apply to the system as a whole are explained.

### Energy Dissipation System

The first design choice that was made is the placement of the energy dissipation system. The energy dissipation system can be placed before the rectifier or after the rectifier. Because the MOSFETs and the resistor that form the chopping circuit do not require a steady input voltage, it does not matter whether they are connected to the rectified voltage or the voltage directly from the generator that is not yet rectified. A disadvantage of dissipation before rectification, is that the unrectified signal has three separate phases, and would thus require three separate MOSFETs and resistor networks to work. Another disadvantage is the direct draw of the chopped current from the motor, which can induce voltage spikes in the motor, while after rectification the capacitor used for rectification will be a buffer for this effect. An advantage would be that there would be less current flow through the rectifier. However the effect this has on the design of the rectifier is marginal, and there are no other advantages of placing the dissipation circuitry before the rectifier, because of this it was decided to place the dissipation system parallel to the rectified voltage.

### Battery Charging Circuitry

The second design choice in the arrangement of the subsystems is the battery charging circuitry. The design choice for the battery charging circuitry is similar to the design choice of the dissipation system: both the rectified and unrectified signal from the generator system can be used as an input for the system. The circuitry needs to deliver a constant DC charging current to the battery. This can be done by designing the battery charging circuit as a regulated DC/DC converter. Another way of generating a direct current output voltage is by designing the rectifier as a buck converter. When the rectifier is implemented as an active rectifier, and the MOSFETs are switched at the right frequency and timing, the output voltage of the rectifier can be regulated. This would require a control system that is even more complicated than a standard MOSFETs based active rectifier as was shortly described in section 3.4.3. This also would mean that when the rectifier is implemented as an AC/DC conversion, the dissipation circuit must be implemented as an AC system, or connected to the output of the rectifier, which is directly connected to the battery. This is not a desirable option, since the battery requires a constant charging current. For those reasons it was decided to place both the battery charging circuitry as a DC/DC converter after the rectifier.

The battery charging circuitry charges the battery when the battery voltage is below 4.2 volts. The battery powers a DC/DC the electronics of the User Interface. Since the battery is connected in parallel to both the output of the battery charging circuitry and the input of the DC/DC converter, the battery charging circuitry can also bypass the battery and power the DC/DC converter directly. For example, when the battery charging circuitry has an output current of 250 mA, and the current that is drawn by the DC/DC converter is 100 mA, the battery is charged with a current of 150 mA.

### Current and Voltage Sensor

To accurately measure the power that is generated by the Generator System, accurate measurements of both the current and voltage are needed. It was decided to measure this voltage at the output of the rectifier, because all the current that is flowing from the generator also has to flow through the rectifier. When the current or voltage would be measured at the output of the Generator System itself, the same problem as before arises: the power output of the Generator System is three-phase. This means that the current and voltage must be measured in threefold when measured before the generator. It could be assumed that the current and voltage in the three different phases is on average approximately the same, but the problem remains that measuring AC currents and voltages is more difficult than DC voltages and currents.

## 3.6 Chapter Summary

The quilitative design choiches were made in this chapter. First, out of different energy dissipation methods, the method of a PWM chopper combined with a resistor network was chosen, because of its simplicity and minimal parts required. Secondly, a method for current sensing and an analog PWM control system was described, that enables the load to draw a constant current from the generator. Finally, different energy storage types were compared, and the lithium-ion battery was selected as the most suited type of energy storage.

# Chapter 4 | Quantative Design

In this chapter, the design that was made in the previous chapter will be elaborated. This includes choice of components and circuit design, as well as simulations of various circuits.

## 4.1 Energy Dissipation System

In this section the implementation of the energy dissipation system as first introduced in section 3.2 will be discussed. First the different options for implementing the controllable resistive load will be compared, then an implementation for the chosen option will be designed and evaluated and finally the heat dissipation for this system will be analysed.

### 4.1.1 PWM Chopper

A chopper circuit is a very simple method of an electrically adjustable electrical resistance. The basic idea consists of a switch implementation in series with the load as shown in figure 4.1, here a chopper is place while being fed by a 11,5V DC source with 3V peak to peak ripple, the PWM signal is simulated by the voltage source V3. By varying the amount of time the switch is closed $t_{on}$ or open $t_{off}$ the effective resistance can be varied, this can be done for both AC or DC sources[23, 24]. Here the effective voltage over the resistance equals $V_{eff} = \frac{V_{in} \cdot t_{on}}{t_{on}+t_{off}}$, or alternatively the effective resistance equals $R_{eff} = \frac{R \cdot (t_{on}+t_{off})}{t_{on}}$. Because of this the effective current also equals $I_{eff} = \frac{V_{in} \cdot t_{on}}{R \cdot (t_{on}+t_{off})}$. In these equations the proportion of time the switch is closed is also directly the ratio between the effective current/voltage and the maximum effective current/voltage. This ratio is called the duty cycle denoted by $D = \frac{t_{on}}{t_{on}+t_{off}}$. This concept is generally seen in devices controlled by PWM, as seen later for more general DC/DC converters in section 4.1.2.

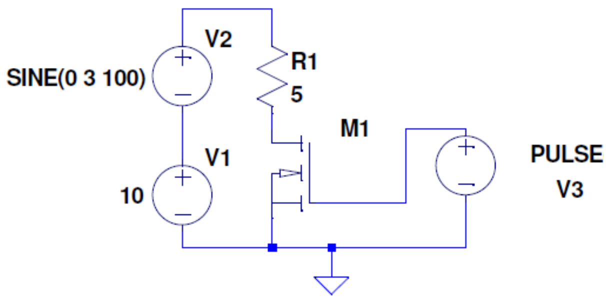


Figure 4.1: Chopper simulation circuit

The resulting current waveform is shown in figure 4.2, by having a high enough switching frequency this constant changing of the current between the maximum and minimum value won't be noticeable to the user, they will experience an adjustable (and with the correct control mechanism speed independent) mechanical resistance. The effects on the electric resistance will not differ much compared to a constant lower input, for an ideal resistance it will not have any influence at all. There are however extra stresses on the rest of the circuit due to higher peak currents and extra frequency content from the switching. One of the most important things that is affected by this side-effect is the current sensing circuit, that is used for the control system.

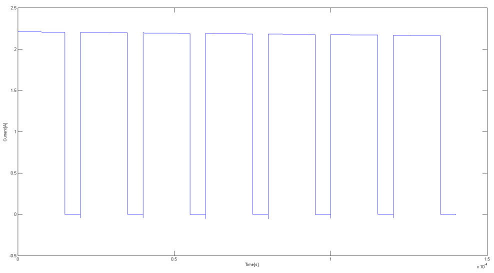

Figure 4.2: Chopper circuit current waveform for 75% duty cycle PWM input

### 4.1.2 DC/DC Conversion

The previously mentioned chopper is actually the simplest version of more general DC/DC conversion. There exist other methods which improve upon the basic chopper design in certain ways. DC/DC converters can control the conversion of the input and output voltage. This means that when a constant resistance is connected to the DC/DC converter output, the input current can be controlled. The buck converter and the buck-boost converter will be discussed in the next sections.

#### Buck Converter

A buck converter is quite similar to a chopper circuit, just like the chopper circuit it can only do down conversion and it does this by limiting the amount of time the power source is connected to the rest of the circuit. The difference is due to the more complex circuit around the load. An inductor, capacitor and a diode are placed around the load as shown in figure 4.3.

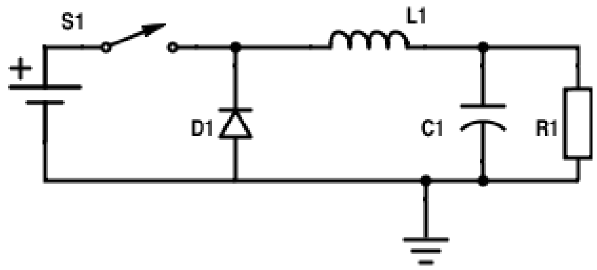


Figure 4.3: Buck converter circuit

A quick summary of the purpose of these extra components is that they provide energy storage, so the same energy as was previously provided to the load during the on part of the duty cycle is now provided over a complete period, so there is less change in the power supplied to the load during one period.
This can be precisely explained as follows: During the on part of the duty cycle the circuit as shown in figure 4.3 effectively changes to the circuit shown in figure 4.4. Here the diode is replaced by an open circuit, this is because the voltage source causes the diode to be in non-conducting mode and the switch is on so it's represented as a short circuit. This leaves a voltage source connected to a simple low pass circuit. Now upon initial closing of the switch the current through the inductor is 0. When the switch is closed the complete voltage of the input source will be over the inductor and the current through it will gradually become higher, storing energy in the magnetic field and lowering the voltage over the inductor. This also means the power supplied to the load will gradually become higher.

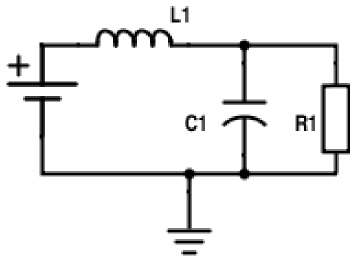


Figure 4.4: Equivalent circuit for buck converter when the switch is closed

Now when the switch is opened the circuit will have the properties of the one shown in figure 4.5, the input source is effectively removed and the diode will be conducting. Now the current through the inductor will be the same as before the opening because a current through an inductor cannot change instantaneously. The current through the inductor will gradually decrease as energy is extracted from the magnetic field.

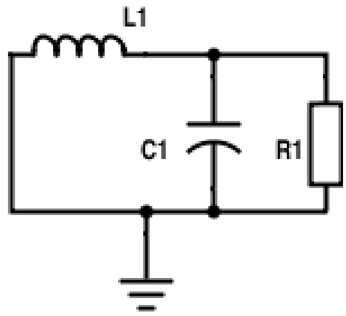


Figure 4.5: Equivalent circuit for buck converter when the switch is open

Now the continuous conducting steady state behaviour of this circuit will be analysed using a simplifying assumption. This assumptions is that the voltage over the load $V_l$ is constant, which can in real operation be approximated by choosing a large enough capacitor. The circuit only being in continuous conducting mode means that either the diode or switch is always conducting, which means that there will always be a current through the inductor.
In steady state the total energy delivered to the inductor while the switch is closed must equal the total energy the inductor delivers to the load while the switch is open, in this way keeping the current through the inductor the same at the start of every period. Since the voltage over an inductor equals $V = L * \frac{di}{dt}$, and by calling the voltage over the load $V_l$ and the source voltage $V_s$ it can be seen that while the switch is closed the voltage over the inductor $V_{i,on}$ must be $V_{i,on} = V_s - V_l$. Now the total energy delivered to the inductor is $E_{on} = t_{on} i_{av}(V_s - V_l)$. The voltage over the inductor while the switch is open $V_{i,off}$ is the voltage over the load with an opposite polarity to the previous voltage so $-V_l$, meaning the total energy delivered while the switch is open is $E_{off} = -t_{off} i_{av} V_l$. Now in steady state the energy stored in the inductor at the start of a period must equal that at the start of the next period, so the energy delivered over the period equals 0, meaning that $E_{off} + E_{on} = 0$. From this follows that $t_{on} i_{av}(V_s - V_l) = t_{off} i_{av} V_l$, which leads to $\frac{(V_s - V_l)}{V_l} = \frac{t_{off}}{t_{on}}$. Now $t_{off} = (1-D)T$ and $t_on = DT$, so $\frac{(V_s - V_l)}{V_l} = \frac{1-D}{D}$ or $\frac{V_s}{V_l} = 1 + \frac{1-D}{D} = \frac{1}{D}$ so $V_l = DV_s$, which is the same as the effective voltage seen earlier for chopper circuits, affirming that a buck converter is a method of implementing a choppers functionality but with a more constant current through the load.[25]
Now just how constant this load current is will be examined, this is most easily done with the same assumptions as previously. The change in load current while the switch is closed is then given by the constant $\frac{di}{dt} = \frac{V_s - V_l}{L}$ and for the time in which the switch is open it is $\frac{di}{dt} = \frac{-V_l}{L}$. The total change must

again be zero so it must hold that $DT\frac{V_s-V_l}{L} = (1-D)T\frac{V_l}{L}$, meaning either of these can be examined to find the ripple. Now $i_{av} = \frac{V_l}{R}$, from this the full expression for the minimum and maximum currents follows: $i_{max} = \frac{V_l}{R} + DT\frac{V_s-V_l}{2L}$ and $i_{min} = \frac{V_l}{R} - DT\frac{V_s-V_l}{2L}$. So this means the ripple normalized by the average current is $\frac{R}{V_l}DT\frac{V_s-V_l}{2L} = \frac{RDT(V_s-V_l)}{2LV_l} = \frac{RDT(\frac{1}{D}-1)}{2L} = \frac{RT(1-D)}{2L}$. Now this analysis assumed the current flowed continuous, so $i_{min} > 0$, to keep control simple L must be chosen so the remains true. So choose L so that $0 < \frac{V_l}{R} - DT\frac{V_s-V_l}{2L}$ or as given in equation 4.1 where the minimum value of L is given in terms of the relevant design criteria of the desired output current, input voltage, period and duty cycle.

$$L > DT\frac{V_s - DV_s}{i_av} = D(1-D)T\frac{V_s}{i_av} \tag{4.1}$$

**Buck-Boost Converter**

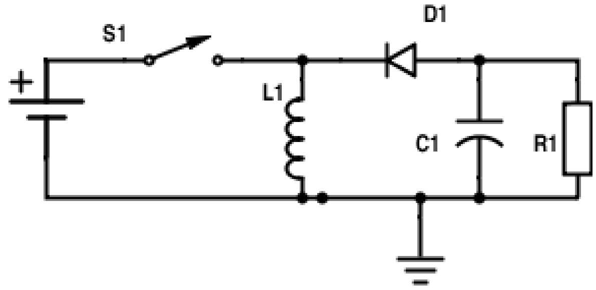


Figure 4.6: Buck-boost converter circuit

Another possibility is the buck-boost converter as seen in figure 4.6. The buck-boost converter is a DC/DC converter topology which allows both up and down conversion. This would be useful to be able to provide large mechanical resistance values at lower speeds. However this can also be done with a chopper by taking a smaller resistor value, which would simply mean that for the lower mechanical resistance values a higher duty cycle is needed, which isn't a problem. The main advantage would thus be that the control circuit doesn't need to know the resistor value.
The analysis for the buck-boost converter is similar to that of the buck converter. While the switch is closed the diode will not conduct, and the equivalent circuit is that shown in figure 4.7, which means the current through the inductor increases with $\frac{di}{dt} = \frac{V_s}{L}$ while the switch is closed.

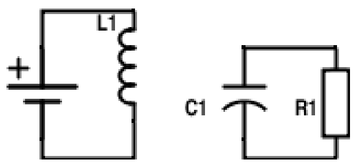


Figure 4.7: Equivalent circuit for buck-boost converter when the switch is closed

At the moment when the switch is opened the current through the inductor must be the same as the current was just before opening, the current will go through the capacitor and load parallel circuit and the diode, with the diode conducting because the current through the inductor is now decreasing, this gives rise to the equivalent circuit in figure 4.8. Now using the same assumptions as previously of a constant output voltage, constantly having a conducting path with the inductor (which means the inductor current can never go below 0) and the circuit being in steady state this circuit can be analysed in quite the same way as before.

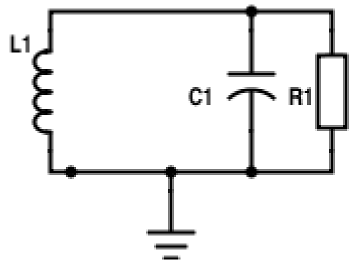


Figure 4.8: Equivalent circuit for buck-boost converter when the switch is open

The energy delivered to the inductor while the switch is closed must again be delivered to the load while it's open. This time while the switch is closed the voltage over the inductor is the full source voltage $V_s$ and because the current again has a constant slope the current can again be taken to be the average current $i_{av}$. This means the energy delivered is $E_{on} = V_s i_{av} DT$. The energy that the inductor delivers to the load and capacitor combination during it's on stage is $E_{off} = (1-D)TV_l i_{av}$. These must again sum to zero so this gives $V_s D = (1-D)V_l$, so $V_l = \frac{D}{1-D}V_l$. Do note the polarity's for these voltages in the circuits shown in figures 4.6,4.7 and 4.8, the output polarity is reversed compared to what was shown for the buck converter.
As before the ripple on the output current can be calculated and what is needed to satisfy the assumption of constant conduction. The maximum current through the inductor is again equal to the average current plus half the increase in current during one cycle of the switch being on, which is $DT\frac{di}{dt} = DT\frac{V_s}{L}$. So with $i_{av}$ again equalling the current through the load this gives $i_{max} = \frac{V_l}{R} + \frac{DTV_S}{2L}$ and similarly $i_{min} = \frac{V_l}{R} + \frac{DTV_s}{2L}$. The amplitude of the ripple normalized with regards to average current is $i_{ripple} = \frac{RDTV_s}{2LV_l}$, combining this with $\frac{V_s}{V_l} = \frac{1-D}{D}$ gives $i_{ripple,norm} = \frac{RT(1-D)}{2L}$. Now the requirement for a continuous conduction is the same as requiring that this normalized ripple is smaller than one, so. $1 > \frac{RT(1-D)}{2L}$, in terms of L this gives equation 4.2.[25]

$$L > \frac{RT(1-D)}{2} \tag{4.2}$$

### 4.1.3 Switchable Resistor Network

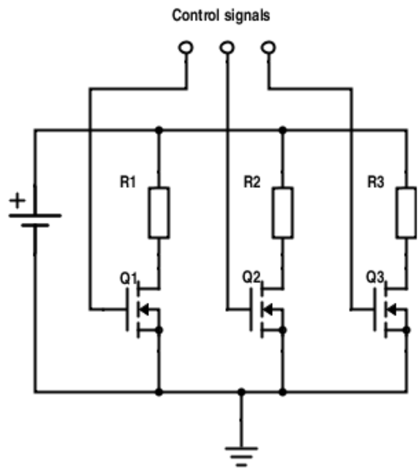


Figure 4.9: Switchable resistor network

A switchable resistor network is a network of resistors and transistors . Which could be a parallel set of resistors in series with transistors as in figure 4.9. The main advantage to this method compared to

the methods mentioned previously is the absence of any higher frequency signals, which simplifies the sensing for the control circuit.
This circuit however has disadvantage in the fact that the possible equivalent resistance values are quantised, there is a finite set of possible resistance settings. This can of course be mitigated by a large enough set of resistor values but this would require more control signals, which depending on the amount of MCU outputs might or might not be a problem. It also makes the MCU necessary for the control, for the previously mentioned methods an analog control circuit could be created. This could also be a problem if the MCU isn't actually fast enough to control for speed independent mechanical resistance.

### 4.1.4 Comparison

In general the switchable resistor network would require too many control signals for all the different transistors, in general making the circuit a decent bit more expensive while not providing any real benefits besides being extremely simple in its concept. However the other possibilities are also quite simple. These different kinds of PWM switched DC/DC converters are quite similar. The simple chopper requires the least care in creating its control signal due to not having any limits on simple operation, which the buck and buck-boost do due to the limit on the continuous conductance operation. The main point in favour of them however is the more constant current through the load, which might help if the control circuit uses infrequent measurements to base its control off of. However this is effectively done through a simple low pass filter to the load, which can also be implemented for a current sensing circuit in the choppers case. The buck-boost converter also has the benefit of being able to both convert up and down, making the maximum current (and thus maximum torque the user experiences) independent from the resistance value chosen, this however isn't actually a very large advantage because it's still effectively limited by the continuous conductance mode limits and because choosing the correct resistance value for the maximum require current is very simple. A large margin can be taken for this choice to even allow some leeway in this. Because of this the simple chopper is the best choice for a simple resistor based dissipation network.

### 4.1.5 Implementation

Implementing the chopper circuit is extremely easy. As shown before in figure 4.1 this just consists of a transistor and a resistance in series. This will then be placed in parallel to the battery charging system. For physically implementing this chopper it's important to consider the heat dissipation. For this purpose it's handy to implement the resistance in series with the transistor as a larger set of separate resistances to allow their distribution over the complete package of the DISQ, in this way making sure there isn't one large hotspot but instead an even distribution of heat over the whole device.
The total resistance of the system can be determined from the motor characteristics, torque requirements and extension speed requirements. These requirements have already been translated into requirement **REQ3.10** which states that a 6A current must be reachable at an input of 5V upto 30V. This requirement is most restrictive at the 5V end and at that point it directly translates into a maximum of 1Ω resistance, which would allow reaching this requirement with the duty cycle set to 1. By using 20 separate resistors for this the heat generated can be spread out over the casing. Each resistor will dissipate $\frac{90W}{20} = 4,5W$, for this purpose the SM_5 $0,9\Omega$ power resistors made by TE will be used, which are rated for 5W dissipation[26].
The transistor in this circuit mostly needs to have a low enough on resistance and a reasonably quick switching speed. The switching speed is based on the frequency of the PWM signal, which should sufficiently high for the user to not notice the switching itself in the resistance, which would mean at least a switching frequency of $100Hz$, however the frequency components this might introduce in the motor must also be considered, which might cause undesirable sounds. To avoid the production of undesired audible noise signals, the PWM frequency should be outside the audible range and for this purpose a $50kHz$ frequency should be good enough. To allow for this the rise and fall times of the transistor should preferably be no higher than $1\%$ of a PWM period to allow sufficiently fine grained

control of the effective duty cycle. The rise and fall times determine the precision with which the duty cycle can be set. Taking this in account, the maximum rise time becomes $\frac{1}{50kHz*100} = 200ns$. For the turn on resistance a reasonable maximum is 5% of the total resistance, which would be 0.05Ω. This under the assumption that a human can't feel a 1% change in resistance. Besides these requirements the transistor must be able to withstand 40V drain to source voltage while it's not conducting to meet requirement **REQ3.9**, and it should preferably not have a gate source threshold higher than $3.5V$, because if it's lower the supply voltage for the interface system is high enough to drive this gate.
To meet these requirements the STD30NF06L N-channel MOSFET made by STMicroelectronics was chosen, with rise and fall times twice as low as required, an on resistance that is slightly lower than required, and it can withstand 60V drain source voltage and with a typical threshold of 1,7V[27]. This meets all our requirements.

### 4.1.6 Heat Dissipation Calculations

If the dissipation is done through a simple resistor this will turn all the electrical energy directly into heat in the resistor. With a maximum of 90W this will require some consideration for the dissipation of the heat. An easy method that generally works to dissipate heat in electric components is a good thermal connection to a large enough plane of metal, if this connection is good enough the thermal resistance between the components and the metal should be negligible. This can be achieved by simply using more of the same resistor to provide a larger surface area. This metal plate is mostly to easily provide the surface area necessary for dissipating heat to the air around it.
The easiest way of calculating this is the thermal circuit analogy for heat dissipation, in this model heat transfer Q is equivalent to current, temperature difference $T_1 - T_2$ to voltage difference, thermal resistance $R$ to electrical resistance and heat capacity $C$ to electrical capacitance[28]. Due to the low thermal resistance for packaging to bulk for the resistors and due to the primary concern being the temperature of the DISQ case the resistance from resistors to the case will be assumed to be 0. This leaves the thermal circuit shown in figure 4.10, where the power source models the electric power converted to heat in the resistors, the resistance models the thermal resistance from the casing to the air and the capacitance models the total heat capacity of the case.

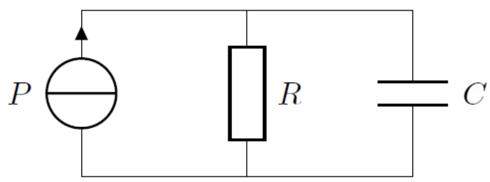


Figure 4.10: Simple thermal circuit for DISQ heat dissipation calculations

For this situation the primary mechanism of heat transfer is convection, which is governed by $Q = h*S*(T_p - T_a)$, where S is the surface area of the plate, h is the heat transfer coefficient and $T_p - T_a$ is the difference in temperature between the plate and the air[29]. Now the value for h is hard to determine, generally the best method is using a convective heat transfer correlation experimentally obtained for your situation, where air flow and case shape determine the value. Now the formula's for this quickly become unwieldy and don't provide much extra insight and the air speed can also be hard to predict. Typical values the heat transfer coefficient for low speed air flows over a flat plate can range from $h = 5\frac{W}{m^2K}$[30] to around $50\frac{W}{m^2K}$.
Now all parameters for the thermal circuit can be given, the assumptions used for finding them are shown in table 4.1. Now the thermal resistance R is $R = \frac{1}{hS}$. For a certain power input P this gives the following differential equation for the casing temperature $T_d$: $\frac{\mathrm{d}T_d}{\mathrm{d}t} = \frac{P-R(T_d-T_a)}{C}$ with initial condition $T_d(0) = T_a$. Solving this gives $T_d = T_a + \frac{P}{R}(1-e^{-\frac{R}{C}t})$.
Two usage scenarios have been specified in requirement **REQ3.14**, a 30 minute workout at 45W input or

| Parameter | Value |
|---|---|
| Total heat capacity C | $0,9\frac{kj}{K}$ |
| Casing surface area S | $0,04m^2$ |
| h minimum | $5\frac{W}{m^2K}$ |
| h maximum | $50\frac{W}{m^2K}$ |
| Ambient temperature $T_a$ | $20C^\circ$ |
| Maximum tolerable temperature | $60C^\circ$ |

Table 4.1: Estimates for relevant paramters for heat dissipation calculation

a 10 minute workout at 90W input. The final temperatures for a range of values of h are shown in figures 4.11 and 4.12. As expected it can be seen that changing the values of h has a larger effect for the longer workout.

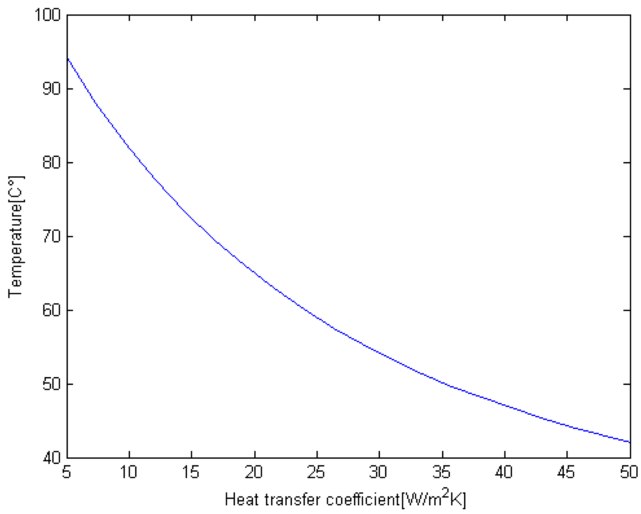


Figure 4.11: Final temperature values for constant 45W input after 30 minutes for varying thermal conductivity coefficients

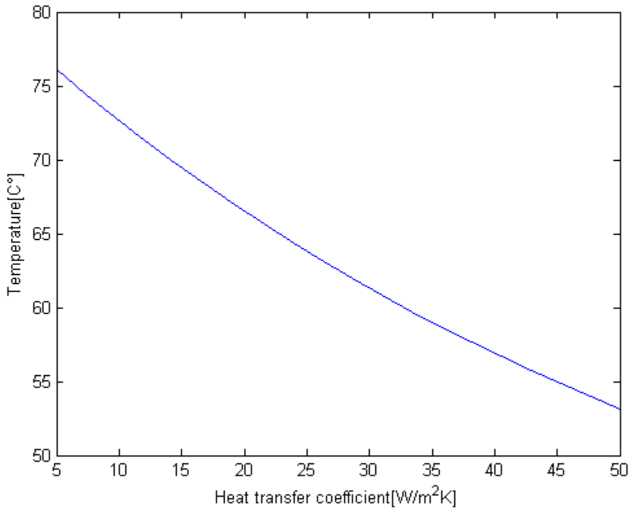


Figure 4.12: Final temperature values for constant 90W input after 10 minutes for varying thermal conductivity coefficients

In general values of h above $24\frac{W}{Km^2}$ for the 45W 30 minutes workout and values above $30\frac{W}{Km^2}$ are for the 90W 10 minutes workout are sufficient to keep the device below $60C^{\circ}$ under the assumptions shown in table 4.1. It's currently not certain that these values of h will be reached, however with the user moving while using the system a decent airflow can be expected, so it's likely these values will be reached. If they aren't the outside of the device would need to have a larger surface area, this could possibly be done by adding fins.

## 4.2 Energy Dissipation Control

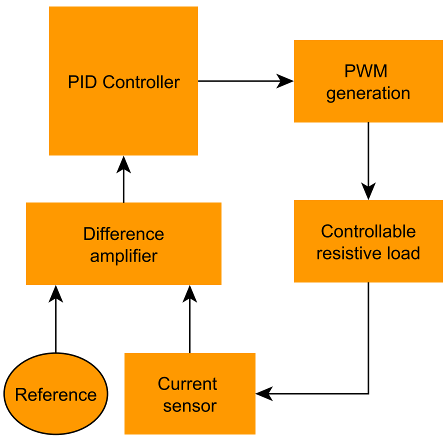


Figure 4.13: Control system overview repeated from figure 3.3,for reference only

In this section the design of an analog system for keeping the current drawn from the motor constant will be discussed, the design of this circuit is done purely as an alternative for the MCU based one of the User Interface. The overall design choices for the control system were discussed previously in section 3.3, the system will control a simple PWM chopper with a resistor in series, this will be done through varying the duty cycle of the system. The implementation of this system will consist of a set of subsystems. First a current sensing circuit will be discussed which provides feedback for the control, then a simple method of generating a PWM signal will be presented, followed by the circuit implementing the control itself.

### 4.2.1 Current Sensor

The control system will require a feedback mechanism. This feedback mechanism will be provided by a current sensor that measures the current delivered to the resistor and the battery management system. The easiest way of doing this is by using a shunt resistor in the current path to convert the current to a voltage and then use an amplifier to amplify this signal to something usable for the control circuit. This circuit could be implemented as in figure 4.14. In this figure, R2 is the shunt resistor in the main current path, and R1 is the main load. The voltage source represents the output of the rectifier.

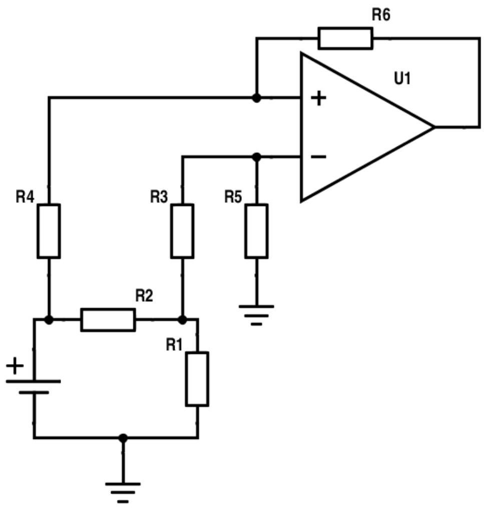


Figure 4.14: Basic current sense circuit measuring current through main power path

In the final circuit the INA139 high side current sensor IC was used. This is because this IC is easily supplied through its wide range of possible voltage inputs[31]. With a shunt resistor of $0,005\Omega$ the input currents ranging from 0A to 6A will be converted to an differential voltage on the inputs of the IC of 0 to 0,03V, this is converted by the IC to an output current between 0A and $30\mu A$ through a transfer function of $g_m = 1000\mu A/V$, this is then turned into a voltage output between 0 and 1,68V. Because the input varies very quickly due to chopper this output will also vary with the same frequency. It might be a good idea to filter this output with an capacitor before providing it to the control system.

### 4.2.2 PWM Generation

For generating the PWM output signal a circuit is needed that can provide a constant frequency approximately square waveform in which the high and low time of the waveform is adjustable by an electric signal, which is the control signal in this case. Now there exists a quite standard method for generating the PWM signal, first a circuit is made that creates a triangle waveform and then that is used as input for a comparator together with a reference voltage that controls the duty cycle. Now when the triangle wave signal is lower than the reference the output of the comparator is $V_{DD}$ otherwise it's 0. The idea here being that the reference is created such that it's between the maximum and minimum values of the triangle wave signal. A graph of how the reference input and the triangle waveform input form the PWM signal is shown in figure 4.15, showing how the PWM output is high when the reference signal is higher than the triangle input. This thus allows the PWM duty cycle to be controlled by controlling the reference signal.

This fairly standard circuit for the triangle wave creation can be seen in figure 4.16[32]. It's made with the combination of a Schmitt trigger circuit and an integrator. The schmitt trigger switches its output

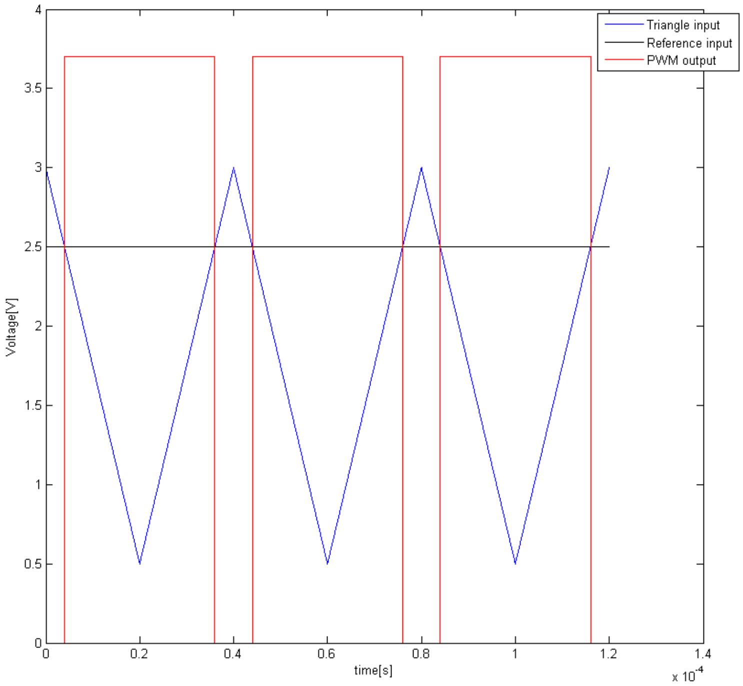


Figure 4.15: PWM generation waveforms

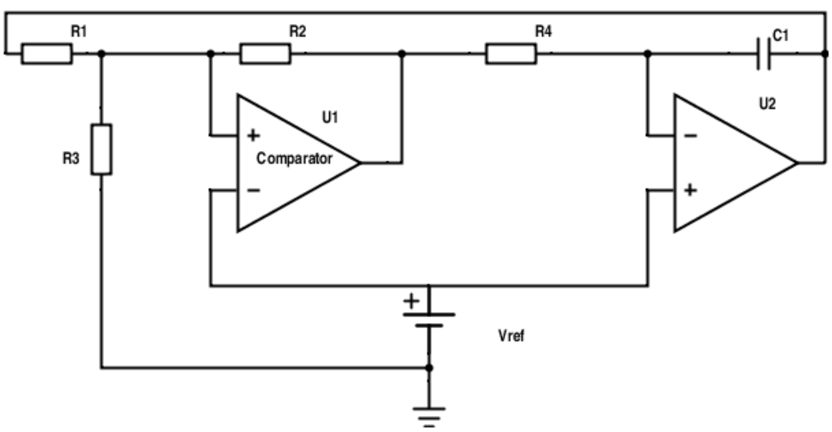


Figure 4.16: Triangle waveform generation circuit

between its lowest or highest every time the integrator reaches a certain output value as set by a reference input to the Schmitt trigger. So the input to the integrator is either a constant low or high signal depending on the state of the switch, integrating this gives ramp output signals for the integrator, because the integrated signal always has the same 2 possible amplitudes the time required for the integrator output to reach the value required for the Schmitt trigger to switch is always the same, which means that this circuit produces a triangle wave output at a constant frequency, it's important to note that this signal has a maximum value $V_{trimax}$ lower than $V_{DD}$ and a minimum $V_{trimin}$ higher than ground, this is due to the thresholds of the Schmitt trigger. The resulting waveforms for both the schmitt trigger threshold and the triangle waveform output are shown in figure 4.17.

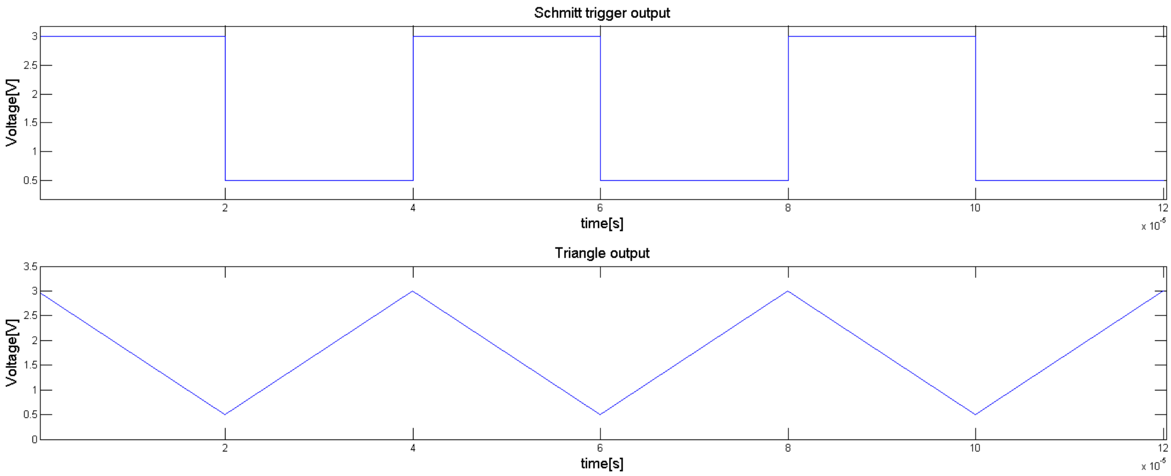


Figure 4.17: Output of both subcircuits for triangle waveform generation

### 4.2.3 Reference Control Generation

With the current sensing input voltage and the triangle waveform available all that is left is designing the circuit that takes a user controlled reference voltage and the current sensing voltage and turns it into a reference voltage for the PWM generation comparator.
The output voltage must be able to vary between atleast 0,5V and 3V to be able to create the complete range of possible duty cycles and the current sensing input will vary between 0 and 1,68V. An easy way of implementing this controller is a difference amplifier with as inputs the reference and current sense signals with an integrator afterwards. The circuit for this can be seen in figure 4.18. In this circuit the user would set the required torque through choosing a setting for R6, which would give a certain fraction of $V_{DD}$ as voltage reference input.

The first opamp configuration is that of a differential amplifier, at this first opamp the reference and current sense inputs are compared, if they don't differ the output is approximately the reference voltage $V_{dd}\frac{R_8}{R_8+R_9}$ as long as $R_8$ and $R_9$ are chosen sufficiently small so the other parallel resistances won't have an effect. Now compared to this reference voltage the voltage on the positive input is $V_{dif-} = V_{sense}\frac{R_4}{R_4+R_3}$. This same value will thus be forced on the negative input, so for a given input reference setting $V_{set}$ from $R_7$ and $R_6$ this gives the output $V_{dif,out} = V_{sense}\frac{R_4}{R_4+R_3}\frac{R_2+R_1}{R_1} - V_{set}\frac{R_2}{R_1}$. If $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ this simplifies to $V_{dif,out} = \frac{R_2}{R_1}(V_{sense} - V_{set})$. A thing to note is that the output signal is positive if the current sense signal is the larger one.
This error signal is then integrated by the next circuit, in this way an integral control system is created. It's also possible to replace this integrating opamp circuit with a direct amplifier circuit for proportional control, or both could be done with a summer, differentiators could also be added for full PID control, however for now just integral control will be used. For the integrator if the error signal is higher than the reference a current runs through R5, in this case this current is $I_{integrate} = V_{dif,out}/R_5 = \frac{R_2}{R_5 * R_1}(V_{sense} - V_{set})$.

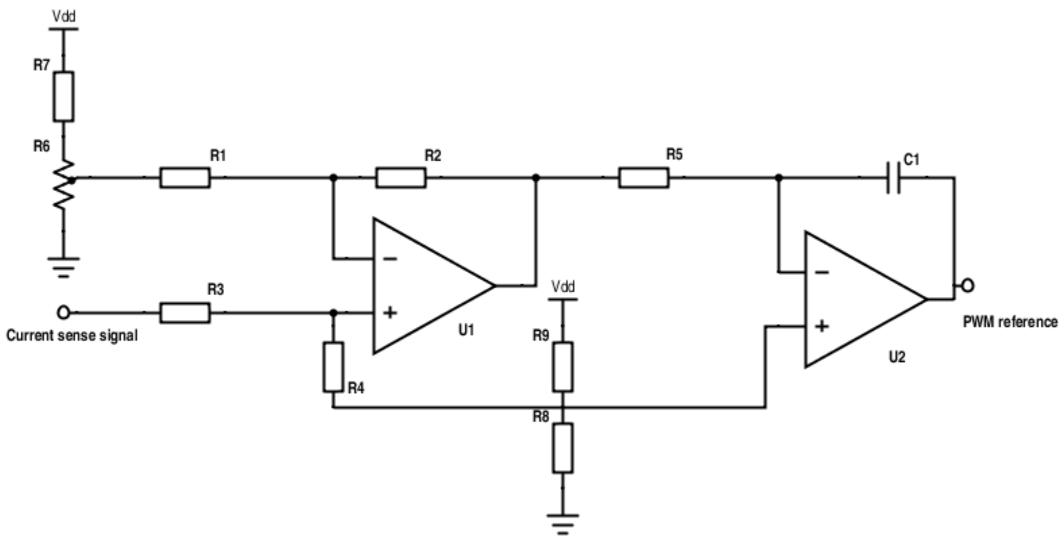


Figure 4.18: Control signal circuit made from difference amplifier and integrator

This is then integrated by passing it through $C_1$.
The values for the components in the combination of integrator and error amplifier will need to be chosen so that the circuit is sensitive to changes in current due to the start of an extension of the cord but preferably not due to the chopper constantly changing the current. For this purpose a decent estimate is that frequency components of the error signal upto $100Hz$ should be passed on and those above $10kHz$ should be mostly ignored. This can be done by making the integrator sufficiently slow, making sure the delay isn't noticeable to humans but turns the full chopping ripple on the current sense input into an at most $10mV$ ripple on the reference signal which is used for the PWM generation comparator.
A good way of determining the values for $R_1$,$R_2$,$R_5$ and $C_1$ is looking at how long it takes to go from a $V_{tri,min}$ output (taken to be 0,5V for this circuit, corresponding to 0 duty cycle) to the correct duty cycle for an extreme case, for example the one posed in requirement **REQ3.10**, being 5V input and 6A required. In this case the duty cycle needs to reach the maximum, which means the output voltage needs to reach the maximum value of the PWM comparator triangle input $V_{tri,max}$, while the input current sense starts at 0V and the current setting reference signal $V_{set}$ is set to the current sense signal corresponding to 6A, which is 1,68V.
Because while the duty cycle increases the error signal decreases the output of the differential amplifier will also change. For this first analysis it will be assumed that there are no delays in the PWM generation and the current sensing circuit. It is also assumed that the output of the current sense circuit will be directly proportional to the average of the current, completely rejecting the higher frequency components due to the chopper. Thus it is assumed that the current output is directly proportional to the duty cycle output, so the current sense signal's value $V_{sense}$ effectively becomes equal to the duty cycle times the maximum current sense value for this input voltage, corresponding to 100% duty cycle. The duty cycle here is $D = \frac{V_{int,out}-V_{tri,min}}{V_{trimax}-V_{tri,min}}$, giving $V_{sense} = (V_{int,out} - V_{tri,min})\frac{V_{set}}{V_{tri,max}-V_{tri,min}}$ however with a minimum of 0. Now $V_{int,out}$ changes through the integration of the difference amplifiers output, so $V_{int,out}(t) = \frac{-1}{R_5C_1}\int\frac{R_2}{R_1}(V_{sense}(t) - V_{set})\mathrm{d}t$. For readability the substitutions $A = \frac{R_2}{C_1R_1R_5}$ and $B = \frac{V_{set}}{V_{tri,max}-V_{tri,min}}$ are made, now the equation can be solved to find:

$$V_{int,out} = \frac{V_{set}}{B} + V_{tri,min} - c_1ABe^{-ABt}$$

Using the initial condition $V_{int,out} = V_{tri,min}$ the value for $c_1$ can be found to be $c_1 = \frac{V_{set}}{AB^2}$, giving equation 4.3 as the final equation.

$$V_{int,out} = \frac{V_{set}}{B}(1-e^{-ABt}) + V_{tri,min} = (V_{tri,max} - V_{tri,min})(1-e^{-ABt}) + V_{tri,min} \tag{4.3}$$

The value for parameter A will mostly be based on the assumption that humans won't notice changes in the torque past $100Hz$, which means delays shorter than 10ms. With this in mind A is chosen so that the time between the step in $V_{ref}$ from $0V$ to $1,68V$ and the output coming within a 5% margin from $3V$ is not higher than 10ms. Keeping this closer to 10ms would be best to avoid overshoot and ripple. Now using equation 4.3 gives $A = -\frac{ln(0,05)}{Bt}$. With B determined by choices for previous circuits and t chosen to be $5ms$ gives $A = 832$.
This value of A needs to be implemented by $A = \frac{R_2}{C_1 R_1 R_5}$, the main considerations for choosing these values are the amount of power used in the circuit and the effect offset errors have on the control, higher power drawn generally meaning a smaller effect from the offset errors. A possible set of values is $R_1 = 50k\Omega$, $R_2 = 100k\Omega$, $C_1 = 0,25\mu F$ and $R_5 = 9k\Omega$, this is quite a reasonable and easily available set of values so this shouldn't give any problems.
In figure 4.19 a graph can be seen for the calculated response in instantaneously setting the requested current from 0A to 6A with a 5V generator output.

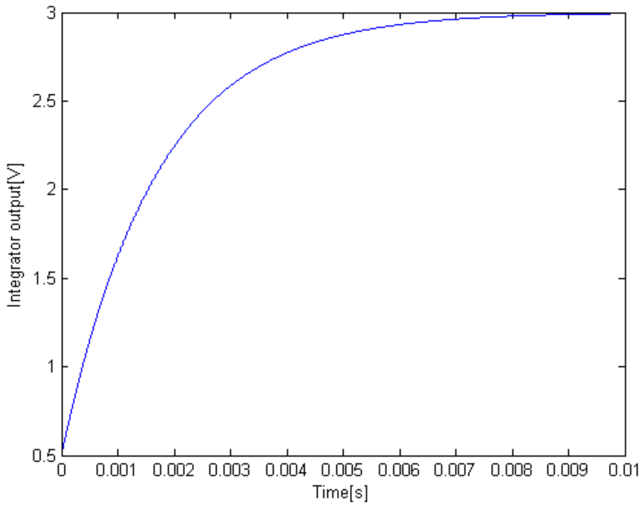


Figure 4.19: Calculated integrator output for step change in the current setting from minimum to maximum

Now this is the theoretical response for the complete control loop for if the rest of the system has no delays in it and the PWM didn't change what percentage of the time the current flowed but instead directly controlled the magnitude of the current. These assumptions are very inaccurate however the inaccuracy can be minimised by having the integrator integrate slow enough so that all the high frequency components are filtered out, thus ignoring the error introduced due to the chopping. If the chopping does turn out to have a large effect this would be seen as a ripple on $V_{out}$, in this case the output of the current sensing circuit needs to be low-pass filtered. It's unlikely that this would be needed because the absolute maximum change of the integrator output in one period of the PWM signal is 0,05V which is a 2% change in duty cycle. The other possible source of errors is that the other delays in the feedback loop are too large relative to the speed of integration, in this case the output should show an overshoot before settling down.

### 4.2.4 Summary

In this section the design of all the blocks seen in figure 4.13 has been discussed. It was seen that most blocks could be implemented quite simply with a small amplifier circuit, with the complete system together implementing a current control system. A large amount of the design choices made depend on assumptions that should be tested on a real world model, because they have to do with assumptions on

| Name | BAK 18650CA-1S-3J |
|---|---|
| Cell voltage | 3.7V |
| Rated capacity | 2250 mAh |
| Weight | 50g |

Table 4.2: The specifications for the battery that is used for the energy storage[34]

what a user would find comfortable.

## 4.3 Energy Storage System

### 4.3.1 Battery Choice

In section 3.4 the design choices was made between different storage methods, and the lithium-ion battery was chosen as storage method due to the high specific energy. This allows for a high energy storage capacity at low weight. Lithium-ion batteries have a decreased lifetime when they are frequently overcharged or deep discharged, because when the battery is fully charged or fully discharged, the regular ionization of the lithium can no longer fully account for the current that is drawn or fed in to the battery, and other irreversible processes start to take place inside the battery [33]. It is therefore desirable to have a battery that has a larger capacity than the absolute minimum as specified in **REQ3.4**, so that the lifetime of the battery can be prolonged, which helps meet **REQ3.5** on the lifetime of the devices.

The battery that was selected for this project is the BAK 18650CA-1S-3J. The specifications of the battery are shown in table 4.2. The battery was selected for its weight. Previously it was determined that the weight of the battery should not exceed 50g. The battery also has a fairly low cost to capacity ratio compared to other batteries. A quick calculation shows that with a nominal voltage of 3.7V and a capacity of 2.25Ah, the battery could theoretically store 8.3Wh. If the control system draws a current of 100mA at 3.6V, the output power is 0.36W. This means that the battery could in theory power the device for almost 24 hours. This is way more than the 5 minutes that were specified in the requirements. This is an advantage, because this means the DISQ will be able to function for a long time even when the workouts are not long enough to charge the battery. This also means that if the battery suffers from capacity fade due to ageing, the capacity still will be more than enough to power the control system.

### 4.3.2 Rectification

The most important design aspect for the rectifier is the choice of the smoothing capacitor. The smoothing capacitor is needed to reduce the ripple and spikes on the rectified DC voltage. Because the rectifier is followed by a chopper circuit, there are discontinuities in the current that is drawn from the rectifier. The generator can be modelled as a voltage source with a series resistance and series inductance. This inductance of the motor can cause high voltage spikes when the current is discontinuous, since the current through an inductance must be continuous. The smoothing capacitor must thus be able to absorb the excess energy from the coil without exceeding its maximum voltage rating and with an acceptable voltage rise. The main problem in the current design will be the voltage spikes that might occur due to the inductances in the generator. The ripple that is introduced by the rectification is not problematic for the current design, since the energy dissipation system does not require a steady DC input voltage. The battery charging circuit does require a DC voltage with low ripple, but is separated from the rectifier by a diode and a large separate capacitor. The calculations on the voltage rise due to the switching are difficult to solve analytically, and therefore some assumptions are made to simplify the calculations. When assuming the current that is coming from the generator is constant, all the current that flows through the load must be able to flow through the capacitor as well. the current-voltage relation of the capacitor can be rearranged, the following expression for the required capacitance is found:

$$C = i\,\frac{\Delta t}{\Delta V} \tag{4.4}$$

Where $i$ is the current that the capacitor needs to be able to absorb from the generator for a time period $\Delta t$ and a voltage rise of $\Delta V$. A current of 3A is assumed, half the maximum current. The time period that the capacitor needs to absorb the voltage will on average be half the period of the PWM signal. As described in section 4.2.2, a reasonable value for the PWM frequency is 50 kHz, resulting in a $\Delta t$ of $10\mu$s. When a voltage ripple $\Delta V$ of 0.1V is required, the size of the capacitor must be at least $300\mu$F. For extra safety margin it was decided to place four SMD capacitors of $100\mu$F in parallel.

### 4.3.3 Output Voltage

The output voltage of the battery is not yet sufficient to use as supply for the other circuits in the complete system. The maximum output voltage is too high and the voltage output of the battery depends on how charged it is, going down as the battery discharges. To fix this some kind of output voltage regulation is required, in this section the implementation of this part is discussed.
The output voltage of the battery varies from a discharge cut-off voltage of 2,3V to a nominal voltage of 3,7V[34]. The input voltage for the output regulator can become even high because the nominal charging voltage of the battery is $4.2V$[34]. To be able to make efficient use of the total capacity of the battery this will thus indeed require both up and down conversion to reach a stable output voltage of 3.6V as required by requirements **REQ3.12** and **REQ3.13**.
A possible method of achieving this is a combination of a buck-boost converter, the design of which was discussed in section 4.1.2, and a control system which measures the output voltage and then regulates it to 3.6V through feedback with a PWM signal to the buck-boost converter, the design of which would be very closely related to the design of the current regulating control system discussed in section 4.2.
The only real differences in designing this system would be the input signals and the supply voltage for this section. For the voltage reference a simple linear regulator could be made, there won't be any power drawn from this signal so a simple circuit like the one shown in figure 4.20 could work. The idea behind the circuit is that the zener diode has a well defined breakdown voltage at which it starts conducting, forcing the voltage over it to become precisely that value. Here $R_2$ is the load that needs to be fed and $R_1$ is chosen so that the required load current and zener current are drawn from the battery.

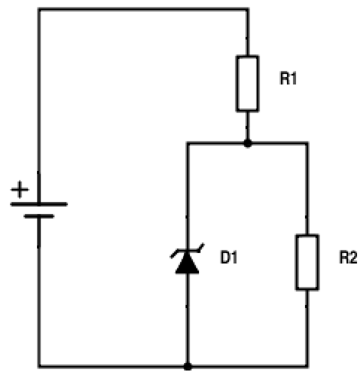


Figure 4.20: Simple voltage regulator based on a zener diode

For the PWM signal generation the opamps chosen just need to be able to work with any voltage between 2,3V and 4,2V, and the mossfet in the buck-boost converter needs to have a threshold voltage below 2,3V. These requirements are both easily attainable so this should be possible to make. It would however use the same amount of opamps seen in the control system design previously, while there exist standard IC's specifically designed to create programmable regulated supply voltages from a lithium-ion battery input. This option is both cheaper and far easier to implement so this route will be taken.
The chosen IC is the LTC3536 [35], it can handle input voltages from 1,8V to 5,5V so this is sufficient for this application. Besides that the output voltage is programmable through resistors around it to any value between 1,8V and 5,5V. The circuit around the IC has been designed following the specification in the datasheet, resulting in the circuit shown in figure 4.21.

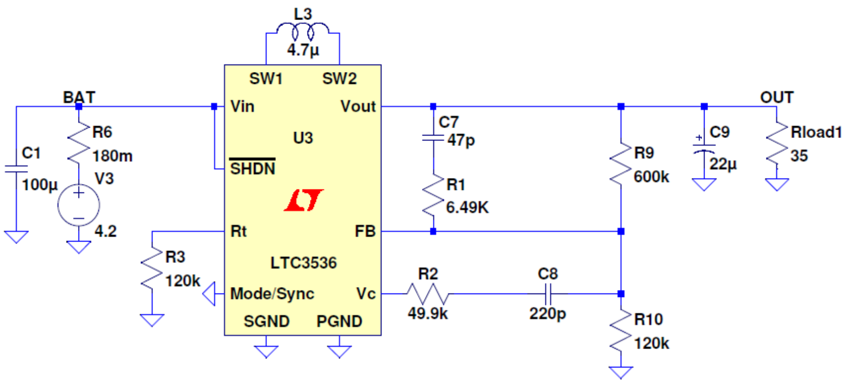


Figure 4.21: Output voltage regulation circuit implementation

### Simulation

The simulations for the circuit were done using the schematic shown in figure 4.21. The most important information is whether the correct output voltage is obtained, the simulation results for this can be seen in figure 4.22. The output voltage can be seen to reach the desired output of 3,6V within 1ms and then it stays constant at this value, so as far as output voltage goes the circuit seems to be functioning.

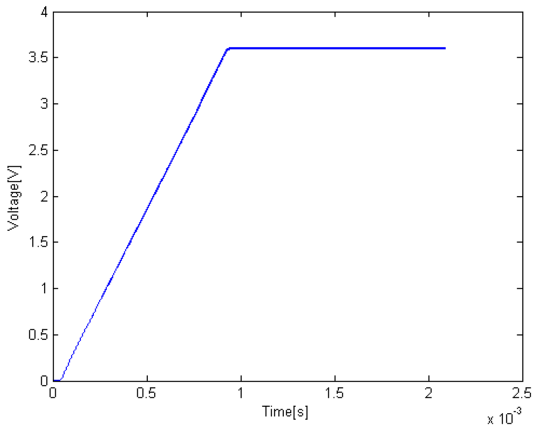


Figure 4.22: Output voltage regulation circuit's output voltage on startup with a 35Ω load

Now another important piece of information is how much current this circuit draws in total, for this simulation look at figure 4.23, all that can be seen from this is that the current drawn varies very quickly, this is logical because of the internal DC/DC converter switching frequency being around 1MHz. For a more understandable graph look at figure 4.24, here the current signal convoluted with a unity area $10\mu s$ long signal is shown, so effectively this is a graph of the $10\mu s$ is shown. This still varies strongly but it can be seen that the current during start up never becomes higher than 0,16A which is a reasonable value and that the current in steady state is around 0,095A. For an input voltage of 4,2V this means a 0,4W power. The output resistor of 35Ω has 3,6V over it, making the power delivered to the load 0,37W. This means the circuit seems to be around $92,5\%$ efficient in steady state for a load which uses about the same power as the MCU at its peak. In general the circuit seems to function as it should.

### 4.3.4 Battery Charging

Similarly to the output voltage regulation circuit a battery management system is also required, this involves similar components to the output circuit for similar reasons. The input voltage to the BMS can

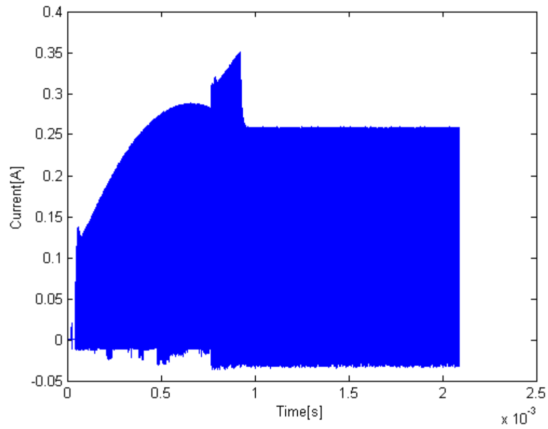


Figure 4.23: Output voltage regulation circuit's current drawn on startup with a 35Ω load

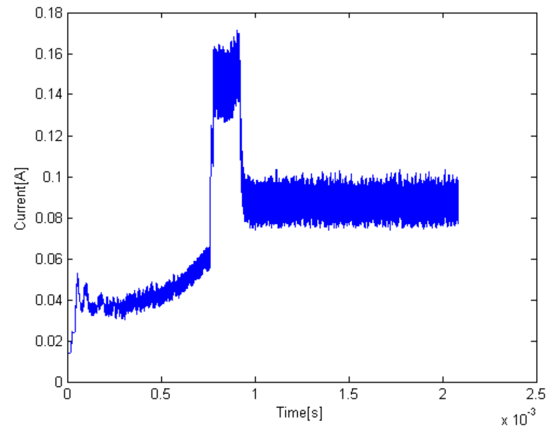


Figure 4.24: Output voltage regulation circuit's current drawn on startup convulted with a 10$\mu s$ unity area rectangle with a 35Ω load

vary between $0V$ and $30V$, as stated in requirement **REQ3.11** the charging system needs to function with input voltages between 5V and 30V. Charging with extremely low voltages can become very hard due to the large boost factors required, for constant power charging this would also mean that at lower voltages the resistance a user experiences would for a large part be due to the battery charging system, which isn't controllable by the current control system. Because an input voltage of below 5V only happens during very slow extension of the cord it isn't a problem if this can't be used anyways.

#### Battery State of Charge Estimation

As said previously most parts of the BMS system are similar to those required for the output voltage regulator, this is logical because like the output voltage regulator this circuit also takes a varying input voltage and needs to provide a regulated output voltage. However the difference in this case is that the required output voltage isn't always the same, it depends on the current state of charge of the battery. For lithium-ion batteries it's very important that the charging voltage doesn't become too high and it's also preferable if they aren't charged beyond a state of charge of around 70% because that negatively impacts battery life.

To be able to change the charging circuits behaviour based on the state of charge it must first be estimated. There are many ways of estimating state of charge for batteries, most of these however are designed to quite precisely know the the state of charge of the battery, this is done for example to show it to the user. For this system high precision isn't necessary, we only need to get a decent enough estimate of the state of charge to be able to stop charging somewhere around 70%, if this happens a bit too soon it isn't a problem because of the large capacity of the battery compared to the expected load as shown in section 4.3.1 if using the full capacity of the battery the DISQ could power the user interface system for 24 hours without charging. This is far longer than would ever be needed and thus some inefficiency in capacity usage can be worth the simpler circuit required.

The first method that might be feasible for the system is a current integration method. The idea here is that the current out of and into the battery is integrated by an integration circuit as previously seen in section 4.2.2. With a known capacity this integrated current will in an ideal case directly correspond to the current state of charge of the battery. However there are a few large problems with this method. Most of all this assumes that the battery's capacity is constant, while this isn't the case, the capacity can vary with temperature and it generally reduces after a certain amount of charging cycles[36]. There is also the problem of offset currents introduced due to the opamp configuration, these will be integrated as well and can become very significant. This will mostly be a problem when the current that actually runs to and from the battery is comparatively small for long periods of time, which is precisely the case in this application. The user interface system will be turned off for long periods at a time and then nearly no current should be drawn from the battery. Then there is also the problem of initial estimation of the state of charge, the integrator only integrates current to and from the battery, so an initial assumption or estimation of the stare of charge is needed, any error in this estimation will remain past that point as well.[36]

The standard way of taking away some of these sources of error is setting the integrator to a known value when possible, for example when charging to the full limit the charging current drops down when it's reached, this can be detected and used to set the state of charge estimations current value to 100%, however in this case we are planning to never fully charge it to improve the lifetime, so we can't use this. Even if we didn't this application will likely often stay somewhere in between fully charged and fully empty because there is no grid connected charging, in this way providing even fewer opportunities to get an really reliable state of charge estimation. Another fix that is used is extensive measurement of battery operation in different situations, using the gathered data to build a model that is then used for the state of charge estimation. This require digital control and a large array of sensors and thus is infeasible.

Another method is based on using the current output voltage of the battery for state of charge estimation, using the lowering of open circuit voltage as the state of charge lower to estimate the state of charge. This is possible however it requires being able to disconnect the load from the battery, which could be done but would require a secondary method of powering the load meanwhile. A more practical approach is using a model that estimates the state of charge while the battery is still loaded, these are however generally less accurate but that can be acceptable for this application.

### Implementation

For the circuit in the complete system we will use an IC which performs a combination of all these functions itself. The IC used will be the LT1513-2 produced by linear technology[37], this is a battery charging IC based on a SEPIC DC/DC converter, which is a similar converter topology to the buck-boost converter discussed before in section 4.1.2, but with another boost stage before it. The LT1513-2 can charge batteries from input voltages between 3V and 30V and it has a programmable output current between $0Aand1A$. For this application a charging current of 1A would be too high, in that case the total power used is 4W, which can be a significant portion, upto around of the total power the user puts into the system for the lower resistance settings. With an charging current of $250mA$ we make sure that during an exercise the device will always charge, with a peak load power usage of around $.35W$ this $1W$ charging will make sure that in the absolute worst case the system can still work upto 2 times the duration of the exercise after the exercise has ended, which together with requirement **REQ3.13** means that we expect atleast a 2,5 minute exercise, which seems very short, so this satisfies the requirement. Besides that an 1W power usage isn't likely to be very noticeable to a user when the typical power inputs are in the range of $20W$ to $90W$. Now the circuit for the BMS can be implemented to the specifications given in the datasheet[37]. The circuit for this can be seen in figure 4.25, in this circuit 2 voltages sources, $V_1$ and $V_3$ are added, these model a perfect rectified motor input and the battery respectively. There is also a fairly large input capacitance added to allow the charging to continue on while the cord is being reeled back in between two extensions of the cord. The capacitance value is based on 1,5 extension per second and a nominal voltage of 20V, with a 1W power draw this requires a capacitance of around $2mF$, which is quite large but enables continues operation of the LT1513-2 IC.

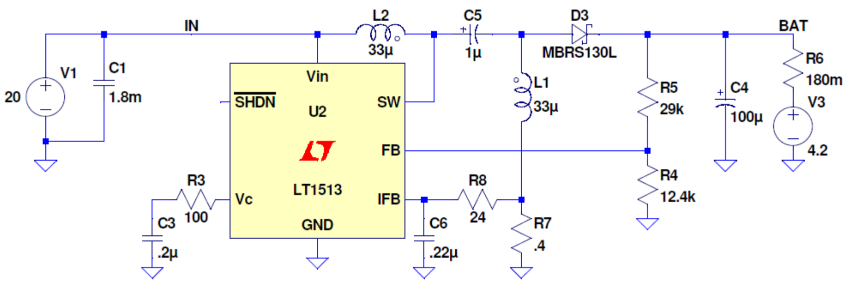


Figure 4.25: The simulation schematic for the BMS circuit

### Simulation

The most important characteristics to check for the BMS are the efficiency in charging the battery, whether the charging current is correctly the $250mA$ current set by the programming resistances and if the BMS stops charging when the battery reaches its maximum of 4.2V.

The first test is during normal charging operation, the battery is set to 3,3V to model a decently empty battery. The charging current for this situation can be seen in figure 4.26. A slightly worrisome current peak can be seen at the start but this only lasts about 0.2ms, so this should not oppose any further problems. After this time, a charging current with an average value of 0.23A is seen, which is close enough to the desired 0.25A. The current drawn from the input source during this time is seen in figure 4.27. As could be expected from the current peak in the previous figure, the input current also has a peak at the start, but again due to the short duration this should be fine. In steady-state the current drawn has an average value of 0.12A. With a voltage of 20V, this means 2.4W is extracted from the input while the battery is charged with a power of $.25A * 3.3V = 0.825W$ making for a very low efficiency of 34%, this is not as would be expected from the datasheet. However it should not be a problem, an extra $0.08A$ drawn shouldn't be noticeable to the user and nothing else really matters because we are trying to dissipate energy anyway.

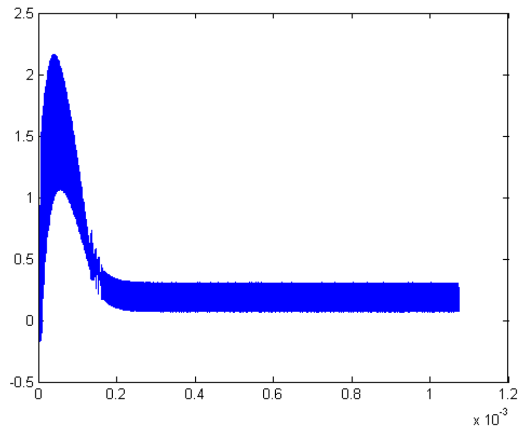


Figure 4.26: The simulated charging current for a battery at 3,3V

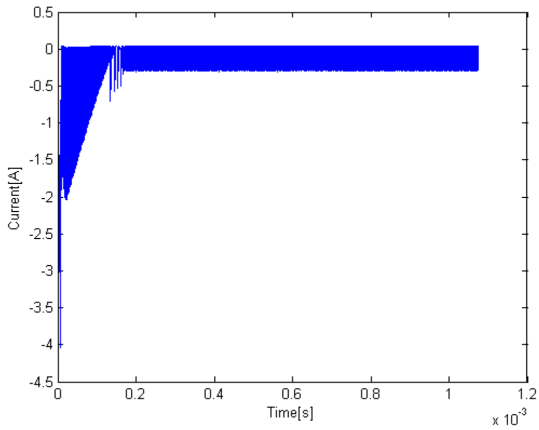


Figure 4.27: The simulated current drawn by the BMS from the input source for a battery at 3,3V

The output voltage for this situation can be seen in figure 4.28. This too starts with a peak, as should be expected from the charging current peak going through the model of the internal battery resistance. It quickly settles to become nearly equal to the current battery voltage.

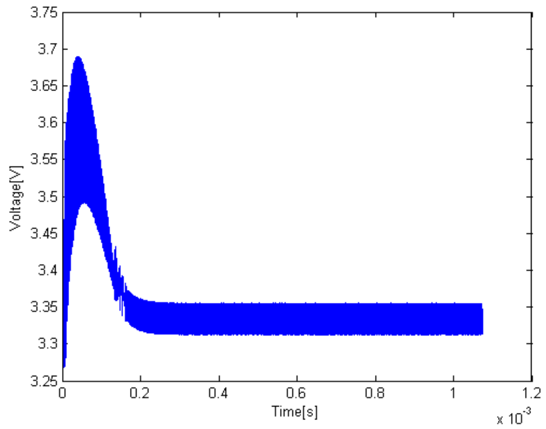


Figure 4.28: The simulated output voltage for the BMS with the battery voltage at 3.3V

For a battery voltage of 4.2V the BMS shouldn't allow any charging, the results of a simulation for this situation can be seen in figure 4.29. The circuit basically immediately reaches steady state, the charging current correctly becomes nearly 0A and the input current is only $40\mu A$, which means all expectations and requirements for this simulation have been met.

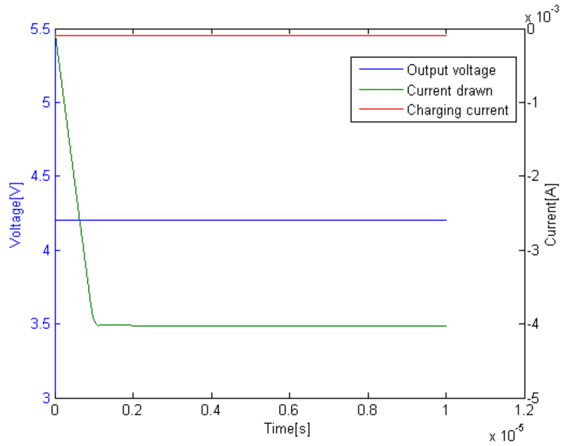


Figure 4.29: The simulation results for a battery voltage of 4.2V

### 4.3.5 Circuit Protection

To ensure safe and stable operation, the energy management system must be well protected. This section will mainly focus on the electrical protection of the circuit, rather than physical protection against moisture, heat and physical damage.

#### Battery Protection

The battery used in the system is a lithium-ion battery. Lithium-ion batteries can be severely damaged, and even release corrosive electrolyte when they are overcharged are short-circuited[38]. To prevent this, it must be assured that these conditions cannot occur. In the design presented in 4.3.4, the LTC1513 IC was chosen because it keeps track of the battery state of charge and stops the charging current when the battery is fully charged. The battery is connected to a separate connector using a connector that does not allow for reverse connection or short circuiting, unless one of the circuit component fails. The battery can be quickly disconnected when the circuit fails.

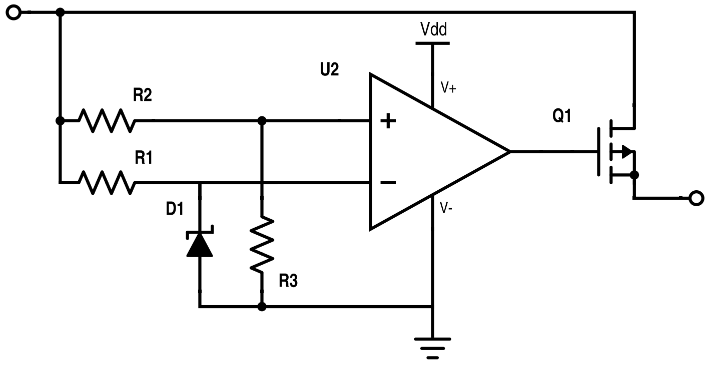


Figure 4.30: The overvoltage circuit that compares the input voltage to a reference. If the input voltage exceeds the threshold, the comparator is trigged and the MOSFET is switched off.

### Overcurrent

The battery charging and the DC/DC converter IC that are used in the system both have a maximum current rating. All the chips that are used in the design have a built-in overcurrent protection, and stop functioning when the current exceeds the maximum rating. This situation should however never occur, because the battery charging IC is set to a maximum charging current of less than 500mA. This means that the current flowing through the battery charger and the battery itself will never exceed 500mA when the circuit functions properly.

### Overvoltage

The only voltage in the circuitry that cannot be regulated by the circuitry itself, is the output voltage of the generator. The rectified voltage of the generator is sent to both the energy dissipation and the energy battery charger. While the battery dissipation is designed with a MOSFET that can handle up to 60V, the battery charger IC, the LTC1513, supports only input voltages up to 30V. The input capacitor of the LTC1513 is rated to 35V. This means that there should be a protection circuit that ensures that the voltage on the input of the battery charger does not exceed 30V. A way of doing this is by measuring the input voltage, comparing it to a reference voltage using a voltage divider network, and switching a MOSFET that is placed between the output of the generator and the input of the battery charger when the voltage is exceeded. This could be done with a comparator, as shown in figure 4.30. In this circuit, a zener diode is used to generate a reference voltage. When the voltage from the voltage divisor exceeds the reference voltage, the comparator toggles the gate of the FET, and the generator is disconnected from the battery charger circuit. There are also ICs available that have built-in comparators and MOSFET gate drivers. The LTC4365 is an IC that can monitor the input voltage, and trigger the gate of a MOSFET when the input voltage exceeds a voltage that is set by an external resistor network. It was decided to use this IC for the voltage protection circuitry. The IC also offers an undervoltage protection. Because the battery charger does not operate at voltages lower than 1.8V, the undervoltage is set to 2V. According to the datasheet of the LTC4365, the overvoltage and undervoltage are determined according to the following formula's:

$$OV_{TH} = \frac{\mathrm{R1}+\mathrm{R2}+\mathrm{R3}}{2\mathrm{R1}} \qquad UV_{TH} = \frac{\mathrm{R3}}{2(\mathrm{R1}+\mathrm{R2})} + 0.5V \tag{4.5}$$

The values that were selected are R1 = 20kΩ, R2 = 270kΩ and R3 = 910kΩ, resulting in an undervoltage treshold of 2.07V, and an overvoltage treshold of 29.5V with an offset of 290mV.

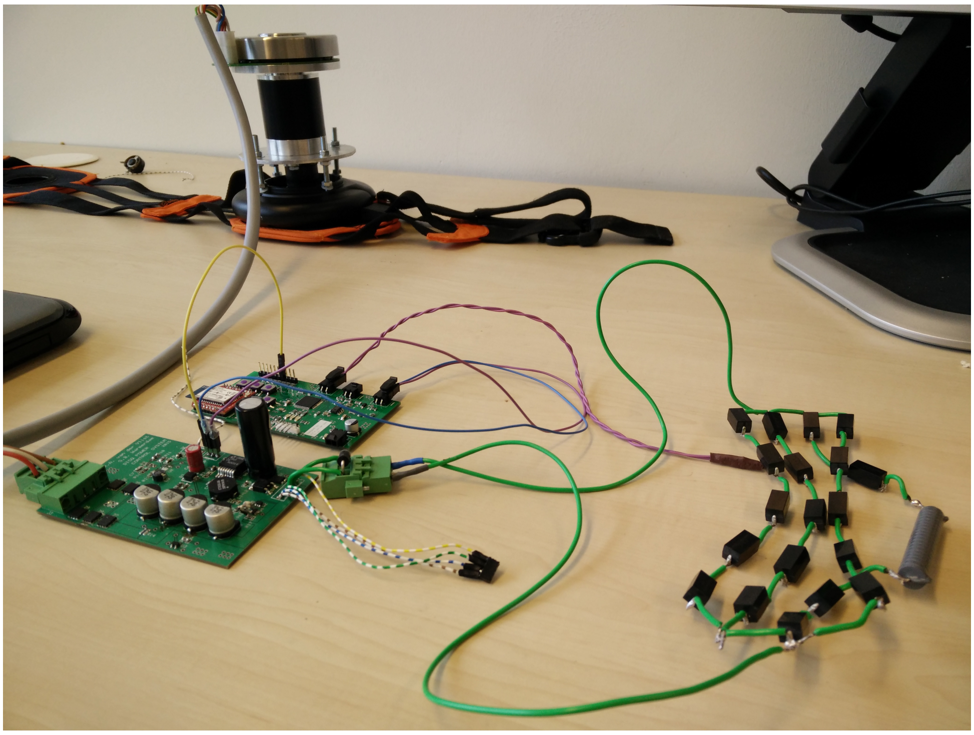

Figure 4.31: A photograph of the prototype. The PCB located at the front left is the Energy Management System. The other PCB holds the User Interface system, and in the back the DISQ along with the generator and gearbox can be seen. To the right, the resistor network of power resistors is shown (one of the resistor was broken and is replaced by a different power resistor).

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## 4.4 Chapter Summary

In this chapter, a quintative design for the Energy Management System was presented. An schematic overview of the implemented system is shown in 3.1. To implement the designed circuits, a PCB was designed, of which the layout can be found in appendix B. An overview of the schematic of the combined system is given in appendix C. A three-rectifier converts the generator output to a DC voltage. The load of the generator is mainly determined by the Energy Dissipation System, which consists of a MOSFET and a resistor network. A 2Ah, 3.7V battery was selected, that is charged using the LTC1513 IC. To protect the battery charging circuitry, an overvoltage protection was implemented using the LTC4365. The User Interface is powered by the battery by means of the LTC3536 buck-boost DC/DC converter.

An photograph of the prototype is shown in figure 4.31

# Chapter 5 | Testing, Results & Discussion

## 5.1 Test Plan

In this section a test plan for the system will be described. To verify the system as a whole is working properly, different parts of the system must be tested first. In this sections a testing plan is set out to verify that all the electronics meet their requirements and comply with the simulations. The system can be divided into four import parts that must be tested:

1. The generation of the output voltage using a DC/DC converter.
2. The battery charging system and overvoltage protection.
3. The energy dissipation consisting of the resistor network and the MOSFET.
4. The rectifier and smoothing capacitors.

First of all, the electric connections in the circuit must be tested. This is done by checking the soldering connections by visual inspection first, and by checking the circuit for shorts using a multimeter.

When the circuit is soldered, it needs to be verified once again that here are no shorts in the circuit, and that the resistors and capacitors have the right value. It was decided to test the DC/DC converter at the output first, since this is a subcircuit that does not depend on any other circuitry, and has only the battery voltage as an input. After the testing of the DC/DC converter, the battery charging system can be tested. On a separate PCB, the rectifier can be tested. When the rectifier is found to work, the overvoltage can be added to this system and tested using a DC input on the rectifier. If both the rectifier and the overvoltage protection work ad intended, the MOSFET of the energy dissipation system can be soldered and tested. Finally, the system as a whole can be tested. When the system as a whole is found to work, it can be connected to the Generator System and the User Interface, and the prototype can be tested.

### 5.1.1 The DC/DC Converter

The DC/DC converter can be tested by connecting a power supply to the battery terminals on the board. The DC/DC converter must produce a constant output voltage of 3.6V with a deviation of no more than 50 mV, with an input voltage in the range of 2V - 4.2V, which is the operation range of the battery. When it is verified that the output voltage is stable, a load can be connected to the output of the DC/DC converter. For testing purposes and to have a safe margin, the DC/DC converter should be able to supply a current of up to 200mA, twice the current of **REQ3.13**.

### 5.1.2 The Battery Charging System

The battery charging circuitry should be able to produce a constant charging current to the battery as specified in section 4.3.4. The battery charging current should remain constant over the input voltage range of 5V - 30V, where 5V is the minimum voltage the battery charger needs to work, and 30V the maximum voltage that the battery charger can handle. When there is no load connected, the output voltage of the battery charging circuitry needs to be 4.2V. When the battery is connected and the voltage is below 4.2V, the battery charging should output a charging current of 250 mA to the battery charger. It should be verified that the battery charger stops charging when the battery reaches its maximum voltage of 4.2V.

### 5.1.3 The Rectifier

Finally, it must be verified that the rectifier works properly. The individual phases of the rectifier are tested using a DC power supply. By connecting the supply with different polarities, it can be verified that the rectifier works in both directions. In total, there are six different ways to connect the DC supply to the rectifier. When each of the phases is tested separately, the generator can be connected. The output should show a DC waveform with almost no ripple when no load is connected.

### 5.1.4 Overvoltage Protection

To test the energy dissipation system, a voltage is applied at the output of the rectifier. The overvoltage should be tested first. When the voltage exceeds 29.5 volts, the power path to the charging circuitry should be disconnected by the MOSFET of the overvoltage IC. When the voltage falls below the over-voltage treshold afterwards, the power path to the battery charging circuitry should be re-enabled.

### 5.1.5 Energy Dissipation System

By testing at various duty cycles it must be verified that the the MOSFET can control the average current through the resistor network. It also should be verified that the resistors and the MOSFET do not exceed the temperatures that were calculated in section 4.1.6. Also, there should be no voltage spikes over the resistors or the smoothing capacitors when the energy dissipation system is active.

## 5.2 Test Results and Discussion

### 5.2.1 The DC/DC Converter

The first time the DC/DC converter was tested, the output was very noisy and the converter did not generate a stable output voltage. When the circuit was simulated, it was found that the resistors for the feedback network had values that caused the circuit to become unstable. Their parallel combination was too small, which caused a current draw from the feedback pin. The values were adjust, and the circuit soldered again. When no load was connected, the DC/DC converter produced an output voltage of 3.62 V with a superimposed noise signal that was less than 20 mV in amplitude. When a 30Ω load was connected (a current draw of 120mA) the voltage dropped to 3.59 with a comparable noise. When connected to the User Interface, the output voltage was 3.59V.

### 5.2.2 The Battery Charging System

At first, the battery charging circuitry produced an incorrect output voltage. Further inspection of the circuit showed that two resistors were swapped in the circuit. When the resistors were re-soldered, the open circuit output voltage was 4.2V. When the battery was connected to the battery charger with a voltage of 3.89V, a charging current of 250 mA was measured.

### 5.2.3 The Rectifier

When a DC source was connected to the rectifier, all of the conduction paths produced a DC voltage of the same polarity as well. When the generator was connected, a DC voltage measured at the output of the rectifier when there was no load connected. For loads with current above 1A, there was a visible ripple on the output DC signal. Figure 5.1 shows the output of the rectifier when the load is switched from a high duty cycle (high current) to a duty cycle of 0 (no current). It can clearly be seen that the ripple is dependent on the current. This is because when there is a high current load, the capacitors are quickly depleted when the rectifier voltage falls below the voltage of the capacitor. As expected, the signal looks now like the standard output of a three-phase rectifier, and the ratio between the maximum and minimum value of the ripple for a high-current load is about $1 : \frac{1}{2}\sqrt{3}$.

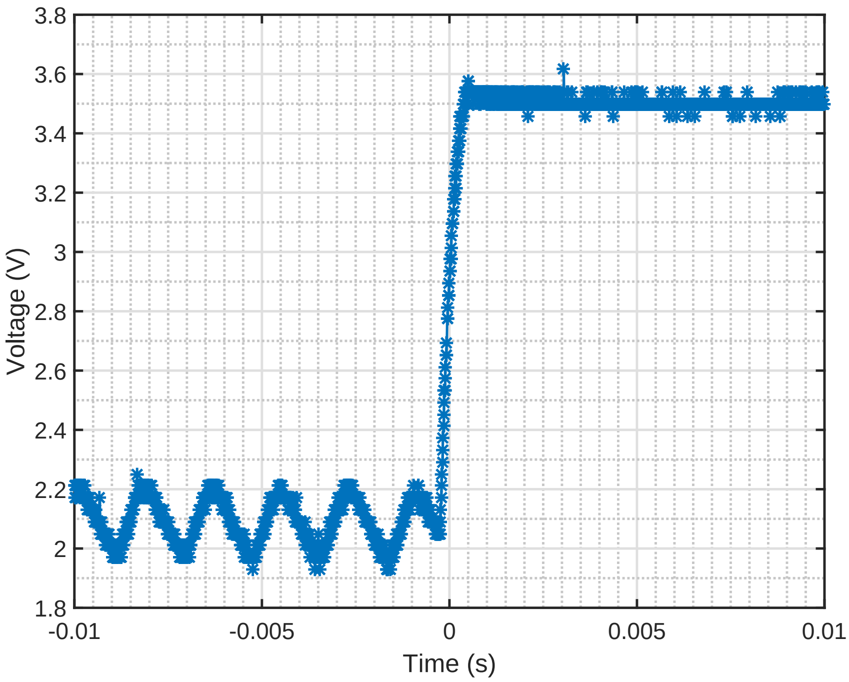


Figure 5.1: The ripple on the output of the rectifier when the load is switched from a high current load to a no-current load.

### 5.2.4 Overvoltage Protection

A DC power supply was connected to the rectifier, and the voltage was slowly ramped up. When the voltage was between 29 and 30 volts, the overvoltage protection was activated and the battery charging circuitry was disconnected from the rectifier.

### 5.2.5 Energy Dissipation System

When the energy dissipation circuit was tested, voltage spikes were detected across the resistor network, with an amplitude of over half the signal amplitude. As expected, there were no voltage spikes over the output of the of the rectifier, as can also be seen in figure 5.1. Most likely, the voltage spikes over the resistor network occurred due to the parasitic inductance of the wires of the resistor network. These spikes did not occur during the simulations, because the resistor network was modelled as an ideal resistor, with no parasitic inductance. To resolve this problem, a flyback diode was placed in parallel to the resistor network, which reduced the voltage spikes to an insignificant amplitude.

### 5.2.6 Discussion

Some of the subsytems did not work at first, due to faults in the design or assembly process. All of these faults were however resolved by replacing or adding a few components. All the subsystems comply with the requirements that were set and the output voltages and current of the subcircuits had values that matched the simulation and design.

## 5.3 Future Development

In the design process, some issues were encountered that could be solved in a more advanced way, but were not feasable within the scope of this project. One of the things that could be improved, is that the inertia of the motor is currently neglected. This causes a higher torque when the rope is pulled at first. One possible way to solve this, would be *inertia compensation*: the generator can be put into motor mode when a small displacement is sensed, to reduce the torque that is experienced due to the inertia. This would however require the rectifier to allow for the current to flow in two directions. This could be implemented by using an active MOSFET-based rectifier instead of a passive rectifier that is currently used. The prototype also currently uses a quite large external gearbox, and more work needs to be done to integrate this gearbox with the DISQ.

Further improvements would include more accurate torque control. In the current prototype the torque control is done digitally by the User Interface system, and more details about this can be found in [10]. It must also be verified that the energy dissipation system does not exceed the prescribed temperatures when it is used for an extensive workout, as described in **REQ3.14**. Finally, the current prototype uses a windows program as a user interface to the DISQ. In the future, an Android app could be developed that communicates with the DISQ.

# Chapter 6 | Conclusion

In section 1.2, the problem statement for this thesis was declared, along with a list of requirements in section 1.3. In this conclusion the problem statement and the requirements that were marked as critical requirements will be reflected upon.

The Energy Management System that was designed, contains a PWM-regulated resistive load. The User Interface generates a PWM signal that controls the current drawn from the generator in this way. Secondly, a control circuit was designed that could control the current from the load as well, as an analog alternative to the control of the User Interface. The Energy Management System also charges a battery, that functions as an energy storage. With a DC/DC converter a stable power supply is generated for the User Interface.

The critical requirement **REQ3.7** on the low resistance of the prototype was met, since the Generator System uses a brushless DC motor, which has few moving parts. The energy storage also is easily capable of powering the User Interface for a prolonged time period, as required in **REQ3.4**. The system was designed to meet **REQ3.14**, the requirement on the input power that the system should be able to dissipate. This was however not extensively tested.

All parts that were designed in this paper are working as should in the current prototype, and a solution was found that meets the critical requirements and the requirements of the problem statement. In order for the prototype to meet the requirement **REQ1.3** of a mechanical resistance that is independent of the speed of extension, the problems that are currently present regarding the control of the current and the inertia of the Generator System must be solved. More work on either the software of the User Interface or the analog control circuitry and testing is needed to meet this requirement.

# Bibliography


[1] M. Gulbahce, D. Kocabas, and I. Habir, “Finite elements analysis of a small power eddy current brake,” in *MECHATRONIKA, 2012 15th International Symposium*, 2012, pp. 1–5. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6415090

[2] P. Hanyecz, “Calculation of braking force in eddy current brakes,” *Electrical Engineering*, vol. 26, no. 3-4, pp. 249–263, 1982.

[3] E. S. Shrivastava, “A parametric analysis of magnetic braking–the eddy current brakes–for high speed and power automobiles and locomotives using simulink,” *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering 08/2014*, 2014.

[4] Z. ding Ying, X. fu Xu, and J. an Zhu, “Analysis of simulation design of the disc eddy current braking device,” in *Computer, Mechatronics, Control and Electronic Engineering (CMCE), 2010 International Conference on*, vol. 5, 2010, pp. 309–311. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5609976

[5] H.-J. Ryoo, J.-S. Kim, D.-H. Kang, G.-H. Rim, Y.-J. Kim, and C.-Y. Won, “Design and analysis of an eddy current brake for a high-speed railway train with constant torque control,” in *Industry Applications Conference, 2000. Conference Record of the 2000 IEEE*, vol. 1. IEEE, 2000, pp. 277–281.

[6] M. Szary, “The phenomena of electrorheological fluid behavior between two barriers under alternative voltage,” *Archives of Acoustics*, vol. 29, no. 2, 2004.

[7] H. Conrad, “Properties and design of electrorheological suspensions,” *MRS Bulletin*, vol. 23, no. 08, pp. 35–42, 1998.

[8] J. Nikitczuk, A. Das, H. Vyas, B. Weinberg, and C. Mavroidis, “Adaptive torque control of electrorheological fluid brakes used in active knee rehabilitation devices,” in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*. IEEE, 2006, pp. 393–399.

[9] L. Does and F. Drijver, “De elektromechanische omzetting voor het draagbare fitnessapparaat ’disq’,” *Bachelor Thesis, Delft University of Technology*, 2015.

[10] T. Qiu and N. van der Veen, “Design of a controller for an adjustable frictionless resistance fitness device, with wireless user feedback,” *Bachelor Thesis, Delft University of Technology*, 2015.

[11] K. Cook-Chennault, N. Thambi, and A. Sastry, “Powering mems portable devices a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems,” *Smart Materials and Structures*, vol. 17, no. 4, p. 043001, 2008.

[12] Y. Narukawa, M. Sano, T. Sakamoto, T. Yamada, and T. Mukai, “Successful fabrication of white light emitting diodes by using extremely high external quantum efficiency blue chips,” *physica status solidi (a)*, vol. 205, no. 5, pp. 1081–1085, 2008.

[13] S. Pimputkar, J. S. Speck, S. P. DenBaars, and S. Nakamura, “Prospects for led lighting,” *Nature Photonics*, vol. 3, no. 4, pp. 180–182, 2009.

[14] T. Horiba, “Lithium-ion battery systems,” *Proceedings of the IEEE*, vol. 102, no. 6, pp. 939–950, 2014.

[15] A. Chu and P. Braatz, "Comparison of commercial supercapacitors and high-power lithium-ion batteries for power-assist applications in hybrid electric vehicles: I. initial characterization," *Journal of power sources*, vol. 112, no. 1, pp. 236–246, 2002.

[16] "Comparison of nicd, nimh, and li-ion batteries," *Tyco Electronics Whitepaper*, [No year given].

[17] Q. Zhang and R. E. White, "Capacity fade analysis of a lithium ion cell," *Journal of Power Sources*, vol. 179, no. 2, pp. 793–798, 2008.

[18] G. Ning, B. Haran, and B. N. Popov, "Capacity fade study of lithium-ion batteries cycled at high discharge rates," *Journal of Power Sources*, vol. 117, no. 1, pp. 160–169, 2003.

[19] D. Zhang, B. Haran, A. Durairajan, R. E. White, Y. Podrazhansky, and B. N. Popov, "Studies on capacity fade of lithium-ion batteries," *Journal of Power Sources*, vol. 91, no. 2, pp. 122–129, 2000.

[20] M. S. Halper and J. C. Ellenbogen, "Supercapacitors: A brief overview," *The MITRE Corporation, McLean, Virginia, USA*, pp. 1–34, 2006.

[21] T. McCawley, "A feasibility analysis for the design of a low-cost high-power energy storage system," *Fung Technical Report No. 2014.05.03*, 2014.

[22] R. S. Rajan and M. M. Rahman, "Lifetime analysis of super capacitor for many power electronics applications," *IOSR Journal of Electrical and Electronics Engineering. Volume 9, Issue 1 Ver. IV PP 55-58*, 2014.

[23] S. Aydemir, S. Sezen, and H. M. Ertunc, "Fuzzy logic speed control of a dc motor," in *Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International*, vol. 2. IEEE, 2004, pp. 766–771.

[24] D.-H. Jang and G.-H. Choe, "Improvement of input power factor in ac choppers using asymmetrical pwm technique," *Industrial Electronics, IEEE Transactions on*, vol. 42, no. 2, pp. 179–185, 1995.

[25] B. Ferreira and W. Van der Merwe, *The Principles of Electronic and Electromechanic Power Conversion: A Systems Approach*. John Wiley & Sons, 2014.

[26] "Smd moulder power resistor type sm series datasheet," TE Connectivity, 04 2012.

[27] "Std30nf06l n-channel 60v - 0.022w - 35a dpak/ipak stripfet power mosfet datasheet," STMicroelectronics, July 2002.

[28] U. Drofenik and J. W. Kolar, "Teaching thermal design of power electronic systems with web-based interactive educational software," in *Applied Power Electronics Conference and Exposition, 2003. APEC'03. Eighteenth Annual IEEE*, vol. 2. IEEE, 2003, pp. 1029–1036.

[29] J. H. Lienhard IV, "Jh lienhard v," *A heat transfer textbook*, vol. 3, 2004.

[30] F. Harahap and H. McManus, "Natural convection heat transfer from horizontal rectangular fin arrays," *Journal of heat transfer*, vol. 89, no. 1, pp. 32–38, 1967.

[31] "High-side measurement current shunt monitor datasheet," Texas Instruments, December 2000.

[32] L. B. Oliveira, J. C. Fernandes, I. M. Filanovsky, C. J. Verhoeven, and M. M. Silva, *Analysis and design of quadrature oscillators*. Springer Science & Business Media, 2008.

[33] R. Spotnitz, "Simulation of capacity fade in lithium-ion batteries," *Journal of Power Sources*, vol. 113, no. 1, pp. 72–80, 2003.

[34] "Specification of li-ion rechargeable battery model no.: 18650ca-1s-3j," ShenzhenBAK, Oct 2013.

[35] "Ltc3536 1a low noise, buck-boost dc/dc converter datasheet," LINEAR TECHNOLOGY, 2011.

[36] S. Pang, J. Farrell, J. Du, and M. Barth, "Battery state-of-charge estimation," in *American Control Conference, 2001. Proceedings of the 2001*, vol. 2. IEEE, 2001, pp. 1644–1649.

[37] "Lt1513/lt1513-2 sepic constant- or programmable-current/constant-voltage battery charger datasheet," LINEAR TECHNOLOGY, 1996.

[38] C. Kallfab, C. Hoch, A. Hilger, and I. Manke, "Short-circuit and overcharge behaviour of some lithium ion batteries," in *Systems, Signals and Devices (SSD), 2012 9th International Multi-Conference on*. IEEE, 2012, pp. 1–5.

# Appendix A | Ethical Considerations

When designing a product, it is very tempting for an engineer to be focused only on the technical aspects of the products, and sometimes also on the marketing and selling points of the product. One thing that is often overlooked however, is the ethical side of product design. We live in a western society, that is full of prosperity of luxury, and tend to neglect the impact our way of living has on the rest of the world. Because of this, we will discuss a number of ethical considerations that need to be taken into account during the design and production of this product. There are three main topics that are presented in this ethical consideration: The use of rare materials, the working conditions during production, and the influence of the product in the society. The chapter ends with an advice.

## A.1 Rare Materials

In this product, a lithium-ion battery is used for energy storage. Lithium-ion is a so-called 'rare metal', which means that the metal is rarely found in nature, and a lot of effort is needed to extract it from the ground. It should be taken into consideration that with the production of lithium-ion batteries, forests and other nature areas may be damaged. A lot of lithium-ion mines are found in areas that have conflicts or very bad working conditions. It should be considered whether we, as western consumers, can raise our own prosperity and wishes over the the needs of the people living in the mining areas and nature reserves. When we apply the principle of universalism to this problem, our reasoning tells us that it would have a highly negative effect on the welfare of the planet if everyone would neglect the preservation of nature and the production circumstances during mining. Therefore, from an universalism viewpoint, it would not be responsible to neglect the impact that the usage of lithium products has on the world. Another aspect that should be taken into consideration when using rare metals is recycling. When we take the Kantian care ethics into account, we should question ourselves whether it is acceptable if we use a metal that is rare now, and discard it, causing problems for future generations. Therefore, a good recycling program for the lithium-ion batteries is needed.

## A.2 Production Conditions

Another aspect that should be taken into account is the working conditions during the assembly stage of the product. It is often cheaper when the product is assembled in an eastern country, where the cost of labour is often lower. A drawback of lower labour costs is that in countries where the labour cost is lower, the working conditions are often also poor. This is a difficult problem, since moving the production to a country with better working conditions and higher labour costs would increase the selling price, and thus reduce sales of the final product. Again, the question arises what we value more, the selling of the product, or the well-being of the unknown workers that produce and assemble the product. This can best be viewed from the point of utilitarianism, with the availability of jobs for locals in eastern countries and the lower costs as arguments in favour of keeping the production there and the reinforcement of local bad working condition practices causing further bad conditions of the local labourers as an argument in favour of moving the production away from there. Making a good estimate of which action provides the largest total utilitarian value would require studies into how much keeping the production there reinforces bad working condition practices. A way to be sure might be to keep the production there but to find a partner willing to improve working conditions and then periodically doing unannounced checks to see if the rules are followed, this would however also cost more money and possibly not be feasible depending on the amount of devices being produced.

## A.3 Influence on Society

When taking the ethical implications of our product into account, we should not forget that there can also be positive side-effects that come with the production of the product. It is generally assumed that having an active lifestyle and being outside has a positive influence on the happiness of men. A healthy lifestyle is one of the virtues of our society. Therefore, from the perspective of virtue ethics, we should take into account that the DISQ portable stimulates the user to go outside, exercise and be active. Thus we can say that the product is aimed at increasing the happiness of the costumers.

## A.4 Advice

During the production process, the working conditions should be taken into account. Because assembly costs are much higher in western countries, it is not feasible to move the assembly to western countries. It must be assured that the working conditions during production are reasonable. Another thing that should be considered, is that moving the production away from developing countries might not solve the problem either. When the demand of products from western falls away, unemployment rates might go up and the country could destabilize. We therefore recommend that the assembly of the product is done in countries with low labour costs, but that the working conditions are actively monitored. There should be a list of requirements on the working conditions for the company where the assembly is outsourced. Since it is technically complicated to design a product that does not use the lithium-ion batteries, it is advised that these batteries are used in the product. However, the recycling of the product is important. Therefore we recommend that there is a decent product liquidation plan for the DISQ that ensures that the lithium in the DISQ is not disposed.

# Appendix B | PCB Layout

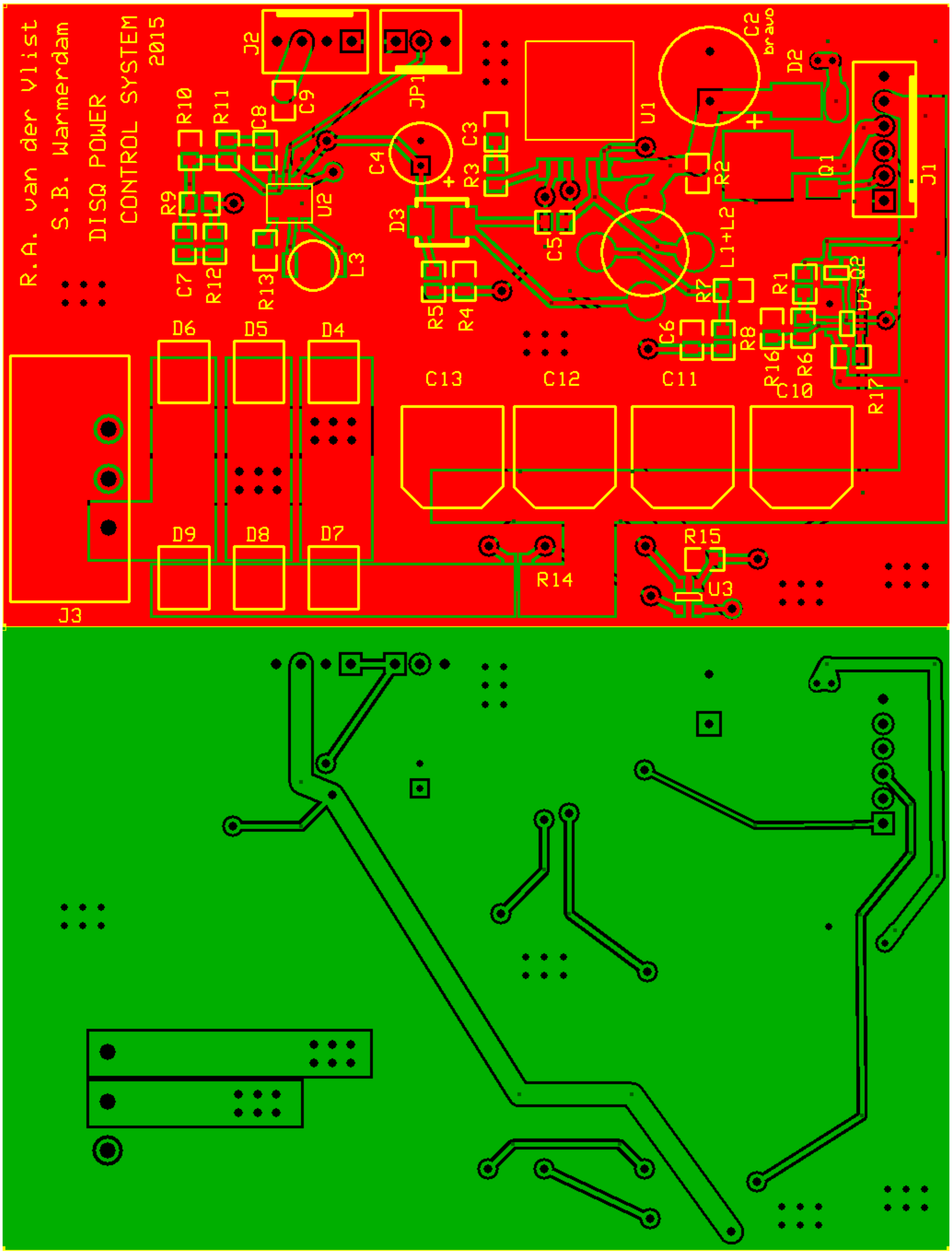


Figure B.1: The top and bottom layer of the PCB that was designed. A schematic for this PCB is shown in appendix C. The large traces on the bottom form the rectifier. In the top right component the resistor network is connected, and the energy dissipation MOSFET is placed. To the left is the battery charging circuitry, and the DC/DC converter is situated on the left of the PCB.

# Appendix C | Electrical Schematic of the Energy Management System

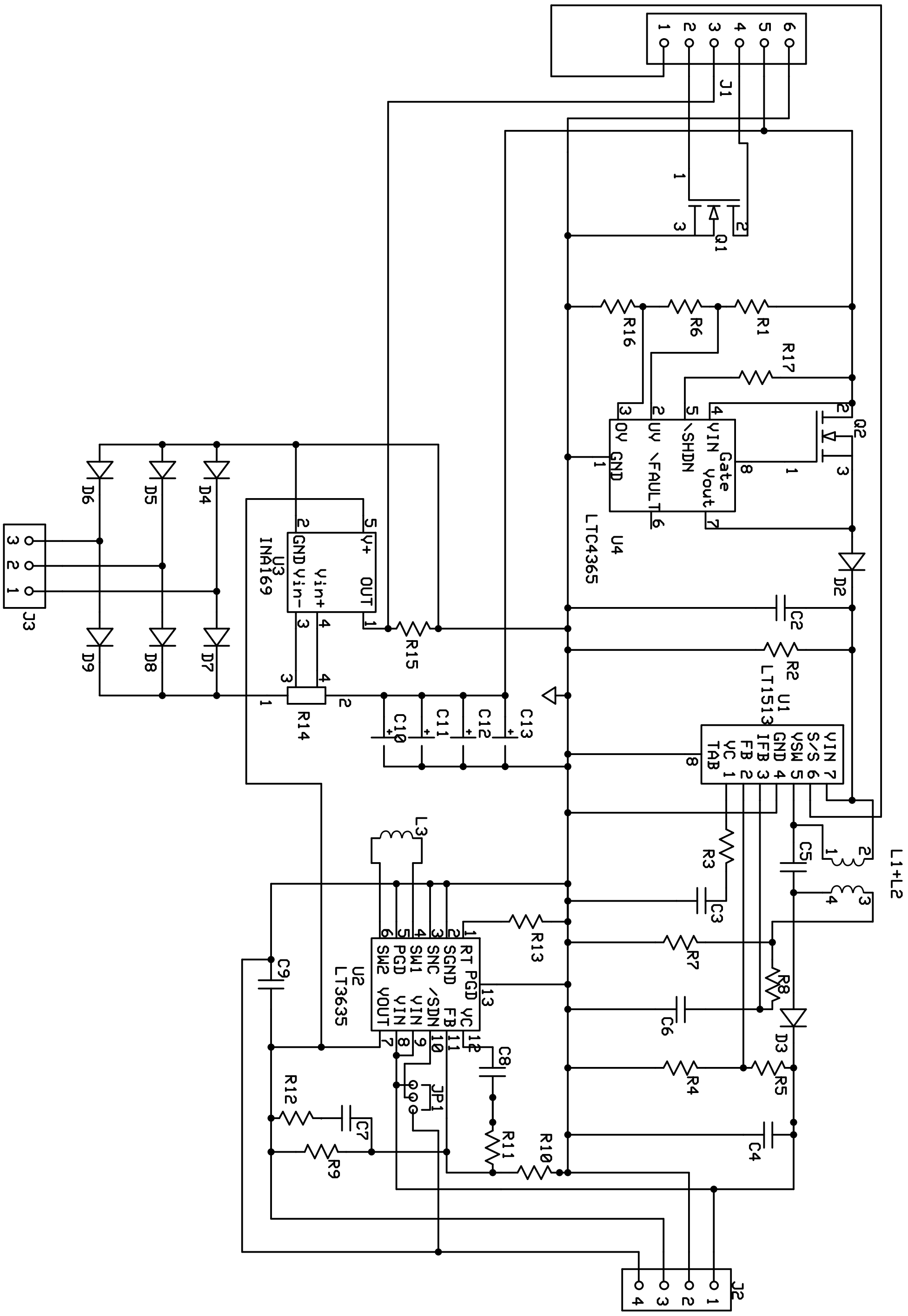


Figure C.1: The full schematic of the Energy Management System. The circuit comprehends the rectifier, overvoltage, current sensor IC, battery charging circuitry and the DC/DC converter.