Bachelor Graduation Project Thesis

Battery Free Jogger Light Energy Storage

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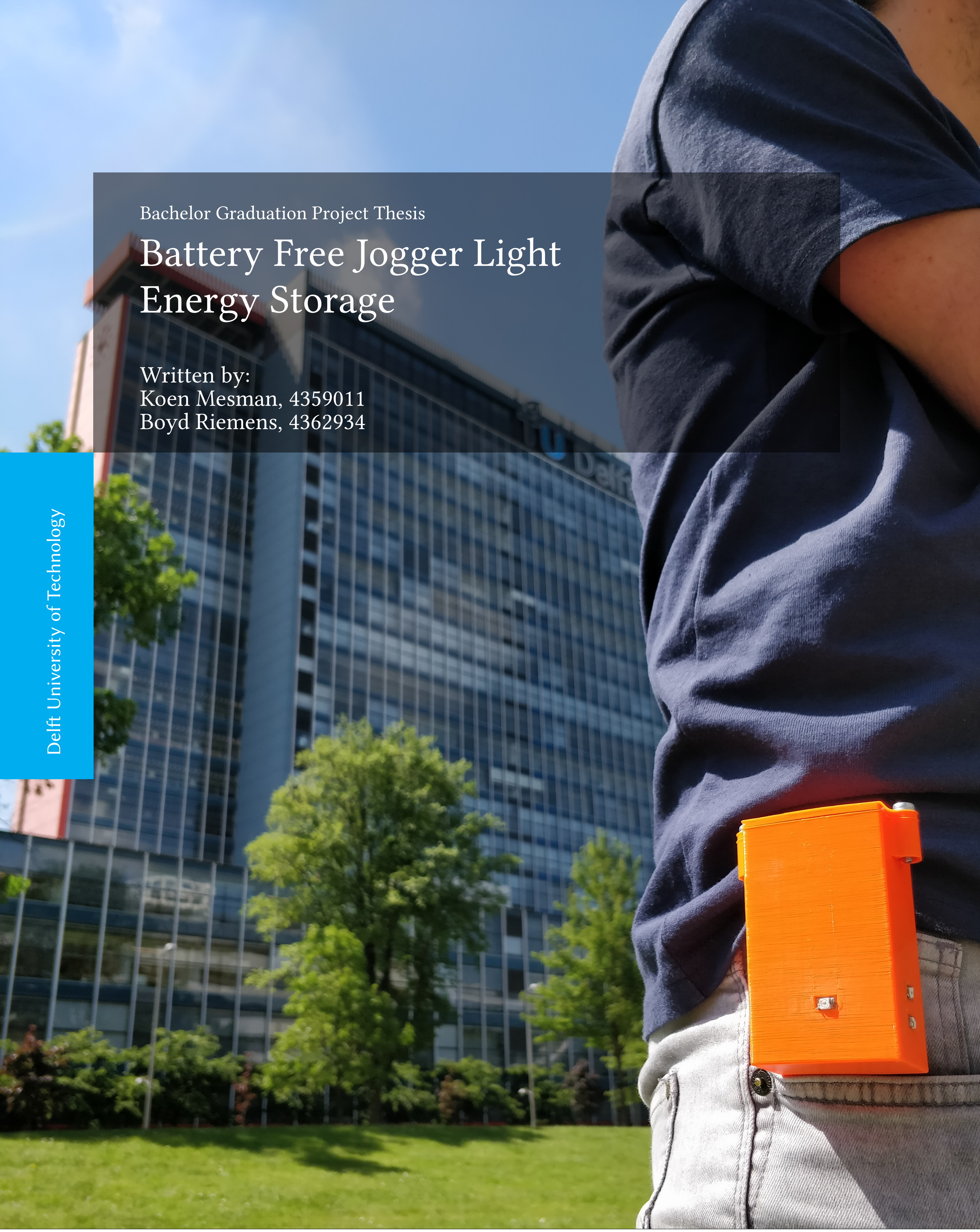

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Challenge the future

Battery Free Jogger Light

Energy Storage

Bachelor Graduation Project

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Abstract

The deliverable of this project is a light for joggers that does not use a battery and keeps blinking for a short period of time after standing still. This research details the design and implementation of the storage part of a battery free jogger's light. The goal of this storage part is that it stores energy delivered by an energy harvester so that it can power LEDs for at least 30 seconds when there is no energy harvested anymore. The system consists of a full-bridge rectifier, a voltage regulator, a supercapacitor to store the energy and a switch to couple or decouple the load. The main trade-off of this research is between the charging and discharging times of the supercapacitor. Results show that LEDs in the rectifier offer advantages, since there is instant lighting when jogging and which makes the charging time less critical. With this feature the discharging time could be increased up to one minute. The total efficiency of this storage system is calculated to be 67.9%.

Preface

This thesis is written in context of the Final Bachelor project of the Bachelor Electrical Engineering at Delft University of Technology.
The goal of this project is to design a battery free jogger's light, which also is able to keep on shining for a short period of time after a jogger stops moving. This report will address the energy storage part of the device.

We would like to express our gratitude to our daily supervisor Dr. Massimo Mastrangeli and Dr. Virgilio Valente, for their excellent guidance during the project. Furthermore we would like to thank Dr. John Schmitz for proposing the project and also mr. Martin Schumacher for providing us with all the components we needed to achieve our goals. Finally we would like to thank our colleagues: Jhorie Slot, Jelle Klein, Bart van Nobelen and Jory Edelman for a productive and enjoyable collaboration.

Koen Mesman & Boyd Riemens
Delft, June 2019

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Chapter 1

Introduction

Back in the days people used to go jogging without any lights, and thus were poorly visible in the dark, which resulted in a high risk of accidents. Nowadays most people have lights when they go jogging in the dark, but these lights are usually powered by batteries which have a chance of running out of power. These batteries are in most cases not rechargeable and not replaceable resulting in a useless light after some time. However, one light exists which doesn't use batteries, the Million Mile Light [1], which emits light based on the joggers movement in a 180° radius to the front. Ideally the light should feature the emission of light after the movement has stopped with a coverage of more than 180° as well as increased visibility and decreased need for maintenance, due to optimisation.

It is important that joggers can run safely in the dark, as not everyone is able to go jogging during the day. So it is of importance that joggers are wearing an attention drawing, comfortable, and durable jogging light, while jogging in the dark. Road-users will benefit of the increase of visibility of joggers. This is why the product should be accessible for a wide-range of joggers around the world. There are currently two types of jogger lights on the market: battery based lights and the Million Mile Light. The battery based lights ensure that joggers are always visible when jogging or standing still, except when the battery is empty. The Million Mile Light ensures that the jogger is always visible when jogging, but not when the jogger is standing still at a traffic light for example. The goal of this research is to develop a product that combines the advantages of the two types of jogger lights that are currently on the market, so improving upon the Million Mile Light by adding the operative function of temporarily maintaining light emission when the jogger's movement has stopped. The product is limited by the amount of power that can be generated per unit volume. This causes a limited amount of light emission when the movement stops, without compromising the comfort of the jogger. Additionally, the light configuration should fan out more than 180° with a single product. Lastly, the frequency of blinking should be independent of the frequency of the jogger's movement.

The environmental footprint of the product should be an improvement over the conventional jogger lights. Since no batteries will be used in the product, the production is more environmental friendly and the durability is increased, which also improves its environmental footprint. However, plastic is made from oil, which will always have a negative impact on environment, but by using recycled and biodegradable materials the impact can be minimised. As it is a small light the impact on light pollution will also be minimal.

1.1 Goal of the Research

The goal of this research is to design a light that joggers can wear, that does not use a battery but is powered by energy harvested from the jogger's environment or movement, called the Battery Free Jogger Light. It should also emit light for a little while when the person stops jogging, for instance at a traffic light. Studies show that a flashing light ensures better visibility in the dark compared to a steady light [2]. That is why the Battery Free Jogger Light should be pulsating instead of steady. Furthermore, the frequency of the flashing light should be independent of the jogger's movement.

This research will focus on the storage of the harvested energy. Some options for the short-term energy storage will be discussed, so that a conclusion can be made about what the best option for short-term energy storage is for this purpose. To store the harvested energy, the obtained signal from the energy harvester needs to be converted to a usable signal that is capable of charging the chosen storage element.

1.2 Document Structure

First the required specifications and goals of the project are defined in Chapter 2. In Chapter 3 the system required for these goals is described in detail and the process of development will be elaborated. The measured results are then presented in Chapter 4 and discussed in Chapter 6. Finally, a conclusion will be drawn in Chapter 7. Additionally, Appendix A will describe the collaboration between the different groups that worked together to deliver the final product.

Chapter 2

Program of Requirements

Mandatory requirements are:

- **Must not have a battery**
- **Must have a flashing light**
- **The frequency of the flashing light must be independent of the jogger's movement**
- Must not obstruct the running movement
- Must not be harmful for the jogger
- Must functions in every moment of the day
- **Must be able to store energy for 30 seconds of lighting, when fully charged**
- **Must be fully charged within 2 minutes of jogging**
- Must at least deliver 4 candela (*cd*) intensity
- The casing must be water-resistant (IP54)
- The degree of lighting must be at least 180°
- Must have a life time of at least 3600 jogging hours (2 hours per day, for 5 years)
- Must be wearable: Max. 250 *g* (incl. casing)
- Max. depth dimension must be 2.5 *cm*
- Max. material costs for the final prototype must be €50

Trade-off requirements are:

- Maximise harvested power
- **Minimise charging time**
- **Maximise flashing duration when standing still**
- Maximise light intensity (*cd*)
- Maximise angle of visibility
- Maximise durability
- Minimise weight
- Minimise volume
- Minimise production costs

The requirements that are put in bold are the requirements that are critical for the storage part of the research. Some other requirements are set for the Battery Free Jogger Light as a whole like durability, weight, volume and production costs. These have to be taken into consideration as well, but these requirements are also dependent on the energy harvesting and lighting & casing parts of the research.

These requirements will be taken into consideration during the research and whether they have been achieved will be discussed in Section 6.6.

Chapter 3

Design Process

3.1 Storage

The system is required to extend the duration of the blinking lights when the user stops moving. In order to achieve this, some means of energy storage is required. Generally, batteries would be used, however considering the requirements stated in Chapter 2 this will be avoided at all costs.

Batteries have a high impact on the environment and a low durability compared to other solutions. Supercapacitors promise a lifetime of several hundred thousands cycles [3, 4] as opposed to batteries having only a few thousand cycles [5, 6].

Considering that the input energy is electrical, it would be interesting to use supercapacitors as energy storage. The supercapacitors offer an affordable solution, as well as having a suitable discharge time and low volume. Flywheels offer similar advantages, but due to being a kinetic energy storage, it would only be applicable in the case that the input is mechanical. Other storage solutions deal with too many conversion losses and a variety of practical disadvantages [7].

3.1.1 Capacitors

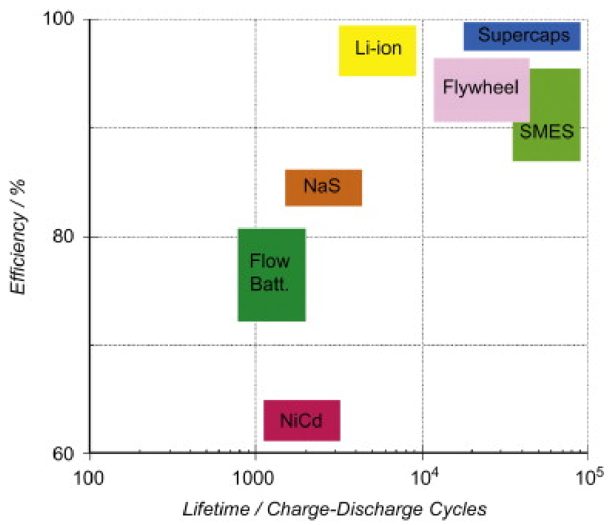


Figure 3.1: Lifetime versus efficiency plot of different kinds of energy storage [7].

Table 3.1: Explanation of the acronyms.

SMES	Superconducting Magnetic Energy Storage
Li-ion	Lithium-ion Batteries
NaS	Sodium Sulfur Batteries
NiCd	Nickel Cadmium Batteries
Flow Batt.	Flow Batteries

Conventional capacitors can be used for storing energy for a short time. This electrical storage is widely used and relatively cheap. The downside of this technique is that capacitors have a very short discharge time, in the order of seconds. By using larger capacitors, this discharge time can be increased, but so does the volume and the price. Using supercapacitors, the same or larger energy capacity can be achieved, but with a higher energy density. This therefore requires less volume. Supercapacitors use a similar principle to capacitors, but use an electrolyte ionic conductor instead of insulating material.

The order of the discharge time can reach to minutes, due to slow ion movement in the electrolytes, making it a viable option for this application. Since the device is electric, the loss is very low (95% efficiency) as there are no conversions [8, 7]. Figure 3.1 shows a comparison in efficiency and lifetime of different kinds of energy storage.

3.2 Conversion

The design of the conversion circuit needs to take two elements into account: the input signal and the storage method. The system designed for charging the supercapacitor is presented in Figure 3.2. In this figure the expected signals after all the blocks are given assuming a function generator is used with an input voltage of 10 V_{pp}, since this is the initially expected voltage that will be delivered by the energy harvester.

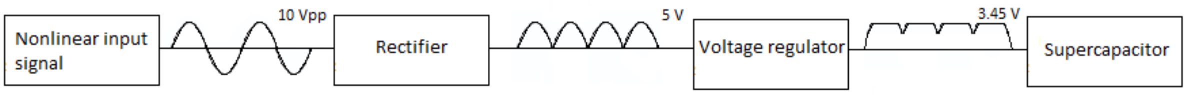
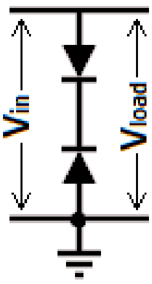


Figure 3.2: Circuit required for charging the supercapacitor.

3.2.1 Voltage Clamping

The first step in the signal conversion block is to analyse the input signal. The input signal is the signal that is obtained from the energy harvester. This signal will most probably be a noisy signal, since it is depending on the jogger's movement and how much energy is harvested from that movement. It might occur that sometimes the jogger walks and the input signal is very small. In this case the supercapacitor uses the stored energy to power the output. But if the energy harvester endures a large impact, the input signal might spike and cause an overvoltage to the circuit. Such an overvoltage is dangerous for the conversion circuit. To protect the conversion circuit from overvoltage, a voltage clamping circuit can be used [9]. A voltage clamping circuit ensures that the signal will stay below a maximum amplitude and by doing so eliminating the spikes from the input signal. The voltage clamping circuit consists of two Zener diodes as shown in Figure 3.3. The two Zener diodes that are chosen allow a maximum amplitude of 24 V. Why this exact value was chosen will be elaborated on in Section 3.2.3.

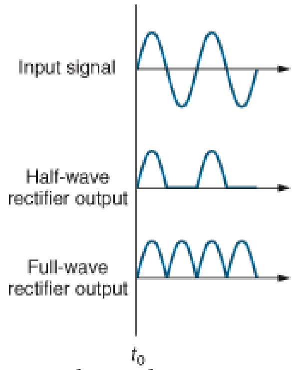
Figure 3.3: A voltage clamping circuit using Zener diodes.



3.2.2 AC/DC Conversion

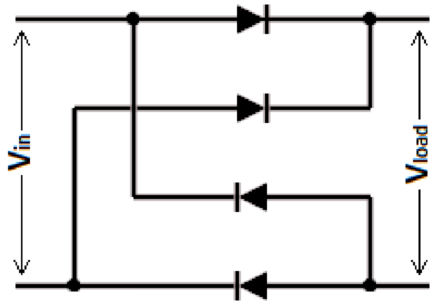
Since it is decided that the energy will be stored in a supercapacitor, a DC voltage needs to be applied at the corresponding voltage rating. Considering the range in capacity, it is necessary to convert the input to 3.6 V. This conversion requires rectification of the input signal and regulation of the voltage. This can be achieved by using a full-wave rectifier or a half-wave rectifier.

Figure 3.4: Output signals of a full-wave and a half-wave rectifier with a harmonic input signal.

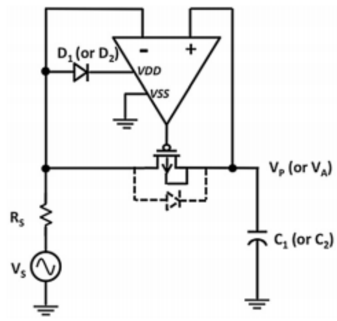


All rectifiers consist of 1 or multiple diodes, which are almost always Schottky diodes since they have a low forward voltage. Normal diodes have a forward voltage of 0.7 V, whereas the chosen Schottky diodes have a forward voltage of just 0.2 V [10]. Full-wave rectifiers, also called full-bridge rectifiers (shown in Figure 3.5a), consist of 4 diodes and flip the negative parts of an AC signal to positive. Half-wave rectifiers are basically just a diode, since they only transmit the positive parts of an AC signal. Figure 3.4 shows these output signals of full-wave and half-wave rectifiers for a perfect harmonic input signal. Half-wave rectifiers can also be implemented as an active diode, which is shown in Figure 3.5b. This implementation does not use a diode and thus has theoretically no voltage drop.

However, this implementation of an active diode is tricky because it uses an OpAmp with a feedback loop. An active diode is only used in circuits with really low voltages, because these low voltage circuits can not afford to have a voltage drop.



(a) A full-bridge rectifier using Schottky diodes.

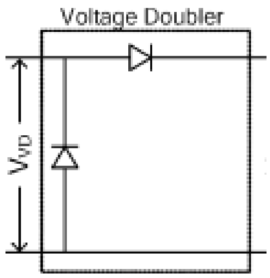


(b) An implementation of an active diode [11].

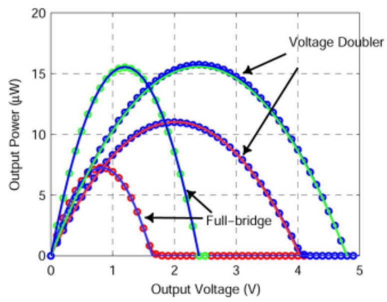
Figure 3.5: Implementations of a full-wave and a half-wave rectifier respectively

Studies show that "half-wave rectifiers offer advantages for vibration energy harvesters over full-wave rectifiers" [12]. Normally, full-wave rectifiers are preferred as they have a higher power factor than half-wave rectifiers. The disadvantage of the full-wave rectifier, however, is the voltage drop, which is relatively smaller for half-wave rectifiers.

Another way to counteract the voltage drop is to use a voltage doubler, which is another type of rectifier that doubles the output voltage compared to the full-wave rectifier [13], this result can be seen in Figure 3.6b. These voltage doublers are usually only used in circuits with small currents and a high load.



(a) A voltage doubler implementation.



(b) Output power and output voltage of a voltage doubler compared to a full-bridge rectifier.

Figure 3.6: Implementations of voltage doubler and its output compared to full-bridge rectifier [13].

Generally harvesters have a low output voltages and need to compensate for this. This system however, has the luxury to choose higher input voltages, as the method of harvesting from the energy harvesting subgroup allows this.

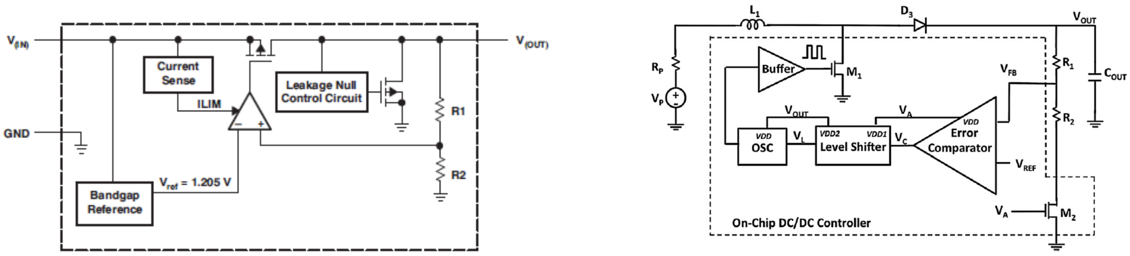
Since the input signal that is obtained from the energy harvester will probably be relatively high (around 10 V), the voltage drop from the full-bridge rectifier is not significant. This is why the full-bridge rectifier is the best option to use as a rectifier, since it is easy to implement.

3.2.3 Voltage Regulation

A maximum charging efficiency for the supercapacitor can be achieved with a stable DC source. The solution for this is a voltage regulator, which assures a stable DC output voltage regardless of the input voltage. A number of systems are capable of doing so, but might not comply with being battery-less [11, 14, 15]. Active voltage regulators use a DC source (battery) to power e.g. an OpAmp. By using a passive voltage regulator, the stable DC signal can be achieved without external power sources [16, 17].

The TPS71533 is capable of keeping a stable 3.3 V on a large capacitor[16]. This application is very suitable as it allows high capacitance loads, whereas many linear regulators cannot [18]. Furthermore, this series allows packages with higher voltages as 3.45 V, 5 V or even fully adjustable. Since many supercapacitors are in the range of 2.1 V to 5.5 V, this application could be very favourable. It also allows for unstable input signals, making it suitable for nonlinear energy harvesters [16].

A different solution could be using a comparator to regulate the output voltage as DC/DC converter [11]. This application uses a battery as reference voltage, but "can be replaced by an on-chip bandgap reference circuit" [11]. However, comparing the controller from Figure 3.7b and the TPS715 series shown in Figure 3.7, it becomes apparent that the TPS715 already has a bandgap reference circuit but does not boost the voltage. Whereas the TPS715 is already in mass production, the DC/DC controller from [11] needs to be custom made. It would therefore be preferred to use the TPS715 in terms of financial and spacial concerns. The drawback of the TPS715 series is that it requires voltages over 2.5 V. Since the voltage limit of the TPS715 is 24 V, the Zener diodes of the voltage clamping circuit are chosen at 24 V. The TPS715 thus has an input range of 2.5 V to 24 V and only is stable with any capacitor greater than or equal to 0.47 μF [18]. Different values for the input capacitor will be tested en discussed in Section 4.1. As the chosen supercapacitor has a nominal voltage of 3.6 V, the TPS715345 will be used, as this version has an output voltage of 3.45 V which comes close to the required 3.6 V. One other requirement of the voltage regulator is that it has a maximum output current of 50 mA. So to prevent the circuit from drawing too much current, a resistor is added after the voltage regulator. With a maximum current of 50 mA and an output voltage of 3.45 V, the resistor value should be at least $R = \frac{V}{I} = \frac{3.45\ V}{0.05\ A} = 69\ \Omega$. Also a diode is added after the voltage regulator to prevent currents from flowing back into the circuit when the supercapacitor is discharging. Since an extra diode causes an extra voltage drop, a Schottky diode is used for its low forward voltage. The implementation of the diode and the resistor (R1) after the voltage regulator are shown in Figure 5.1.



(a) TPS715 IC with fixed output voltage (from [18]). **(b)** DC/DC converter using a comparator (from [11]).

Figure 3.7: The TPS715 and a DC/DC converter; both possible solutions as a voltage modulator.

The alternative to the voltage regulator is a dynamic buck-boost controller or a switch-mode converter. The output voltage of a buck-boost controller is described as Function 3.1.

$$\frac{V_{out}}{V_{in}} = \frac{-D}{1-D} \quad [19] \tag{3.1}$$

The idea of a dynamic voltage regulator is to change the duty cycle D to regulate a varying input to a set output voltage [20, 21]. A switch-mode converter switches between buck, boost and buck-boost mode to regulate the voltage [22]. Using these methods, less power is wasted, as every voltage level is adjusted rather than blocked. The challenge is the complexity of such implementations. The complex circuits use many and large components, making it unfeasible for this application. Furthermore has the requirement of a DC reference, and therefore a band-gap reference, which increases the size of the circuit even more.

3.3 Load Matching

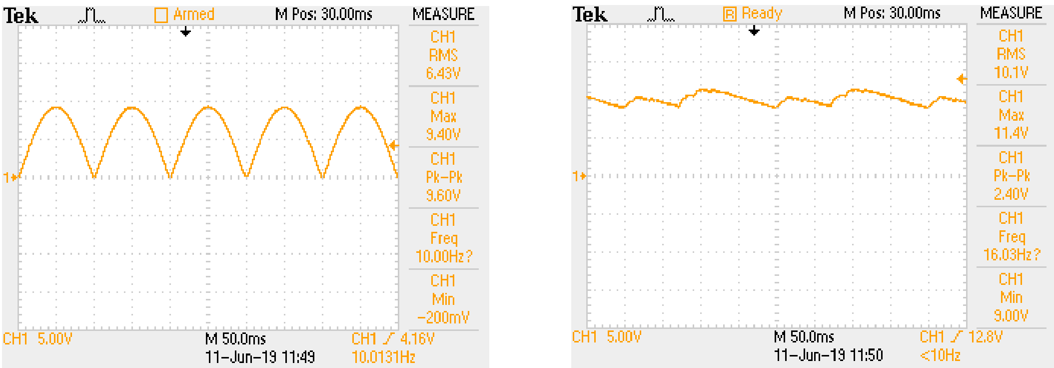
Since the load must be powered for a minimum of 30 seconds as discussed in Chapter 2, the size of the supercapacitor and the amount of current drawn from the load must be optimized. A trade off must be made, as increasing the capacitor value to increase discharge duration will also increase charging time. The resistance of the load can also be increased to improve discharge time, but will reduce the current through the LEDs and therefore reduce visibility.

Chapter 4

Implementation and Results

This chapter will elaborate on the implementation of the design and the measurements[1] with the implemented circuits.

4.1 Rectifier



(a) Voltage over a 1 $k\Omega$ resistance after a full-bridge rectifier.

(b) Voltage over a capacitor of 470 nF after a full-bridge rectifier.

Figure 4.1: Rectification of an input signal of 10 V peak to peak.

For the rectifier, the full-bridge implementation of Figure 3.5a was used. Measurements were done with a resistance of 1 $k\Omega$ as a load. Figure 4.1a shows this full-wave rectified signal and that this signal has a large ripple. To reduce that ripple a capacitor can be used as a load. Since the voltage regulator needs an input capacitor of at least 470 nF as mentioned in Section 3.2.3, the measurement of Figure 4.1b was done with a capacitor with this value. From this figure can be seen that the voltage slightly increases compared to Figure 4.1a. This is due to residue charge left in the load capacitor.

The RMS value also increases due to the smaller ripple in the signal, this can be confirmed with a calculation. The equation for the RMS value of a rectified signal is shown in Equation 4.1. For the signal in Figure 4.1a, $V_{DC} = 0\ V$ since it has no DC value and $V_{Peak} = 9.40\ V$. This results in an RMS value of 6.65 V. For the signal in Figure 4.1b it is a little bit different. This signal has a DC value, which is the average value of the signal. This can be written as Equation 4.2. The peak voltage in this case is the peak over the DC value, which is $\frac{1}{2}V_{PP}$. If this is combined with Equations 4.1 and 4.2, Equation 4.3 is obtained. Filling in Equation 4.3 for the values from Figure 4.1b gives an RMS voltage of 10.24 V. These values correspond to the values measured from the oscilloscope and shown in Figure 4.1.

[1] All measurements with the function generator were done with an input signal of 20 V_{pp} and a frequency of 5 Hz, unless stated otherwise. The measurements with the energy harvester were done with the second version of the energy harvester, which delivers 20 V_{pp}.

$$V_{RMS} = \sqrt{V_{DC}^2 + \frac{V_{Peak}^2}{2}} \quad (4.1)$$

$$V_{DC} = V_{Max} - \frac{1}{2}V_{PP} \quad (4.2)$$

$$V_{RMS} = \sqrt{(V_{Max} - \frac{1}{2}V_{PP})^2 + \frac{(0.5V_{PP})^2}{2}} \quad (4.3)$$

$$\eta = \frac{V_{RMS_{OUT}}}{V_{RMS_{IN}}} \cdot 100\% \quad (4.4)$$

Figure 4.1a shows that the rectified signal has peaks of 9.40 V. With an input of 20 V_{pp}, which has peaks of 10 V, this gives an efficiency of $\eta = \frac{6.65}{7.07} \cdot 100\% = 94.1\%$ for the full-bridge rectifier, using Equations 4.1 and 4.4. This voltage drop is due to the Schottky diodes in the full-bridge rectifier. A full-bridge rectifier has a forward voltage of two diode voltage drops. The total voltage drop over the full-bridge rectifier is 0.60 V, which means the voltage drop of one Schottky diode is 0.30 V. This is slightly higher than the discussed forward voltage of a Schottky diode from Section 3.2.2.

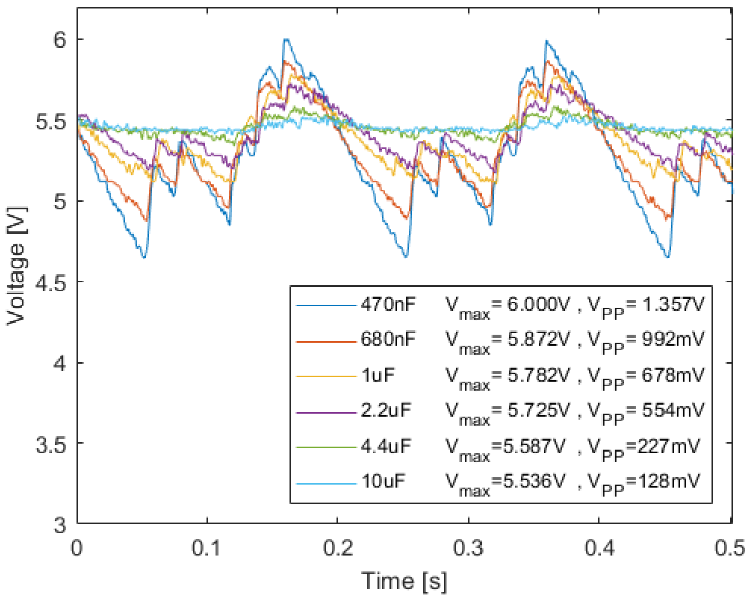


Figure 4.2: The output of the rectifier with different capacitors as a load (with an input signal of 10 V_{pp}).

Table 4.1: RMS values of output signals of the rectifier driven by the different capacitors.

Capacitor	V_{RMS}
470 nF	5.338 V
680 nF	5.387 V
1 μF	5.448 V
2.2 μF	5.456 V
4.4 μF	5.474 V
10 μF	5.472 V

As mentioned before, the voltage regulator needs an input capacitance of at least 470 nF. The measurement in Figure 4.1b shows that the capacitor of 470 nF decreases the ripple significantly compared to the rectified signal over a resistor. To reduce the ripple even more, larger capacitors can be used. The disadvantage of using larger capacitors is that they take longer to charge, but since the values of the capacitors that are used are still in the range of a few micro farads, this charging time is not significant. Figure 4.2 shows the output of the rectifier with different capacitors used as a load. With the maximum voltage and the peak to peak voltage of the different plots in the figure, the RMS voltage can be calculated using Equation 4.3. These RMS voltages are shown in Table 4.1.

For the rest of the measurements the 4.4 μF capacitor will be used, since it has the highest RMS value due to a small ripple.

4.1.1 Results with the Energy Harvester

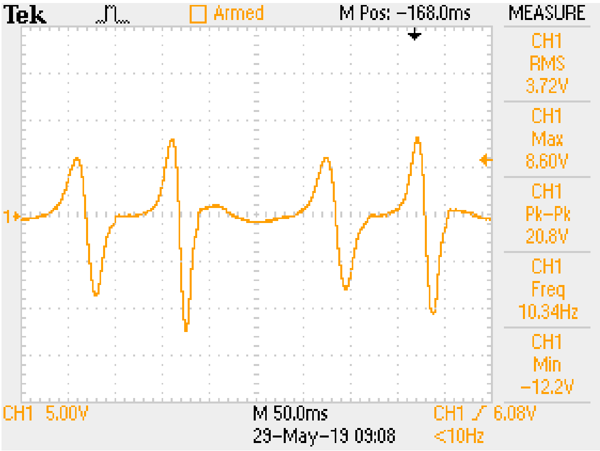
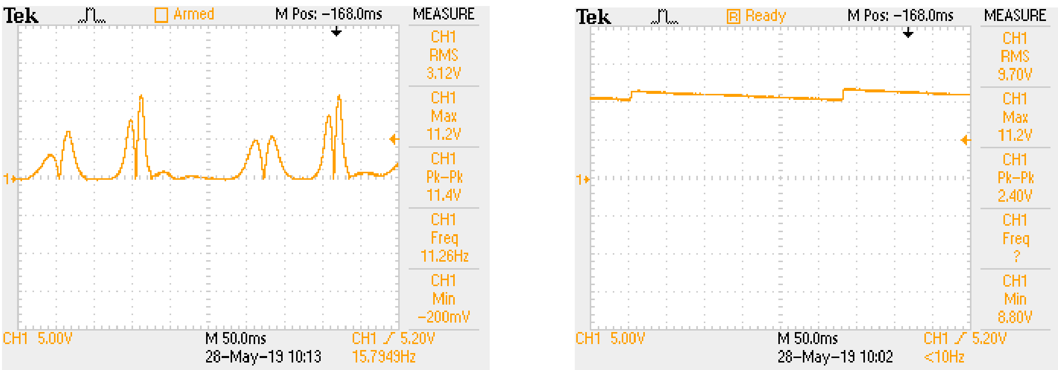


Figure 4.3: Input signal generated by the energy harvester.

The full-bridge rectifier was also tested with the energy harvester as an input source. The signal that the energy harvester generates is shown in Figure 4.3. From this input signal on the rectifier, the signal in Figure 4.4a follows on the output of the rectifier with a load of 1 $k\Omega$. This figure shows that all the negative parts are flipped to positive. From the measured values out of these two plots and Equation 4.4 the efficiency of the rectifier is $\eta = \frac{3.12}{3.72} \cdot 100\% = 83.9\%$, but this efficiency calculation has a much larger error margin than the calculated efficiency with the function generator, which will be further elaborated in Section 6.1.

Figure 4.4b shows the output of the rectifier when the 4.4 μF capacitor is used as a load. What this figure shows is that the discharge time of this capacitor is just long enough to hold the peaks of 11.2 V long enough that the voltage does not drop below 8.8 V. As can also be seen in Figure 4.4b the RMS voltage increases significantly compared to the RMS voltage in Figure 4.4a, this is due to the capacitor. The maximum voltage stays the same with peaks of 11.2 V.

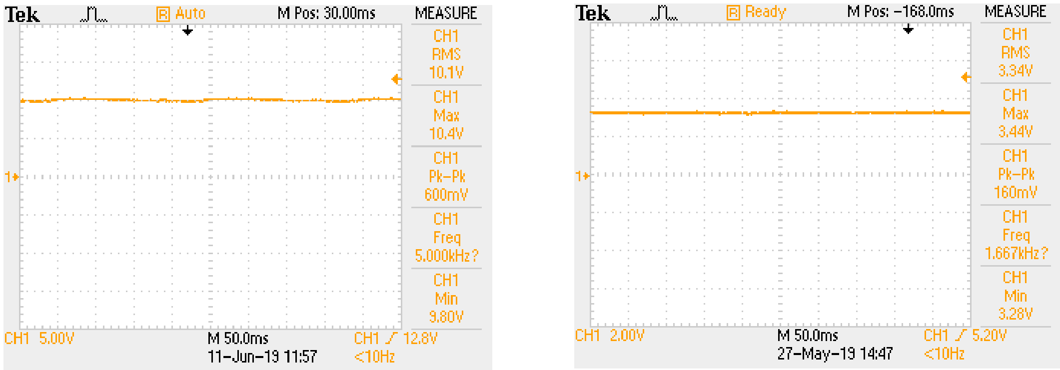


(a) Voltage over a 1 $k\Omega$ resistance after a full-bridge rectifier.

(b) Voltage over a capacitor of 4.4 μF after a full-bridge rectifier.

Figure 4.4: Rectification of the signal from the energy harvester.

4.2 Voltage Regulator

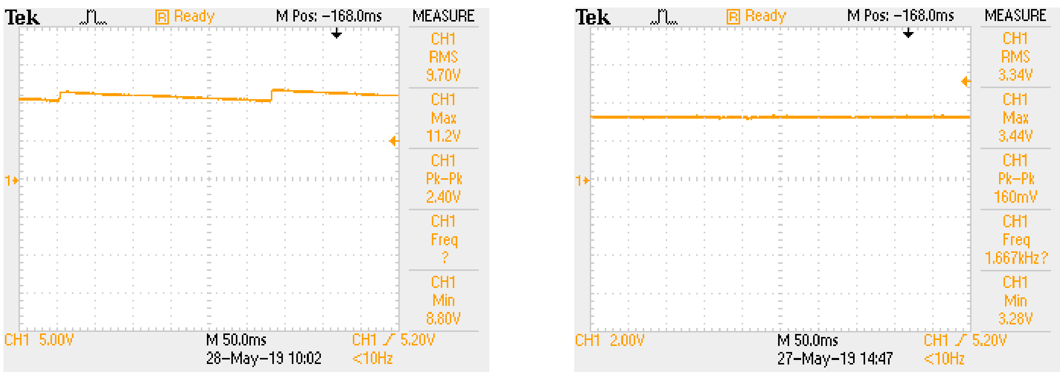


(a) (b)

Figure 4.5: The input (a) and the output (b) of the voltage regulator.

In order to regulate the voltage, a TPS715345 is used. This voltage regulator IC will ensure the output voltage will not exceed 3.45 V. The voltage regulator has a voltage drop of 0.2 V to 1.55 V which needs to be taken into account. When the input of the voltage regulator falls below 3.45 V, the voltage regulator acts as a resistor, causing the voltage drop. Since the voltage regulator can only supply a 50 mA current, the output needs to be adjusted to keep the regulator in its operating region. Figure 4.5 shows that an input signal of over 3.45 V gives a 3.44 V DC output. The efficiency when testing with the function generator can then be calculated with Equations 4.3 and 4.4 as $\eta = \frac{3.44}{10.10} \cdot 100\% = 34.1\%$.

4.2.1 Results with the Energy Harvester



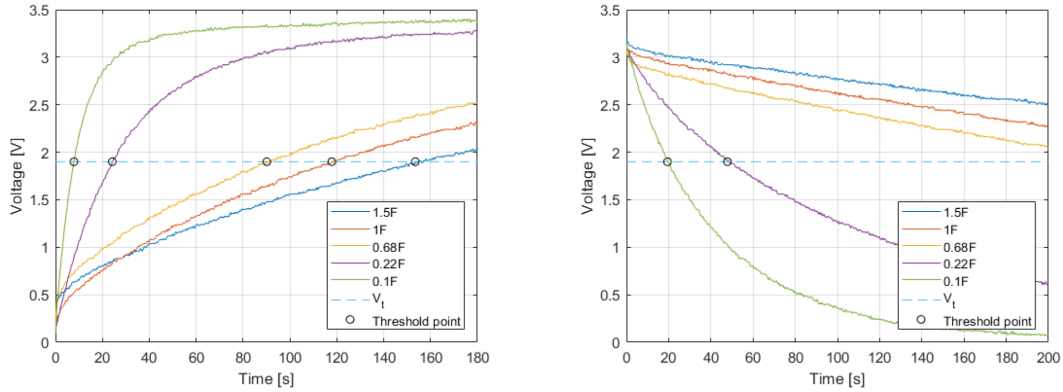
(a) (b)

Figure 4.6: The input (a) and the output (b) of the voltage regulator when connected to the energy harvester.

Testing the voltage regulator on the energy harvester shows larger voltage drops on the input, as the input is not a perfect sine and therefore the practical power is far lower than a function generator can produce. The effect on the output, however, is minimal and can be treated as a consistent DC output. The efficiency of the voltage regulator driven by the energy harvester is then $\eta = \frac{3.44}{10.04} \cdot 100\% = 34.3\%$, using Equation 4.3 for the RMS voltages.

4.3 Supercapacitor

To choose which supercapacitor is going to be used to store the harvested energy and to power the LEDs, the charging and discharging times need to be evaluated. Ideally, the supercapacitor reaches its maximum voltage rating quickly and takes a very long time to discharge. Unfortunately, the charging and discharging times of supercapacitors are directly proportional. If the charging time decreases, so does the discharging time and vice versa. This is where a trade-off needs to be made between these two factors and to choose which aspect is more important. Figure 4.7 shows the charging and discharging times of five different supercapacitors. They are compared with the "threshold" voltage (V_t) the LEDs need to shine bright enough that they produces visible light, this voltage is determined to be 1.9 V. The points where the voltage of the capacitor reach this V_t are marked with black circles and are called "threshold points" in the plots. From these figures can be noticed that the smallest two supercapacitors have a way better charging time than the largest three, namely 8 seconds and 24 seconds for the 0.1 F and the 0.22 F supercapacitor respectively. The drawback of these supercapacitors is that the discharging time is significantly smaller than that of the larger supercapacitors, but since it is still within the range of the requirement set in Chapter 2 (30 seconds), the next measurements are only done with the 0.1 F and 0.22 F supercapacitors.

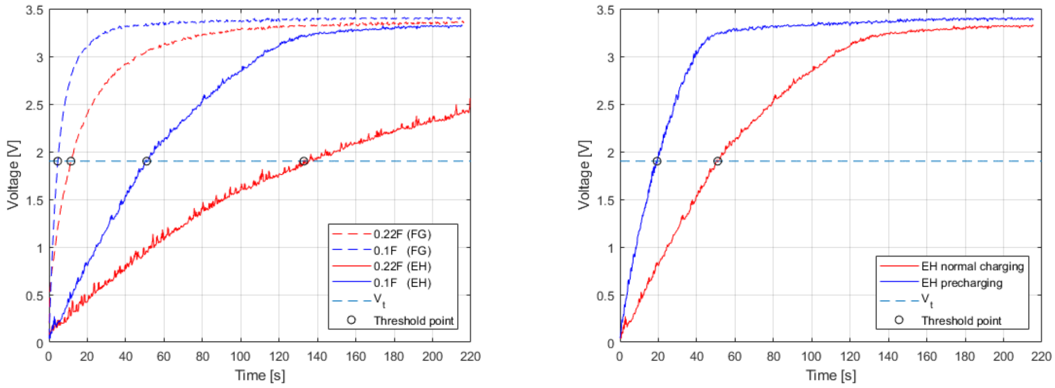


(a) **(b)** Discharging over a load of 680 Ω.

Figure 4.7: Charging and discharging times of various supercapacitors.

4.3.1 Results with the Energy Harvester

The results in Figure 4.7 are done with the function generator with a sine wave of 10 V_{pp}. Since the signal obtained with the energy harvester has much narrower peaks, the expectation is that charging the supercapacitor will take a longer time. Figure 4.8a confirms this expectation and shows that the 0.22 F supercapacitor also takes too long to charge (over 2 minutes). With the energy harvester the 0.1 F takes around 50 seconds to reach V_t, which is also a relatively long time. This is why the idea to pre-charge the supercapacitor was opted for. Figure 4.8b shows the pre-charging time versus the normal charging time and shows that pre-charging significantly increases the charging time.



(a) Charging times with the function generator (FG) versus the energy harvester (EH).

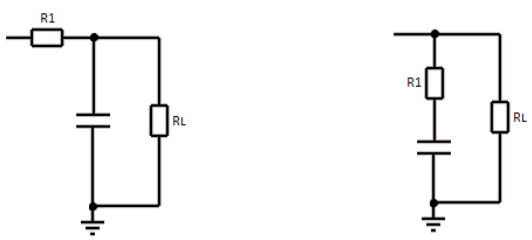
(b) Pre-charging versus normal charging the $0.1\ F$ supercapacitor using the energy harvester.

Figure 4.8

4.4 Load Matching

All of the previous measurements regarding the charging of the supercapacitors are done without a load. If a load is attached, the supercapacitor will charge and discharge at the same time if a voltage above the threshold voltage of the load is reached. Because of this simultaneous charging and discharging, the supercapacitor will not charge up to its maximum voltage rating, because the supercapacitor discharges faster than it can be charged. The dotted lines in Figure 4.10 show the difference in charging with or without a load using the function generator. As can be seen the maximum voltage over the supercapacitor is lower with a load connected. This is also because a voltage division is created with resistor R1 in Figure 5.1 and the connected load, this is depicted in Figure 4.9a. Equation 4.5 shows that only when $R_L \gg R_1$ the voltage over the load is equal to the voltage over the output of the voltage regulator.

$$V_L = V_{in} \cdot \frac{R_L}{R_1 \cdot R_L} \tag{4.5}$$



(a) **(b)**

Figure 4.9: The output of circuit with (a) and without (b) voltage division of the load.

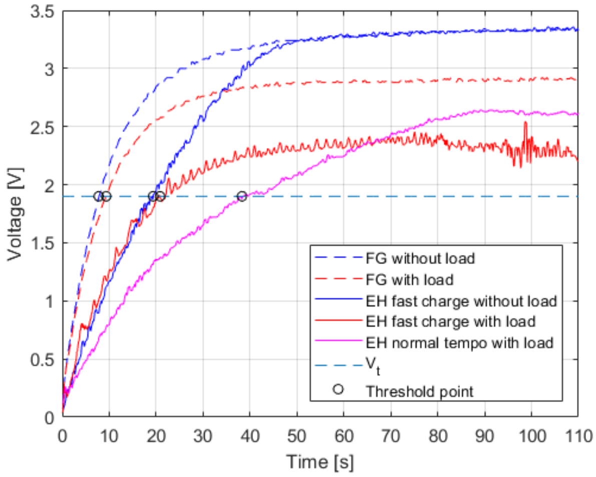
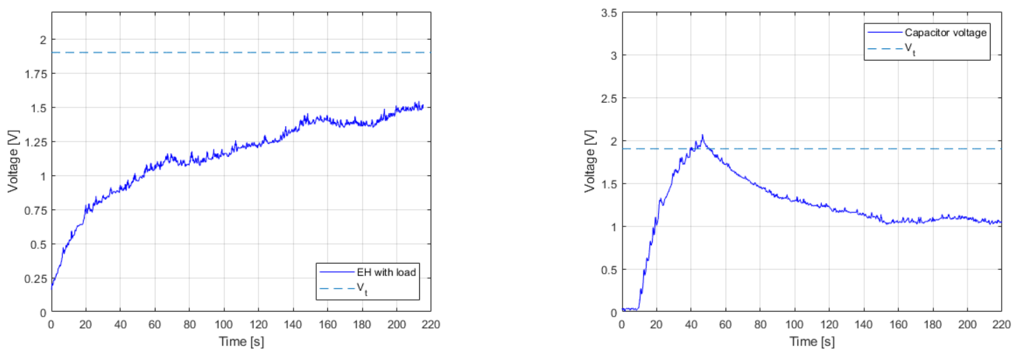


Figure 4.10: Capacitor voltage comparison between the function generator and the energy harvester with a load and without a load.

4.4.1 Results with the Energy Harvester

With this voltage division, the charging of the supercapacitor will be a challenge, since it can not reach the maximum voltage rating and the supercapacitor will still discharge at the same time. This problem is depicted in Figure 4.11, where 4.11a shows that the voltage over the supercapacitor will not reach the threshold voltage of the LEDs within 220 seconds with normal charging. Using the discussed pre-charging method in Figure 4.11b shows that the threshold of the LEDs can be reached, but the voltage drops if the pre-charging stops and normal charging takes over, which causes the voltage to drop under the threshold of the LEDs again. This is why a solution is needed for the voltage division. If resistor R1 in Figure 5.1 is put in the branch of the supercapacitor as shown in Figure 4.9b, this voltage division is solved. The voltage over the supercapacitor can still not reach the output voltage of 3.45 V due to the voltage drop over resistor R1, but the voltage over the load will be equal to the voltage over the output of the voltage regulator. However, the initial voltage over the load will not be the 3.45 V of the output of the voltage regulator, since the supercapacitor will draw the most current when it is depleted. This current through the supercapacitor will decrease as the supercapacitor charges.



(a) **(b)**

Figure 4.11: Normal charging (a) and pre-charging (b) the supercapacitor with a load connected using the energy harvester.

With this change in the circuit, the charging of the supercapacitor with the energy harvester can be seen in Figure 4.10 as the red and the pink line. The red line shows the charging of the supercapacitor using the pre-charging method and the pink line shows the normal charging of the supercapacitor. Compared to the blue line (pre-charging without a load) the red and pink lines reach a lower maximum voltage. This is caused by the voltage division between the resistor R1 and the supercapacitor. Also shown in Figure 4.10 is that the voltage over the supercapacitor decreases after a certain time, this is again because the supercapacitor charges and discharges at the same time.

As the voltage over the supercapacitor does not reach the maximum voltage rating, the voltage over the load should reach a higher voltage. This can be seen in Figure 4.12. The voltage over the load increases as the supercapacitor charges and is a little bit higher than the voltage over the supercapacitor. The noise on the load is caused by the voltage regulator following the input. As the input consists of voltage spikes, these are reproduced on the output. These do not drop below the capacitor voltage due to superposition, resulting in the exponential curve.

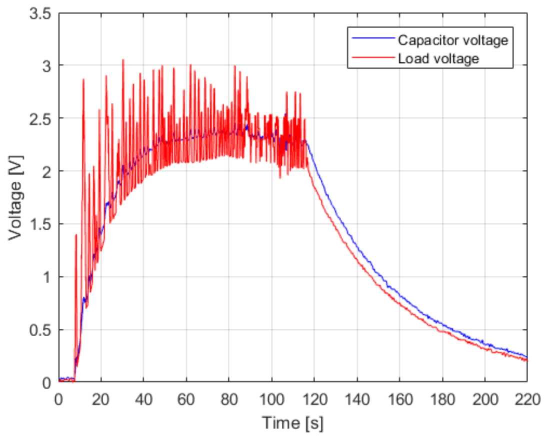


Figure 4.12: The voltage over the supercapacitor versus the voltage over the load.

Chapter 5

System Improvements

5.1 Design Process

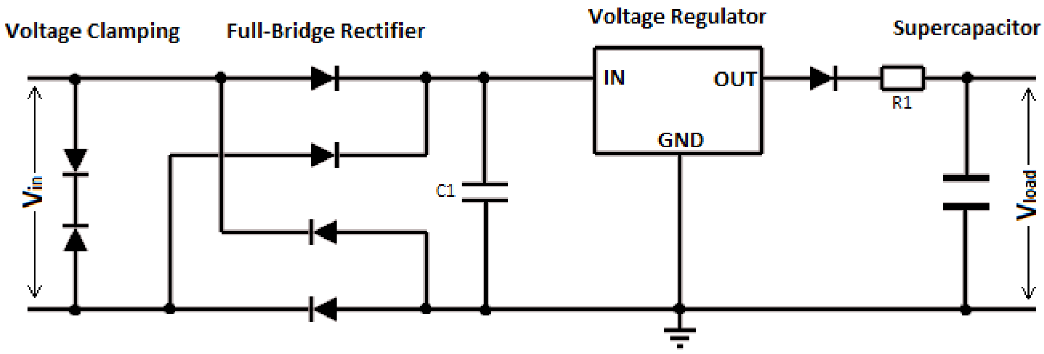


Figure 5.1: Complete circuit overview.

The complete designed circuit thus far is shown in Figure 5.1. This circuit still has its flaws, that is why some improvements are needed.

As the design process continued, it became apparent that the energy harvesting device can produce a higher voltage than initially anticipated. Now voltages of 20 V_{pp} are expected instead of the 10 V_{pp} that was expected previously. The problem now arises that the 3.45 V voltage regulator blocks most of the power, which results in a very low efficiency. The system must be adapted to higher voltages in order to increase efficiency. To do this, a 5 V voltage regulator is used. Since the output voltage of the voltage regulator is increased, the resistor R1 in Figure 5.1 can be increased. The new value of the resistor should at least be $R = \frac{V}{I} = \frac{5\ V}{0.05\ A} = 100\ \Omega$. This also means that the voltage rating of the supercapacitor must be adjusted. Supercapacitors with a rating of 5.5 V will be used to avoid damage.

The main problem during the design process is that the LEDs only start emitting light after the supercapacitor is charged to the threshold voltage of the LEDs, since they are parallel to the supercapacitor. This problem was initially "fixed" with pre-charging the supercapacitor, but this is not an ideal solution. Pre-charging the supercapacitor means that the jogger has to shake the Battery Free Jogger Light before jogging so that the supercapacitor reaches the threshold voltage of 1.9 V so that the lights are shining when the jogger starts running. But then the idea of using LEDs as rectifying diodes was brought up, since the input voltage is sufficiently high. These LEDs require voltage peaks of over 1.9 V in order to produce useful light. The advantage of this implementation is that there is a direct light source, and does not rely on the charging time of the supercapacitor. The disadvantage this gives is that the LEDs have a larger forward voltage than the Schottky diodes, so the efficiency of the rectifier will be lower. But since the voltage regulator needs an input above 5 V and the input signal obtained by the energy harvester is 20 V_{pp}, this forward voltage will not cause problems. As consequence, when the supercapacitor is charged and there is still an input, both the rectifier LEDs and output LEDs will flash with a different frequency. Not only is this undesired for aesthetic reasons, it is also very inefficient.

The solution for this problem is to us a switch to couple or decouple the load and power the LEDs in the rectifier and in the output independently of each other, depending on the input signal. The other advantage this brings about is that the supercapacitor is charged without a load connected, which prevents charging and discharging at the same time and results in more efficient charging. This switching is achieved with a p-channel MOSFET. The FET is placed between the supercapacitor and the load, and closes when there is no voltage applied to the input. To avoid frequent switching when the user is running, the gate is connected after the rectifier, where the input capacitance will hold the voltage for a short while. This will cause the FET to close only when the input capacitor is discharged below the threshold voltage, meaning the user has stopped running. A resistor needs to be placed parallel to the input capacitance, as this capacitor needs to discharge. This resistor is depicted in Figure 5.2 as R2. If the capacitor does not discharge, the input voltage will be held and the Gate-Source voltage (V_{GS}) will not drop below 5 V. The resistor will also allow current to flow through the rectifier, ensuring that the LEDs in the rectifier will work even if the supercapacitor is fully charged.

The forward voltage of the FET is also very important, as the supercapacitor cannot discharge further than the sum of the forward voltage of the FET and LED. Reducing the forward voltage of the FET will increase the charge and discharge time. The ideal FET to use in this implementation is one with a minimal forward voltage, because this way the supercapacitor can discharge up to the forward voltage of the LEDs and achieve the longest discharge time. The drawback of this low forward voltage is that the FET might detect that the jogger has stopped running when this is not the case. The FET compares the voltage over the gate with the voltage over the source, so the voltage over the output of the voltage regulator and the voltage over the supercapacitor respectively. If V_{GS} is lower than the threshold voltage V_T, the switch is closed and the current flows from the supercapacitor to the load. Initially, V_{GS} drops below V_T when the input is not stable enough. These voltage dips cause the PMOS to close frequently while there is still an input. This problem can be solved by increasing V_T, but this will result in less voltage on the output and therefore less discharge time. Another solution is increasing the RC time on the input by either placing a capacitance after the voltage regulator (C2), or increasing the discharge resistance R2. Increasing the resistance will however decrease the current through the rectifier LEDs when the supercapacitor is charged. Therefore the ideal solution would be to place a larger capacitor after the voltage regulator (C2). The practical constraint is that conventional small capacitors are not available for values above 22 μF and using multiple capacitors will take up too much space. A combination of using a large capacitor and a sufficiently large resistor to increase the time that the input signal is hold, while maximizing the current through the rectifier LEDs.

All these design improvements are implemented in a new circuit, which is shown in Figure 5.2.

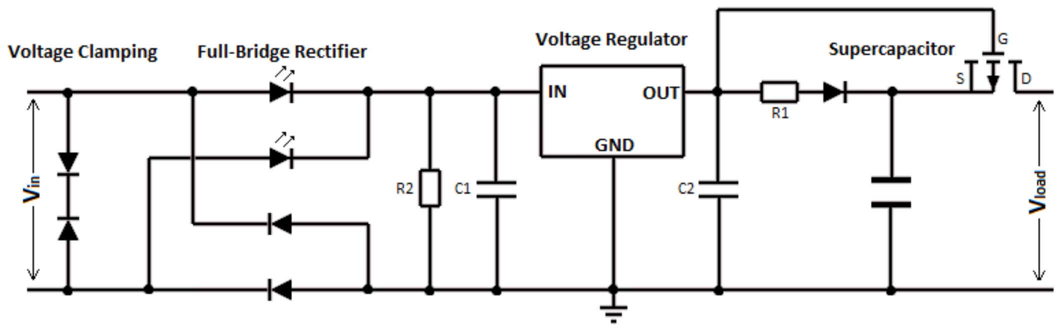


Figure 5.2: Improved circuit overview.

5.2 Implementation and Results

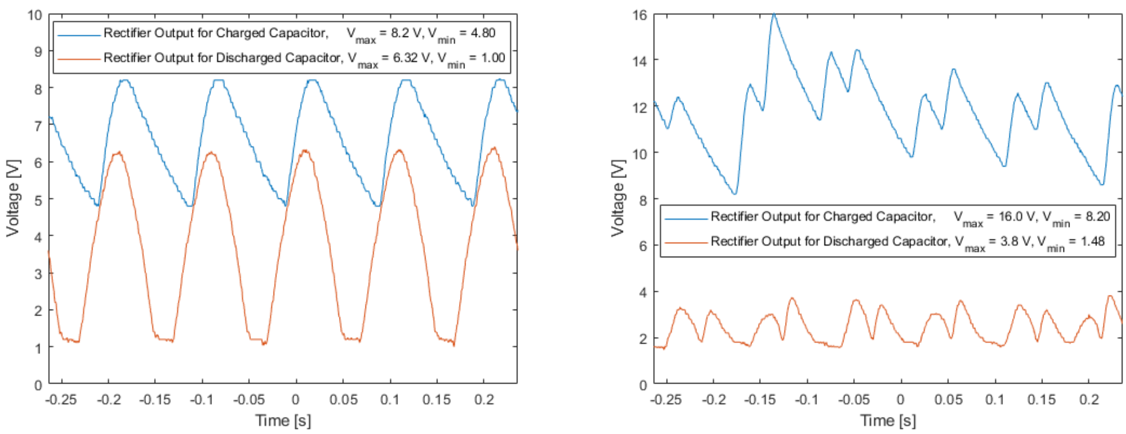
After the design alterations discussed in Section 5.1, further measurements were done. The results of the improvements are presented in this section.

5.2.1 Rectifier

The improved rectifier implementation consists of two Schottky diodes and two LEDs. These LEDs replace the other two diodes to ensure there always is light during jogging. One disadvantage is that the forward voltage of the rectifier increases, since the forward voltage of an LED is higher than the forward voltage of a Schottky diode.

Another drawback, which can be seen from Figure 5.3, is that the output signal of the rectifier decreases significantly when the supercapacitor is fully discharged. The voltages in Figure 5.3 are measured over capacitor C1 and resistor R2 from Figure 5.2. This decreased signal on the output of the rectifier is caused by the fact that the supercapacitor draws almost all of the current from the input when it is not charged yet, which results in a small current through capacitor C1 and resistor R2 and a smaller current results in a smaller voltage. As the supercapacitor charges, it can be seen that the output signal of the rectifier increases, since the supercapacitor acts as an open circuit and all the current goes through capacitor C1 and resistor R2. With the energy harvester (Figure 5.3b) this difference is even bigger.

With these measurements the efficiency of the improved rectifier can be calculated with a fully charged and fully discharged supercapacitor. With a fully discharged capacitor the efficiency is $\eta = \frac{4.12}{7.07} \cdot 100\% = 58.3\%$ and with a fully charged supercapacitor the efficiency is $\eta = \frac{6.61}{7.07} \cdot 100\% = 93.5\%$, using Equation 4.3 for the RMS voltages. Also from the measurement with the fully charged supercapacitor the forward voltage of the rectifier can be calculated, which is 1.8 V. This forward voltage is caused by one Schottky diode and one LED. Since a Schottky diode has a forward voltage of 0.3 V, calculated in Section 4.1, the forward voltage of the LED is measured to be 1.5 V.



(a) (b)

Figure 5.3: The output of the rectifier when the supercapacitor is fully charged and fully discharged using the function generator (a) and the energy harvester (b).

5.2.2 Voltage Regulator

Since the improved energy harvester delivers a higher input than before, a lot of its energy is unused due to the 3.45 V voltage regulator. This becomes clear from Section 4.2, where the efficiency of the voltage regulator is said to be about 34%. This is why a 5 V voltage regulator is used in the improved circuit, namely the TPS71550. This voltage regulator operates the same as the TPS715345, but this one is limited to 5 V instead of 3.45 V. This means that for the signals with a fully charged supercapacitor from Figure 5.3, the voltage regulator IC gives a steady DC output voltage. However, the signals with a fully discharged supercapacitor are not (fully) above the 5 V and the voltage regulator will follow the signal up to 5 V.

With the signals from Figure 5.3a the voltage regulator IC has an efficiency of $\eta = \frac{4.9}{6.61} \cdot 100\% = 74.1\%$ with a fully charged supercapacitor and $\eta = \frac{3.32}{4.12} \cdot 100\% = 80.6\%$ with a fully discharged supercapacitor, using Equation 4.3 for the RMS voltages. With an efficiency of 74.1% for the voltage regulator, the Schottky diode after the voltage regulator is not included yet. Since this diode also has a forward voltage, the voltage over the supercapacitor can not reach the 5 V of the output of the voltage regulator. In fact the maximum voltage over the supercapacitor is measured to be 4.8 V, as can be noticed in Figure 5.4. If this forward voltage of the Schottky diode is included in the efficiency calculations for the voltage regulator, an efficiency of $\eta = \frac{4.8}{6.61} \cdot 100\% = 72.6\%$ is achieved.

Since the 5 V voltage regulator IC is implemented in the improved circuit, the resistor R1 is adjusted to a 100 Ω resistor to limit the maximum current to 50 mA. By measuring the voltage over this resistor, the current can be calculated using Ohm's law. With the energy harvester this resulted in a voltage of 2 V, which can be translated to a current of $I = \frac{V}{R} = \frac{2\ V}{100\ \Omega} = 20\ mA$.

5.2.3 Switch

The initial decision was made to choose a JFET over a MOSFET as a JFET is cheaper, smaller and not susceptible to static discharges. A JFET however produces more noise, but this is not expected to be significant as the switching should not be sensitive to low voltage noise. However, due to the lack of availability of a useful JFET, a MOSFET is implemented.

Using the switch to decouple the load, efficient and therefore faster charging can be achieved. A comparison is made between charging with a function generator and the energy harvester without a load, and is shown in Figure 5.4. This gives an indication of the time required to charge the supercapacitor. The charging using a function generator is much faster, as the energy harvester can only deliver a limited power. The reduction of charging time can be deducted by comparing the charging rates in Figure 4.10. Above the threshold voltage the load can dissipate power and a significant drop in charging rate can be seen.

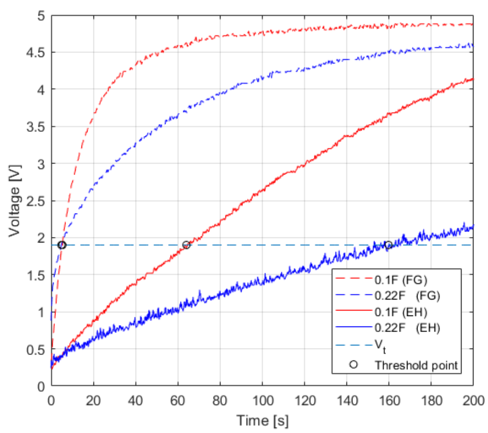


Figure 5.4: Charging a 0.1 F and 0.22 F supercapacitor using a function generator (FG) and an energy harvester (EH). The measurements are compared to the threshold voltage of the load circuit V_t.

Tests with the voltage regulator show that at low frequencies, the output voltage will show significant voltage drops, as seen in Figure 5.5. These dips cause problems with decoupling the load, as V_{GS} drops below V_T during these drops. To compensate, a output capacitance is connected of 10 μF. As result, the voltage drop is reduced by 1.264 V. The voltage drops can be further reduced by increasing R2, as discussed in section 5.1.

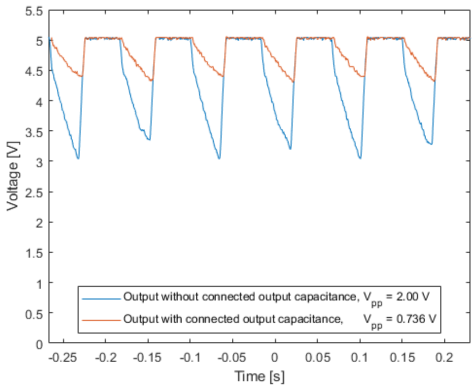


Figure 5.5: Output of the TPS71550 voltage regulator, comparing the voltage drop with and without a connected capacitance at the output, when using the function generator.

5.2.4 Load matching

To optimise the system to the connected load, measurements of the discharge time were done. The discharge time is taken of supercapacitor voltages between 4.8 to 2.0 V, as this is the frame between a fully charged supercapacitor and the threshold of when the LEDs still generate sufficient visible light. By increasing the used resistance in the output system, the drawn current can be regulated and by doing so the discharge rate of the supercapacitor. This resistance is the resistance used in series with the LEDs to regulate the current, and is not the total resistance of the load. The total resistance of the load is not constant and therefore not suitable for measurements. Initial measurements have shown that using a 0.22 F supercapacitor and a short-circuit in the output system the discharge time was far longer than intended. With the short circuit maximum current is drawn from the supercapacitor, but resulted in a discharging time of 81 seconds. As this discharging time was considered to be too excessive, the decision was made to measure using only the 0.1 F supercapacitor.

Resistance [Ω]	Discharge time [s]	Peak current [mA]
99.2	68	17
82.4	60	20
68.4	58	23
56.1	55	23
46.9	55	29
38.6	51	29
33.2	48	33
27.1	47	35
22.0	46	36
14.9	43	43
12.3	43	39
10.2	42	39

Table 5.1: Discharging times from 4.8 V to 2.0 V and peak currents with different resistances for a 0.1 F capacitor.

The measurements done with a 0.1 F supercapacitor are presented in table 5.1. The range of resistor values was chosen to comply with the discharge time requirement of 30 seconds, and the minimum peak current which generates proper visible light. The visibility requirement is done optically and is prone to subjectivity. It does however give a good estimation of the limiting values.

Total Load

To optimise the power delivered to the system, a measurement of the total load is made. Analytical derivation would be difficult due to the active components, and would likely be inaccurate compared to practical results. For this reason the current is measured for a set voltage to calculate the total resistance of the system. The current decreases as the supercapacitor charges, as the voltage difference decreases. Figure 5.6 shows how the resistance increases as the supercapacitor is being charged. When the system is charging, the load is decoupled and therefore the resistance of the load is not included in this measurement. The plot fitted through the measured data is exponential, which is to be expected considering the exponential charging of the capacitance.

For the measurement a 10 Ω resistor is placed between the function generator and the system. By measuring the voltage over this resistance, the current can be calculated with Ohm's law. By dividing the known input voltage of 10 V_{peak} by the peak currents, the resistance can be derived. By also measuring the voltage over the supercapacitor, the resistance of the system can be plotted against the voltage over the supercapacitor. As the measurements were done separately, the plots are calibrated by the start time of the first measured voltage above the noise voltage. The code to generate the plot is given in Appendix B.

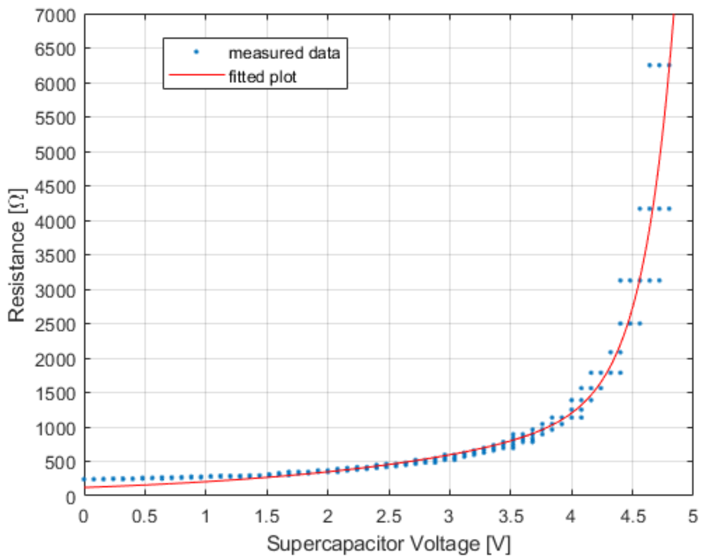


Figure 5.6: Input resistance of the complete system increasing over time, as the capacitor voltage increases by charging.

Chapter 6

Discussion

Firstly, all of the measurements with the energy harvester probably have a high error margin, since for these measurements the harvester was shaken by hand and every time this shaking frequency and amplitude was different, which gives different results. This makes it hard to get a clear comparison between different measurements with the energy harvester. For good comparisons it is desired to shake the energy harvester with the same frequency and amplitude for every measurement.

Also the energy harvesting group did research on using magnets on the top and bottom of the energy harvester to reduce the loss of power due to the clash with the top and bottom of the tube and also to increase the frequency of the signal. They found out that the use of these magnets increased the power they can supply. The measurements done in this research do not use these magnets on the top and bottom of the tube, which is why the results with the final product will slightly improve.

Finally, all of the measurements with the energy harvester in this research are done with the improved energy harvester, which delivers an input signal of 20 V_{pp}. This is done because this way the results of the improved design could be easily compared to the results with the first design, while the first design was designed for lower inputs.

6.1 Rectifier

The results of the rectifier in Figure 4.1a match the expected output of the rectifier that is depicted in Figure 3.2. The only difference is that the expected signal in Figure 3.2 has a peak voltage of 5 V, since that was the initially expected signal delivered by the energy harvester. Later on the expected signal from the improved energy harvester had peaks of 10 V. This value is not reached due to the forward voltage of the Schottky diodes, but the rectifier could not have been implemented in a more efficient way, since other diodes have a higher forward voltage than the used Schottky diodes. The implemented full-bridge rectifier has an efficiency of 94.1% with an input signal of 20 V_{pp}. For higher inputs the rectifier will have a relatively higher efficiency, since the input signal will be higher, but the forward voltage of the Schottky diodes will not change.

The calculated efficiency of the rectifier driven by the energy harvester is lower than the efficiency of the rectifier driven by the function generator. However, the same efficiency is expected. This difference in efficiency is due to the irregular frequency and amplitude of the signal from the energy harvester, which is discussed at the beginning of this chapter. Also, the RMS values used for the efficiency calculations are read from the oscilloscope, which may also be a bit inaccurate. These two deviations give a higher error margin in the efficiency calculation and result in a lower efficiency with the energy harvester.

Furthermore, the rectifier was tested with a capacitor as a load to choose the right capacitor for the input of the voltage regulator. Figure 4.2 and table 4.1 show that the 4.4 μF capacitor has the highest RMS value and also has a small ripple. These two properties make the 4.4 μF capacitor the best option to use as an input capacitance (C1). Figure 4.4b shows that this capacitor discharges just long enough to hold the peaks of 11.2 V and give a sufficiently stable signal for the voltage regulator.

6.2 Voltage Regulator

The voltage regulator works as expected; the input is followed below the maximum, and capped at 3.45 V. The maximum current of 50 mA is not reached, allowing the regulator to work in its operating region. The output of the regulator is observed to be a steady DC with insignificant voltage drops. This result was also seen with the harvester. While the high input voltages result in a very stable DC output, the efficiency becomes very low due to high losses on voltages over 3.45 V. Improving the efficiency of 34.1% is further discussed in Section 6.5.2.

6.3 Supercapacitor

The charging and discharging times of the different supercapacitors have already briefly been discussed in Section 4.3. What can be concluded from Figure 4.7 is that the three largest supercapacitors take too long to charge. The 0.68 F supercapacitor reaches V_t in 90 seconds, which is way too long and the other two take even longer to reach V_t. Also, after 3 minutes these three supercapacitors have not reached their maximum voltage. On the other hand the discharging time is very long, which should not be a disadvantage, but it is not desired that the jogger's light keeps flashing for a couple of minutes when the jogger comes home and puts it away. This is why the 0.1 F and 0.22 F supercapacitors remain as usable options. Charging them with the energy harvester results in longer charging times than with the function generator, since the function generator delivers more power as already discussed in Section 4.3.1. This can also be confirmed by Figure 4.8a. Since the powering of the LEDs was only dependent of the voltage over the supercapacitor at this stage and not of the movement of the jogger, the pre-charging was needed to prevent jogging in the dark for the first minute. This pre-charging increased the charging time of the 0.1 F supercapacitor to 20 seconds. This means that the jogger would have to shake the light for 20 seconds before running. This solution is not ideal, but still better than jogging without a light. These charging times are the main reason the 0.1 F supercapacitor was chosen. The discharging time of this supercapacitor is around the required 30 seconds and could still be increased by increasing the load. The drawback of increasing the load is that the charging time will also increase.

6.4 Load Matching

As the load dissipates more power than the input can deliver, the decision was made to switch between coupling and decoupling the load, further elaborated in Section 6.5.4. This way, the voltage division described in Section 5.2.4 is no longer a problem. The current limiting resistor R1 is placed before the switch, while the current limiting resistor of the load is applied in the output circuit. Choices for the values of these resistors are presented in Section 6.5.

6.5 System Improvements

6.5.1 Rectifier

With the LEDs in the improved rectifier, the main problem was solved. The jogger's light does not need to be pre-charged anymore, since the LEDs in the rectifier start flashing at the moment the jogger starts running. The disadvantage of this implementation is that the efficiency of the rectifier is reduced due to the higher forward voltage of the LEDs, which leaves less power to charge the supercapacitor. The efficiency discussed in Section 5.2.1 can not be compared to the efficiency from the initial rectifier of Section 4.1, since the improved rectifier is only tested with the supercapacitor attached and the initial rectifier only without the supercapacitor attached. However, the efficiency of the improved rectifier can be calculated theoretically. The output signal of the rectifier has peaks of 8.2 V when the supercapacitor is fully charged, this can be compared to the output of the rectifier when there is no supercapacitor attached, because a fully charged supercapacitor acts like an open circuit. Only in this case there is a resistor and a capacitor placed after the rectifier, contrary to the initial rectifier, which was tested with only a resistor or only a capacitor. If the improved rectifier would be tested with only a resistor as a load, the signal would resemble that of Figure 4.1a, but with peaks of 8.2 V. The efficiency can then be calculated with Equations 4.1 and 4.4, which results in an efficiency of $\eta = \frac{5.80}{7.07} \cdot 100\% = 82.0\%$. Comparing the results, the efficiency of the rectifier drops from 94.1% to 82.0%.

The efficiency of the improved rectifier driven by the energy harvester is not calculated, since the output signal deviates too much from the input signal that it would not result in a representable efficiency.

6.5.2 Voltage Regulator

Initial tests with a supercapacitor as load show significant voltage drops on the output of the rectifier, as the supercapacitor drew too much current. A resistor was added to regulate the output to keep the voltage regulator in its operating region. This however proved to be insufficient to resolve the voltage drop. Later tests with a higher power energy harvester and a 5 V voltage regulator improved the voltage level significantly. Tests with a connected load however, reintroduced this problem as all power was needed to power the load. This mismatch was solved by decoupling the load, as explained in detail in 5.1. This implementation resolved the issue very effectively.

To limit the current drawn from the voltage regulator, a resistor is placed in series (R1). This resistor is chosen as 100 Ω, as this limits the current to the maximum of 50 mA for an output of 5 V. Practically, this current is never achieved and lower values would be possible. While it was expected that the current increases as the resistance is lowered, the current does not exceed 20 mA in normal use with the energy harvester. Since the gains from lowering the resistance are insignificant, the value is kept at 100 Ω to ensure the TPS71550 does not break down with high power input tests with the function generator.

The higher input of the new energy harvester required the voltage regulator to be changed from the 3.45 V model to the 5 V model. Since this allowed the regulator to pass a larger portion of the input power compared to the 3.45 V model, efficiency increased from 34.1% to 74.1%. Measurements with a discharged supercapacitor show efficiencies of 80.6% however these are not considered representable. When the supercapacitor is not fully charged, the voltage on the input of the regulator is lower. While the input is below 5 V required for the regulator output, the input is followed on the output resulting in a near 100% efficiency and is therefore not interesting. Using a charged capacitance will be similar as measuring with a open circuit. This way a better indication of the efficiency of the voltage regulator can be measured, rather than the efficiency of the voltage regulator with a connected capacitance.

While the regulator has an input lower than 5 V, the regulator cannot provide 5 V on the output. As consequence, no DC signal can be delivered to the capacitance. This results in inefficient charging and would preferably be improved upon. Increasing the input voltage is however not an option, as the ensuing losses would be more significant than the expected gain.

Efficiency could be further increased by using a switch-mode converter or a dynamic boost converter. As explained in Section 3.2.3, this would be a very space demanding solution. If time and budget would allow, an integrated implementation could be developed. By using SMD devices for other components, room could be created to implement this. This would take a lot of development, and since the designed integrated circuit needs to be custom manufactured it would become very expensive for the final product. The current implementation shows that with the achieved efficiency it is possible to comply with the requirements, and further increase in efficiency might not be required.

6.5.3 Supercapacitor

Since the input delivered by the energy harvester is higher and the 5 V voltage regulator is used, a 0.1 F supercapacitor with a voltage rating of 5.5 V is used. A supercapacitor with a higher voltage rating results in a larger charging time, since more energy can be stored. The increased charging time can be seen by comparing Figures 5.4 and 4.8a. The charging time with the energy harvester is increased from 50 seconds to 65 seconds. However, since the LEDs are implemented in the rectifier, the charging time of the supercapacitor is not that critical anymore as there instantly is light when the jogger starts running.

6.5.4 Switching

Implementation of the transistor to switch between load coupling proved to be an effective way to improve charging time. The reduction of charging time can be deducted by comparing the charging rates presented in section 5.2.3.

The unstable output of the voltage regulator however, proves to be problematic. The significant drops connect the load when it should remain decoupled. As explained in section 5.1, the drop is reduced by increasing the output capacitance (C2). The output capacitance is increased to 22 μF, as this was the largest value available at the moment. Using tests with the energy harvester and different values for resistance R2, the value 47 $k\Omega$ was chosen. For this value, the input voltage is held for long enough to keep the load decoupled while running. While larger values would also work, using the minimum resistance allows maximum current through the rectifier LEDs.

6.5.5 Load

Preferably, the load of the total system should be equal to the internal resistance of the energy harvester. The value of this internal resistance is provided to be 1 $k\Omega$ and is within the range of the resistance of the system. Increasing the starting resistance from 250 Ω to 1000 Ω would be more efficient as this increases the charge rate at the start of operation. However, in order to do this, additional resistors must be added, which increases power loss. As a large part of the system is within range of the 1 $k\Omega$, it has been decided not to compensate the internal resistance to avoid losses.

The load of the output is adjusted to the desired discharge time and LED brightness. Since the results are well within the boundaries of the requirements, there is room to choose an ideal value. This is however a subjective decision as weighing between discharge time and visibility are mainly opinion based rather than optimal values. The decision was made to use a 47 Ω resistor, as the discharge time was close to a minute (55 seconds) and the LEDs show plenty of visibility. While other values gave similar results, the chosen value has an equal peak current to using a 38.6 Ω resistor, and the discharge time was measured to be as long as for the 56.1 Ω resistor. If there would be reason to prefer longer discharging time instead of brighter LEDs, or vice-versa, there would be room to do so. The RC time of the supercapacitor and the load cannot the analytically determined, as the resistance of the load is not constant but is determined by the state of the active circuit.

The decision to choose a larger supercapacitor was opted for as this gives a higher discharge time while allowing a higher peak current as well. However, this discharge time was deemed too long. Considering that the charge time increases as the supercapacitor increases, it would be disadvantageous to do so.

6.6 Requirements

The designed system has no reliance on external DC sources and is therefore battery free, in compliance with the requirements. The LEDs in the rectifier allow the system to emit light immediately, inducing no start-up time. The discharge time specified in Chapter 2 is achieved almost twofold, performing for 55 seconds compared to the required 30 seconds. The charging time is no longer a bottleneck in the improved system, but is charged to the threshold point in 20.3 seconds and reaches 90% charge in 2 minutes and 30 seconds with normal usage. The pre-charging method charges the supercapacitor faster, but is not required. These measurements were done using the setup shown in Figure 6.1. By attaching the energy harvester to multiple points on the body, the power delivered to the capacitor can be derived by measuring the reached capacitor voltage.

(a) Energy harvester mounted on the upper arm. **(b)** Energy harvester mounted on the waist. **(c)** Measurement setup for determining delivered power.

Figure 6.1: Setup for power measurement while jogging.

The current frequency of the blinking of the LEDs while jogging is equal to the frequency of the jogger's movement, as this is determined by the input signal. The frequency while discharging is determined by the output system. As these systems cannot operate at the same time due to the switching, the frequencies do not interfere. In this respect the battery free jogger's light does not satisfy the requirement specified in Chapter 2. This requirement could be complied with when using the initial rectifier and the pre-charging method, but since this is even more unfavourable the choice was made to not entirely satisfy this requirement.

Since the system does not rely on batteries, the lifetime of the system depends on the electrical components. The supercapacitor is likely the most critical component, as it is susceptible to deterioration. The expected lifetime of supercapacitors are measured to be around 10 years. As the system does not charge the supercapacitor to its maximum voltage rating, but to 90%, optimal usage can be assumed, maximising the lifetime of the supercapacitor. Due to the isolation of the supercapacitor by diodes, the supercapacitor depletes only at the minimal rate of the leakage current of the diodes. For this reason, the supercapacitor does not fully deplete, which adds to optimal usage. Other electrical components do not bear excessive electrical or thermal stress. For this reason, the lifetime of these components are not expected to be lower than 10 years.

The volume of the total system fits on a 82.3mm x 29.84mm PCB shown in Figure 6.2. This fits perfectly in the first prototype which can be seen in Figure 6.3. Further size reduction is still possible, as all components are chosen to be hand soldered and can be reduced to SMD components. This could allow future improvements with an integrated switch-mode converter, or a dynamic boost controller.

It could also allow the entire product to be reduced in size, if energy harvester could be reduced in size as well.

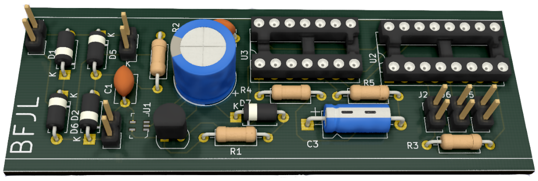


Figure 6.2: PCB realisation, including the energy storage and load circuit.

Figure 6.3: PCB implemented in the first prototype casing.

The system is measured to be far below the weight constraints, and is therefore not of any concern. The current prototype costs are significant as single PCB orders are cost inefficient. A total cost of around 50 euros was needed to produce the first prototype circuit. Large scale fabrication is expected to bring the cost down to below 5 euros per PCB, including components.

Using the results from Sections 5.2.1 and 5.2.2, the total efficiency can be calculated as $(0.935 \cdot 0.726) \cdot 100\% = 67.9\%$. These are the efficiency values of the improved rectifier with a supercapacitor attached and the 5 V voltage regulator with the Schottky diode. Practical tests prove this efficiency to be sufficient.

Chapter 7

Conclusion

As the most efficient method to store electrical energy is to use a supercapacitor , this is implemented as storage element. In order to store the energy delivered to the system, the non-linear signal is converted to a stable DC voltage. This is done by rectification and voltage regulation. By decoupling the load circuit during charging, efficiency is improved. LEDs are placed in the rectifier to produce instant light when an input is present. Lighting during off-time (no input) is maximised by controlling the current drawn by the output. For this decision, the discharge time is maximised while keeping the LED intensity plenty visible.

The supercapacitor used is a 0.1 F capacitor, as this provides enough energy to power the load for 55 seconds when fully charged. While a larger capacitance would increase discharge time, using a 0.1 F capacitance maintains a practical charge time. The rectifier output is stabilized by connecting a 0.44 μF capacitance C1. This value was chosen since it yields the most stable input and maximum RMS voltage.

To improve switching behaviour, capacitance C2 of 22 μF is added to hold the input voltage for a longer period. As practical constraints limit the capacitance value, the RC time is extended by increasing R2 to 47 $k\Omega$. The drawback being, that current through the rectifier while the supercapacitor is charged is decreased.

The output current of the voltage regulator is limited to 50 mA, as this is the absolute maximum rating for the voltage regulator. A 100 Ω resistor is implemented for this purpose. Lower values would be possible as this maximum current is generally not reached, but as decreasing this value would not increase efficiency significantly, the 100 Ω resistor is kept for safety reasons.

7.1 Achieved Results

In terms of requirements, the goal for 30 seconds discharge time is extended to 55 seconds, but the goal of a fully charged system within 2 minutes is not reached. This requirement is however not as critical as initially thought, as the new design does not require the system to be charged to emit light while jogging.

The requirements state that the frequency of the flashing lights should not be dependent on the movement of the jogger. This is only partially achieved, as during charging the LEDs flash on the frequency of the jogger. This is deemed as acceptable as it allows immediate lighting. The frequency of the LEDs during the discharge state is independent of the jogger's frequency and therefore meets the requirements.

7.2 Further Improvements

The current achieved efficiency is measured to be 67.9%, which is in practical experiments proven to be sufficient. The efficiency might be further improved in future designs including either a switch-mode converter or a dynamic boost converter. The solutions would require integrated circuits in order to fit in the final product. Production costs and product size reduction should be taken in account as well for such a decision, as it could be a space demanding and costly improvement.

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Appendix A

Collaboration

We worked with a group of six people on this project, consisting of three subgroups of two persons. To achieve the best result with a working prototype, good communication between the three subgroups was needed. Before the bachelor graduation project started, we had a group meeting to make the following time schedule for this period:

Week	Scheduled activity
0	Make a group division
1	Literature research
2	Conclude the literature research and start with the design
3	Finalising design
4 + 5	Building and testing + Green-light assessment
6	Make a working prototype
7 + 8	Writing the thesis
9	Finishing the thesis + thesis deadline
10	Preparing the thesis defense
11	Thesis defense

During the bachelor graduation project we worked in the Tellegen Hall every day. This way all of us were in the same room, so if we had a problem or a question, we could ask the other groups directly. Every day we started with a brief meeting, discussing the things we were going to do and we ended every day with a brief meeting what was achieved and what our struggles were. This way all the group members were kept informed on the progress of every subgroup and they could give advice on the things that were decided. Furthermore we had a meeting with the supervisors (almost) every week to keep them informed about our progress and ask questions if we hit a roadblock. This form of communicating proved to be very efficient, since everyone was kept up to date.

The made time schedule seemed a bit optimistic at first, but we thought a strict timeline would be a good motivator to achieve the best result. The time schedule was eventually followed very strictly because of the good collaboration and communication between the subgroups. The only deviation was that the building and testing started earlier than planned and filled up the most of the weeks, since not every part of the system worked instantly.

Altogether, a working result was achieved due to the excellent collaboration, which made this bachelor graduation project a pleasant experience.

Appendix B

Matlab Code

```
clear all
[d0] = readtable('./ALL0006/Load_in_t.csv','Format','%f%f');     %data voltage input resistance
[d1] = readtable('./cap_charge/F0003CH1.csv','Format','%f%f');   %data supercap charging
x = d0.x(115:2003);      %allocate data to var
y = abs(d0.y(115:2003));
V_C = d1.y(202:2087);
%%
i =0;          %string of maximum values to compare with peak voltage
xt = [];
yt = [];
for i = 1:1886

    [m,k] = max(y(i:1889));
    xt    = [xt x(i)];
    yt    = [yt y(k+i-1)];

end
yt = yt.';
xt = xt.'-4.52;              %displace time data to match supercap charging
rt = 10./(yt./10);           %R = 10 V_p_p /(V_measured / 10 Ohm)
%%
count = 0;
for i = 1:length(rt)
    if rt(i)<= 1500 && rt(i)>= 666.7
        count = count + 1;
    end
end
%%
plot(V_C,rt,'.')          %plot resistance against supercap voltage
hold on
plot(fittedmodel)
hold off
grid on
xlabel('Supercapacitor Voltage [V]')
ylabel('Resistance [\Omega]')
ylim([0 7000])
yticks([0:500:7000])
lgd = legend('measured data', 'fitted plot')
```