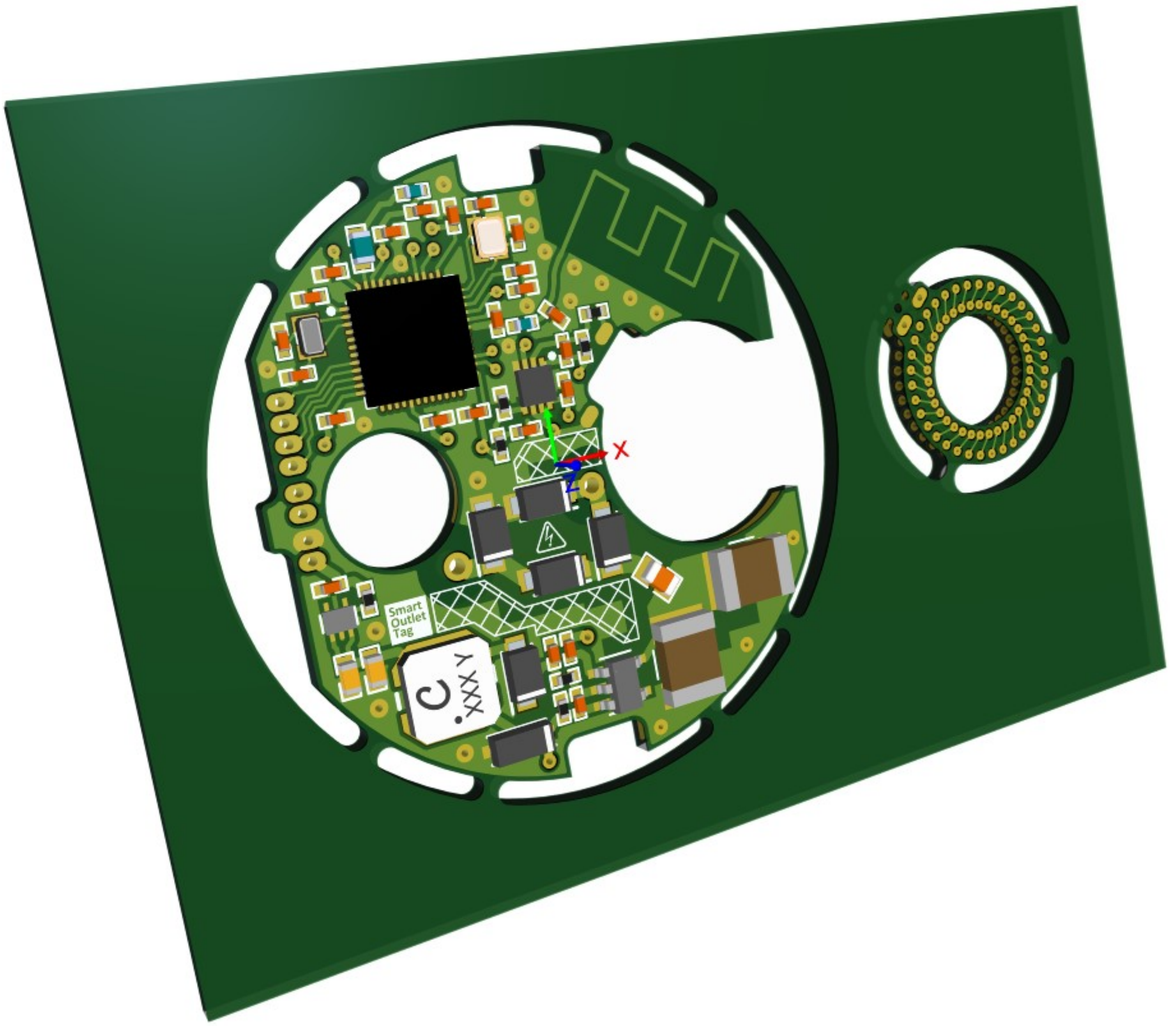
Smart Outlet Tag

Ies Verhage

June 2022



Voorwoord

Dit document is opgesteld voor het afstuderen aan de Hogeschool Rotterdam bij stagebedrijf Crownstone. Dit bedrijf sloot goed aan bij mijn eigen interesses en ik ben blij dat ik hier terecht kon. Dit verslag zal langs de belangerijkste gebeurtenissen en keuzes van deze stage lopen en is bedoeld om gelezen te worden door docenten en collega's. Ook kan dit onderzoek nuttig zijn voor mensen die een soortgelijk onderzoek doen of geintereseerd zijn in de werking van de Rogowski coil. Mijn dank is groot naar Crownstone en haar medewerker die meedachten en ondersteunden in het process. In het bijzonder wil ik Anne van Rossum en Peet van Toor hartelijk danken voor de begeleiding en samenwerking.

Ik wens u veel leesplezier toe.

Ies Verhage

Rotterdam, 1 juni 2022

Version history

Version	Desicription	Date
0.1	Calculations Rogowski coil	04-03-2022
0.2	Adding DCD / DFD and overal improvements	25-03-2022
0.3	Archtecture section	05-04-2022
0.4	Adding graphs of power supply	14-04-2022
0.5	Completing amplifier circuit	01-05-2022
0.6	Completing capacitors chapter	04-05-2022
0.7	Adding Introduction and Conclusion	01-06-2022
0.8	Improvements	02-06-2022

Abstract

De Nederlandse variant afronden en vertalen.

Samenvatting

Crownstone is een fabrikant van slimme stekkers en connectoren. Op het moment maakt Crownstone voornamelijk kastjes die het stroomverbruik kunnen meten, appraten kan aan en uitschakelen en de locatie van een gebruiker kan lokaliseren. Deze kastjes kunnen achter een stopcontact of lamp aangesloten worden. Crownstone is op zoek naar een nieuw product dat in plaats van achter het stopcontact, in het stopcontact geplaatst kan worden. Dit zal voor installatie veel makkelijker zijn en het product ook laagdrempeliger maken. Idealiter kan het stopcontact dan nog steeds door apparaten gebruikt worden, en daarom zal het dus ook heel dun moeten zijn. Zaken als een Bluetooth verbinding en het kunnen meten van stroom zijn een pre. Een groter probleem is het voeden van het apparaat. Een directe verbinding zou namelijk lastig zijn op deze schaal en als andere apparaten ook hun energie uit het stopcontact moeten kunnen halen. Daarom wordt eerst onderzoek gedaan naar de mogelijkheid om inductief energie te harvesten. Deze informatie zal ook gelijk handig zijn voor hoe de stroom gemeten kan worden. Om antwoord te geven op al deze vragen is de volgende centrale hoofdvraag gesteld: "Hoe kan er een dun apparaat, ter grootte van een stekker, ontwikkeld worden dat uit het stopcontact gevoed kan worden, draadloos data kan versturen en het meten van stroom?"

Dit onderzoek is zowel praktisch als theoretisch gedaan. Vooral zijn bronnen van het internet gebruikt, echter is ook praktisch onderzoek nodig om tot bepaalde antwoorden te komen. Daarnaast is er ook gebruik gemaakt van de kennis en expertise van de medewerkers van Crownstone. Allereerst volgt er een onderzoek dat ingaat op het inductief stroom opwekken. Vervolgens zal beschreven worden hoe de diverse units ontworpen zijn en welke beslissingen daarbij gemaakt zijn. Tot slot worden de units getest op hun requirements.

Uiteindelijk zal blijken dan het inductief energie harvesten niet mogelijk is. De opgewekte stroom uit de ontwikkelde Rogowski coil zijn te laag. Echter is de coil wel geschikt voor het meten van energie, dit zal daarom ook geïmplementeerd worden. Om het eindproduct toch te kunnen voeden is er voor gekozen in dit prototype een 230V AC naar 3.3V converter te integreren. Voor het draadloos communiceren is er een Bluetooth antenne op het PCB aangebracht. Aan het einde van het verslag is een eerste prototype van het product vervaardigd. Om antwoord te geven op de hoofdvraag is er een dun apparaat ontwikkeld die de belangrijkste zaken kan uitvoeren.

Echter zijn er nog diverse verbeteringen die in een volgend ontwerp doorgevoerd kunnen worden. Zo kunnen er kleinere weerstanden en condensatoren gebruikt worden om meer ruimte voor andere modules te creëren. Deze ruimte kan besteed worden aan het toevoegen van een extra trap van het stroom meet circuit. Het inductief stroom harvesten is volgens het gedane onderzoek niet mogelijk, hier kan later nog extra onderzoek naar gedaan worden om nieuwe methoden te ontwikkelen die dat beter kunnen.

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1 Introduction

Crownstone, a company based in Rotterdam, is a manufacturer of smart plugs and connectors. Their main product is an all-in-one box that can be placed behind a socket or lamp. Think of functionalities such as a 16A switch, LED dimmer, power meter, soft fuse, standby killer and presence sensor. The purpose of this product is to provide ease of use to the end user and to prevent unnecessary energy consumption. A unique selling point of the Crownstone equipment is the position tracking of smartphones and wearables. By receiving Bluetooth signals, it can be determined where a device is located in a room. This makes it possible to automate certain things, such as switching lighting on or off. There is also interest from the healthcare industry in implementing this technique. In a hospital, for example, it could be determined where a patient is. This is also possible in houses/rooms with people in need of help, such as dementia, for example. By monitoring the resident's activity and location, this can provide valuable information about his or her condition.

Crownstone wants to further expand the product range and needs a new product. The current module can be placed behind a socket or lamp, but in case only position tracking is required, this step can be quite difficult, especially for a non-technical individual. It would be an addition to develop a simple module that can easily be plugged into a socket. It is extra beneficial if this module has the form factor of a socket safety protector. In that scenario, the position could be determined and the socket is still available for use. An additional advantage is that this solution is very minimalistic and will hardly stand out. However, it is still unclear to what extent this is possible, which has given life to this project.

The aim of this project is to develop a module that is the size of a socket protector and has Bluetooth functionalities. The modules will function in a so-called mesh network so that different modules together make one large system. A very preferable item to have is to measure the used current by the plugged in device. This can give the Crownstone insight in energy usage and activity. The challenge will mainly be in making a compact/thin design and feeding the system. To achieve this, it is necessary to carefully consider which components will be used and the use of a ultra thin PCB is unavoidable.

This paper is first going to discuss the overview of the system and the required functionalities the product has to have. Secondly there is a research about inductive current measuring and harvesting. After that the different parts of the system are discussed. In this part design decisions are made and are being substantiate. After that the process of making the PCB in Altium Designer is discussed. Finally the different parts are tested on their requirements.

2 Definition phase

To visualize in a simplistic way what the system have to do a pseudo-Yourdon method is used. By doing this, a picture is formed in a structural way of what the Smart Outlet Tag should do.

2.1 Data context diagram

Below a simplified overview of the Smart Outlet Tag is shown. The main process of the device is to collect or measure data and send it over a Bluetooth connection to a mesh network. As discussed earlier the collected data (such as power usage or the location of a Bluetooth device) can be used to meet the users needs. The conduction wire are the pins on a plug that will be plugged into a power outlet. These metal pins create a magnetic field that can be collected by the device. Also by advertising (sending small messages and waiting for a reply of a device) in the Bluetooth spectrum, information can be gathered with respect of the distance to the Smart Outlet Tag. When multiple of these plugs are installed on tactical locations, the location of the Bluetooth device can be estimated. This (mesh) network of plugs can communicate with each other to share information. For the developing phase, also connections have to be made in terms of programming and monitoring to debug the device.

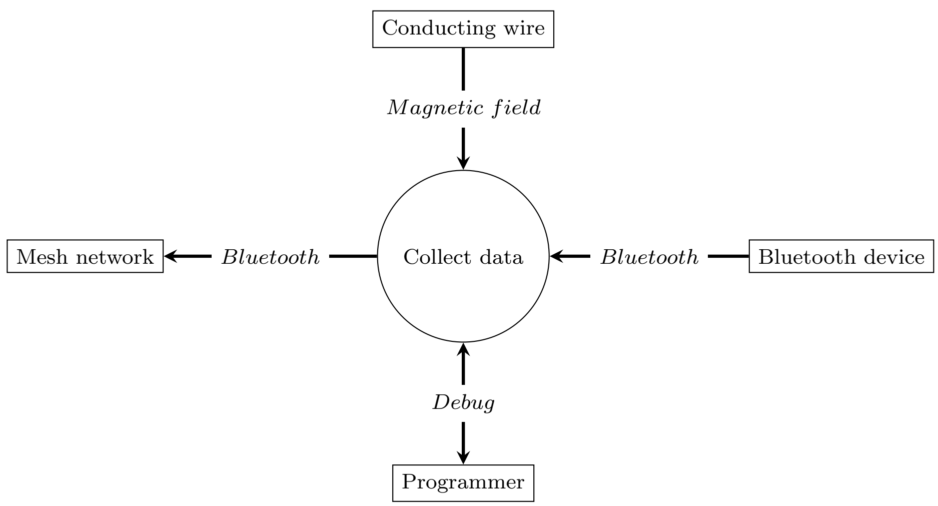


Figure 1: Data Context Diagram

2.2 Data flow diagram

The figure below shows the data flow diagram. This provides a deeper insight into how the system works internally. The processes used are there to divide the system into simpler parts. The process ”manage system” is the brain of the outlet tag, where all data comes together. All incoming information will be processed here and forwarded to the ”wireless communication”. Furthermore, the system speaks for itself.

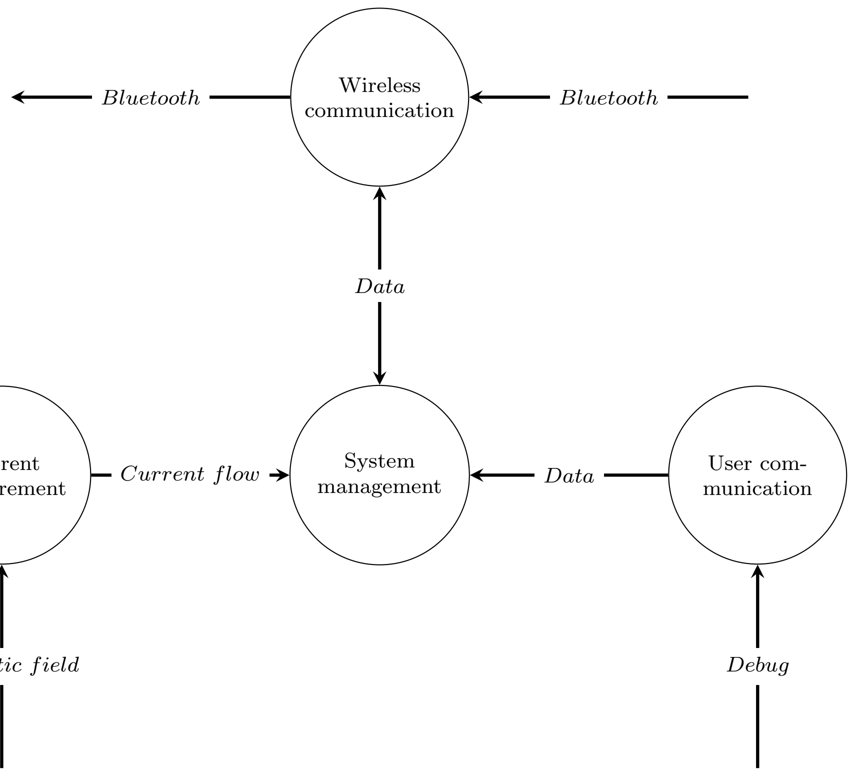


Figure 2: Data Flow Diagram 0

2.3 System functionality

All the wishes of Crownstone are documented in attachment "user requirements". Each requirement is carefully studied for feasibility. In the sections below, all the processes from the Yourdon analyses are described with their matching requirement. The requirements are prioritized using the MoSCoW analysis.

2.3.1 System management

For a correct working of the system there has to be a central processing unit. The main function of this part is to control all the other parts in the system. Also the basic function of the system are included.

Stimulus and response

REQ-F1 [MH] The device can be powered directly from a 207V - 253V AC power source.

> *This voltage is following the European norm NEN-EN 50160 wich states that the power providers generate a voltage of 230V AC with a 10% deviation. This is a important requirement and because of that a must have.*

2.3.2 User communication

This part of the system is responsible for the programming and developing part. The important connectors and the specifications of them are included.

Stimulus and response

REQ-F2 [MH] The device can be programmed with a J-Link programmer.

The Nordic nRF52 series uses the SWDCLK and SWDIO pins to be programmed. This can be done with a J-Link programmer (from Segger) and is a must have requirement.

REQ-F3 [SH] The device can communicate using UART on a baudrate of 115.200kb/s.

For debugging an easy way for communicating can be a nice to have so it should have it. This can be done on a standard 115.200kb/s baudrate connecting to the TX and RX pins.

2.3.3 Wireless communication

This process controls the Bluetooth antenna. It discovers Bluetooth devices and meshes data to the Crownstone network.

Stimulus and response

REQ-F4 [SH] The antenna S11 parameter has to be less than -10dBm within the frequency range of the Bluetooth communicating protocol (2.4000GHz to 2.4835GHz).

For this prototype the device should communicate correctly (read: radiating distance) on the Bluetooth frequencies. Futher in the document is stated why -10dBm is an acceptable value.

2.3.4 Current measurement

This process has everything to do with the measurements of current and collecting the magnetic field.

Stimulus and response

REQ-F5 [MH] The device has to measure the current of a connected outlet plug inductively in the rang of 100mA - 16A, this only for pure resistive loads. The measuring precision has to be 5%.

This is for Crownstone an important feature, but in the beginning it was not clear if it was possible. Further in the document will be discussed what values are achievable.

2.3.5 Non Functional

REQ-NF1 [MH] The microcontroller has to be the nRF52832 or nRF52840 from Nordic Semiconductors.

Over the past, Crownstone worked mainly with the Nordic nRF52 series. Their current systems consist of a nRF52832 and in the near future they will transfer to the newer nRF52840. For easy development, one of these chips has to be chosen. Therefore it's a must have requirement.

REQ-NF2 [MH] The components on the PCB can't have a thickness more than 1.3mm but preferably 1.1mm on its maximum.

Crownstone doesn't want the final product not to be thicker than 3mm. Thin PCB's can be made with a thickness of 0.5mm. Plastic moldings can be 0.7mm but for smaller surfaces 0.5mm can be enough. The components may to be higher than 1.1mm and but an exception for 1.3mm is possible. Further in the document is explained where the values come from.

REQ-NF3 [MH] The PCB has to be 0.5mm smaller than a outlet plug (CEE 7/4) on all sides.

The size of the PCB has to be no larger than an outlet plug (to meet the CEE 7/4 standard) with a clearance of 0.5mm (because of the plastic casing).

REQ-NF4 [SH] The PCB can have a maximum temperature rise of 7°C.

Following the ASTM 1055 standard, 32 degrees is a temperature that's comfortable to the human touch. With some margin for a enclosure, 27 degrees is the maximum allowed temperature. Measured in a standard 20 Degrees room that means a temperature rise of max 7 degrees.

2.4 Won't have requirements

REQ-W1 [WH] The device can communicate through the UWB protocol.

Ultra Wide Band isn't currently supported on a nRF52 chip. Because of the extra complexity this is a won't have requirement

REQ-W2 [WH] The device is capable of communicating with NFC.

Because of the extra complexity this is a won't have requirement.

2.5 Requirements

In the following table all the requirements are summed up.

REQ-F1	MH	The device can be powered directly from a 207V - 253V AC power source.
REQ-F2	MH	The device can be programmed with a J-Link programmer.
REQ-F3	SH	The device can communicate using UART on a baudrate of 115.200kb/s.
REQ-F4	SH	The antenna S11 parameter has to be less than -10dBm within the frequency range of the Bluetooth communicating protocol (2.4000GHz to 2.4835GHz).
REQ-F5	MH	The device has to measure the current of a connected outlet plug inductively in the rang of 100mA - 16A, this only for pure resistive loads. The measuring precision has to be 5%.
REQ-NF1	MH	The microcontroller has to be the nRF52832 or nRF52840 from Nordic Semiconductors.
REQ-NF2	MH	The components on the PCB can't have a thickness more than 1.3mm but preferably 1.1mm on its maximum.
REQ-NF3	MH	The PCB has to be 0.5mm smaller than a outlet plug (CEE 7/4) on all sides.
REQ-NF4	SH	The PCB can have a maximum temperature rise of 7°C.

Table 1: Requirements

3 Research inducting harvesting

3.1 Introduction

The following paragraphs discussing the the overall plan and purpose of the research.

3.1.1 Problem

To get a working Smart Outlet Tag it needs obviously a power supply. A physically connected supply for 230V AC to 5V DC conversion is well known and there are a lot of solutions to achieve this. Power can also be generated through other spectra like temperature, mechanical stress, RF and light. One more possible option is power harvesting using inducting. But due to the limited space and relative small currents this isn't an easy task. Besides that, there are not many papers describing a solution for this. Therefore, this research is needed to answer this question.

3.1.2 Objective

The main objective is to propose a way to harvest power inductively. There are two parts that need to be discussed; inductively measuring current and inductively harvest energy to power electronics. Because of the limited online information about this specific topic, also a lot of other engineers with a similar problem can have a benefit from this research.

3.1.3 Research questions

Main question

How can electricity be generated inductively?

Side questions

Which topology is best?

How can this be designed? I

How can this be calculated?

How can this be simulated?

How can this be designed? II

What is the difference between reality and theory?

Can there be enough harvested for a microcontroller?

3.1.4 Demarcation

There are a lot of other solutions to generate power wireless, but this research will focus only on the inductive solutions. Because of the presence of a nearby generated electric field due to the power outlet, it's a logical choice that this energy source is the most practical and the most promising in this environment. The focus will be on ultra thin (sub 2mm) and small current (sub 16A) solutions only. Also is manufacturing cost an important aspect and it needs to be fabricated quite easily.

3.1.5 Approach

Due to the lack of data on this specific area, paper research has to be done, but also some experimental research. First of all it's important to know how to calculated the expected output voltages. To confirm these hypothesis, a practical experiment can give some deeper insides in the problem and can validate the formula's. Besides that, a lot of basic papers will give a better understanding in this field. At the end, an estimation will be made for the expected on time for a microcontroller.

3.2 Which topology is best?

Current monitoring is mainly done with Current transformers (CT) and Rogowski coils. Current transformers are too large and therefore not usable in this situation [1]. A custom transformer can be wound but will also affect the total production cost and does not have the preference. The Rogowski coil is used for generating an induced voltage proportional to the rate of change of the measured current (di/dt). The induced voltage can then be integrated to regenerate the sensed current waveform [2]. Active integration has to be used because of better low-frequency characteristics [3]. For generating this voltage a Fishbone structure with return line is the best approach for having lower variation from outside sources. Saw and triangle are a lot easier to create and give similar performance if they make use of a return line [1]. The influence of outside current is minimized by using a return line. It become clear that the placing of a return line results in much less magnetic noise. Looking at the formulas in [4] a higher PCB, longer PCB traces, more turns results all in a larger output voltage. Longer PCB traces are logarithmic to the output voltage, and the turns are proportional. So more turns have a higher priority than longer traces. A coil printed on 2 layers that are not far apart (say 0.3mm) will have difficulties forming a sizable induced voltage, because of its limited mutual inductance per turn [2]. More turns results in a smaller error but it lowers the bandwidth. None of the citations (and other articals) discused small current applications therefore testing has to take place in order to give a final answer.

PCB design consists of 2 Rogowski coils with a saw topology. Both can be connected easy in series or in parallel if that's needed. The only difference is that by one of the designs both of the Rogowski coils are winded clockwise (if viewed from the perspective of the conductor). The other design has the same design but one of the coils is winded counter clockwise. Also the return line can be connected optionally. Therefore the design is very flexible and many scenario's can be tested.

The saw topology is chosen because of the simplicity of design and the available space. On this scale, a fishbone topology is difficult to full fill.

3.3 How can this be designed? I

In the following paragraph will be discussed how the PCB Rogowski coil was designed. The measurements are not optimal in this stage but will gave a good view ow a potential end product will perform. As a starting point a Schuko power cord will be analysed on its dimensions. The following picture will make this clear.

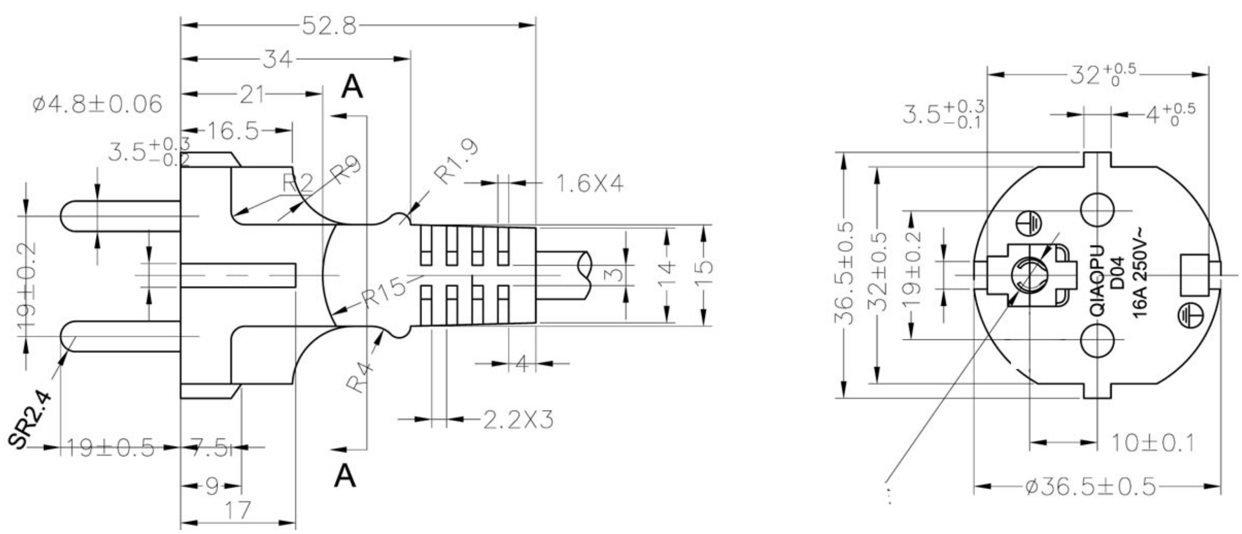


Figure 3: Dimensions of a CEE7/7 power cord.

First of all the holes in the design has to be calculated. The pins on the power cord have a diameter of 4.8mm but there has to be a margin so the holes will be 5.3mm. In a customer friendly area the PCB can not be exposed and has to be plated of with a thin layer of plastic. In this case this will be 0.5mm en that's on both sides of the holes so the total hole size will be therefore 6.3mm with a radius of 3.15mm.

The distance from the middle point of the hole to the border of the power cord is 6.5mm (measured to long flat side not the small hump in the design). Also on that side 0.5mm has to be reserved for a plastic package so that distance will be in total 6.0mm.

The total length of for the coil that will be left over is 6.0mm - 3.15mm = 2.85mm. To give a clear view of all the measurements the picture below will discuss this.

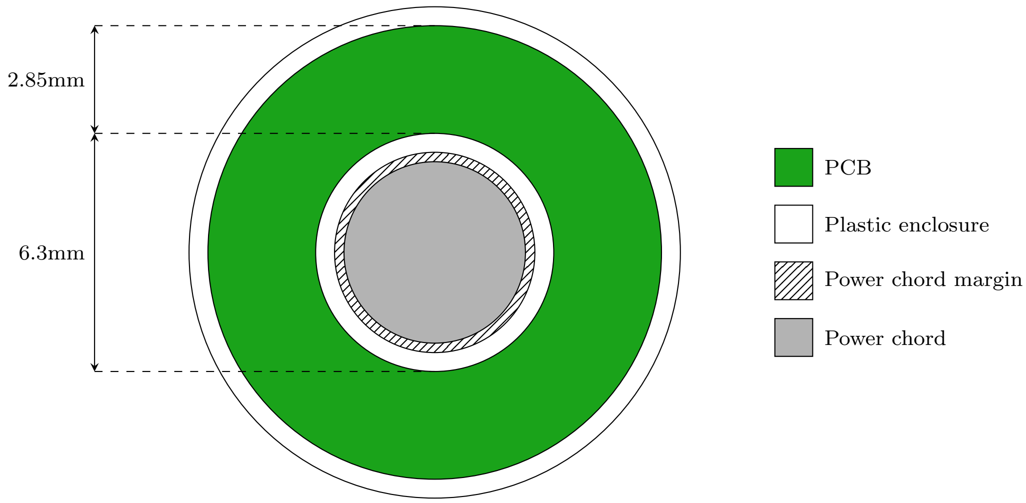


Figure 4: Schematic view of Rogowski coil

3.3.1 PCB capabilities

Every PCB manufacturer has his own capabilities of fabricating a PCB. For the Rogowski coil its important that all parts can be placed as small and close to each other as possible. Because of the limited budget a prototype PCB cannot cost too much. Professional manufactures (such as Eurocircuits) can make design a little bit better but for testing its import to get an indication how the system will perform. The choice will be made between Aisler and JLCPCB. The table below shows the minimum values of the most important parts.

	JLCPCB	Aisler
Trace width	0.09	0.125
Trace spacing	0.09	0.125
Drill diameter via	0.2	0.2
Annular ring	0.125	0.2
Distance PTH /PTH	0.254	0.25
Distance via-pad / via-pad	x	0.125
Distance via-pad / trace	0.2	0.125
Distance pad / PCB-edge	x	0.3

Table 2: PCB capabilities (in mm)

A very important specification is the minimum distance a via can be from the border of a PCB. JLCBPCB is not clear on its website what the minimum requirements are, only on that fact Aisler is a better choice because the PCB has to be fabricated well. After getting in contact with the customer service they stated that a minimum of 2 to 3 mm is required. Maybe with a error margin taken into account its way to large and not suitable for this task.

With the given specifications the most important measurements can be calculated. In the figure below can be seen what the measurements are. De most important factor in calculating is the number of turns and the lenght of a trace. Given Aislers specifications a via's minimums radius size is 0.3mm and the distance between the via pad and the PCB edge has to be also 0.3mm. Because both the inner and outer edge of the PCB needs a via the total size used is therefore 1.2mm. The PCB is 2.85mm minus 1.2mm is a maximum trace length of 1.65mm.

To calculate the maximum loops in the coil the following formulas are needed [4]. Where dϕ is the angle between two via's, d is the distance between two via's, a is the length between the a via and the middle of the Rogowski coil and N the number of via's.

$$d\phi = \sin^{-1}\frac{d}{a} \tag{1}$$

$$N = \frac{360}{d\phi} \tag{2}$$

The radius of a via is 0.3mm as calculated before. The distance between two via's has to be 0.125mm so the total space between the two middle points of a via (d) is 0.725mm. The radius of the inner circle of the coil is 3.15mm, the radius of a via is 0.3mm and the distance between the PCB edge and via has to be also 0.3mm. When added up we receive the distance between the middle of the Rogowski coil and the middle of a via (a) with a value of 3.75mm.

When calculated the maximum number of loops is equal to 32.29, so in practice there will be 32 loops. In the figure below is showed how it looks like. Note that the dotted lines between the via's (black dots) are not straight but curved. The oblique trace can be calculated with some standard algebra.

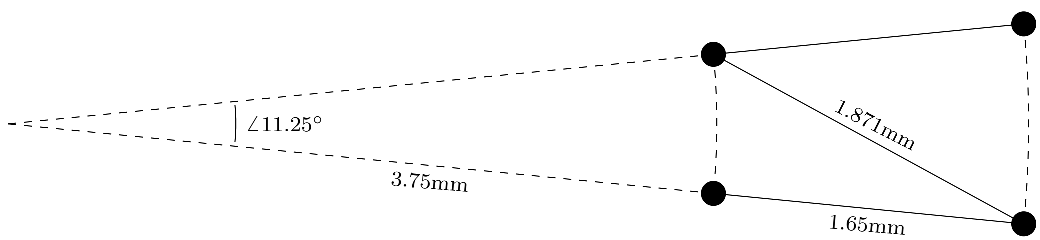


Figure 5: PCB measurements

3.4 How can this be calculated?

When the measures of the coil are calculated the next step is to calculate the electrical parameters. The output of a Rogowski coil is expressed as a electromotive force. The electromotive force, or ε, stands for the voltage over the terminals when no current is flowing. To calculate the electromotive force generated by the Rogowski coil, two ways of calculating are proposed. The input current can be expressed by the following equation. This is done by taking a 50 Hz signal and a standard current of 1 A rms.

$$I(t) = I_{rms}\sqrt{2}\sin(2\pi f t) \tag{3}$$

All equations shown below are standard physics formula's of electromagnetism. For a more brief explanation about these, take a look at the book University Physics from Young and Freedman [5]. Chapter 28 and 29 will discuss the basic principle. Formula's from other places are discussed separately.

3.4.1 Calculation 1

The magnetic field (B) around a current carrying conductor on a given distance (r) can be calculated using the following equation. Where I is the current through the conductor and μ_0 the magnetic constant. The effective magnetic field can be calculated with the average distance from the conductor. In this case this is $3.75 + 1.65/2 = 4.575mm$.

$$B = \frac{\mu_0}{2\pi r} I \tag{4}$$

The magnetic field that travels through the loops of the coil generate an induced voltage. Each turn of the coil can be seen as a window where the magnetic field fly through, this area needs to be calculated. Because of the zigzag pattern of the coil, the effective area needs to be calculated. The magnetic field crossing an area is also called magnetic flux.

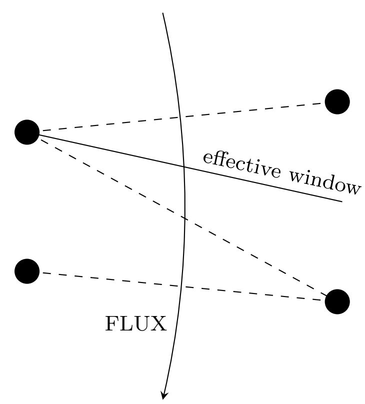


Figure 6: M2

The exact values can be calculated using standard geometric formula's. The line that is perpendicular to the field has an angle of $\angle 0$ with a length of 1.65mm. The line that's crossing the field has a average angle of $\angle 28.642$ and a length of 1.871mm. The total average window can be stated as a line of length of 1.7605mm and a angle of $\angle 14.321$.

The following formula can be used to calculate the effective window, where l is the length and h is the height.

$$A = hl \tag{5}$$

To calculate the magnetic flux trough the given area the following formula can be used.

$$\Phi_B = BA\cos\theta \tag{6}$$

With the law of Faraday the generated electromotive force due to N turns can be calculated with the following equation.

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{7}$$

3.4.2 Calculation 2

To see the difference with the described calculations in the previous paragraph, an other way of calculating is used. The formula [6] has a differences in terms of calculating the effective area of a window. The following formula uses a for the distance from the centre of the coil to the inner via and b for the distance from the centre to the outer via.

$$\Phi_B = \frac{\mu I h}{2\pi} \times ln(\frac{b}{a}) \tag{8}$$

Also as in calculation 1, Faraday's Law is also used.

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{9}$$

3.5 How can this be simulated?

Calculating the output can be handy but for this research a simulation is much more convenient. A Rogowski coil can be represented as a equivalent circuit a shown as below. In fact, a Rogowski coil is the same as a inductor so the equivalent circuit will looks very similar. This circuit consist of a inductor and resistor in series with a parallel capacitor. See the circuit below as example.

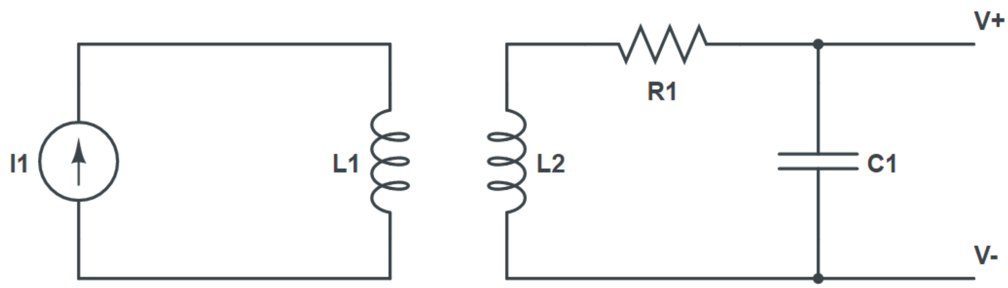


Figure 7: Rogowski coil equivalent circuit

The mutual inductance between the two inductors can be calculated using the following formula as described in [7], [8] and [9].

$$M = \frac{\varepsilon}{dI/dt} \tag{10}$$

The self inductance of the Rogwoski coil can be calculated as followed [10].

$$L_2 = M \times N_2 \tag{11}$$

For the simulation, the inductance of the first coil is given by [11] and [12]. Both generate the same answer if the coupling factor (k) is 1 or the turns of the first coil (N_1) is equal to 1.

$$M = k\sqrt{L_1 \times L_2} \tag{12}$$

$$\frac{L_1}{L_2} = (\frac{N_1}{N_2})^2 \tag{13}$$

The resistance can be calculated using a well known formula [5]. But the resistance can also be easily measured if a coil is already created. To lower the deviation between the theoretic and practical answer a measured resistance is used. The Rogowski coil has a internal resistance of around 0.6 Ohms.

$$R = \rho\frac{l}{A} \tag{14}$$

As well as the resistance the capacitance can also be measured. This value is around 15uF for the crafted coil. If no real coil can be used for measurement the capacitor can be left away. For simplification it turns out that the capacitance does not have a magnificent factor in the simulation, also [13] discovered the same.

When calculated following the two calculation methods, the values of the components are as followed.

	Calculation 1	Calculation 2
L_1	119.31pH	116.69pH
L_2	122.18nH	119.49nH
R_1	600mΩ	600mΩ
C_1	15uF	15uF

Table 3: Calculated Rogowski coil values

3.6 How can this be designed? II

This section point the production of the Rogowski coil out. The Rogowski coil is made in Altium Designer. The design has a few features. First of all there are 2 times 2 coils, P1 and P2. The coils of P1 are both wired anti clock wise. The coils of P2 are wound clock wise and anti clock wise. This is to prove and understand the current flow in the coil dependent of the current flow through the wires. This is not the main point of this research but to get a deeper understanding of the coil.

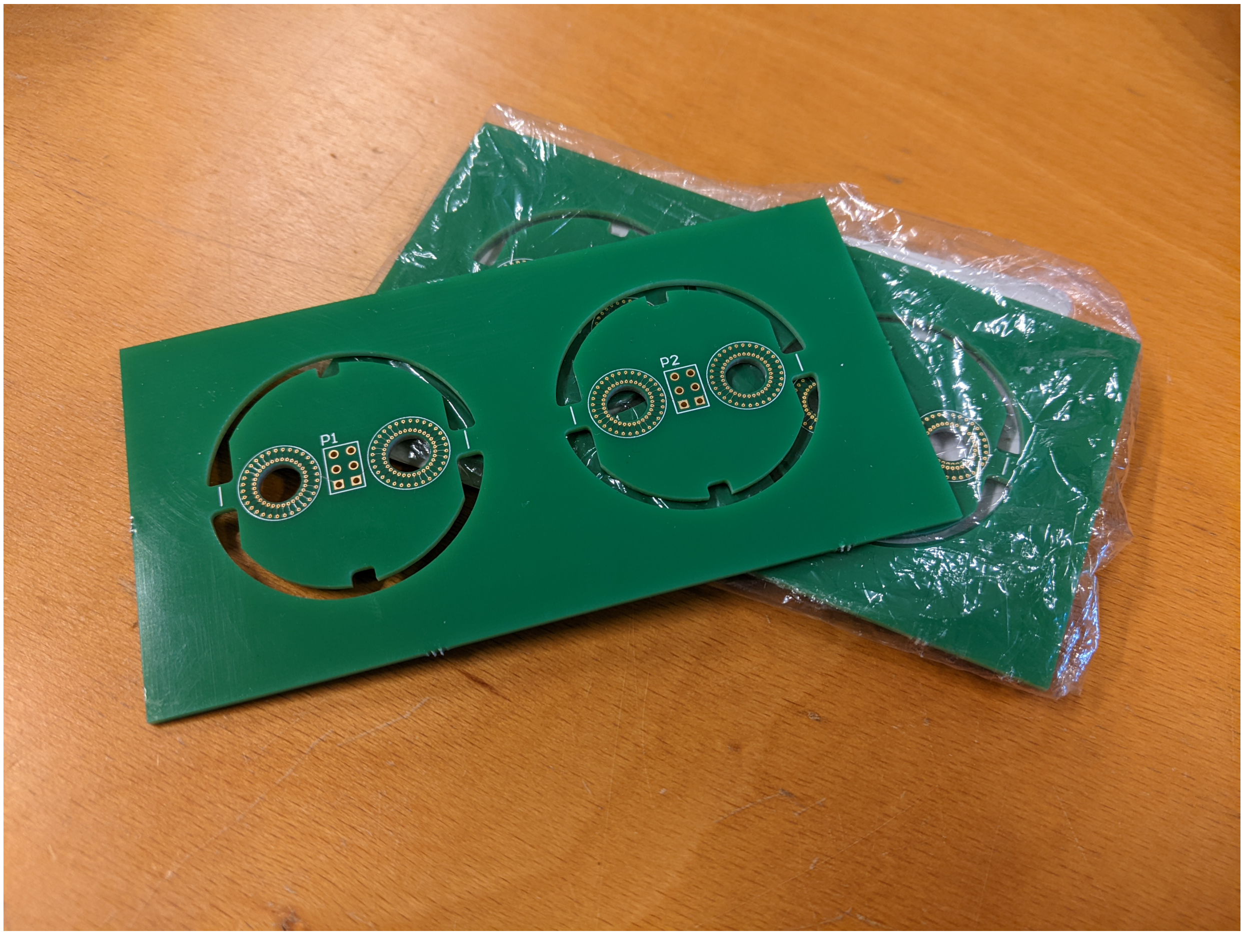


Figure 8: Rogowski coil

After testing it appears that it doesn't care if the coil is wound clock wise or counter clock wise. To know the flow of the current the right hand rule is the way to go. With this rule it becomes clear which direction the magnetic field has. When looked at a single turn, the wires of the coil convert the magnetic field into a current using also the right hand rule. When curling the right hand around the wire of the coil, the curling of the hand it must match the flow of the magnetic field.

3.7 What is the difference between reality and theory?

3.7.1 Simulation

Because of the little to no change in the calculations, there can be said that the outcome is the same. The ADA4891 is an other chips then used in the test but has similar performance as the TL074.

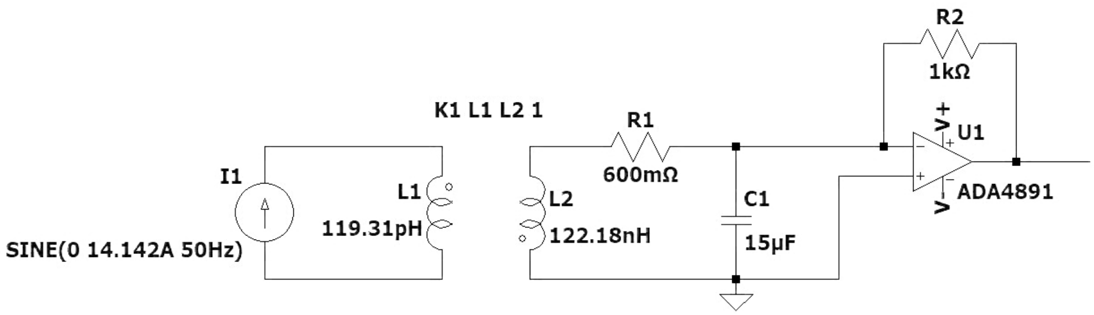


Figure 9: LTSPICE

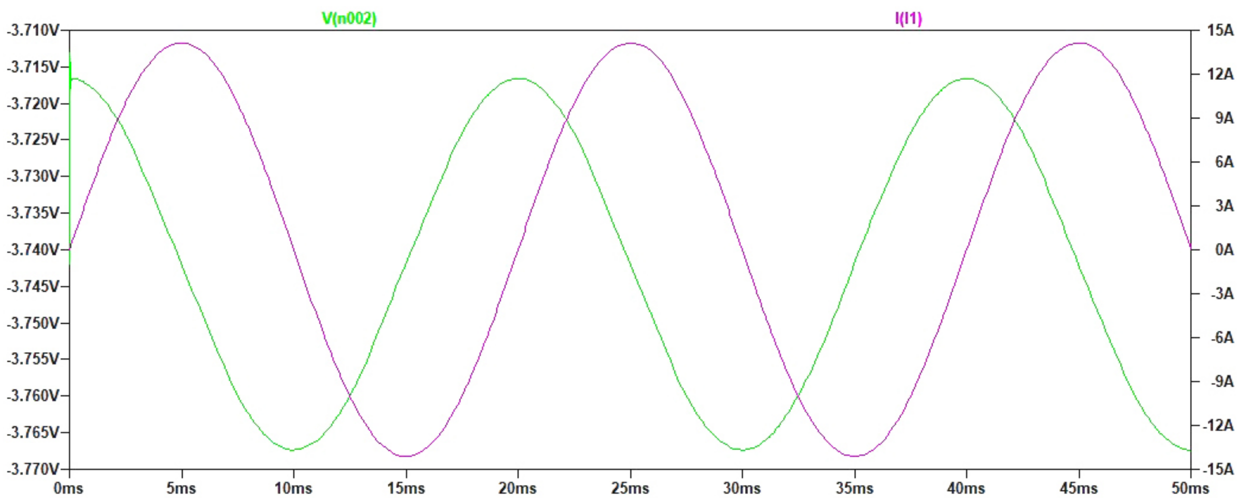
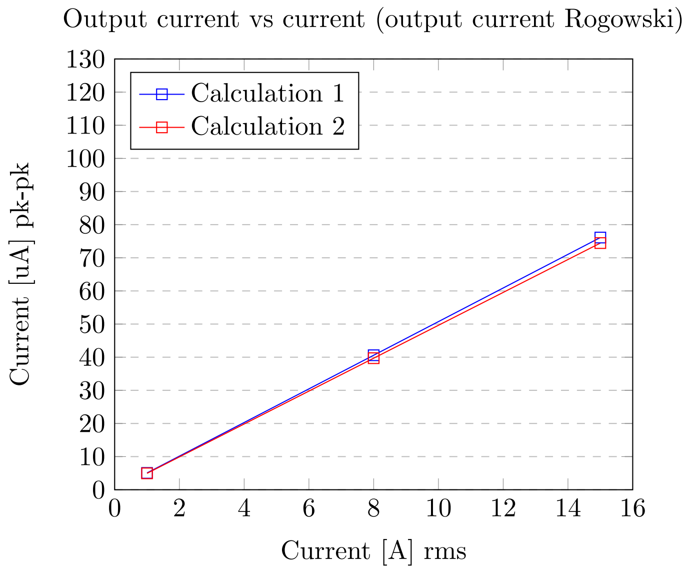


Figure 10: LTSPICE

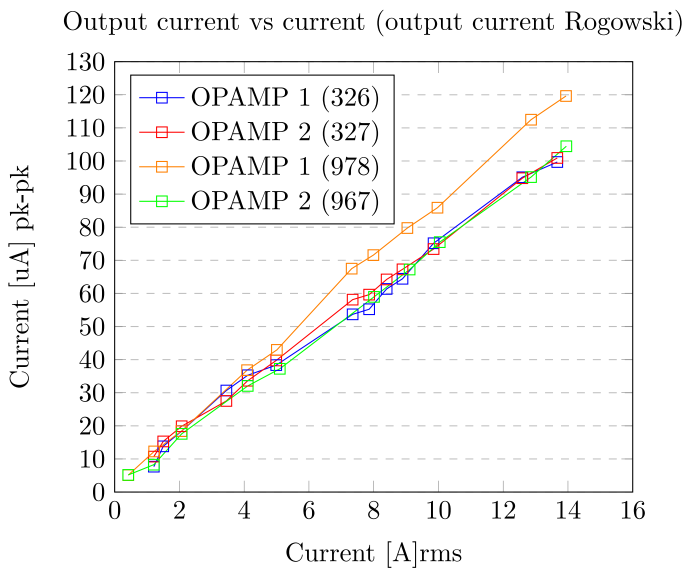
When simulated in LT spice, we can validate the formula's because the electromotive force is the same as calculated earlier. Also can be seen that the output voltage is 90 degrees shifted with respect to the current source. The differences between the two calculations methods is shown below.



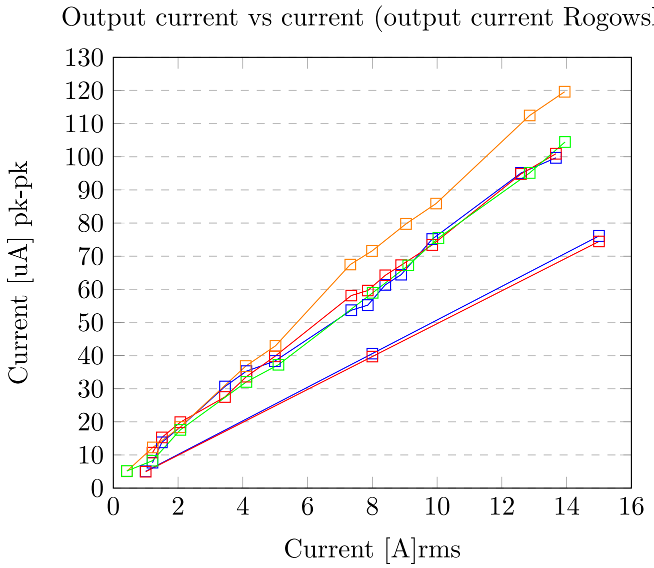
3.7.2 Practical test

The testing is done with a standard off the shelf TL074. This chip is not perfect and has a large voltage offset. This is a big limiting factor because of this a high gain results in a high offset voltage. If the offset is too high, voltages can fall outside the voltage range of the opamp and can cause clipping. So the offset voltage plus the signal can't be higher then the voltage rail. The test circuit has a ground that is changeable with a pot meter. Therefore, the offset voltage can be compensated to around 0mV. With a oscilloscope can be precisely zoomed in and measure the generated voltage. The gain of the opamp is equal to 330 Ohm and 1000 Ohms to see if there are differences. Higher gains aren't possible because of the clipping.

The test is done with purely resistive loads (such as light bulbs and heaters). Due to different configurations, the ouput voltage can be precisely measured.



3.7.3 Differences



With the measurements can be stated that the ouput current is proportional to the current source, also on on sub 1A source currents. Below 500mA the pk-pk voltage can be hard to read due to noise, with a FFT much lower measurements are possible. The lowest current measured was a 50mA current.

The calculations differ a little bit from reality. The measured signal are generally around 1.5 times higher than the calculated values.

3.8 Can there be enough harvested for a microcontroller?

When the Rogowski coil is connected to a perfect matched load of 600mΩ, the coil generates around 300pW on average (on a load of 14 Amps). This power equals to a constant generation of 300pJ per second. A standard low power microcontroller uses about 5mW, or in other words, consumes 5mJ per second.

When power conversion can be done without any loss, such as conversion losses or losses due to the energy storage in and out of a battery; For every second of working the coil has to generate for over $\frac{5E-3}{300E-12}$ = 16.666.666 seconds, that's over 4.630 hours or 193 days.

3.9 Conclusion

It's not possible to use a Rogowski coil for power harvesting. The values are way too low. But monitoring the power usage can be done. If the values where a little bit higher there can be made improvements to the coil. Such as a higher turn count or trying other patterns or instead of one loop from layer 1-4, making two loops on layer 1-2 and layer 3-4. But the performance need to be at least 1000 times better to overthink the options and to find a use full use case. And besides that, also a ultra high efficiency harvester needs to be designed. If power harvesting is still required in the future, other implementations should be tested.

4 Architecture

4.1 Diagrams

Below are 2 figures that illustrate the connections between important blocks. First, this is done in the Architecture Context Diagram (ACD), which makes clear how the connections work outside the Smart Outlet Tag. The Architecture Interconnect diagram goes one layer deeper and will show the internal connection between internal blocks.

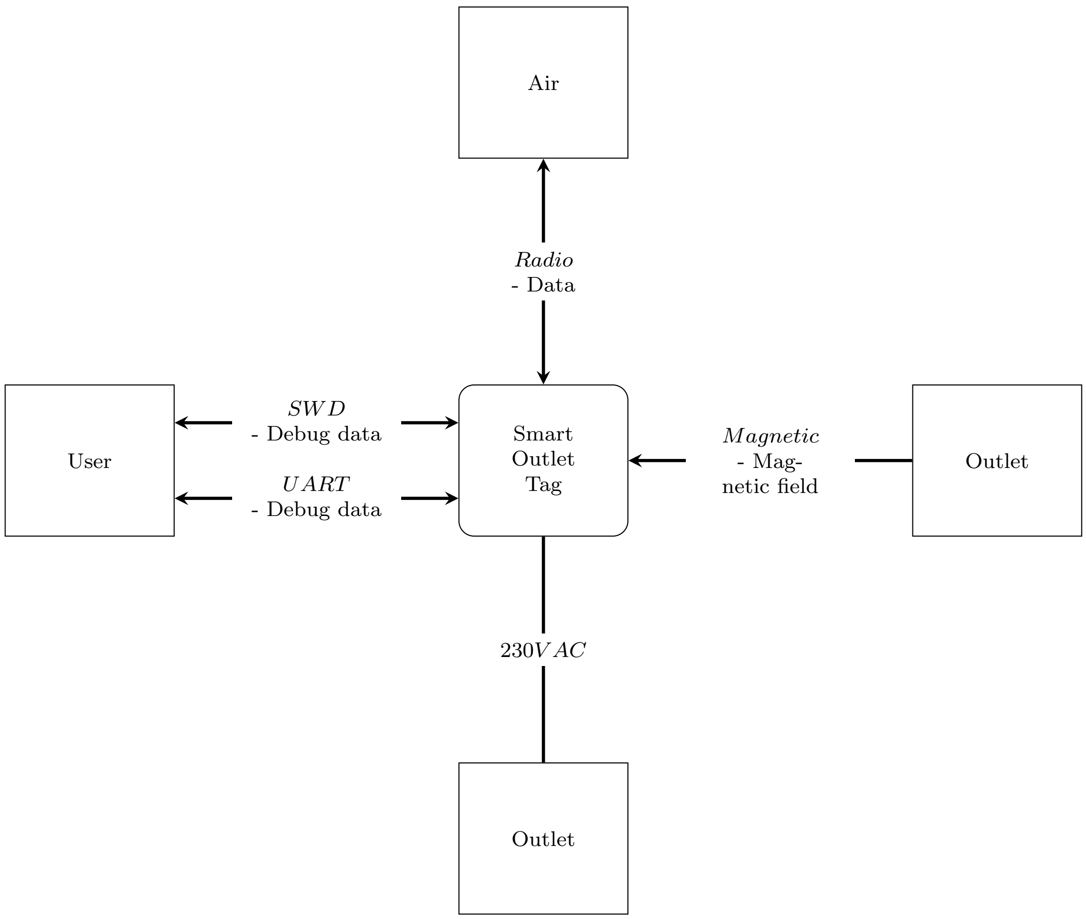


Figure 11: Architecture Context Diagram

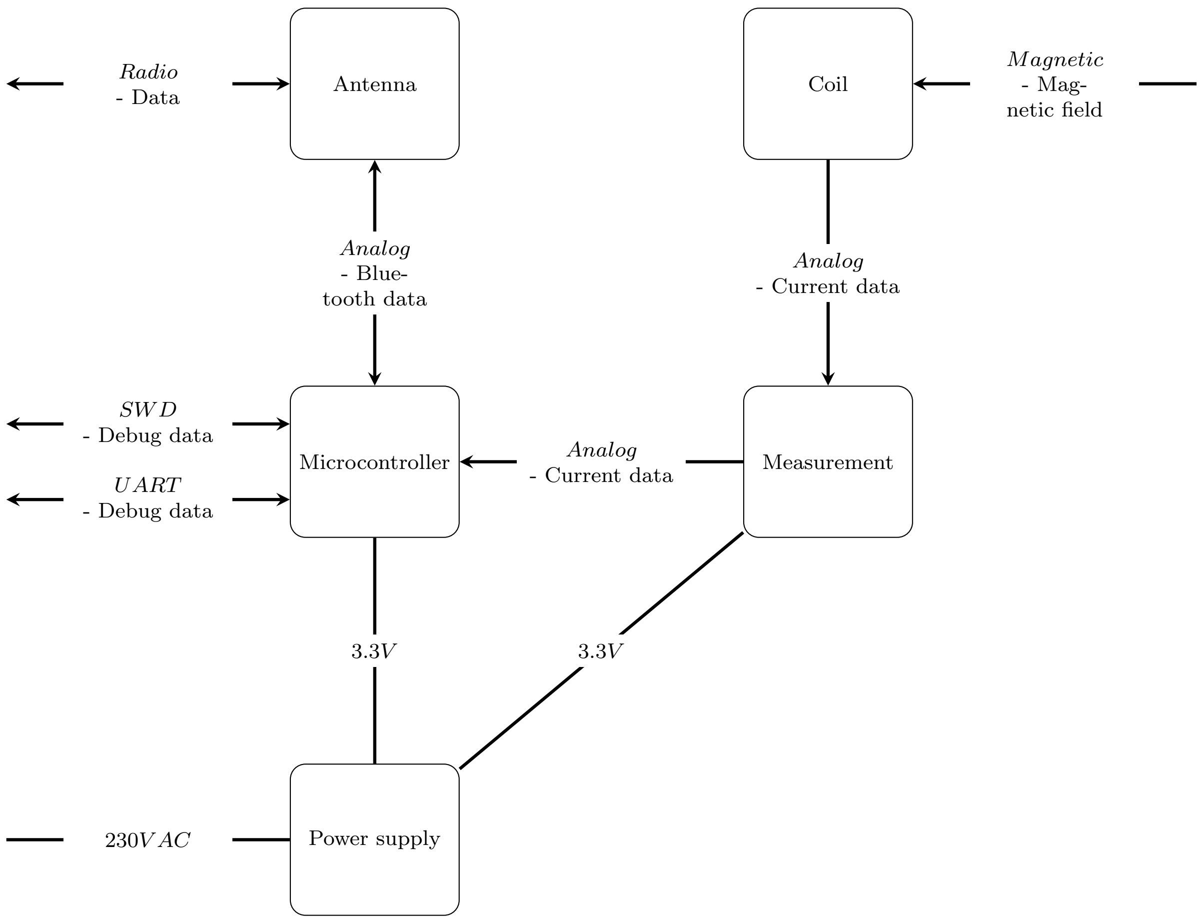


Figure 12: Architecture Interconnect Diagram

4.2 Units

It has become clear in the previous figures what the different units are. In the following paragraphs it will be briefly mentioned what each unit does.

4.2.1 Microcontroller

This unit is the central point where everything comes together. This is where the signals from the Bluetooth antenna are received and processed. This is also where the data from the amplification circuit comes in. The microcontroller works on a voltage of 3.3V and can be programmed via the SWD protocol. For other debugging purposes, a standard UART connection can be used.

4.2.2 Power Supply

This power supply will convert the voltage from the outlet into a usable voltage for the system. The voltage will be converted from 230VAC to 3.3VDC.

4.2.3 Measurement

The current measurement unit will amplify the very small signals from the coil to a higher level. This unit will operate on a voltage of 3.3 volts.

4.2.4 Coil

The coil as discussed earlier is there to convert magnetic fields into a current. This inductive way of generating current is used to get an idea of what the waveform of the current looks like.

4.2.5 Antenna

The Antenna is used to receive and transmit Bluetooth signals.

4.3 Traceability

Below is the table that links all units to the associated requirements.

	Microcontroller	Power Supply	Measurement	Coil	Antenna
REQ-F1		X			
REQ-F2	X				
REQ-F3	X				
REQ-F4					X
REQ-F5			X	X	
REQ-NF1	X				
REQ-NF2	X	X	X	X	X
REQ-NF3	X	X	X	X	X
REQ-NF4	X	X	X		

Table 4: Traceability table

5 PCB type

An important decision for the end thickness of the end product. There are two main options, a standard Rigid PCB or a Flex PCB. THe product will probably be made on a 2 or 4 layer PCB. Due to the many components on a small place routing could be difficult, therefore a 4-layer PCB is chosen. For a Rigid an Flex PCB the thicknesses will be respectively 0.4mm and 0.25mm (after some research on the internet). Pricings will be around €200,- for a Rigid an €450,- for a Flex PCB. If it turns out a 2-layer PCB will be enough, the costs and/or thickness can be decreased further.

The kind of PCB will affect the stiffness of the enclosure that will be put around it. Also, the thickness of the enclosure also impacts the maximum size of the board and the size of the Rogowski coil. Therefore it's important to minimize this case. Because of the lack of knowledge on this field the student got in contact with companies and experts.

To be sure the pricings are correct a quotation is made by Rayming PCB, a company that manufacters Rigid PCB's as well as Flex PCB's. The quotation is for a standard 4-layer PCB.

Order Quantity	Unit Price (USD) Rigid PCB	Unit Price (USD) Flex PCB
500 pcs	1.34	5.20
5000 pcs	1.18	4.24

Table 5: PCB Quotation Rayming PCB

The company recommends a Flex PCB, a Rigid PCB can be damaged in a thin case. A possible problem is small cracks in the tracks of the PCB.

The get an estimate on how thick the enclosure will be is not easy. The to go answer is 1.5-2.0mm because that's a universal and proven thickness for many products. Thicknesses around 0.7mm will probably also be possible unless a stronger kind of plastic is used (ABS or PC for example). The minimum thickness is partly dependent on the flow path of the plastic. That's the distance the plastic have to travel from the point where the plastic will be put in. This can only be simulated in software but that's out of the scope of this project. A important note is that a stiff case has the preference because a loose case will make a bad quality impression.

At the end there are two points of view:

- A Flex PCB needs a thicker enclosure to make sure the product is stiff enough.
- A Rigid PCB needs a thicker enclosure to make sure the PCB don't get damaged or broken.

With the stakeholder is discussed that for a first prototype a Rigid PCB will be enough. The price will be more suitable and it's not quite clear if a Flex PCB is better.

Integrating the Rogowski coil inside the main PCB will affect the performance dramatically. Test are done with a 1.6mm PCB, moving to a 0.4mm means a 4 times lower output signal (thickness is linear to the output). A solution to this problem is making a separate component of the coil. Two possible options are a coil that can be put on the main PCB and has the same height as the highest components. Or the main PCB will have cutouts where the coil can be put in to get a few extra tenths of a millimeter.

6 Microcontroller

The chip has two supply voltage modes, normal and high voltage. The chip automatically sets the system to the right mode dependent how the power supply is connected [14]. How is displayed in the table below.

VDD	VDDH	MODE	Voltage range (Min. / Typ. / Max.)
Vin	Vin	Normal Voltage Mode	1.7V / 3.0V / 3.6V
Vout	Vin	High Voltage Mode	2.5V / 3.7V / 5.5V

nRF52840 in QFN48 heeft geen High Voltage Mode!!!

This info states that the internal power supply can be used to power other electronics [14, p. 80]. If the voltage is 'clean' enough can only be find out if the chip is tested with the earlier designed off the line power supply. The nRF52832 is only capable of a normal voltage mode [15].

6.1 Difference between versions

The nRF52840 and nRF52832 both have a lot of functionality. To choose wich one is the most suitable for this application only the biggest differences are going to be compared. Things that both have in common are not noted here.

	nRF52840	nRF52832
Connectivity	Thread, Matter, Zigbee	x
Bluetooth long range	Yes	No
TX power	+8dBm	+4dBm
Max Flash storage	1 MB	512 kB
Max Ram	256 kB	64 kB
Max GPIOs	48	32
High Speed SPI	Yes	No
QSPI	Yes	No
SPI channels	4	3
UART channels	2	1
USB	Yes (2.0)	No
Arm TrustZone	CryptoCell 310	x
Input voltage	1.7V - 5.5V	1.7V - 3.6V
Voltage regulators	2 (with output)	1
Smallest package (WLCSP)	3.5mm x 3.6mm	3.0mm x 3.2mm
BOM components (note 1)	22	19
Price (note 2)	4.985 USD	3.000 USD
Price (note 3)	2.50 EUR	1.50 EUR
Energy usage (note 4)	13μA	11μA
Energy usage (note 5)	6.4mA	5.3mA
CoreMark (note 6)	212	215
CoreMark per MHz	3.3	3.36
CoreMark per mA	59	58

Table 6: nRF52840 versus nRF52832 specifications

Note 1: Reference designs of Nordic (QFAA models with DC-DC converter).

Note 2: Median price for a quantity of 1000 parts on octoparts.com (March 2022). NRF52840-QIAA-R / NRF52832-QFAA-T

Note 3: Crownstone Prices (will possibly go up in the future).

Note 4: Power Profiler for Bluetooth LE (https://devzone.nordicsemi.com/power/w/opp/2/online-power-profiler-for-bluetooth-le) with the following settings: (Voltage: 3.5 / DCDC regulator: on / LF clock: External crystal / Radio TX power: 4dBm / Role: Advertising (TX/RX) / Advertising interval: 1000ms / TX payload: 0 Byte).

Note 5: https://www.nordicsemi.com/-/media/Software-and-other-downloads/Product-Briefs/nRF52832-product-brief.pdf?la=enhash=2F9D995F754BA2F2EA944A2C4351E682AB7CB0B9. 0dBm DC/DC at 3V.

Note 6: From datasheet nRF.

6.2 Hardware Proposal

The following hardware proposal is discussed with the company, taken from the perspective of the nRF52840.

Pro's:

- Higher transmit power; Bluetooth signals will reach further (without obstacles around 30
- More flash memory (x2 improvement); Shrinking the firmware is not needed.
- More RAM (x4 improvement); Larger datasets are possible with asset tracking.
- Connectivity of Thread, Matter, Zigbee; The possibility to have a better integration within smarthome systems.

Con's:

- More expensive (nRF52832 is 40 percent cheaper).

The final choice is fallen on a nRF52840 in a QFN48 package. The QFN package is chosen because of the ease of soldering, with respect to the aQFN73 or WLCP package.

7 Power supply I

Inductive power harvesting is not an option at the moment. As alternative a power supply with a direct connection will be used. In this chapter will be discussed how such a power supply will be designed.

7.1 Research

The main purpose of the power supply is to convert a 230V AC signal to a lower, for example, 5V DC signal. It is desirable to have a very stable output voltage because of the very precise measuring equipment that will also be onboard. NEN-EN 50160 states that the mains voltage always stays between 207-253V AC. The formula below states the maximum voltage:

$$V_{max} = V_{rms} * \sqrt{2}$$

So a peak voltage of 358V has to be taken into consideration. Normally in a power supply like this, a transformer is used to lower the voltage to a more respectable level. But due to the large size of a transformer this is not possible and the signal has to be rectified. Looking at a bridge rectifier there are 2 main options: a full bridge rectifier and a half bridge rectifier. A half bridge rectifier has a much larger periodic interval that means that a larger capacitor is required. So a full bridge rectifier has to be used but even then a relatively large filtering capacitor is needed. The biggest capacitors on the market having a high enough voltage rating and a low profile package (less than 1.5mm) have a value around the 100nF. Circuits like a capacitor multiplier won't work because such a circuit isn't used to store electrons. Overcoming the problem of having to less capacitance isn't possible so a large ripple stays in the signal. A formula to calculate the expected output ripple is stated below:

$$V_{ripple} = \frac{I_{DC}}{2fC}$$

If the equation is filled in with a frequency of 50Hz and maximum current of around 0.5mA the ripple will be somewhere around the 50-100V.

7.2 Requirements

The following specs are additional requirements for the power supply. These specs ensures that this unit works well on its own.

PSU-USPEC-1 The output voltage must be 3.3 V with a maximum deviation of 5 percent.

> *The typical voltage of the nRF chipset is 3.0 volts, but a 3.3 voltage is more common and easier to search components for. In order to ensure the output voltage is stable, the voltage must not deviate more than 5 percent.*

PSU-UPSEC-2 The chip must be able to deliver a current of 25 mA.

> *The average nRF microcontroller can take up to 16 mA of current. In order to work properly, Crownstone wants a safety margin on this value.*

7.3 Design

Given the very specific application of the power supply, it is difficult to indicate on the basis of the datasheet whether the design will work or not. From datasheets alone it can be hard to get clear how 'clean' a output will look like. Besides that, the given values in the datasheet can deviate from reality.By testing the parts in practice, it immediately becomes clear how the design responds and what the performance are. After this, it can be evaluated whether the design is satisfactory or whether adjustments are necessary. The table below lists the chips with the most potential. A few things are important here such as a large input voltage range and compact/thin chip. Given the heat development and the need for sufficient efficiency, only switching power supplies will be chosen (in some cases with built-in or external LDO's).

The table below shows a quick research to potential chips for this application. This is to test chips as fast as possible and give feedback on the performance. The goal is to take a few different chips to give a overview of what's possible and what are the focus points. The footprint size is the total length of the chip multiplied by the total width (including the end of the pins). In stock means in stock at big suppliers where Crownstone orders frequently, this include Mouser, Digikey and Farnell.

Component	Manufacturer	Stock	Thickness	Footprint
AL17050	Diodes	Non-Stocked	1.01mm - 1.40mm	9.3mm^2
MP100L	Monolithic Power Systems	In Stock	1.30mm - 1.70mm	29.4mm^2
MP103	Monolithic Power Systems	In Stock	1.30mm - 1.70mm	29.4mm^2
MP158	Monolithic Power Systems	In Stock	0.70mm - 1.00mm	8.12mm^2
MP173A	Monolithic Power Systems	In Stock	0.70mm - 1.00mm	8.12mm^2
SR036	Supertex	Non-Stocked	0.94mm - 1.09mm	14.4mm^2
SR086	Supertex	In Stock	1.25mm - 1.70mm	29.4mm^2
LNK302	Power Integrations	In Stock	1.35mm - 1.75mm	29.4mm^2
VIPer011	ST Microelectronics	In Stock	1.35mm - 1.75mm	29.4mm^2
UCC28880	Texas Instruments	Non-Stocked	max 1.75mm	29.4mm^2

When selecting the best chip, one thing is important and that is the size of the design. The table below describes the most important properties of each chip in terms of size. A lower BOM size results in a smaller design, so it has a advantage to look a these. Besides that, high voltage capacitors generally have a larger package.

Component	Small package	No inductors	Low voltage capacitors	internal LDO	Internal BJT
MP100L	-	x	x	x	x
MP103	-	x	x	x	-
MP158	x	-	-	-	x
MP173A	x	-	-	-	x
SR086	-	x	x	x	-
LNK302	-	-	-	-	x
VIPer011	-	-	-	-	x

The MP100L has a lot of potential with a lot of integrated options. The MP103 is almost the same except that the BJT is external. The MP158 and MP173A have a lot in common, only the MP173A have a higher maximum load and a 700V switch instead of a 500V. The LNK302 is a commonly used chip by Crownstone and has proven to work, therefore this chip is also taken into account. The LNK302 has a 700V internal switch, and because the MP173A has almost the same features the MP158 is chosen to measure the differences. Because all the chips are available at Mouser except for the MP100L, the MP103 is chosen to reduce shipping costs.

The following figures will show the used circuits and components to test the chips.

7.3.1 MP158

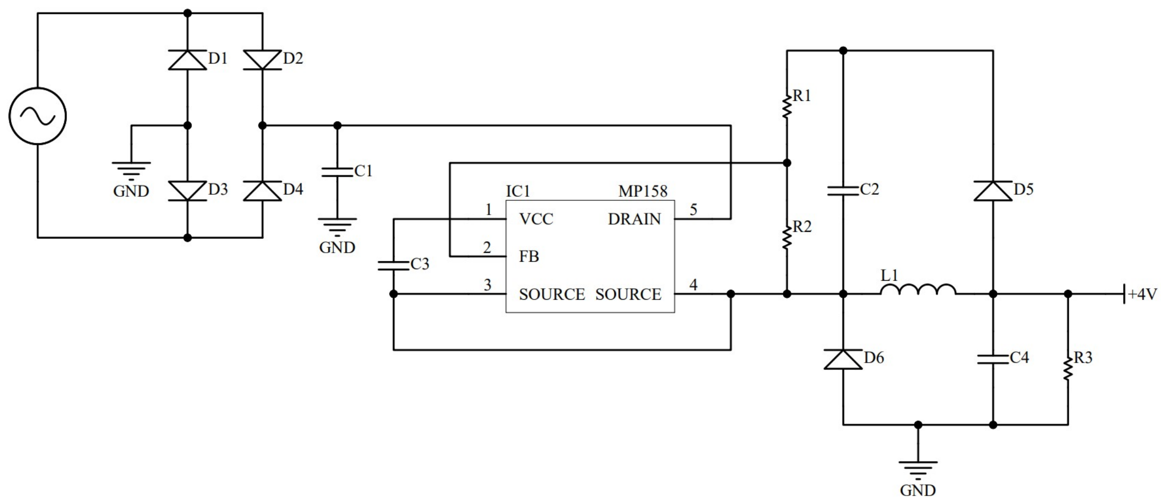


Figure 13: A test circuit for the MP158.

C1	100nF/400V
C2, C3	
C4	10uF/6.3V
D1, D2, D3, D4, D5	1N4007
D6	EGC10JH
L1	1mH
R1	3kΩ
R2	5kΩ
R3	3kΩ

7.3.2 MP103

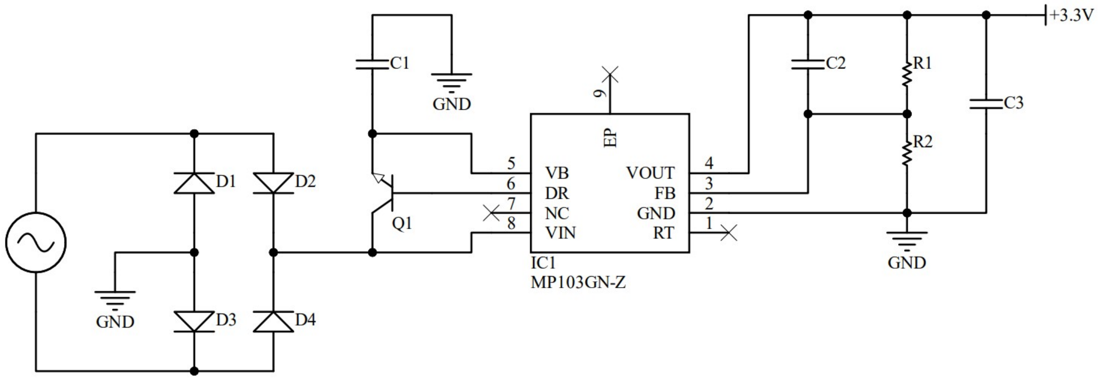


Figure 14: A test circuit for the MP103.

C1	10uF/35V
C2	470pF/50V
C3	4.7uF/16V
D1, D2, D3, D4	1N4007
Q1	FJP5027
R1	16kΩ
R2	10kΩ

7.3.3 LNK302

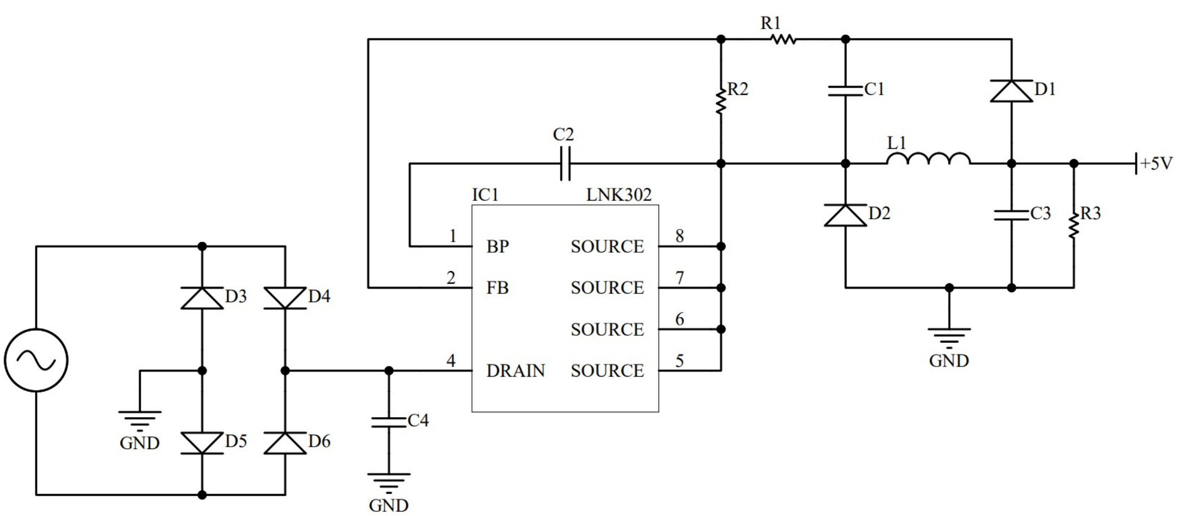


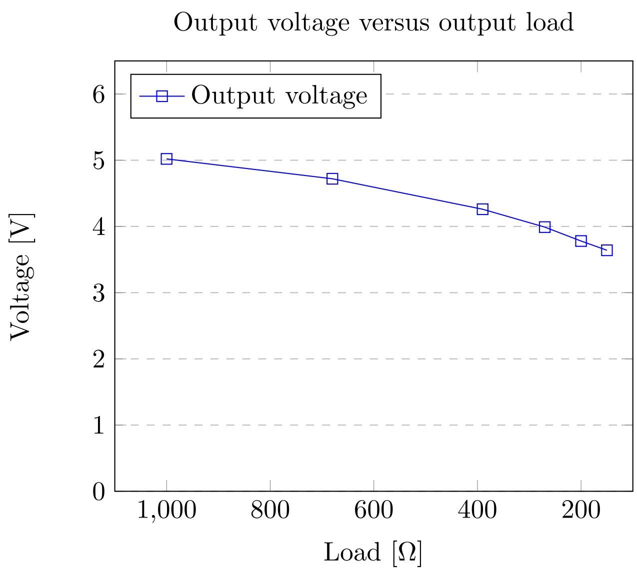
Figure 15: A test circuit for the LNK302.

C1, C2, C4	100nF/400V
C3	10uF/25V
D1	1N4007
D2	1N4007 (fast switching?)
D3, D4, D5, D6	1N4007
L1	1mH
R1	2.2kΩ
R2	2.2kΩ
R3	1.6kΩ

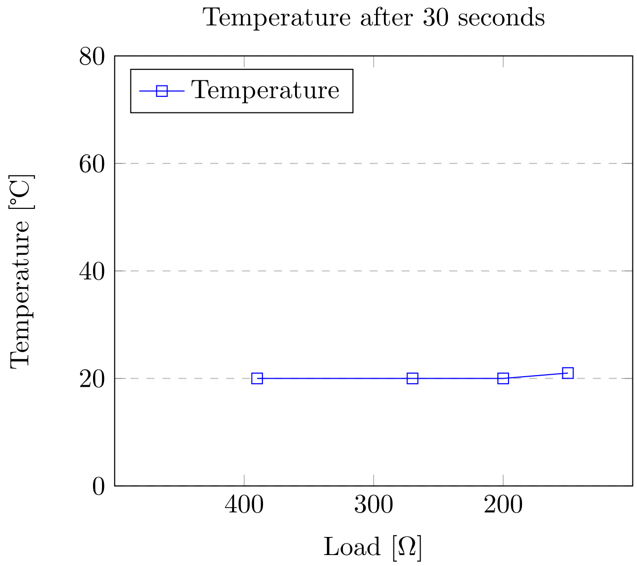
7.4 Testing

After testing there can be said that the MP103 is very vulnerable. When not taking care this chip will for sure blow out, in contrast to the LNK302 which is hard to damage. A possible declaration is the lower 500V internal switch. Because of the limited space in the final product a good internal protection circuit could be hard to create. Therefore only 700V or higher chips should be used in the future.

7.4.1 LNK302

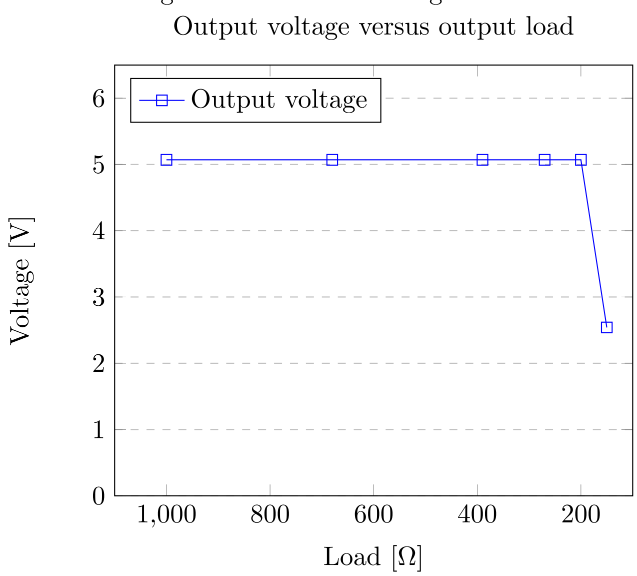


Een thermistor is met isolerende tape geplakt aan de behuizing van chip.

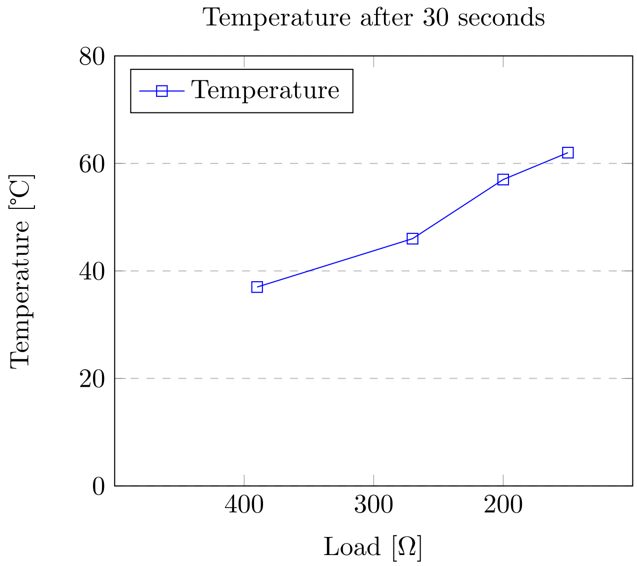


7.4.2 MP103

Output voltage by a given load. Bij een te grote belasting loopt de condensator sneller leeg dan dat deze kan opladen. Dit resulteert in dat de chip uitvalt en vervolgens weer opstart. Dit zou opgelost kunnen worden door een grotere condensator te gebruiken.



Een thermistor is met isolerende tape geplakt aan de behuizing van de BJT transistor.



7.4.3 MP158

After several attemps the MP158 is not working in this configuration. Probably because of the 500V intern transistor. Due to the unreliability is not a good choice for the final design.

8 Power supply II

8.1 Requirements

After the first test, a new set of requirements are made.

PSU-USPEC-3 The power supply must have a minimum absolute rating of 600 volts.

> *To ensure the power supply has a little but more protection against transients. The minimum voltage rating must be 600 volts or higher. This should be achievable with the components that are on the market.*

8.2 Design

Only internal transistors with at least a maximum voltage of 700V will be acceptable. The only topology that will be used is a standard buck converter topology. In the previous paragraphs is discussed why is chosen for this topology. Besides that only chips with a low profile case will be chosen. As seen in the table below, there isn't much choice.

Component	Manufacturer	Stock	Thickness	Footprint
MP171A	Monolithic Power Systems	In Stock	0.70mm - 1.00mm	$8.12mm^2$
MP172A	Monolithic Power Systems	In Stock	0.70mm - 1.00mm	$8.12mm^2$
MP173A	Monolithic Power Systems	In Stock	0.70mm - 1.00mm	$8.12mm^2$
MP174A	Monolithic Power Systems	Non-Stocked	0.70mm - 1.00mm	$8.12mm^2$
LNK302	Power Integrations	In Stock	1.35mm - 1.75mm	$29.4mm^2$
VIPer011	ST Microelectronics	In Stock	1.35mm - 1.75mm	$29.4mm^2$
VIPer20	ST Microelectronics	In Stock	1.35mm - 1.75mm	$29.4mm^2$
UCC2888x	Texas Instruments	Non-Stocked	max 1.75mm	$29.4mm^2$
NCP1060	Onsemi	Stocked	1.25mm - 1.75mm	$29.4mm^2$
AP3917	Diodes	Non-Stocked	1.50mm - 1.70mm	$29.4mm^2$
AP3928	Diodes	Non-Stocked	max 1.75mm	$29.4mm^2$
RAA223011	Renesas	Stocked	0.70mm - 1.10mm	$8.12mm^2$
RAA223012	Renesas	Non-Stocked	0.70mm - 1.10mm	$8.12mm^2$
RAA223021	Renesas	Non-Stocked	1.35mm - 1.75mm	$29.4mm^2$
LNK320x	Power Integrations	Stocked	1.35mm - 1.75mm	$29.4mm^2$
LNK329x	Power Integrations	Stocked	1.35mm - 1.75mm	$29.4mm^2$

For this second test the MP171A and RAA223011 are chosen. These are the only two packages that meeting the requirements and have a small package. For comparison, the LNK302 will also compete against these chips because this chip has been used for a while by Crownstone.

The main goal in this testing is to see which chip produces the best results. But before testing that there has to be some component considerations. Testing all chips with the exactly same components is not fair, because some chips produce better values with specific chips then others. But optimize each chip following the rules in the datasheet isn't fair either. If a chip is a much smaller output ripple in contrast to one other but has double the size of the capacitor that isn't a fair match.

One good thing is that all 3 circuits are almost identical in design. So there are some rules fore each circuit.

Things that has to be the same:

- All diodes are the same.
- The inductor is the same (given the datasheet the have each the same value).
- The input capacitor has to be the same
- The output capacitor has to be the same
- The dummy load. (fair to measure the efficiency of the chip itself.)

Things that are case dependent:

- The feedback circuit. (consisting of 2 resistors and a capacitor)
- The circuit for powering the chip.

Op de voorwaarde dat de componenten die hetzelfde moeten zijn voor elke chip capabel genoeg zijn om te kunnen functioneren.

In terms of safety, the electrical engineer stated that the chips have almost identical behaviour at lower AC voltages (except the part that there can be generated much less power. So all test are done with a maximum voltage of 100 volts.

Besides that, all systems will be calculated in CCM instead of DCM. This will lead into a smaller ripple current/voltage and a lower EMI. Also the components can be smaller.

x	LNK302	MP171A	RAA223011	Chosen
Input capacitor	136nF < C	219nF < C	220nF < C	300nF
Inductor	0.87mH < L < 1.29mH	0.13mH < L	0.16mH < L	1mH
Output capacitor	0.17uF < C	0,29uF < C	6uF < C	10uF

8.2.1 LNK302

THe datasheet stateds that lower C1 values causes a poorer load regulation. But it also happens to be that it voltage ripple will be worse. Low values like 100nF are too low. But a value of 1uF will doing just a little better.

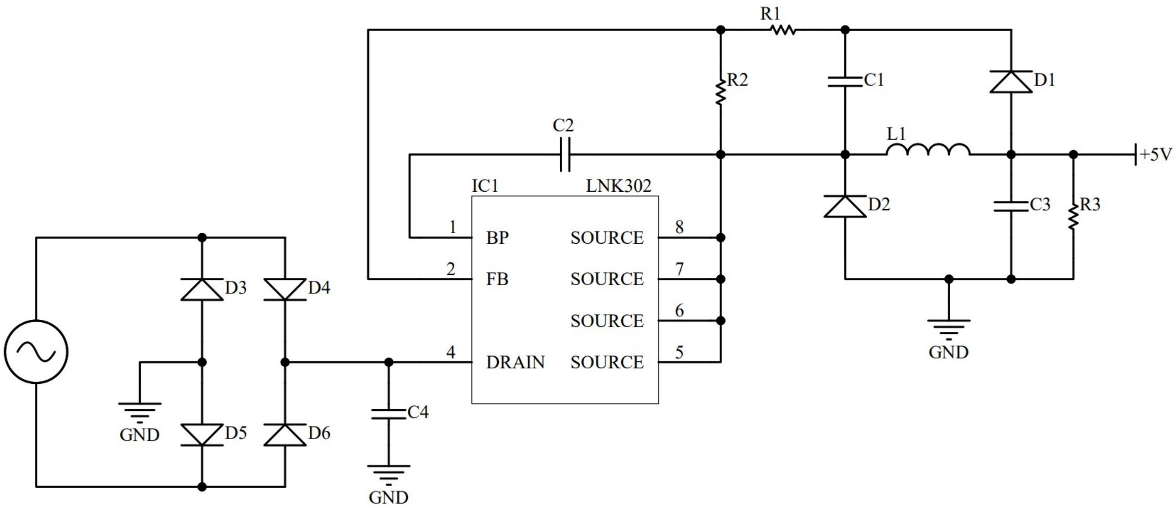


Figure 16: A test circuit for the LNK302.

C1	1uF/35V
C2	100nF/50V
C3	10uF/25V
C4	300nF/630V
D1	1N4007
D2	UF4007
D3, D4, D5, D6	1N4007
L1	1mH
R1	4.3kΩ
R2	2.2kΩ
R3	1.6kΩ

8.2.2 MP171A

MP171AGS-P SOIC-8

For testing this chip is chosen but for the end product the MP173A is chosen because of suppliers availability.

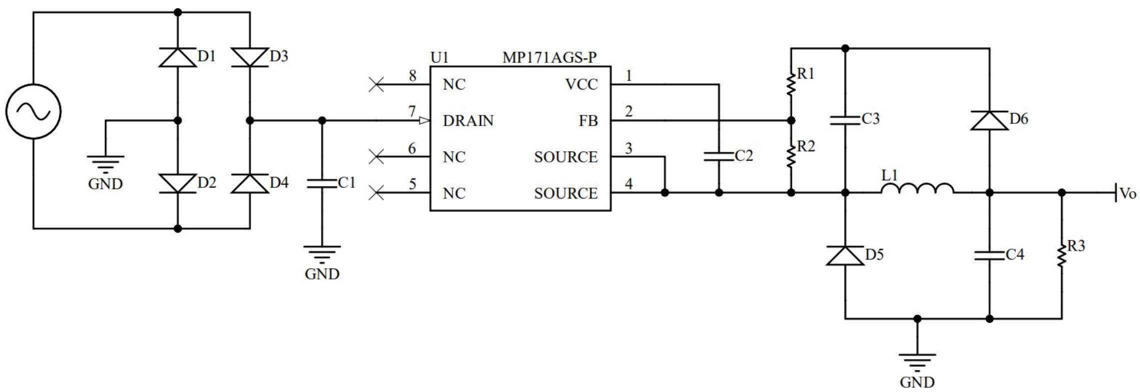


Figure 17: A test circuit for the MP171A.

C1	300nF/400V
C2	2uF/25V
C3	100nF/50V
C4	10uF/25V
D1, D2, D3, D4	1N4007 (SOD-123-FL package omdat deze veel voorkomt en laag is)
D5	UF4007(SOD-128Flat-2, M-flat, SOD-123-H waren het laagst. 123 gekozen)
D6	1N4007
L1	1mH
R1	10kΩ
R2	10kΩ
R3	1.6kΩ

8.2.3 RAA223011

The orderd chip RAA2230114GP3NA0 seems to be obselete, buth there is a chip RAA2230114GP3JA0 that will replace it, and it has the same specs and packages. It only comes in bigger reels. SOT23-5 package

D6 en C2 moeten eigen nog aan elkaar.

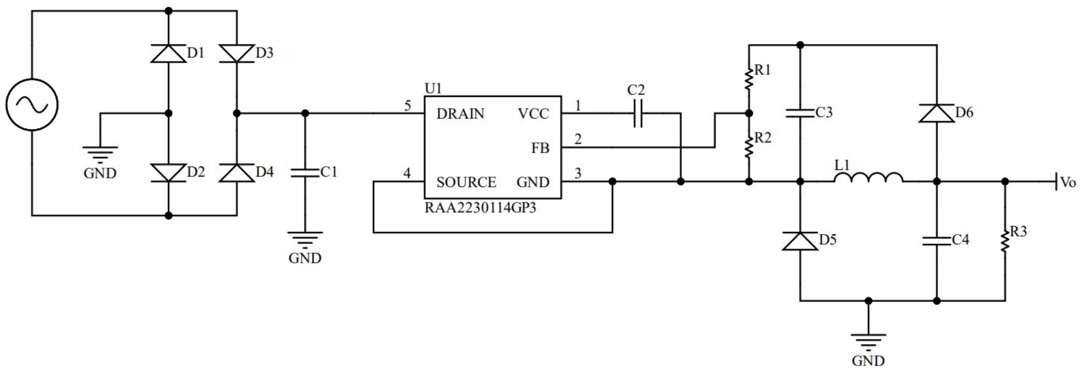


Figure 18: A test circuit for the RAA223011.

C1	300nF/630V
C2	1uF/16V
C3	10nF/50V
C4	10uF/25V
D1, D2, D3, D4	1N4007
D5	UF4007
D6	1N4007
L1	1mH
R1	110kΩ
R2	100kΩ
R3	1kΩ

8.3 Testing

All the components of the circuits are calculated so they can now be compared to each other. A list of important characteristics of a buck converter [16] are shown below.

- Voltage regulation
- Load Regulation
- Output ripple
- Transients
- Efficiency
- No load power
- Heat dissipation

All the test performed and their procedures are documented in attachment 'Power supply'. In terms of voltage regulation and load regulation the chips have no remarkable differences and are performing the same.

The biggest differences are seen at the output ripple and transients. The MP171A shows the highest output voltage ripple but in contrast to that the transients are very low. Transients are high of frequently and normally a voltage ripple is at a lower voltage. This will mainly effect the topology of filtering. The output ripple of the RAA223011 is at lower loads remarkable better, but the transients contain really high voltages and can therefore be dangerous for the other chips. Good filtering will be a must have for this chips. But still after testing a second filter on 1.59kHz the spikes are still unacceptable high. The LNK302 is a mid performer and will be a jack of all trades.

Because of the clean output voltage of the MP171A the efficiency is therefore a little bit worse in contrast to the RAA223011. Therefore we can say, the cleaner the output voltage, the more efficient the chip is.

Part	Octopart price
LNK302	0.50 USD (SOIC8)
RAA223011	0.81 USD
MP171A	0.93 USD

Part	Pro
LNK302	Cheapest
RAA223011	Most efficient
MP171A	Best performer

For making a first prototype it's best to get things working. Therefore the MP171A is chosen. Because of having the same footprint as the RAA223011, it can later on be swapped if needed.

To generate a steady output, an extra power supply stage is needed. To do so, one of the next options can be chosen.

- Passive filter
- Zener diode
- Buck converter
- LDO regulator

For this implementation is chosen for a LDO regultor, to generate an regulated output with much less switching distortions. A zener diode also would meet the requirements but in general a LDO regulator is better in terms of efficiency and the regulation is better.

9 Current measuring

9.1 Research

To convert the measured analog signals to a digital signal an A/D-converter is needed. Currently, most analog to digital converters are expensive or or out of stock, especially the ones with a programmable gain (which can help reading signal at larger ranges). The nRF52840 does have a integrated ADC that can operate on 8/10/12/14 bits including a gain amplifier. The gain can be set to the following values: $\frac{1}{6}$, $\frac{1}{5}$, $\frac{1}{4}$, $\frac{1}{3}$, $\frac{1}{2}$, 1, 2 and 4. If possible the integrated converter has to be used to decrease BOM quantity and cost. The Rogowski coil generate currents that can be positive as well as negative. To measure this an A/D-converter with negative power supply is needed as well as a negative power supply. A solution for this problem is using a virtual ground at VCC/2.

Nordic included a formula in the datasheet to calculate the digital output values [14]:

$$RESULT = (V(P) - V(N)) * (GAIN/REFERENCE) * 2^{(RESOLUTION-m)} \tag{15}$$

When rewritten the formula, the input voltage range can be calculated:

$$V(P) = \frac{RESULT}{(GAIN/REFERENCE) * 2^{(RESOLUTION-m)}} + V(N) \tag{16}$$

The max resolution for a differential signal (m = 1) is 12 bits. The 14 bits resolution is only achievable when oversampling is used (m = 0). The downside of this option is that the signal will be referenced to ground. Because of using a virtual ground, oversampling and thus 14 bit resolution is not possible. The reference can be set to an internal regulator of 0.6V or a voltage of VCC/4.

The smallest voltage range of the nRF52840 is +/-150mV. With a virtual ground voltage of 1.65V on the V(N) pin the smalles range is 1.5V-1.8V. Voltage V(P) can be negative with respect to V(N) (as long as the voltages stay within the power supply rails). The smallest theoretical voltage steps of the A/D-convert would be 73uV. Voltage down to 1mV should be read correctly.

To make optimal usage of the resolution, the largest output signal of the opamp has to cover the whole voltage range. Smaller signals can be measured by adjusting the gain of the A/D-converter. A 16A current will induce at it's maximum a current of 140uA, an amplification of around 23500x is needed to extent this to a voltage range of 3.3 volts. This kind of gains can cause multiple problems, limited bandwidth, noise and offset voltage.

Due to higher gains, the bandwidth gets more important. Mostly, a signal of 50Hz will be measured, but spikes and other transient behaviour operates at much higher frequencies. Basic pure restive loads are no problem, but when for example a lamp is dimmed, high frequency signals enter the waveform. Due to the nature of the Rogowski coil, high frequent signals will generate more current, later on this will be discussed later on. The higher the bandwidth of the opamp the better, but to measure correctly a minimum bandwidth of 500Hz will be set. To calculate this the following formula can be used:

$$GBP(GainBandwidthProduct) = Gain * Bandwidth \tag{17}$$

An amplification of 23500x with a minimum bandwidth of 500Hz requires a GBP of around the 12MHz. This is only possible with high bandwidth opamps. Having that said, the next problem is going to occur, offset voltage. Standard opamps have offset voltages off around 1mV, filling in the following formula's the output voltage offset can be calculated:

$$R_f = Gain * R_{rog} \tag{18}$$

$$Gain_{Vos} = 1 + \frac{R_f}{R_{rog}} \tag{19}$$

A gain of 23500 with an internal resistance of the Rogowski coil of 0.6 Ohms and a feedback resitance of gets an output offset voltage of 23.501 volts, which is clearly unacceptable. Overcoming this problem can be done by choosing an opamp with a super low offset (generally sub 10uV). That brings the offset voltage back to 235mV which is not ideal because this DC offset will makes the total gain lower. When an AC-signal gets added up by large DC offset, there is a change the signal will clip to its power supply rails. When all values are recalculated and with the given voltage offset of 10uV the total gain will be 22000x.

In high gain amplifiers noise is an important characteristic. When to much noise is added to the output, small signals can be hard to measure. In opamp circuits there are three main sources of noise, internal noise of the opamp, current noise and Johnson noise. All resistances will generate Johnson noise and this can be calculated with the following formula.

$$e_n = \sqrt{4kTBR_1 || R_{rog}} \tag{20}$$

With a bandwidth of 500 Hz and a temperature of 300 Kelvin (= 26,85 °C) the generated noise by the resistors will be 2.229nV or 99.68pV/$\sqrt{Hz}$. With the current Rogowski coil signals to a minimum of 50mA can be measured, this will result in a output voltage of around 10mV. To be sure, a maximum noise voltage of 5mV or 223.61 uV/$\sqrt{Hz}$ can be acceptable. With the following formula the maximum noise density of the opamp can be calculated [17].

$$e_{n-total} = \sqrt{e^2_{n-opamp} + e^2_{n-Johnson}} * Gain \tag{21}$$

The total noise for the opamp can be not higher than 10.16 nV/$\sqrt{Hz}$.

Also a low input bias current is advised, this can be achieved whit a JFET or CMOS opamp. These amplifiers normally ranges from several pico amps to a few hundreds of pico amps. Normally a opamp with a sub 1nA input bias current will be enough.

Also, to maximize the gain, a opamp with a rail to rail ouput is prefered. Below are the most important characeristics stated of the opamp.

Symbol	Parameter	Value
V_{os}	Input Offset Voltage	< 10uV
GBW	Gain Bandwidth Product	> 12MHz
e_n	Voltage Noise Density	$< 10\text{nV}/\sqrt{Hz}$
I_B	Input Bias Current	< 1000pA
$(V^+ - V^-)$	Supply Voltage	3.3V
RRIO	Rail to Rail	Output

If the final Rogowski coil has the same performance as researched, the gain can be left on his value. If the Rogowski coil's performance decreases, smaller currents are generated and a higher gain has to be used to make use of the full input voltage range. The calculated values are guidelines and have some safety margin, with little gain increases recalculation is not needed. The most important thing to keep in mind is that the output signal can not clip to the voltage rails.

To solve all the problems an opamp with a GBP of 12MHz, noise density of $10\text{nV}/\sqrt{Hz}$ and a offset voltage of 10uV is needed. Unfortunately there are not much chip that can do this in a ultra small package, especially for a reasonable price. There are three options that are possible:

- Two opamp's to divide the gain and having a larger bandwidth.
- An offset cancellation circuit (also needing multiple opamps).
- One more expensive opamp.

The first option has one main advantage. The nRF52840 has multiple analog input pins, and having two gain stages each output of the stages can be connected to them. Therefore, not only a programmable gain but also a external gain can be set. This will give much more opportunities for example having the first gain stage amplifying high transients that can be analysed. Or another option is to set the first gain for large signals and the second gain for small signals. Therefore the waveform can be analysed more precisely because its more easy to set the gain to the full voltage range.

This circuit looks really like a trans-impedance amplifier because of converting the currents from the coil to a voltage. Normally a trans-impedance amplifier doesn't need a ultra low voltage offset. Such an amplifier is mainly used for converting the currents of a photodiode to a voltage. The difference between a photodiode and a Rogowski coil is the difference in internal resistance. Where a photo-diode has a quite large resistance, a Rogowski coil has a maximum resistance of a few ohm's. Due to the presence of this resistance and the feedback resistance the opamp acts as a normal inverting amplifier.

9.2 Design

The virtual ground can be created with a fairly simple circuit, a voltage divider with a opamp as buffer. This opamp can be a generic one and it doesn't really matter what kind of opamp it is. Choosing an opamp is done with BOM cost in mind. Besides that, it's better to have a opamp in a common package. When the opamp doesn't perform that well or it will be swapped with another one it can be done without making a new PCB. When searching on electronic website such as Farnell, Mouser, Digikey, it can be found that a packages as SC-70-5, SOIC-8, SOT-23-5 and SOT-23-6 are the most common ones. The SOIC-8 package is a quite large, and despite the SOT-23-5 is the most common one, most of them have a max height of 1.45mm. The SC-70-5 have a maximum thickness of around 1.10mm, therefore this package is chosen. For a amplifier with two channels a DFN-8 package is recommended.

In an earlier stadium a wrong assumption was made, namely that the opamp was in a transimpedance configuration. In such a configuration bandwidth and dc voltage offset are less important. Because a voltage to voltage conversion is not the same as a current to voltage. So does the formula's for the first one not hold up for the second one. The current circuit has a single amplifier, but this can not amplify enough to make use of the full range. All the calculations in the previous paragraph can still be used. This will be an improvement for a next generation.

10 Antenna

Antenna's are a profound electrical subject for decades. Therefore, there are a lot of papers describing the basic working principles of it. In this chapter the main focus is to collect data to find and make the optimal antenna for this product. A good books for the basic understanding of antenna's can be found here [18].

10.1 Research

An antenna is a structure that operates as the transition between free space and a guiding device (also known as a transmission line) [18]. This structure is used to transport electromagnetic energy from the source, through the transmission line, to the radiating antenna. The reverse happens when radio waves are received by the antenna.

For communicating with other devices Bluetooth will be used. This can be Bluetooth Mesh or Bluetooth Low Energy. Bluetooth uses the 2.4GHz ISM band that ranges form 2400MHz to 2483.5MHz [19]. To get a perfect match, the antenna has to be tuned at a resonant frequency of 2441.75MHz (normally a value of 2.44GHz will be good enough). Besides that, the antenna needs to have enough bandwidth to cover the whole spectrum. The bandwidth in this case will be 83.5MHz. To ensure all frequencies in this bandwidth are useful, the antenna needs to have a maximum VSWR of 2.5 (matching coefficient, 1 means no reflection).

To have an overview of the available typologies of antenna's, the most common ones are listed below. Due to the restricted space only PCB trace antenna's are described. So radiating metallic plate antenna's and chip antenna's are not included. Due to the changing enviroment of the antenna (Plastic case, imperfect groundplane, thin PCB, presence of a outlet plug). There is chosen to not use a chipantenna. For basic testing this is good enough but for a perfect antenna in this product a PCB trace antenna is the best choice. Also the dipole antenna's are not discussed because the nRF chips only support a single source. So this document is focused on monopole antenna's.

- Monopole
- ILA (Inverted L Antenna)
- MILA (Meander Inverted L Antenna)
- IFA (Inverted F Antenna)
- MIFA (Meander Inverted F Antenna)
- ZOR
- Patch
- MLA (Meander Line Antenna)

To simplify this chart the topologies are categorised.

- Monopole, ILA (Inverted L Antenna)
- MLA, MILA (Meander Inverted L Antenna)
- IFA (Inverted F Antenna)
- MIFA (Meander Inverted F Antenna)
- ZOR
- Patch

The easiest antenna designs consists of a standard monopole antenna. There aren't that much variables to deal with. To calculate the length of the antenna the following formula can be used [20].

$$\lambda = \frac{v}{f} = \frac{299792458}{2440000000} = 0.1229m => 0.1229 * 0.75 = 0.09215m => 0.09215/4 = 0.023037m = 23mm \quad (22)$$

Because a monopole uses the groundplane as the second antenna (dipole), ideally the groundplane needs to be as long as the antenna [20].

Designing an antenna consists of several steps. The most common way to do this and most described way is written down below. The following design steps are from NXP Semiconductors [21].

- Select the antenna type.
- Roughly calculate the antenna dimensions.
- Simulate the antenna with simulation software.
- Adjust the dimension until the result meets the requirement.

10.2 Requirements

REQ-F7 [CH] The impedance has to be 50 Ohms with a deviation of 10 Ohms at a frequency of 2.44GHz.

De antenne moet zoveel mogelijk tegen de achterkant van de behuizing aanzitten. Want als er heel dichtop een stekker komt te zitten zal de radiation minder worden.

HFSS underscore GUY on instagram

Patch antenna has a perferct forward facing radiation pattern.

A smaller length will return in lower bandwidth

To understand how a antenna works. A antenna consists of a resistor, capacitor and inductor all in series. Due to these components there is a resonant frequency.

Hele testprocedure omschreven!!! [21]

11 PCB design

11.1 Capacitors

The device needs to made durable to sustain for a long period of time. The components that suffer a lot from aging are capacitors. Capacitors have different characteristics that all have impact on the long term capacitance. The following characteristics are important to take into account.

- Chose a higher quality dielectric.

  When choosing a high quality dielectric such as X7R or C0G the capacitance drop over time will be much lower.

- Chose a larger package.

  The smaller the package, the smaller the internal structure of the capacitor. This will cause more instability in the capacitance value.

- Chose a higher voltage rating.

  When the voltage over a capacitor is close to it's maximum ratings for a long time, the capacitance will eventually drop.

- Chose a higher capacitance.

  To compensate for the capacitance drop, a higher capacitance can be chosen.

Due to the limited space, larges capacitors are definitely not preferred. Choosing a larger capacitance is a good way to be sure the circuit works fine, but over time the capacitance will drop and the characteristics of the device will change. A high quality dielectric is better but comes with the disadvantage that the costs will go up. A capacitor with a higher voltage rating doesn't rise that much in price and should maintain the capacitance for a longer period of time because a smaller region of the voltage is be used [22]. For general capacitors, a X5R should be enough with a rated voltage of around 25V. When a ceramic capacitor has a bias voltage larger than 20 percent, the capacitance will drop fast. Because the overall voltage is around 3.3V and 5V, a 25V rating should be the minimum [23].

11.2 Placing

To protect the sensitive chips from the switching regulator, for arcing or EMI, it's best to divide the PCB in two parts. One part for the power supply, and one part for all the low power circuitry. Also its best to place the power inductor as far as possible from sensitive components, such as the Rogowski coil or the antenna. The connections for the hot and neutral line can best be placed in the centre next to the holes for the plug. If in the future a way is found to make a durable connection between the Smart plug and the outlet, the connections for this would be over here.

Components as close as possible to each other.

11.3 Clearance

One important subject to take into account is the clearance an creepage. Signals like 230V AC with respect to ground (or 3.3 volt, that doesn't really matter) can cause arcing if placed too close to each other. There are standards for these kind of distances like IPC-2221. This standard states the distance between conductors on different layers and with or without a coating. It's not possible to fulfill the standard everywhere. Following the standard also the distances between the pads of a diode too close to each other. Except for these all other parts need to have enough clearance.

11.4 Via's and tracks

All high voltage lines (at the primary side of the regulator) have a thickness of 1mm where possible. The secondary side have tracks of around 0.5mm. Individual power lines to chips have a general thickness of around 0.3mm. Signal tracks have a track width of 0.15mm to 0.3mm. For all these voltages can be said the ticker the track, the better.

The normal via hole size is 0.3mm, for spaces with less room 0.25mm. Via's for higher current flows have a hole size of 0.4mm. It is a good practice to place a much via's as possible. This will help by getting a solid ground with less ground loops. These via's are also called stitching via's.

11.5 BOM

In the attachment "BOM", the total cost of the components can be found. We can say that there is about ... left for the enclosure if a standard PCB costs about ...

11.6 Building process

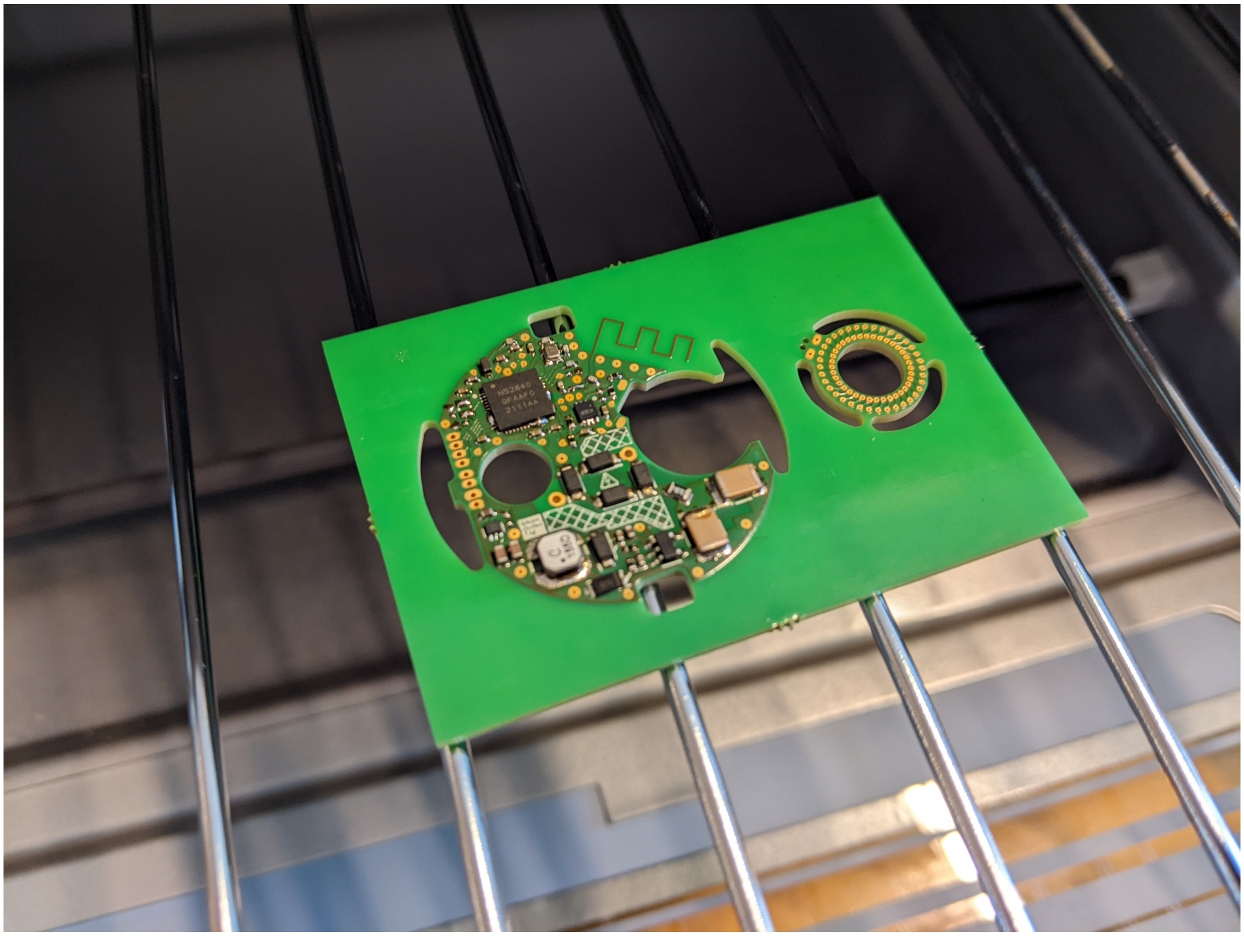


Figure 19: Reflow

12 Testing

All the unit tests and acceptation tests are described in the attachment "testing". In the table below is a quick overview of the tests that did pass and did not pass.

13 Conclusion and discussion

13.1 Conclusion

In the beginning the following main question was asked: ”How can a thin device, the size of a plug, be developed that can be powered from the socket, transmit data wirelessly and measure current?” From this research it appears this is possible. In an ideal case, the product is able to harvest energy inductively from the socket. As far as this paper goes is this not possible and an alternative way has to be chosen. This is in the form of a offline regulator that can convert the AC voltage to a lower DC voltage.

13.2 Discussion

In the current design everything fits barely. A good advice would be to use 0201 resistors and capacitors in the next design. This will make it way more difficult to develop the device but it will clears a lot of space to fit extra components. Also the nRF52840 is quite large in its current QFN package, the smaller WLCP package can be an outcome. With the extra gained space a few extra units can be implemented, such as:

- Adding an extra coil.

  Adding an extra coil, double the energy can be generated. Because of the very low power the chip still can't be powered but it could be more interesting if a better coil could be developed. Besides that, an extra can be help full for current measurement. This will result in double the generated energy and can therefore be used to measure even smaller signals more accurately.

- An extra stage amplifying the current.

  With an extra amplifying stage the current the generated currents can be amplified with different gains. The ADC can be configured to focus on the larger or smaller signals. This can be better for measuring low currents but also for measuring high inrush currents, by how you configure it.

- Reading the voltage from the power line.

  By adding a circuit for lowering the AC voltage to an AC voltage of around 3V, this signal can be also measured by the ADC. By analysing this, it can say something about the quality of the line voltages. Also can this be used to calculate the power factor of the plugged in device.

First the main focus will be on improving the current design, but in a later stage more features can be added. This paper do have a few ”Won't have” requirements that can still be implemented.

Also not enough testing is done in terms of EMI and noise. The created offline converter produces EMI (thats a characteristic of all switching power supplies). It can be interesting to know if these magnetic waves can interfere with the Bluetooth signals of the device. If so, the power supply has to be improved to make the range of the range of the Bluetooth signals as large as possible.

Some extra testing has to be done in terms of safety. The current system works but it is not clear how reliable it is under extreme conditions (high voltage spikes on the power lines for example).

The current BOM is already quite small due to the limited space. For future BOM optimization there are three possible ways; dropping features, buy components cheap, change chips for a discrete variant (which can be cheaper and less reliable on advanced components).

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