Instituut voor Engineering en Applied Science
Opleiding Elektrotechniek

Smart Outlet Tag

Crownstone

Bachelor thesis

I. Verhage

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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 belangrijkste 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 anderen die een soortgelijk onderzoek doen of geïnteresseerd zijn in de werking van de Rogowski coil. Mijn dank is groot naar Crownstone en haar medewerkers die meedachten en ondersteunden in het proces. In het bijzonder wil ik Anne van Rossum en Peet van Tooren hartelijk danken voor de begeleiding en samenwerking.

Aan alle lezers wens ik veel leesplezier toe.

Ies Verhage

Rotterdam, 15 juni 2022

Version history

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0.2	Adding DCD / DFD and overall improvements	25-03-2022
0.3	Architecture section	05-04-2022
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Abstract

Crownstone is a manufacturer of smart plugs and connectors. At the moment Crownstone mainly makes boxes that can measure power consumption, switch devices on and off and pinpoint a user's location. These boxes can be connected behind a socket or lamp. Crownstone is looking for a new product that can be placed in the socket instead of behind the socket. This will be much easier for installation and will also make the product more accessible. Ideally, the socket can still be used by devices, and therefore it will also have to be very thin. Things like a Bluetooth connection and being able to measure current are a plus. A bigger problem is powering the device. A direct connection would be difficult on this scale, especially if other devices also have to be able to get their energy from the socket. That is why research is first being conducted into the possibility of inductively harvesting energy. This information will also be useful for how the current can be measured. To answer all these questions, the following central question was asked: "How can a thin device, the size of a plug, be developed that fits into a socket, can transmit data wirelessly and measure current?"

This research was done both practically and theoretically. Resources from the internet have mainly been used, but practical research is also needed to arrive at certain answers. In addition, the knowledge and expertise of Crownstone's employees was also used. First of all, there will be a study that examines inductive power generation. Subsequently, a description will be given of how the various units have been designed and which decisions have been made. Finally, the units are tested for their requirements.

Ultimately, it will become apparent that inductive energy harvesting is not possible. The energy generated from the developed Rogowski coil is too low. However, the coil is suitable for measuring energy, so this will also be implemented. In order to be able to feed the end product, it was decided to integrate a 230 V AC to 3.3 V converter in this prototype. For wireless communication, a Bluetooth antenna is mounted on the PCB. At the end of the report, a first prototype of the product was produced. Ultimately, a thin device has been developed that can do the most important things.

However, there are still various improvements that can be implemented in a subsequent design. For example, smaller resistors and capacitors can be used to create more space for other modules. This space can be used to add extra measuring circuits for measuring current or voltage. According to the research done, inductive power harvesting is not possible. Additional research can be done later on to develop new methods that can do this better.

Samenvatting

Crownstone is een fabrikant van slimme stekkers en connectoren. Op het moment maakt Crownstone voornamelijk kastjes die het stroomverbruik kunnen meten, appraten aan en uit kan schakelen 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, zeker 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 in een stopcontact past, draadloos data kan versturen en stroom kan meten?"

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 energie uit de ontwikkelde Rogowski coil is 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 230 V AC naar 3.3 V 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. Uiteindelijk is er een dun apparaat ontwikkeld dat 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 extra meet circuits voor meten van stroom of voltage. 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 16 A 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's possible to determine 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, there could be determined where a patient is or if there are people present. 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 valuable 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 device that's plugged in. This can give the Crownstone insight in energy usage and activity. The challenge will mainly be in making a compact/thin design and supplying 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 research is done by an (4th year) student at Hogeschool Rotterdam, Electrical engineering. The research has to be done from begin February to the end of June 2022. In this period of 5 months the student has to deliver a proof of concept. The derivable is only a hardware design and not the software that measures the distance to other devices or collecting the measured currents. The used method for this project is scrum, a company standard of Crownstone. This is chosen because scrum will allow to iterate quicker and to get feedback of tests that are done. With scrum some problems can be prevented which isn't always possible with a V-model method.

This report 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 being discussed. In this part design decisions are made and are being substantiated. After that the process of making the PCB in Altium Designer is discussed. Finally the different parts are tested on their requirements. The plan of action can be found in appendixG this is written in dutch and is called "Plan van Aanpak"). For al the important technical documentation a Github repository is used, it can be visited via "https://github.com/iesverhage/crownstone-smart-outlet-tag". A competency accountability and a reflection can also be found in appendix I and H. Appendix J will show the rating and feedback of the student.

2 Definition phase

To visualize in a simplistic way what the system has to do a pseudo-Yourdon method is used. By doing this, diagrams are formed in a structural way displaying what the Smart Outlet Tag should do. After that the wishes of Crownstone are being analysed and converted to requirements.

2.1 Data context diagram

In figure 1 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 wireless 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 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.

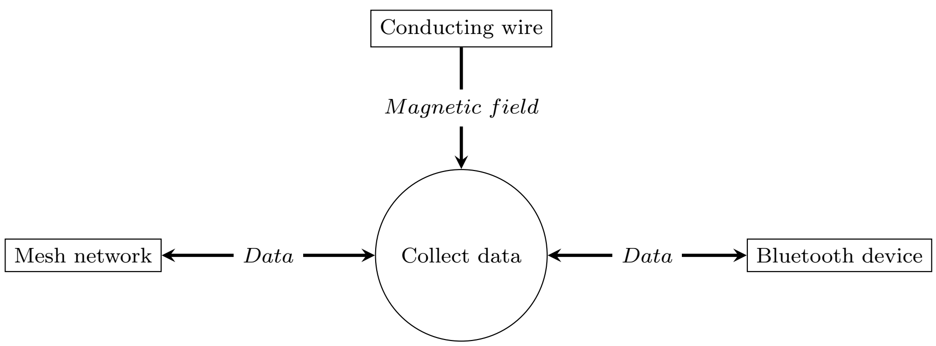


Figure 1: Data Context Diagram

2.2 Data flow diagram

Figure 2 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". Process "Current Measurement" is responsible for converting the magnetic fields into readable signals.

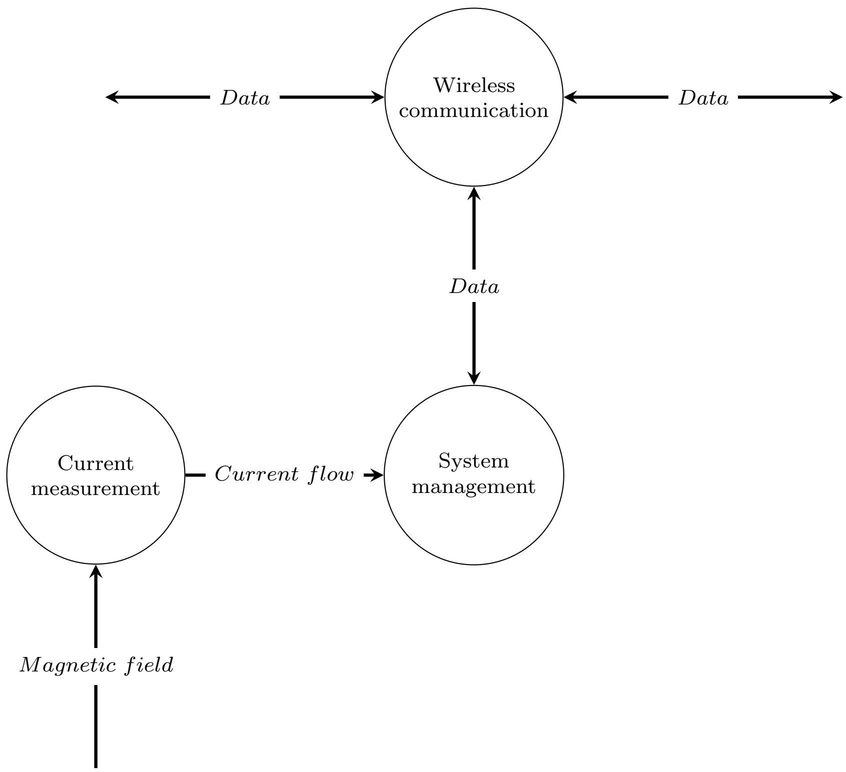


Figure 2: Data Flow Diagram

2.3 System functionality

All the wishes of Crownstone are documented in appendix A. 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 process to ensure the system works. The main function of this part is to control all the other parts in the system.

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 Wireless communication

This process controls the wireless data transmission and reception.

Stimulus and response

REQ-F2 [MH] The product has to have Bluetooth communication that can send data over 20 meter. The receiving device has to pick up at least -100dBm.

The product needs to have a sufficient range to communicate with other devices. Because of the different characteristics of receiving devices, multiple needs to be tested. This is an important requirement because this is the only communication medium of the device.

2.3.3 Current measurement

This process has everything to do with the measurements of current and collecting the magnetic field. This is an important feature for Crownstone.

Stimulus and response

REQ-F3 [MH] The device has to measure the current of a connected outlet plug inductively with currents higher than 10A (10 percent), this is only for pure resistive loads.

This test is focused on measuring high currents. Because of the high magnetic fields that are generated this should be possible and is therefore a must have requirement.

REQ-F4 [SH] The device has to measure the current of a connected outlet plug inductively with currents higher than 1A, this is only for pure resistive loads. The measurement can not deviate more than 5 percent from the expected output value.

This test is focused on measuring medium currents. This requirement should be a little bit harder than the previous requirement but is also desirable.

REQ-F5 [CH] The device has to measure the current of a connected outlet plug inductively with currents higher than 100mA, this is only for pure resistive loads. The measurement can not deviate more than 5 percent from the expected output value.

This test is focused on measuring small currents. Crownstone doesn't expect to measure such low currents but it would be a very nice to have.

2.3.4 Non Functional

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

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 diameter of the PCB has to be 0.5mm smaller than a outlet plug (CEE 7/4), this results in a maximum diameter of 35.5mm.

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 [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. Because this is only for development purposes this is a non functional requirement.

REQ-NF5 [SH] The device can communicate using UART on a baudrate of 230.400kb/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 230.400kb/s baudrate connecting to the TX and RX pins. Because this is only for development purposes this is a non functional requirement.

REQ-NF6 [SH] The price of the design should be no higher than 9 euros.

The price has to be a fifth of the total resale price of a Crownstone product. Only the PCB and components are covered by this value. This requirement is a should have because if the requirement is not met, it's not a show stopper.

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.

REQ-W3 [WH] The device should remembering the time when the power goes out.

Because of the extra complexity and to ensure the project will exceed within the time period this is a won't have requirement.

2.5 Requirements

In table 1 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 product has to have Bluetooth communication that can send data over 20 meter. The receiving device has to pick up at least -100dBm.
REQ-F3	MH	The device has to measure the current of a connected outlet plug inductively with currents higher than 10A (10 percent), this is only for pure resistive loads.
REQ-F4	SH	The device has to measure the current of a connected outlet plug inductively with currents higher than 10A (10 percent), this is only for pure resistive loads.
REQ-F5	CH	The device has to measure the current of a connected outlet plug inductively with currents higher than 10A (10 percent), this is only for pure resistive loads.
REQ-NF1	MH	The microcontroller has to be the nRF52832 or nRF52840 from Nordic Semiconductor.
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 diameter of the PCB has to be 0.5mm smaller than a outlet plug (CEE 7/4), this results in a maximum diameter of 35.5mm
REQ-NF4	MH	The device can be programmed with a J-Link programmer.
REQ-NF5	SH	The device can communicate using UART on a baudrate of 230.400kb/s.
REQ-NF6	SH	The price of the design should be no higher than 9 euros.

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 230 V AC to 5 V 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.

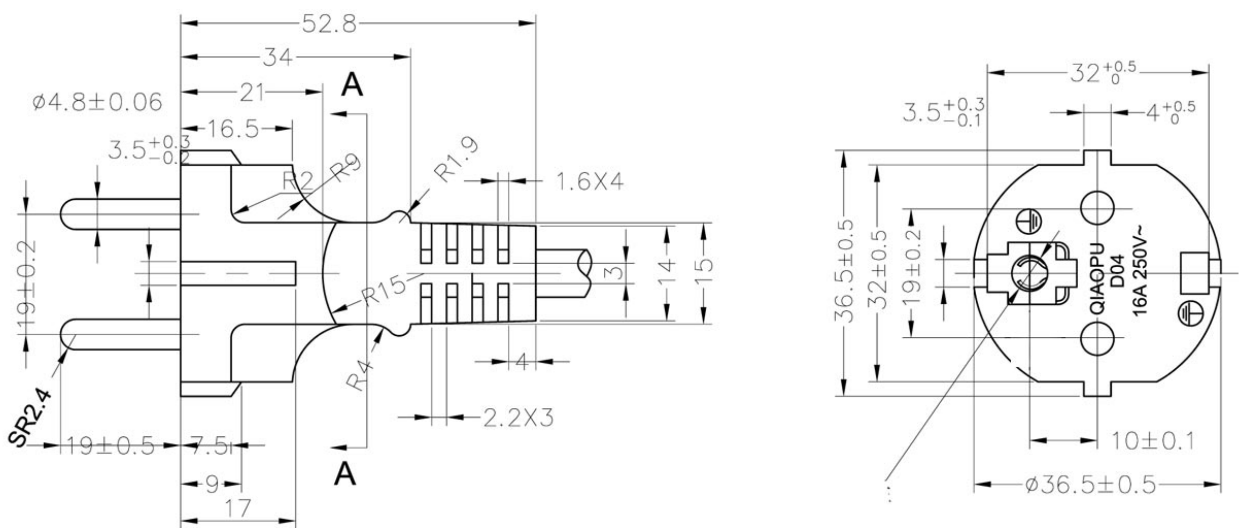


Figure 3: Dimensions of a CEE7/7 power cord.

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.

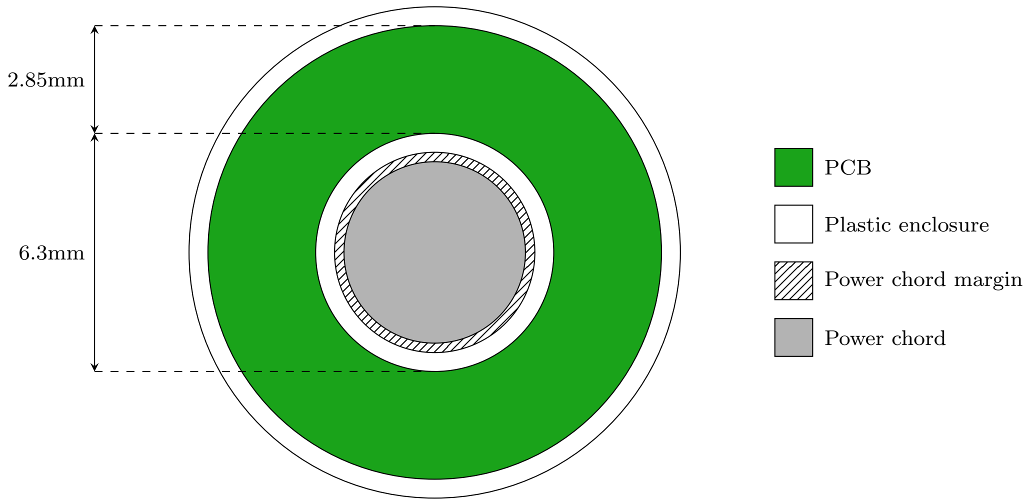


Figure 4: Schematic view of Rogowski coil

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. JL-CBPCB 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.

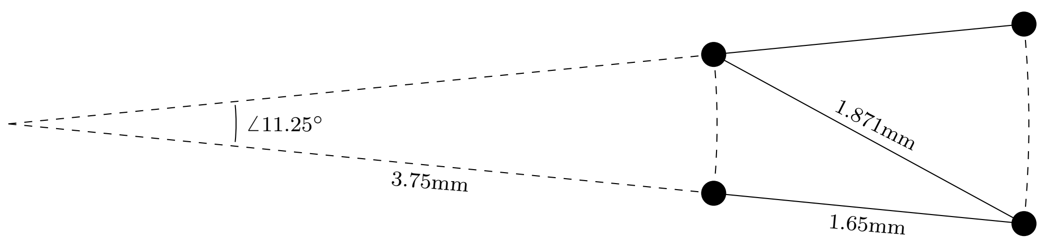


Figure 5: PCB measurements

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.

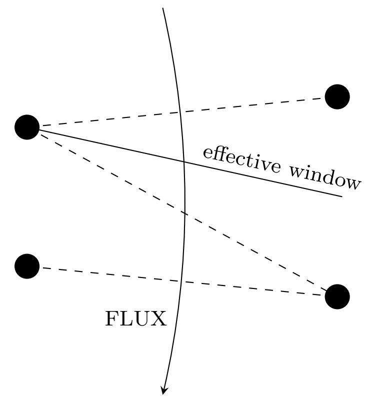


Figure 6: Flux through a Rogowski coil

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.

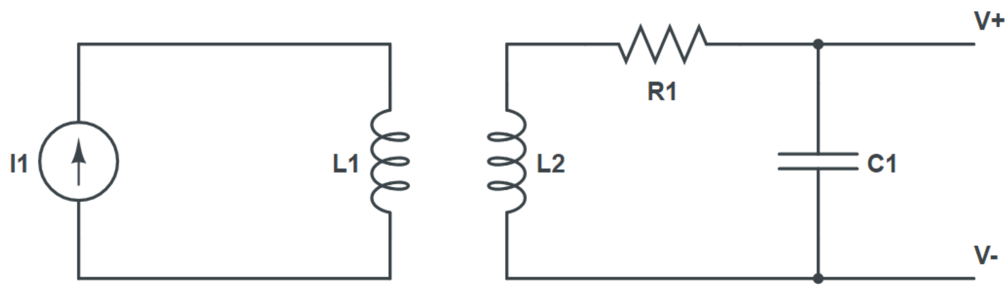


Figure 7: Rogowski coil equivalent circuit

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.

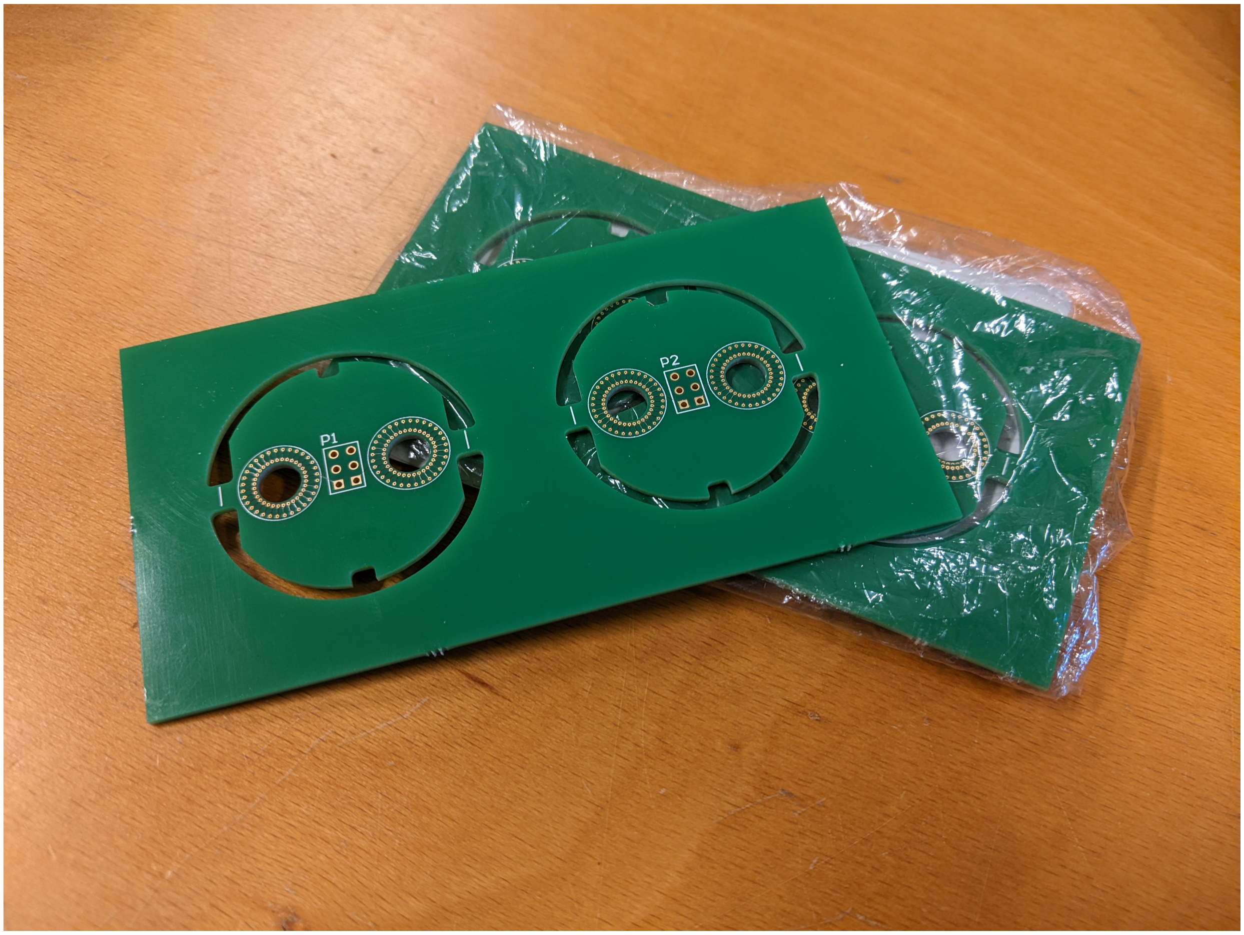


Figure 8: Rogowski coil

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.

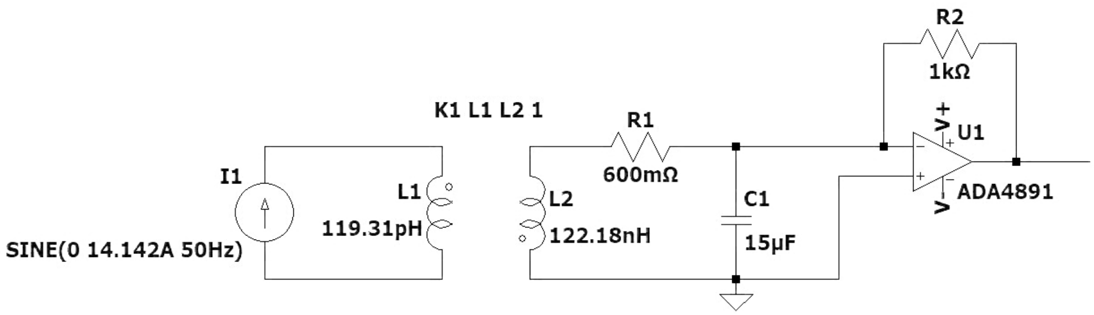


Figure 9: LTSPICE

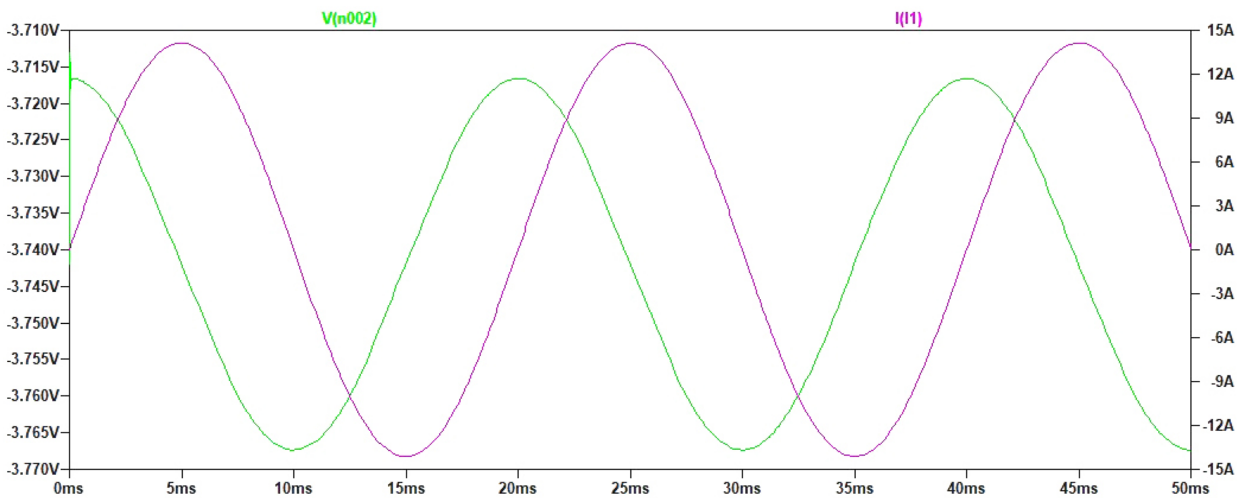
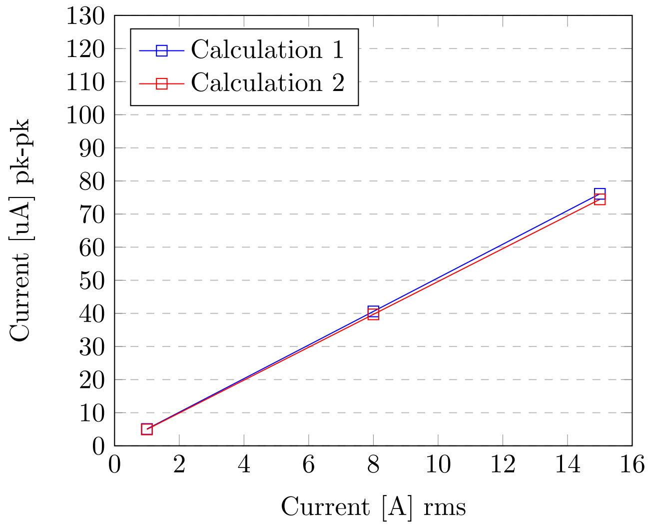


Figure 10: LTSPICE

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.

Output current vs current (output current Rogowski)

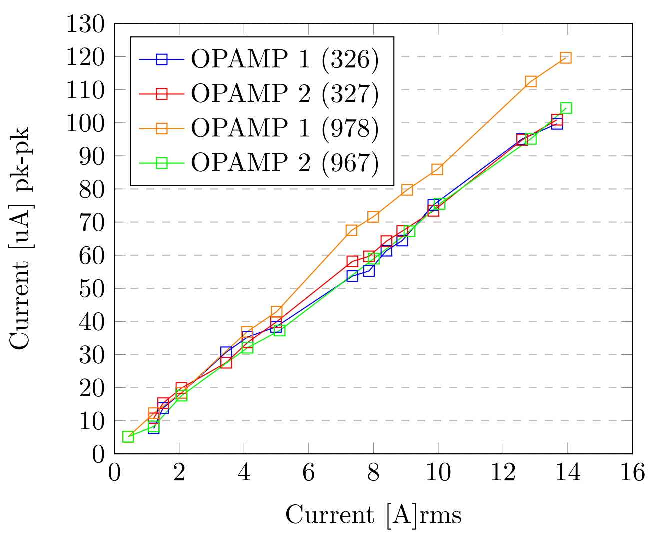


3.7.2 Practical test

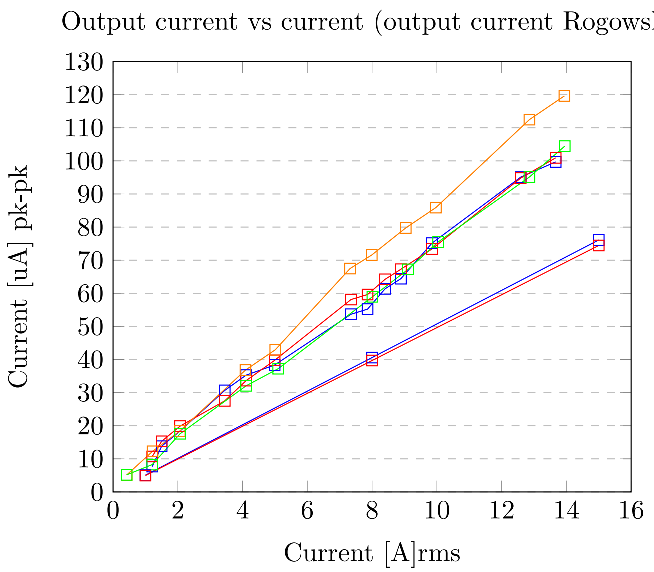
The testing is done with a standard off the shelf TL074. This chip is not perfect and has a large voltage offset. This is a big limiting factor because of this a high gain results in a high offset voltage. If the offset is too high, voltages can fall outside the voltage range of the opamp and can cause 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.

Output current vs current (output current Rogowski)



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.

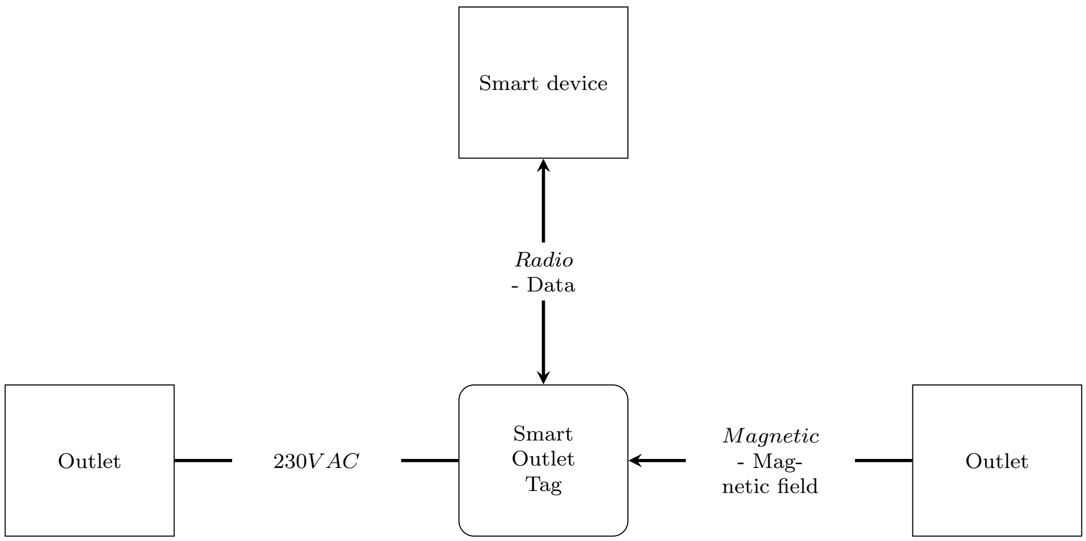


Figure 11: Architecture Context Diagram

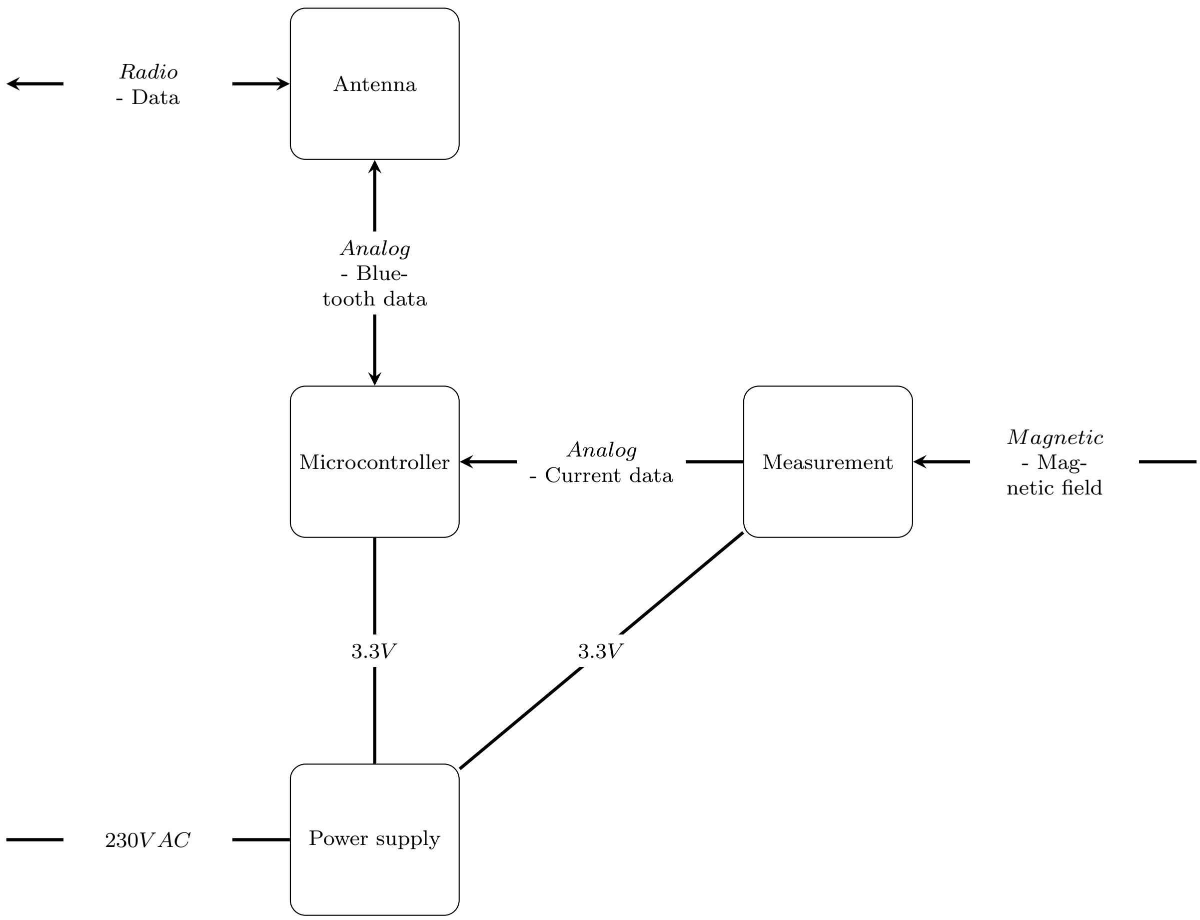


Figure 12: Architecture Interconnect Diagram

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 3.3 V.

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. 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. This unit will operate on a voltage of 3.3 volts.

4.2.4 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	Antenna
REQ-F1		X		
REQ-F2				X
REQ-F3			X	
REQ-F4			X	
REQ-F5			X	
REQ-NF1	X			
REQ-NF2	X	X	X	X
REQ-NF3	X	X	X	X
REQ-NF4	X			
REQ-NF5	X			
REQ-NF6	X	X	X	X

Table 4: Traceability table requirements

5 Units

In table 5 are extra requirements stated to make sure an unit works sufficient on it's own. This list is a quick overview, in the respective unit sections they will be discussed further on why they are chosen and where the values came from.

Most units have a similar way of writing. First of all a research will be done to gather some extra information about the subject. Secondly the requirements will be drawn up. After that the circuits are made and if needed some additional testing is done. Testing the requirements of the units will be discussed later on in section 13.

REQ-PSU1	The output voltage must be 3.3 V with a maximum deviation of 5 percent.
REQ-PSU2	The chip must be able to deliver a current of 25 mA.
REQ-PSU3	The power supply must have a minimum absolute rating of 600 volts.
REQ-AMP1	The output of the measurement circuit contains a signal from a 10 A resistive load above the noise level.
REQ-AMP2	The output of the measurement circuit contains a signal from a 1 A resistive load above the noise level.
REQ-AMP3	The output of the measurement circuit contains a signal from a 100 mA resistive load above the noise level.
REQ-ANT1	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-ANT2	The VSWR or return loss needs to be less than 2.5 dB within the frequency range of the Bluetooth communicating protocol (2.4000GHz to 2.4835GHz).

Table 5: Unit requirements

REQ	PSU 1	PSU 2	PSU 3	AMP 1	AMP 2	AMP 3	ANT 1	ANT 2
REQ-F1	X	X	X					
REQ-F2							X	X
REQ-F3				X	X	X		
REQ-F4				X	X	X		
REQ-F5				X	X	X		
REQ-NF1								
REQ-NF2	X	X	X	X	X	X	X	X
REQ-NF3	X	X	X	X	X	X	X	X
REQ-NF4	X	X	X	X	X	X	X	X
REQ-NF5								
REQ-NF6	X	X	X	X	X	X	X	X

Table 6: Traceability table unit requirements

6 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 7: 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.

7 Microcontroller

In this section, the main microcontroller for the Smart Tag is chosen. First the choice for Nordic semiconductors is discussed shortly. After that, a comparison is made between two chips and a final choice is made.

7.1 Why Nordic?

In the past Crownstone had a wish to track smartdevices in a room. Most smartdevices consist of two connection methods, WiFi and Bluetooth. Creating even more WiFi hotspots generate more pollution in the WiFi spectrum. Besides that, WiFi is much less focused on privacy. Bluetooth can be turned off if no tracking is required. Therefore Bluetooth is chosen as the main protocol.

At the time there was one manufacturer that was specialised in Bluetooth connectivity, Nordic Semiconductors. Still today Nordic is used in many many applications (for example, the Apple Tag). Also, Nordic offers a good value.

7.2 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 8: 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.

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].

7.3 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 percent improvement).
- 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).

After discussing the pro's and con's with Crownstone the final choice is fallen on a nRF52840. Important features are the possibility for Matter connectivity and having a larger flash memory. For the design the QFN48 package is chosen. In contrast to the aQFN73 package it does not have support for 5 V supply voltage. The QFN48 package is chosen because of the ease of soldering, with respect to the aQFN73 or WLCP package. This will make it easier to develop a prototype.

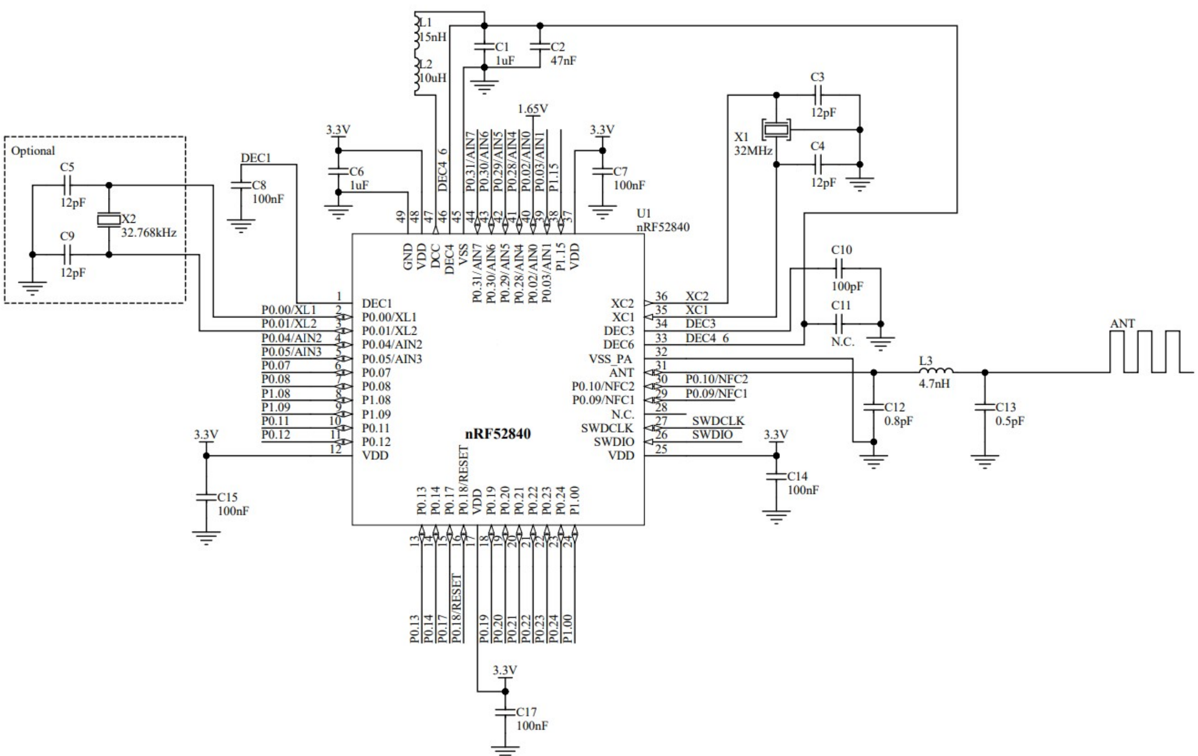


Figure 13: nRF52840 circuit

8 Power supply I

After doing research to the Rogowski coil, the conclusion is that inductive power harvesting is not an option at the moment. As an alternative a power supply with a direct connection to the gird will be used. In this chapter will be discussed how such a power supply can be designed. The power supply is divided into two sections, part I and part II. That's done because the two parts have there own separate hardware design and testing.

8.1 Research

The main purpose of the power supply is to convert a 230 V AC signal to a lower, for example, 5 V 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 - 253 V AC. The formula below states the maximum voltage:

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

So a peak voltage of 358 V 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 first 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. The biggest capacitors on the market having a high enough voltage rating and a low profile package have a value around the 100 nF. Circuits like a capacitor multiplier won't work because such a circuit isn't used to store electrons. So a full bridge rectifier has to be used but even then a relatively large filtering capacitor is needed. Overcoming the problem of having less capacitance isn't possible so a large ripple stays in the signal.

8.2 Requirements

The following requirements are additional for the power supply. These requirements ensures that this unit works well on its own. Each requirement will have a short description to point out why certain values are chosen.

REQ-PSU1 The output voltage must be 3.3 V with a maximum deviation of 5 percent.

The typical voltage of the nRF52840 chipset is 3.0 volts, but a 3.3 voltage is more common and easier to search components for. The maximum voltage the nRF can have is 3.6 V so a stable voltage is needed. In order to ensure the output voltage is stable, the voltage must not deviate more than 5 percent. This is a common value for voltage regulators so it's achievable and will be sufficient for most use cases.

REQ-PSU2 The chip must be able to deliver a current of 25 mA.

The average nRF microcontroller within Crownstone can take up to 16 mA of current. In order to work properly some safety margin is preferable on this value. Besides that, for this prototype it would be unfavorable if the other units will be disadvantaged by a shortage of current. But because the other units aren't expected to consume a lot of energy, so 25 mA would be sufficient.

8.3 Design

Given the very specific application of the power supply (small form factor, suboptimal components), 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 is. 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 a compact chip. Given the heat development and the preference for efficiency, only switching power supplies will be chosen (in some cases with a built-in or external voltage regulator).

Table 9 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 the focus points are. 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 mainly includes Mouser, Digikey and Farnell.

Table 9: Power supply I converters

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	-.–mm - 1.75mm	29.4mm^2

When selecting the best chip, one thing is important and that's the size of the design. Table 10 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 so it would be preferable when these can get eliminated.

Table 10: Power supply I converter choice

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 for the fact 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. All of the circuits are copied from the datasheets and aren't changed much.

8.3.1 LNK302

The LNK302 is a fairly simple buck converter with a SOIC-7 package. The output voltage is 5 volts. The output voltage is set to 5 volts.

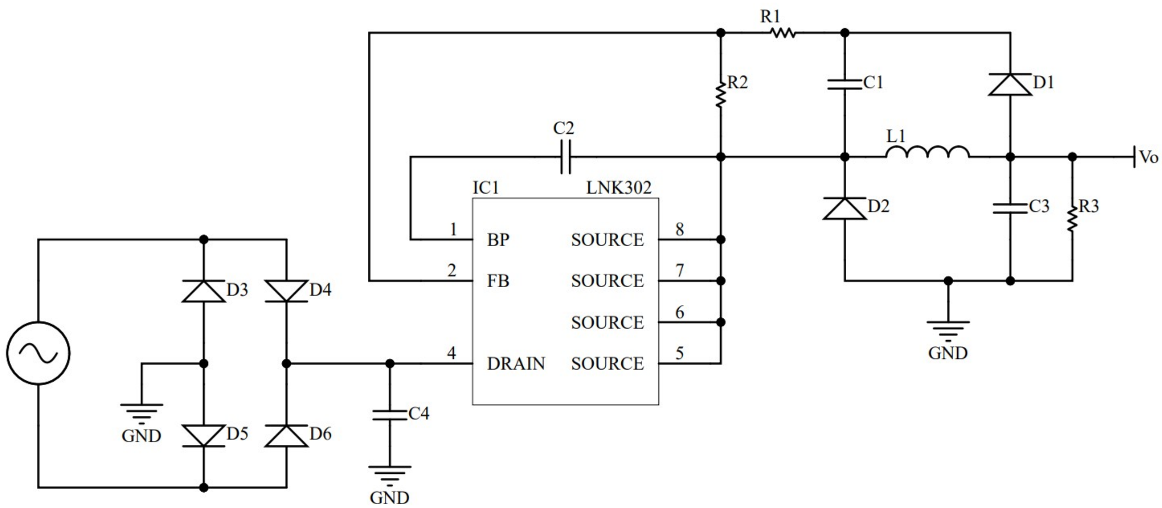


Figure 14: LNK302 circuit

Table 11: LNK302 component values

C1, C2, C4	100nF/400V
C3	10uF/25V
D1	1N4007
D2	UF4007
D3, D4, D5, D6	1N4007
L1	1mH
R1	2.2kΩ
R2	2.2kΩ
R3	1.6kΩ

8.3.2 MP158

The MP158 looks very similar to the LNK302. The output voltage in this circuit is set to 4 volts.

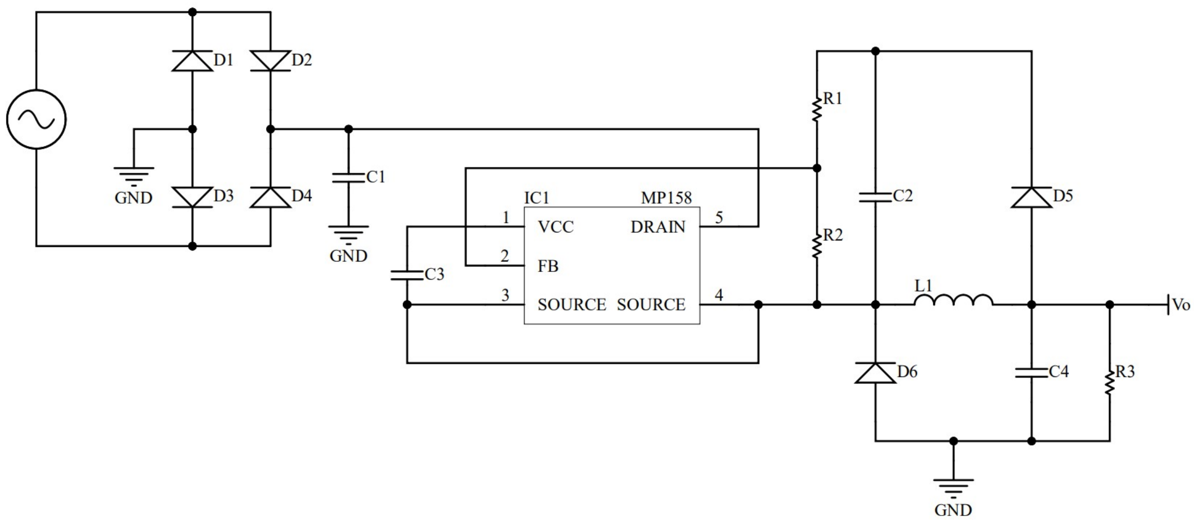


Figure 15: MP158 circuit

Table 12: MP158 component values

C1	100nF/400V
C2	100nF/400V
C3	1uF/50V
C4	10uF/6.3V
D1, D2, D3, D4, D5	1N4007
D6	EGC10JH
L1	1mH
R1	3kΩ
R2	5kΩ
R3	3kΩ

8.3.3 MP103

The MP103 is a unique approach of converting a high to a lower voltage. The circuit has an integrate LDO with a voltage of 5 volt.

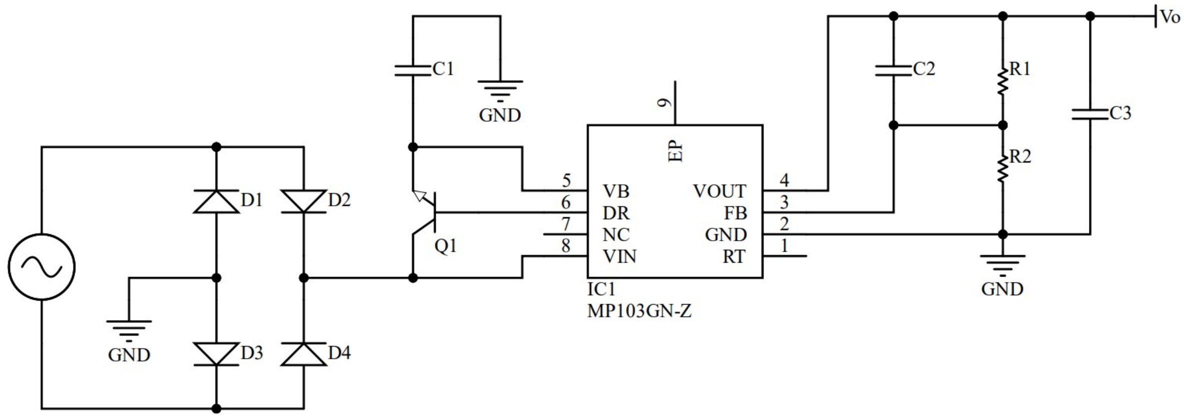


Figure 16: MP103 circuit

Table 13: MP103 component values

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

8.4 Testing

The focus for testing these chips is to get an indication of which chips perform good and which don't. This is not an extensive testing phase, only parameters that stand out will be discussed in this part. With the obtained information in this tests further research will be easier.

8.4.1 LNK302

In figure 17 and 18 the tests performed on the LNK302 can be seen. These tests are chosen because they deliver the most valuable information for this short test. The temperature is measure with a IR thermometer with a room temperature of 19.5 degrees. As can be seen is the behaviour of this chip very predictable. The temperature is constant and the voltage of the output gradually decreases when the load rises. Not ideal but the output voltage can be tuned to a higher value and with a voltage regulator the problem can be solved.

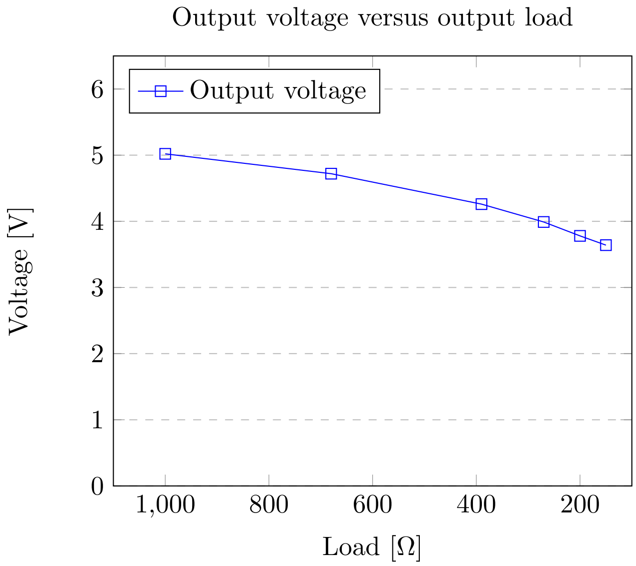


Figure 17: LNK302 voltage regulation

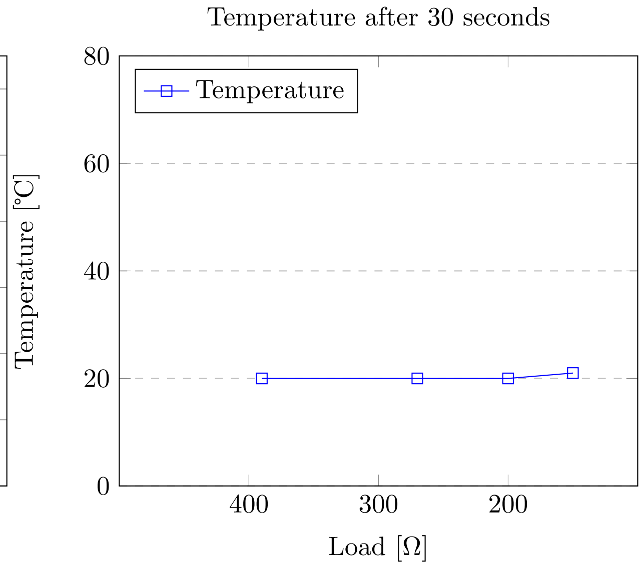


Figure 18: LNK302 temperature

8.4.2 MP158

After several attempts the MP158 is not working in this configuration. The 500 V internal mosfet is not protected enough when supplying it from the grid. Extra safety equipment can be taking into design considerations but this costs space. Due to the unreliability of this chip it is not a good choice for the final design and it is therefore not needed to test this chip on other aspects.

8.4.3 MP103

The test results of the MP103 can be seen in figure 19 and 20. The voltage output is very constant but drops on a certain point very hard. This is because of the low capacity capacitor that's used. When the load is too high the capacitor will drain faster than it can be 'filled' with energy. A bigger capacitor will solve this problem. The temperature of the MP103 is more noticeable, after a small period of 30 seconds the temperature raises to ridiculous values. The mosfet is the spot that gets so warm. Such temperatures are definitely not wanted in the prototype so this will not be an option anymore.

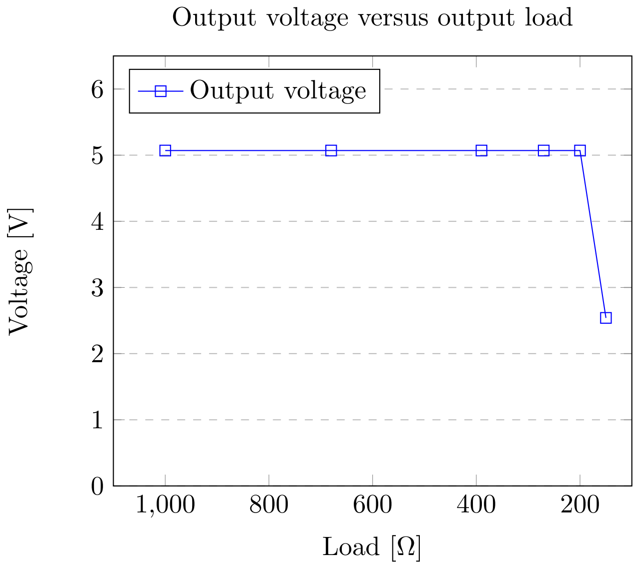


Figure 19: MP103 voltage regulation

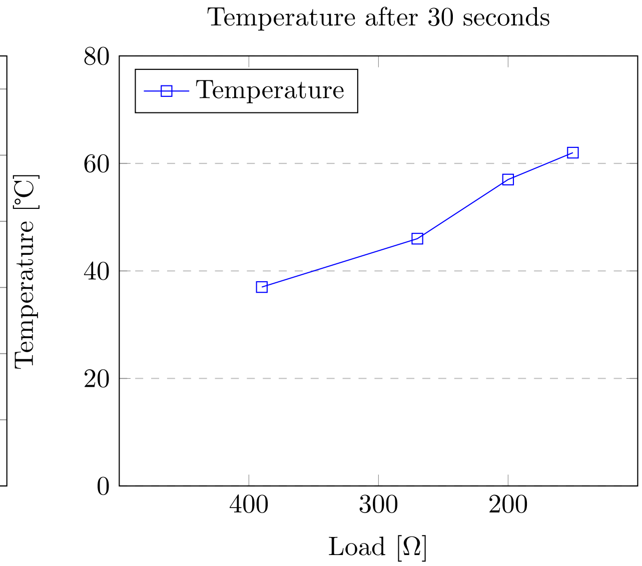


Figure 20: MP103 temperature

8.4.4 Conclusion

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. Because of the small place what the product is in and because of the thermal isolation of that location (because a plug will cover the Smart Outlet Tag entirely), high temperatures are not preferable.

9 Power supply II

This section is the second part of the power supply design. This part will focus on testing a few extra chip with the information gathered in the previous part. At the end of the section the final design will be chosen.

9.1 Requirements

For building a reliable design an extra requirement is made.

REQ-PSU3 The power supply must have a minimum absolute rating of 600 volts.

To ensure the power supply has 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. Rectifier diodes have voltage ratings of 1000+ volts and off the line voltage regulators mainly have a voltage rating of 700 volts. Capacitors generally don't go higher in capacity than 600 V or 630 V. Therefore a requirement is made to ensure there is a minimum voltage rating.

9.2 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 (sub 1.10mm) will be chosen. As seen in table 14 there isn't much choice. The table shows most of the common off line converters with a 700 V internal mosfet or higher.

Table 14: Power supply II converters

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 meet 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 the next test phase 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 components then others. But optimize each chip following the rules in the datasheet isn't fair either. If a chip has a much smaller output ripple in contrast to an other chip 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. The following list will sum up which components has to be the same.

- All diodes are the same.
- The inductor is the same.
- 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.)

The folowing components are case dependent and can be chosen to meet the circuits need.

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

One important thing to point out is when all the values are the same and a value isn't sufficient enough for the correct working of a chip this component should be fixed to work for all chips. 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. All the datasheets have formula's to calculate the most important values for the circuit. All these formula's are put into Excel sheets to compare the values with each other. THe results are shown in table 15.

Table 15: Power supply II components

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

9.2.1 LNK302

The datasheet stated that lower C1 values cause a poorer load regulation. But it also happens to be that at the standard capacitance (10 uF) the voltage ripple will be worse. Low values like 100 nF are too low and won't work either. After trying 1 uF circuit performs better so that value is chosen. The output voltage of the chip is set on 5 volts.

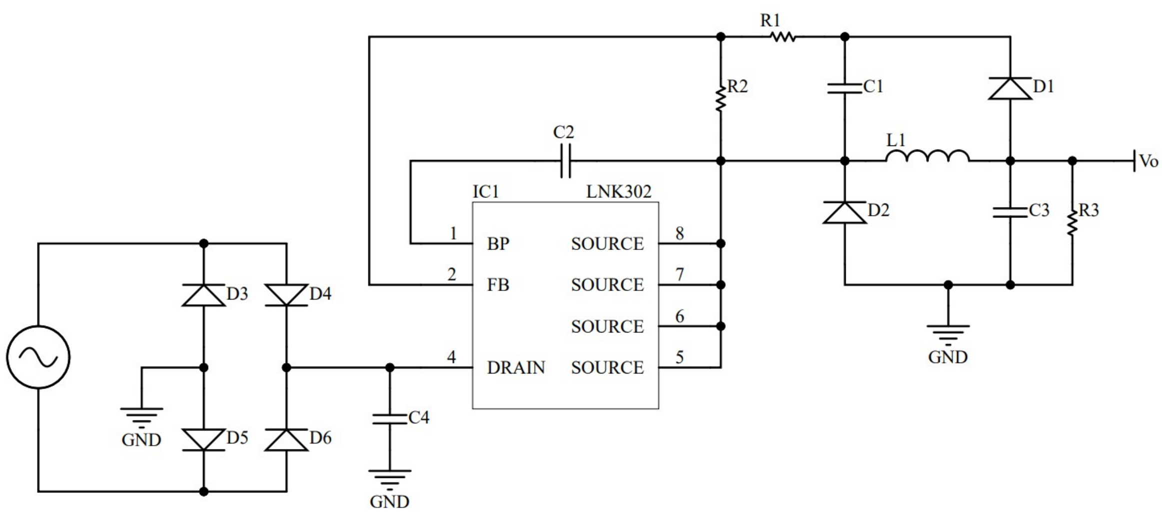


Figure 21: LNK302 circuit II

Table 16: LNK302 component values II

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

9.2.2 RAA223011

The RAA223011 is ordered in a SOT23-5 package. The output voltage is set to 5 volt.

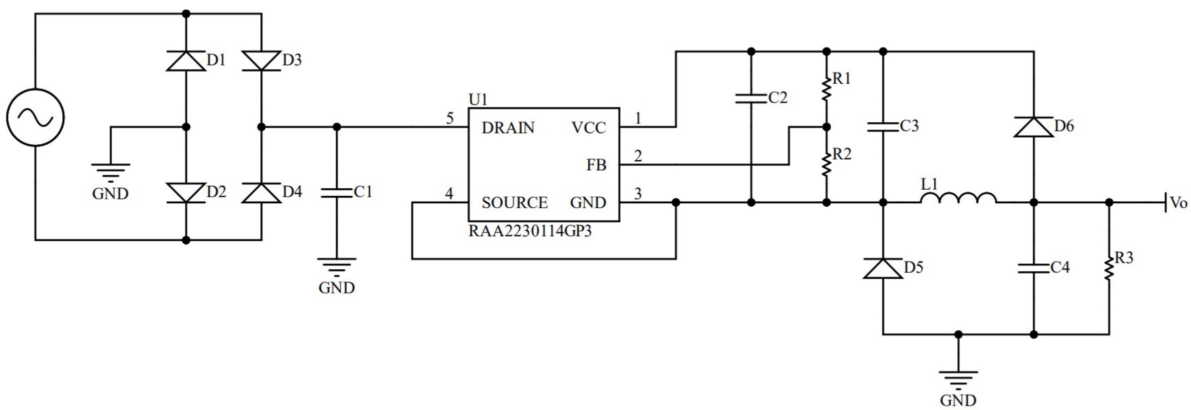


Figure 22: RAA223011 circuit

Table 17: RAA223011 component values

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

9.2.3 MP171A

For this test the MP171AGS-P in a SOIC-8 package is chosen so all components can be ordered by one company. The prototype on scale will use the MP173A because the MP171 and MP172 aren't available in a small package. The only difference between those chips is the maximum current output, but it should make no difference for the performance.

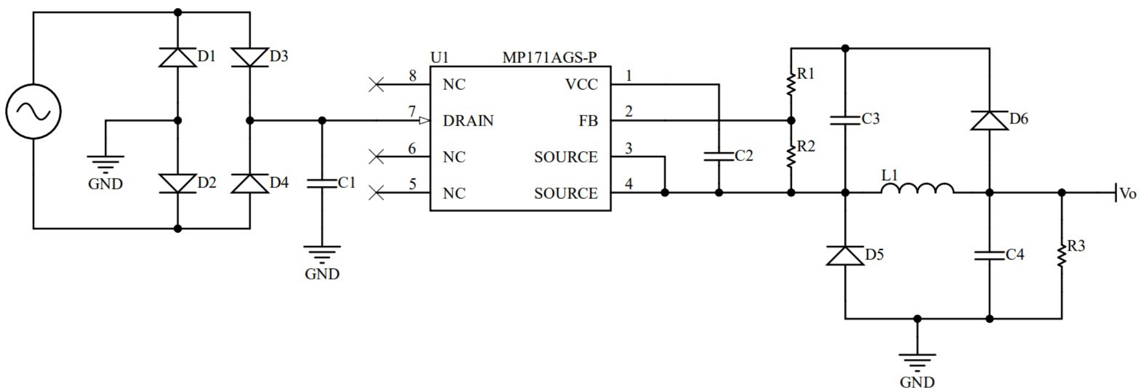


Figure 23: MP171A circuit

Table 18: MP171A component values

C1	300nF/400V
C2	2uF/25V
C3	100nF/50V
C4	10uF/25V
D1, D2, D3, D4	1N4007
D5	UF4007
D6	1N4007
L1	1mH
R1	10kΩ
R2	10kΩ
R3	1.6kΩ

9.3 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 appendix B. 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 frequency and normally voltage ripples are 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 chip. 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.

Table 19: Power supply prices

Part	Octopart price
LNK302	0.50 USD
RAA223011	0.81 USD
MP171A	0.93 USD

Table 20: Power supply pro's

Part	Pro's
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.

9.4 Voltage regulator

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

The regulator should have an output voltage of 3.3 V. Also, to reduce the ripple on the output of the MP171A needs to suppress the incoming signal with at least 65 dB at a frequency of 1.5 kHz. The output signal of the MP171A generally have a signal of 1.5 kHz. On the highest current consumption the voltage ripple is around 1.5 V, to reduce that to a 1 mV signal, the needed suppression is 65 dB.

For choosing a LDO regulator a low profile package (1.1mm) is preferable. Much of the available chips that have such a low profile are WLCP packages, for development not a pre because of the extra difficulty.

A chip that is easy to solder and meet the requirements is the TCR2EE33. The design of the voltage regulator have higher capacitors for better filtering but the circuit itself is identical to the circuit of the datasheet.

9.5 Conclusion

Figure 24 show the power supply design. At the output of the voltage regulator resistor R8 is placed. When the output is not stable enough, extra filtering can be added. Also with R8 the power supply circuit can be disconnected to supply the board with an other power supply. The diodes have a SOD-123 package because these are generally low in profile.

Resistor R4 is empirically chosen and is meant for limiting the current flow. Also when extra filtering is needed this resistor can also be swapped by an inductor.

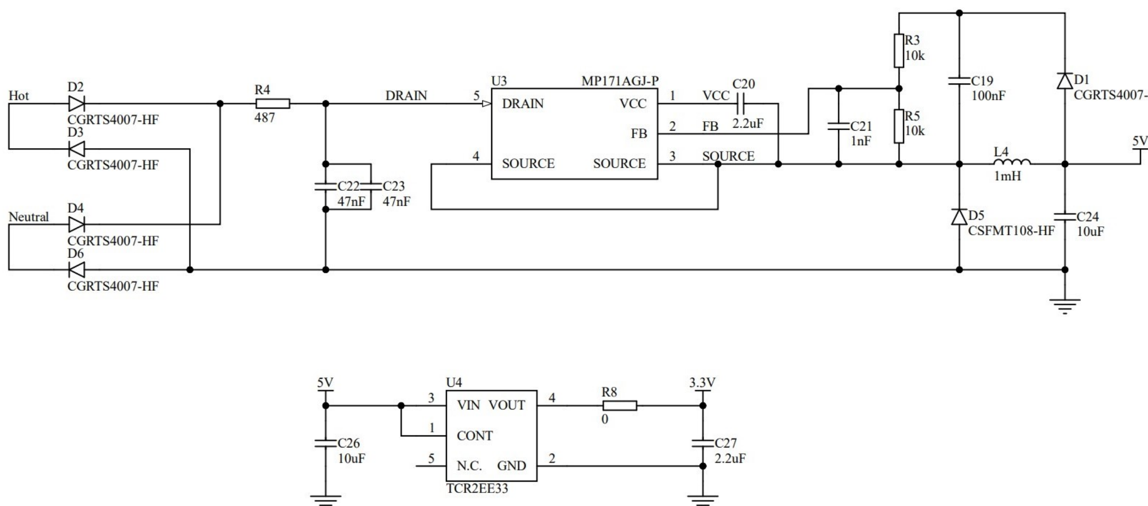


Figure 24: Power supply circuit

10 Current measuring

This part will have the focus on making an amplifying circuit to use the Rogowski coil as a current measurement tool. This section will go into the design considerations of an opamp and into the final design of the circuit.

10.1 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 smallest 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 resistance 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.

$$e_{n-Johnson} = \sqrt{4kTBR_1||R_{rog}} \tag{20}$$

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

Table 21: Amplifier specifications

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

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].

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

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 characteristics stated of the opamp.

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 10nV/$\sqrt{Hz}$ 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.

10.2 Requirements

These requirements are to test if the amplifying circuit can convert the current from the coil to high enough voltages. The requirements looks very similar to the project requirements but the goal here is to measure the output of the amplifier with an oscilloscope with FFT possibilities.

REQ-AMP1 The output of the measurement circuit contains a signal from a 10 A resistive load above the noise level.

If a signal can be detected above the noise floor then it can be used as a indication that there is a current flowing through the coil.

REQ-AMP2 The output of the measurement circuit contains a signal from a 1 A resistive load above the noise level.

If a signal can be detected above the noise floor then it can be used as a indication that there is a current flowing through the coil.

REQ-AMP3 The output of the measurement circuit contains a signal from a 100 mA resistive load above the noise level.

If a signal can be detected above the noise floor then it can be used as a indication that there is a current flowing through the coil.

10.3 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 need any specialized characteristics. It's better to have a opamp in a common package. When the opamp doesn't perform that well, it can be swapped with an other one 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.

When designing the PCB there was very little space. In order to fit everything the trade off is made to let one amplifier stage drop and use a dual package opamp for the reference voltage and for the amplifying stage. When searching for DFN-8 opamps with the previous calculated values, no opamp can be found. When dropping the gain a little bit, parameters such as voltage offset, GBP and noise are less important. When searching for a chip the LTC2051 stands out but this is also a very expensive opamp (6 EUR). This amplifier should be enough to test the performance of the Rogwoski coil an draw conclusions. Due to a fault an other opamp is ordered, the TSZ122IQ2T. The main disadvantage is the very low GPB, but in contrast to the opamp that's used in the research stage (TL074) this should perform still better. The current circuit 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.

This amplifier has a bandwidth of 400kHz, much lower than desired but at 50 Hz signals can still be amplified 8000 times. Higher frequency signals will be damped by this amplifier but because of the resistive loads higher frequency are for now less of interest. The amplifier has a maximum voltage offset of 8 uV so as calculated before this should be no problem. Because of the less gain, also less noise will be generated.

In the design in figure 25 a resistor of 22k is still used, this should be no problem because when a gain is too high, the opamp will amplify the signal on the maximum possible gain.

Capacitor C16 is placed if Crownstone ever wanted an active integrator (to correct the phase shift of the coil). R2 is placed for extra flexibility and has no use case right now. The rest of the circuit speaks for itself.

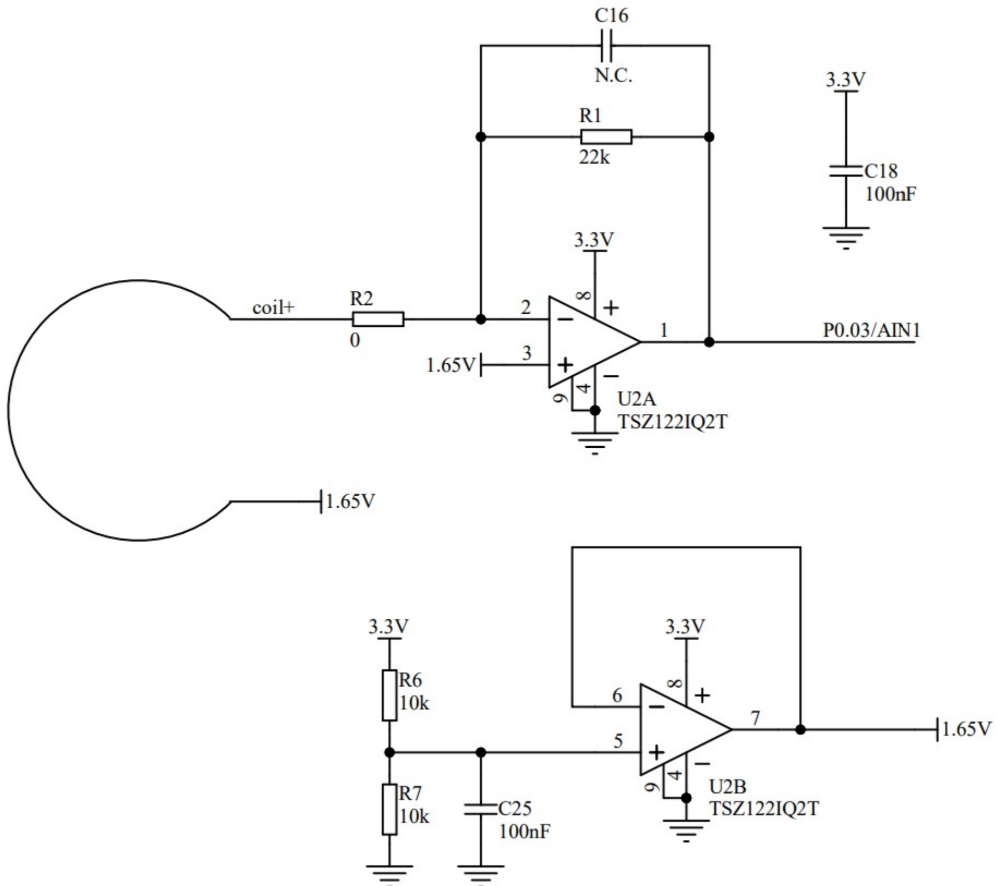


Figure 25: Current measurement circuit

11 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 book for the basic understanding of antenna's can be found here [18].

11.1 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 a transmission line, to the radiating antenna. The reverse happens when radio waves are received by the antenna.

The Smart Outlet Tag will use Bluetooth for communicating with other devices. 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 aren't reflected back to the source, the antenna needs to have a maximum VSWR of 2.5. This is also called the matching coefficient where 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 and chip antenna's are described. So radiating metallic plate antenna's are not included. Due to the changing environment of the antenna (Plastic case, imperfect ground plane, thin PCB, presence of a outlet plug). There is chosen to not use a chip antenna. For basic testing this is good enough but for a perfect antenna in this product a PCB trace antenna is the best choice. One important thing to note is that a chip antenna needs a specific layout. When no care is taken the specs of the antenna will differ. A PCB antenna also suffers from drastic changes to the ground plane design, but it can be tweaked in much more ways than a chip antenna. In short, a PCB antenna is more flexible and can be implemented in much more applications than a chip antenna. Also the dipole antenna's are not discussed because the nRF chips only support a single source.

- 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)

The easiest antenna designs consists of a standard monopole antenna. This is the simplest antenna to design and is the basis for other antenna designs. 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].

More advanced antenna's work in the basis exactly the same, the length of the antenna can be used to tune the frequency. But by a meander antenna design, the distance to the groundplane, the distance between the traces, the height of the trace all does impact the performance and the resonance frequency.

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.

11.2 Requirements

For testing S11, impedance and VSWR a standard vector network analyser can be suitable. Testing efficiency, radiation pattern and gain requires a more advanced test setup. Therefore only the S11 can be use full parameter for a prototype. [22]

REQ-ANT1 [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).

After doing research the following things are important to point out. [21] Over the total operating frequency the S11 parameter has to be less than -10dB.

REQ-ANT2 [SH] The VSWR or return loss needs to be less than 2.5 dB within the frequency range of the Bluetooth communicating protocol (2.4000GHz to 2.4835GHz).

11.3 design

Because of the difficulty of designing a meander antenna there is chosen to copy a prefabricated antenna design. Nordic Semiconductor has multiple development kits with there PCB design free for download on their website. The USB dongle for the nRF52840 has a small meander antenna on the 2.4GHz band that can be used for this design. Even the distance to the groundplane is important for the antenna, so the antenna design is copied one to one. For matching antenna a standard PI-network is placed in the design. With this network most common configurations of matching can be made, so afterwards matching will be possible. The used matching can be seen in the figure below.

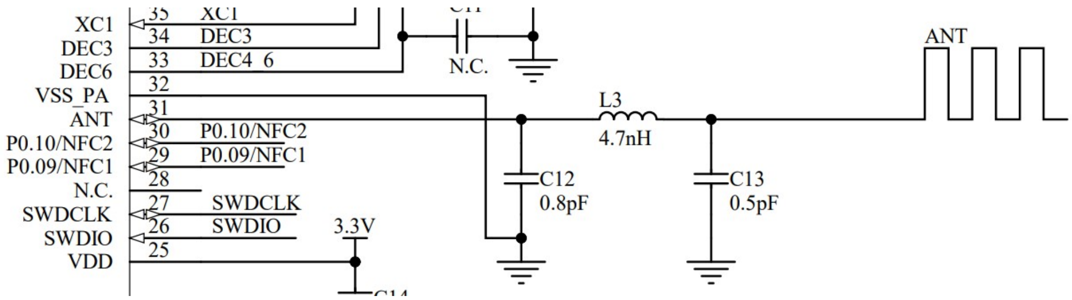


Figure 26: Antenna circuit

The transmission line is also an important part of the circuit and needs to be matched to 50 Ω. The thickness of the transmission line and the distance to the groundplane can be calculated using a Coplanar Waveguide Caculator (such as [23]). Also Altium Designer has an internal function to calculate the impedance of a given trace. On this design the calculated width is 0.24mm with a distance to the groundplane of 0.254mm. Important to notice is that short transmission lines, for example this case, don't experience a disadvantage as much as longer transmission lines. Also, the transmission line needs to have rounded curves and no sharp corners in order to prevent reflection.

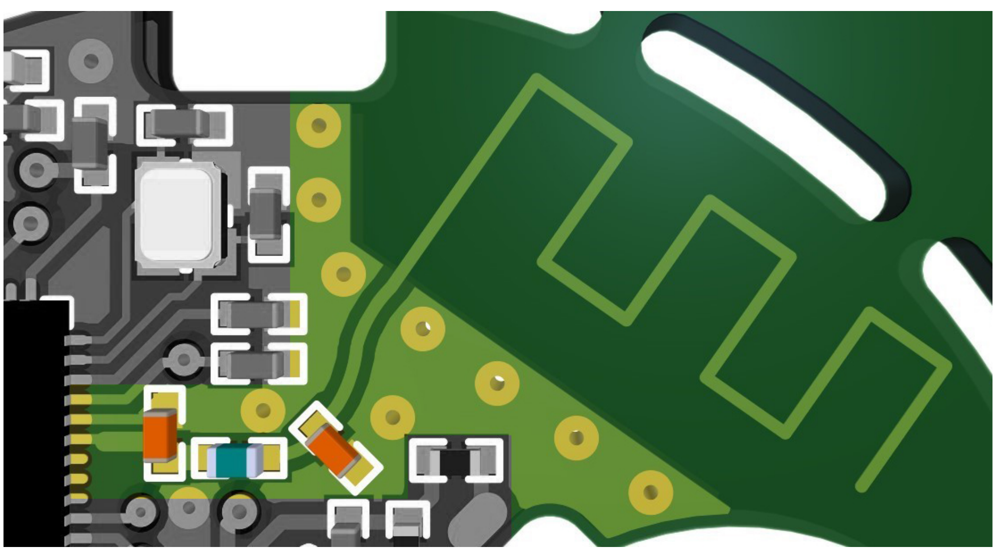


Figure 27: Antenna design

The via's around the antenna are important because they will ensure the ground is very stable at that point. The via's are connected to other ground planes so it will also be beneficial for the rest of the circuitry. Even when the ground is very stable around the antenna, the board has as specific layout with cutouts on different places. Due to the not ideal groundplane and limited space (normally an antenna needs a bigger groundplane) the matching circuit has to be tuned afterwards to compensate for this.

11.4 Antenna tuning

When testing an antenna is measured, care has to be taking in the process. By changing the test setup or environment, the test results can variate. For testing a VNA (Vector Network Analyser) is used, in this case it's a Nano VNA V2. The first step is to make a testboard with a SMA connector that can be connected to the VNA. The goal is to make the impedance that's seen by the VNA is equivalent of what the microcontroller sees. This can be done to solder the wires of the SMA cable direct to the RF pins on the PCB. It's important to notice that the ground shielding around the SMA cable needs to stay as long as possible around the signal wire. When not doing this, the signal wire is going to radiate on it's own and makes a little antenna. In the figure below the used test setup is shown.

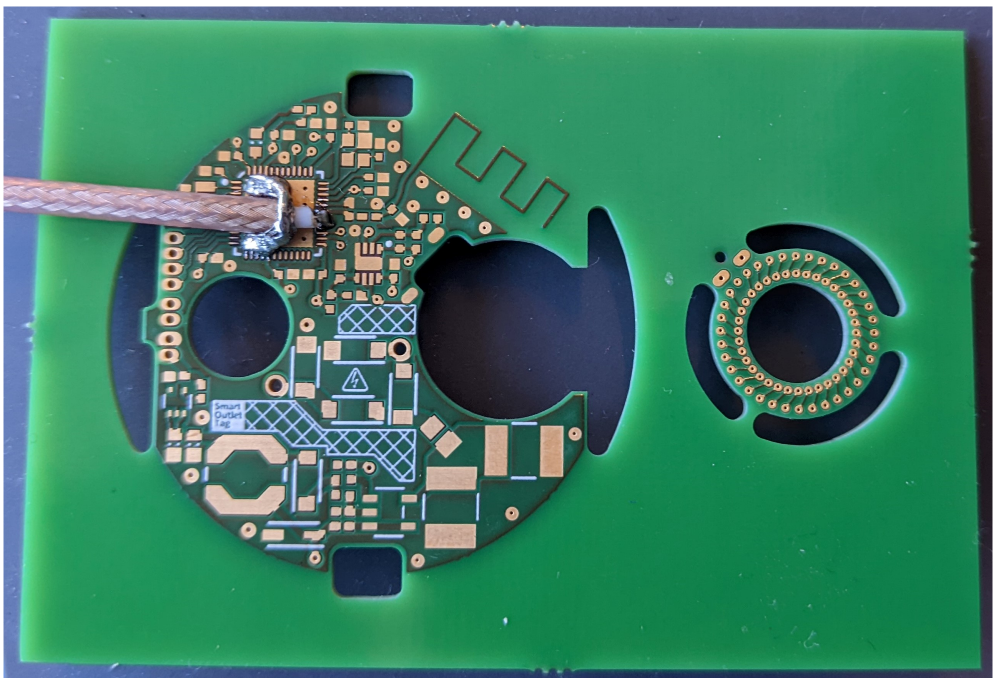


Figure 28: Antenna test setup

Be aware when measuring an antenna the VNA is fully calibrated to the test board. When not doing this the measurements are not valid. In short the VNA can be calibrated in 3 steps by measuring different resistances; An open connection (∞ Ω), a shorted connection (0 Ω) and a resistance of 50 Ω. These resistances can be placed on the laying SMD pads. When the VNA is calibrated, the inductor to the antenna is shorted to measure the impedance. This impedance is also called the S11 parameter and is displayed as a smith chart.

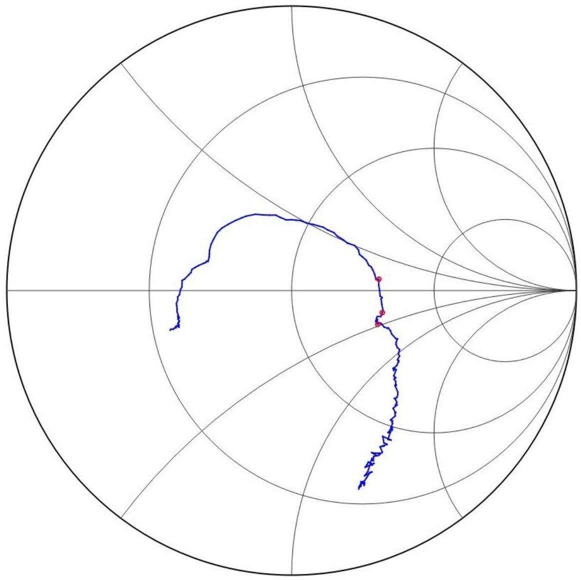


Figure 29: Antenna without matching

The 3 red dots represent the 3 important frequencies of the antenna (2.4, 2.44 and 2.483 GHz), where 2.44GHz is the dot in the middle of the three. The antenna is going to be matched to that frequency. The current impedance of that frequency is 94.80 -j16.48 Ω. Using software on the internet (such as [24]) the needed matching circuit can be determined easily. Keep in mind that the black box (starting point) is the antenna, and that the viewing point of the matching circuit is from the antenna to the microcontroller.

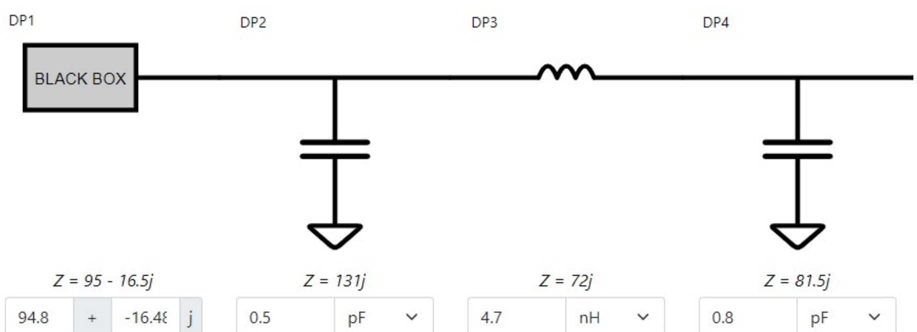


Figure 30: Antenna matching circuit

The easiest way is to use an online smith chart tool to match the antenna really close to 50 Ω but due to differences in the real world the VNA is used to tune the antenna perfectly. When filling in the standard matching circuit for this antenna type, the smith chart looks as followed when comparing the same matching circuit with the real world.

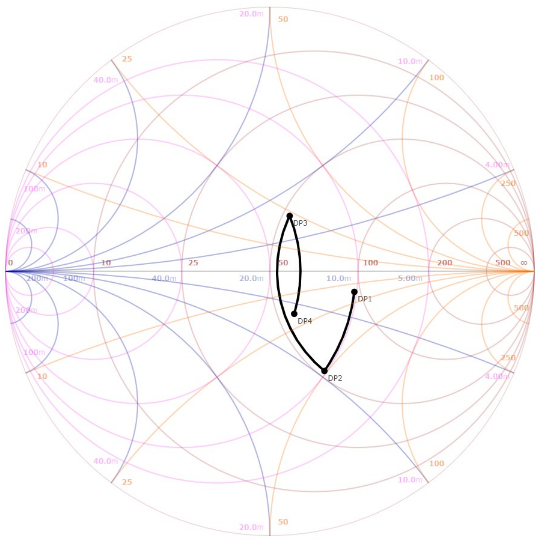


Figure 31: Smith chart simulation

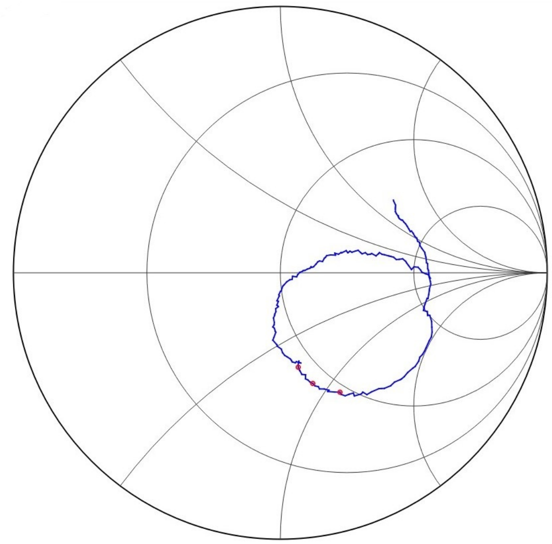


Figure 32: Smith chart VNA

After all the perfect fit is a matching circuit with a 0.5pF close to the microcontroller and a 0.8pF next to the antenna (the inductor stays the same). In the figure below the final matching can be seen. The middle red dot is close to the middle of the smith chart so there can be said that the antenna is impedance matched well.

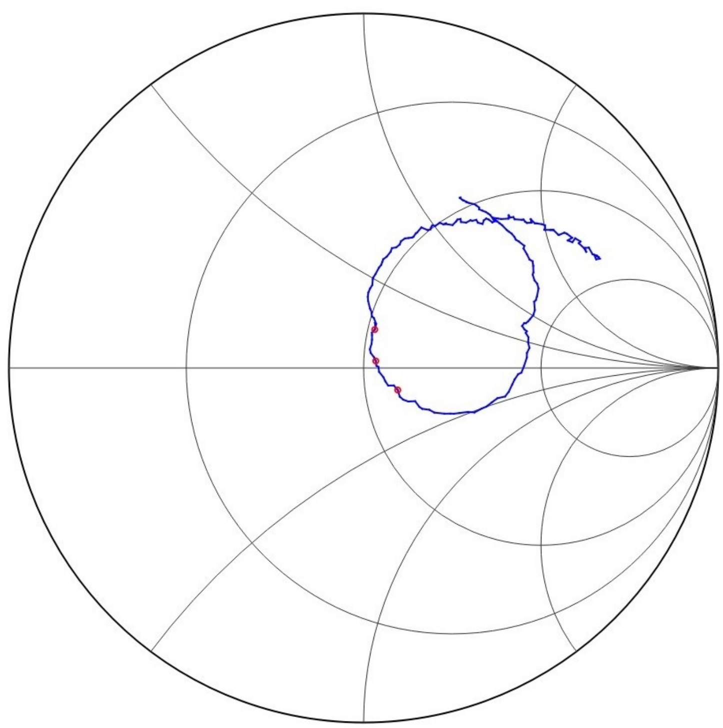


Figure 33: Antenna final matching

Keep in mind when developing a plastic enclosure for the device the previous steps have to be repeated. Because there is currently no enclosure developed, matching for the end product can't be done.

12 PCB design

In this section a few important steps of making the PCB are described. Figure 35 Show the final PCB design.

12.1 Rogowski coil

In contrast to the previous developed Rogowski coil this coil is a little bit smaller. That's because extra margins for a plastics enclosure are taken into account. So can the size of the PCB variate a little bit, and the same goes to the enclosure. The inner circle is a little bit larger, so the distance from the middle of the coil to a via is larger. The distance from the middle of the coil to the inner via is 4.2 mm and 5.501 mm to the outer via. But because of that there is more space for turns, in this case 36. The idea of the Rogowski coil is to have it as a component on the main board. When a version with a thin PCB is done, the Rogowski coil cannot shrink in size because this will limit the performance. In the best case the Rogowski coil will have a height that's the same as the highest part on the board. To test the idea of having the Rogowski coil as a part, the coil is made separate on the PCB. With connection pads and pink wire, these boards can connect with each other.

12.2 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 [25]. 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 [26].

12.3 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.

12.4 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.

12.5 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. Besides that, a thicker track has less resistance so there is less heat dissipation.

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.

12.6 Pinout

The used pinout in this project can be seen in figure 34.

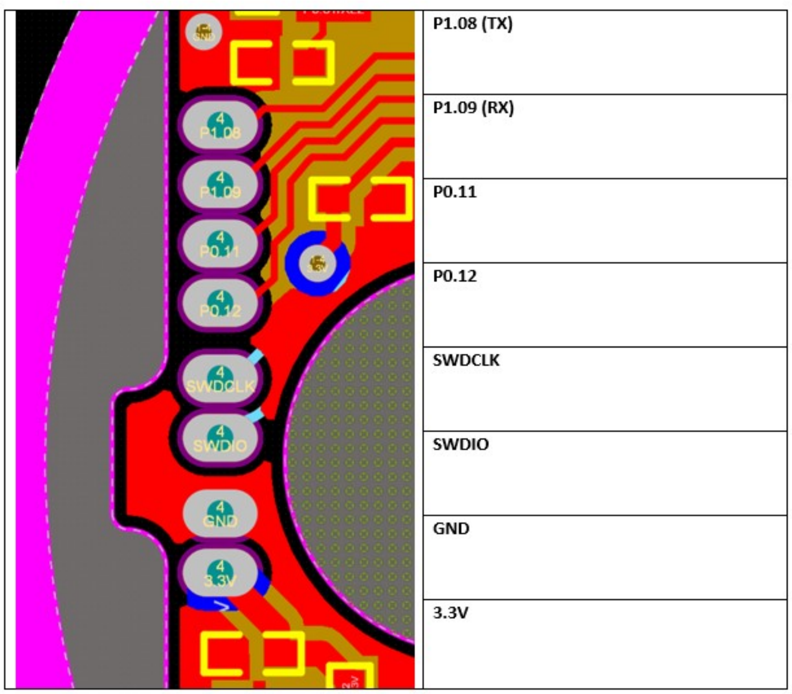


Figure 34: Smart Outlet Tag pinout

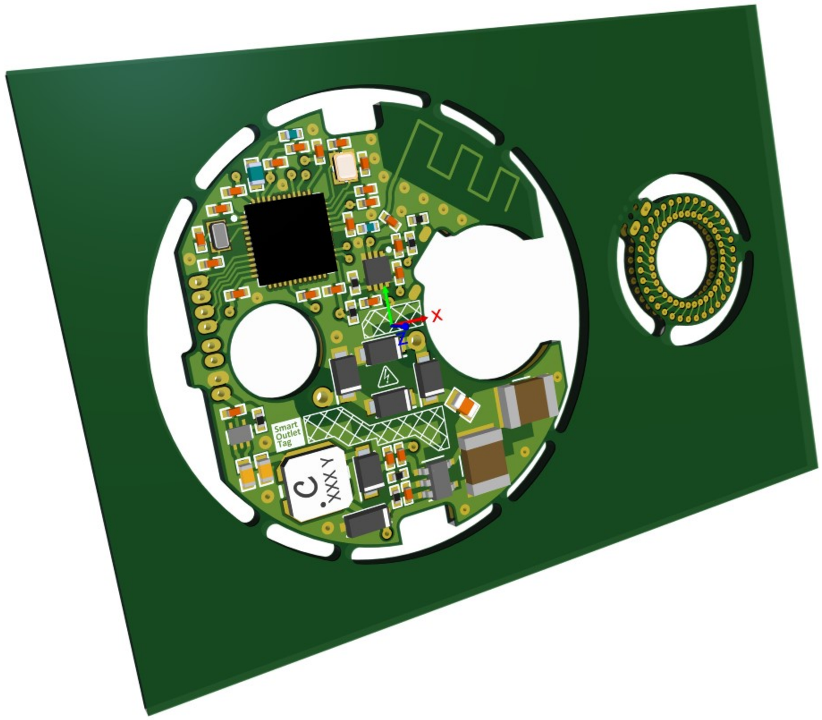


Figure 35: PCB 3D-model

13 Testing

All the unit tests and acceptation tests are described in appendix C and D. This part will focus on testing the product to check whether the requirements are met or not.

13.1 Software

The firmware that's running on the Smart Outlet Tag is the same firmware as the other products of Crownstone. The main goal was to test as fast as possible due to limited time. The software is therefore mostly the same to the original, only critical values were changed to get the firmware working. One important thing to notice is that the firmware is running on an ADC amplification of $\frac{1}{6}$ which is lower than desired. Besides that, the signals can be read in the Crownstone app but it only has buffer of 20 ms so the maximum that's visible is one 50 Hz cycle of the grid.

13.2 Test setup

The following test setups are used to test the requirements.

Test setup 1

For test setup 1 the following thinks are needed.

- A variac that is capable of tuning the output voltage between 207V and 253V AC. For safety always put the voltage to 0 volts before turning on the variac.
- Cables that can be plugged into a variac and clips on the ends to connect to the power input of the Smart Outlet Tag. See figure 36.

- A smartphone with a configured Crownstone app and a Bluetooth intensity meter (such as 'Bluetooth Intensity').

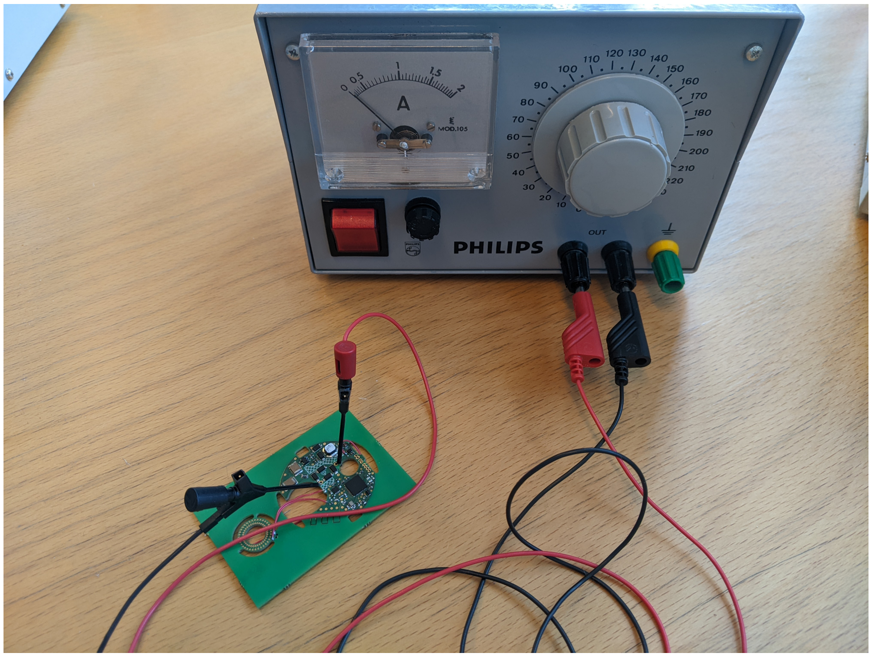


Figure 36: Test setup 1

Test setup 2

For test setup 2 the following thinks are needed.

- A cable with a plug and a socket where the wires can be disassembled. One of the wires needs to go through the coil of the Smart Outlet Tag.
- A power meter plug that can measure current.
- A power strip to connect multiple devices.
- Different resistive devices (such as old lamps and heating devices). The point of these different devices is to generate a variety of current flows though the cable.

First the power meter is plugged into the outlet, then the cable that goes through the Smart Outlet Tag. After that the power strip is connected where the different devices can be plugged in. See figure 37 for a overview, note that the resistive device are missing.

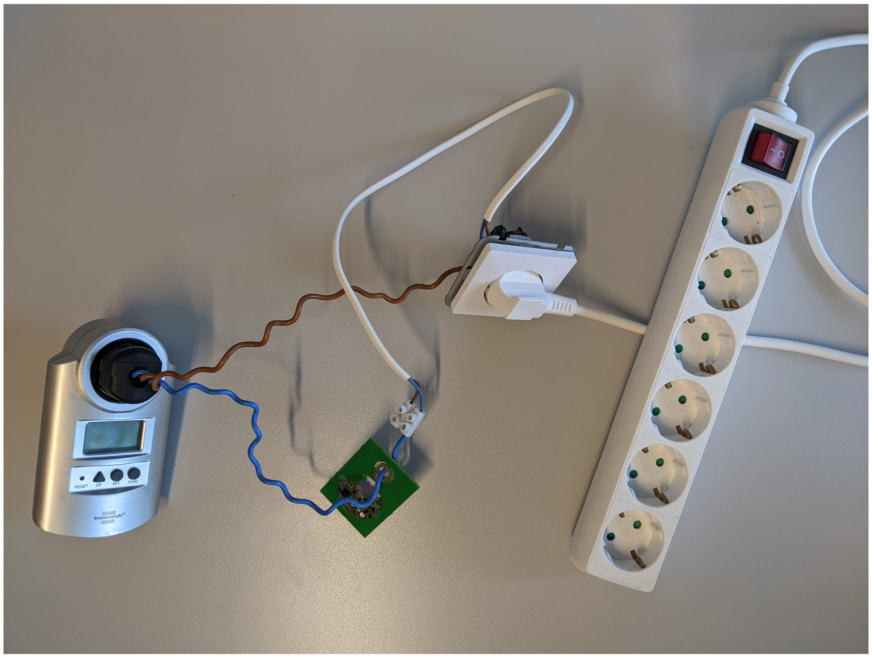


Figure 37: Test setup 2

13.3 Test results

In the table below is a quick overview of the tests that did pass and did not pass.

Table 22: Passed unit requirements

REQ-PSU1	Yes
REQ-PSU2	Yes
REQ-PSU3	Yes
REQ-AMP1	Yes
REQ-AMP2	Yes
REQ-AMP3	No
REQ-ANT1	Yes
REQ-ANT2	Yes

Table 23: Passed requirements

REQ-F1	MH	Yes
REQ-F2	MH	Yes
REQ-F3	MH	Yes
REQ-F4	SH	Yes/No
REQ-F5	CH	No
REQ-NF1	MH	Yes
REQ-NF2	MH	Yes/No
REQ-NF3	MH	Yes
REQ-NF4	MH	Yes
REQ-NF5	SH	Yes
REQ-NF6	SH	Yes

13.4 Conclusion

The most unit tests did pass but one important thing to notice is the output of the current measuring circuit. When compared to the research the signals are much lower in amplitude and thus much lower currents can be measured. The final coil is a little bit smaller but also have more turns. This is important to do some research to because this is an important part of the device. Right now it's unclear what the problem is and due to time constraints this have to be researched later on.

14 Conclusion and discussion

This last section will discuss the conclusions of the project and there will be some recommendations.

14.1 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 this is not possible and an alternative way has to be chosen. The generated energy is around hundreds of pico Joules which is too less to power a microcontroller for a sufficient amount of time.

To power the system a direct connection is chosen. This is in the form of an offline regulator that can convert the AC voltage to a lower 3.3 V DC voltage. The output voltage is stable and doesn't have large voltage spikes. The total peak to peak voltage is sub 100 mV which can be seen as a stable output.

Most of the requirements are met. The requirement of measuring a 100 mA current signal is not met. The Rogowski coil in the research was able to measure signals with a FFT of sub 100 mA. The final Rogowski coil with measurement circuit performed worse. The coil is a little bit smaller but the opamp has way better characteristics. Due to time limits there was not enough time to research the cause of this problem. Future work should focus first on understanding why this does occur.

The antenna performed really well despite there was no perfect ground plane for the antenna. The maximum distance measured with the antenna was around 25 meters what can be seen as a good range. When further development has taken place and an enclosure is made the antenna needs to be tuned again. So the antenna circuit is only a temporary solution.

The board space of the PCB turned out to be exactly enough. No more circuits or extra features can fit in the design right now. It was also possible to find the necessary components to make a prototype this thin. Only one part was larger than allowed but this was because of the chip shortage, later on the larger chip can be swapped with a smaller one.

Right no its unclear what the performance should be of the system because the written software is just for testing and not for getting the output values perfect. When later on a FFT is implemented in the system there can be said more certainty what the actual minimum current is that's possible to be read by the system.

14.2 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).

If the direct way of supplying the system will stay in the design it is important to research the possible ways of making a mechanical connection. Right now the AC outlet pins are on a location that maybe not can be used. When proposing a mechanical design the PCB design can adapt to this and check whether it's possible or not.

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A User requirements

Introduction

All the requirements below are formed by discussing the features with Crownstone. Each requirement is researched on feasibility.

User requirements

The microcontroller needs to be a nRF52832 or nRF52840 from Nordic Semiconductor. It should be no problem to implement one of these chips.

The system must be able to communicate with a Bluetooth connection to scan and mesh data. A device on a 20 meter distance should be able to make a connection without any obstacles. To establish a connection with a Bluetooth device the receiving device needs a signal strength of at least -100dBm. Following the information on the Bluetooth.com website. A 20 meter range is a normal range, and most device achieve this distance so this has to be possible.

The device must be able to get powered directly from the outlet, regardless of whether there is a plug in it, or in an inductive way. Since there is no mechanical design yet, it is still unclear what is possible in the field of powering the device. This falls outside the scope of this project, so preconditions must be taken into account. Powering the product can be through a direct connection to mains voltage or with energy harvesting using a magnetic field that's created by a connected device. There are two possible scenarios:

Scenario 1 There is a plug in the socket; The energy can be obtained from the grid or in an inductive way.

Scenario 2 There is no plug in the socket; Energy can only be obtained from the grid.

In both cases the product works as long as there is a direct connection to the 230 V AC, so this always works. However, this creates a mechanical challenge to make this connection. An inductive way of feeding avoids these obstacles. By conducting research, it can be determined whether it is possible to harvest energy. However, the research that has been done shows that it is currently not possible to harvest energy inductively, which is why a direct connection to the grid has been chosen.

The product must fit into a Schuko socket with a thickness of 3mm. A Schuko socket is also called CEE 7/3 for the outlet and CEE 7/4 for the plug. In the report is described what the thicknesses of the components needs to be and what the measures are.

The design must comply with CE/NEN. The CE marking is a standard mandatory sign to be allowed to trade products in the EU. To comply with this standard, a test report is required demonstrating that the product is safe to use. This cannot be seen as a requirement as it does not relate to the functionalities of the product.

The NEN is the Dutch institute for standards. These standards are behind a paywall and are therefore more difficult to comply with. This cannot be used literally as a requirement. Requirements must be concrete, so the specific NEN, if they are discussed, will be named in the report.

The design must comply with Dekra/VDE. These are stricter standards to meet. Dekra and VDE are institutes that test products and provide them with a quality mark. This wish is quite heavy and difficult to fulfill. This is not yet important for a prototype.

The system must be able to communicate via UWB. Ultra Wide Band is a new way of communication. Until now, it is supported on few smartphones, but in the future this technique could lead to a much more accurate way of determining location. Housing the UWV protocol requires an extra chip in the product. In order to guarantee the feasibility of the project, this requirement is not included for now.

The system must be able to communicate via NFC. A possible expansion of NFC makes it possible to implement plugs with an NFC chip. This allows a plug to transmit certain information that may be of interest. An NFC antenna can be easily implemented because the nRF528xx series already has a connection for this. However, it only costs extra space and time. In order to guarantee the feasibility of the project, this requirement is not included for now.

It must be possible to measure the power consumption of a connected device inductively. The power consumption of a connected device can reveal information about the activities within a room. According to Crownstone, this has the highest priority of all extensions. The lower the currents that can be measured the better. To test this different milestones can be set with each milestone has a lower current that can be measured.

The design should not adversely affect the current functionality of the outlet. This wish is too broad and must be split into several requirements in order to remain concrete. At the moment, however, it is still difficult to estimate which things impair the safety of the socket.

The product must be robust and can often be plugged in/out of a socket. The student has little or no experience in designing a solid mounting mechanism. This wish is therefore difficult to fulfill within this time period. If a fastening mechanism is being worked on, it cannot be expected from an electrical technician that it is of quality.

The mounting system must be able to work with sockets from recognized companies. This includes companies such as Gira, Niko and Busch Jaeger. As stated before, the student has little knowledge about attachment mechanisms. Making a prototype at all would be more than enough. Meeting different brands and types of sockets is too difficult.

Remember the time in the event of a power failure. This is a customer wish as soon as enough time is left. It is possible to put a battery in the product, but there will be very little space available for that. This requirement is not included in the final product for now.

The product must be able to be programmed with J-Link. For programming the product, connections must be available to which a J-Link connector can be connected. This includes a SWDCLK and a SWDIO connection. Since the nRF528xx series has these connections, this should not be a problem.

As soon as the device is plugged in, an external programmer must be able to make contact. In particular, a galvanic isolation should be considered, so that the two separate units are electrically separated from each other. But because this costs space and because ready-made modules can be purchased, this is not a requirement of the product itself. Segger sells modules that can galvanically isolate the J-Link, this is called a SWD Isolator.

A lifespan of 7-8 years would be nice. The reliability of the product can be taken into account. The component choice will be tailored to this wish, but this cannot reasonably be tested.

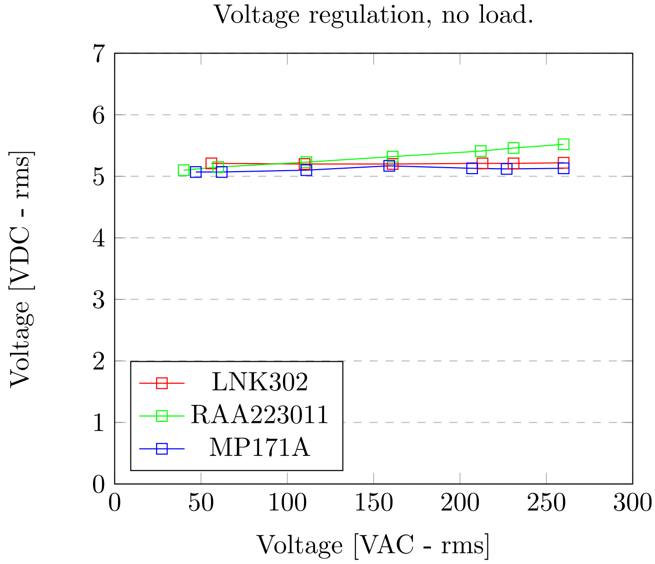
The cost of the finished product may be the cost of a Crownstone divided by 5. This will only include the pricing for the electrical part, not the plastic enclosure. For a fair evaluation only prices for 1000 pieces will be used. The cost of a Crownstone is 45 euros so the end price should be no higher than 9 euros.

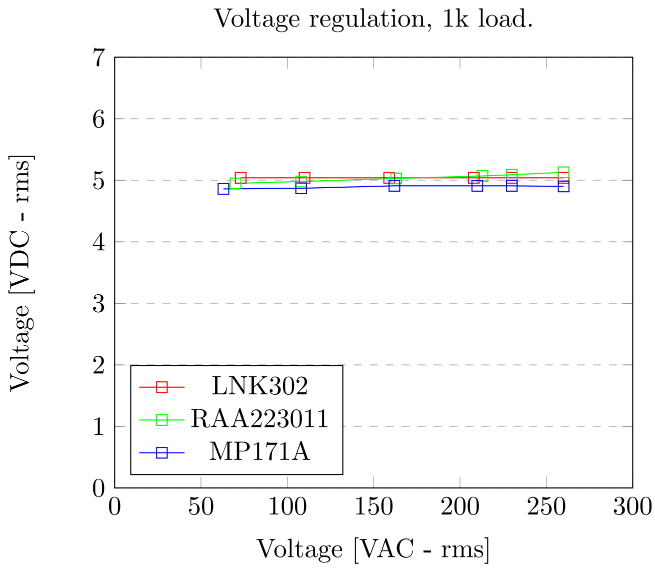
The system must be as energy efficient as possible. The relevance of this requirement depends on whether the power will be inductively or directly from the mains. The total power consumption is small, most of the energy will be lost at the power supply or the nRF chip (depending on what the chip is doing).

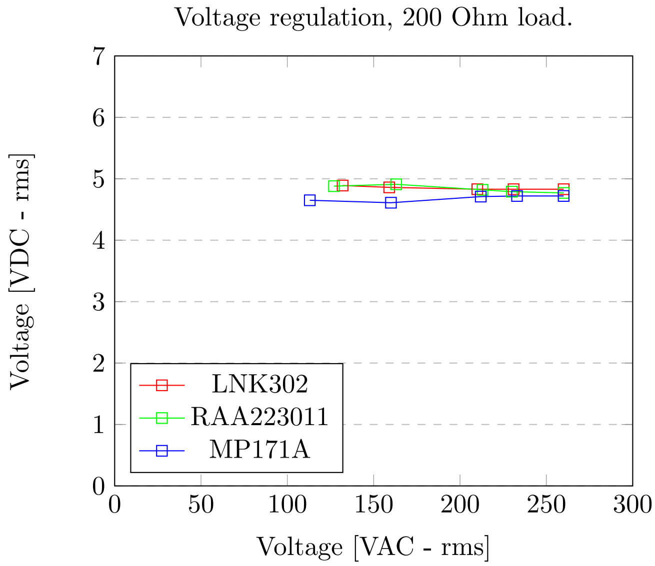
As many test pads as possible for debugging capabilities. For easy of debugging extra pads for testing is always useful, but it's more a tip than a requirement. For ease of developing an UART connection can be handy. So that's a useful extra feature.

B Power supply testing

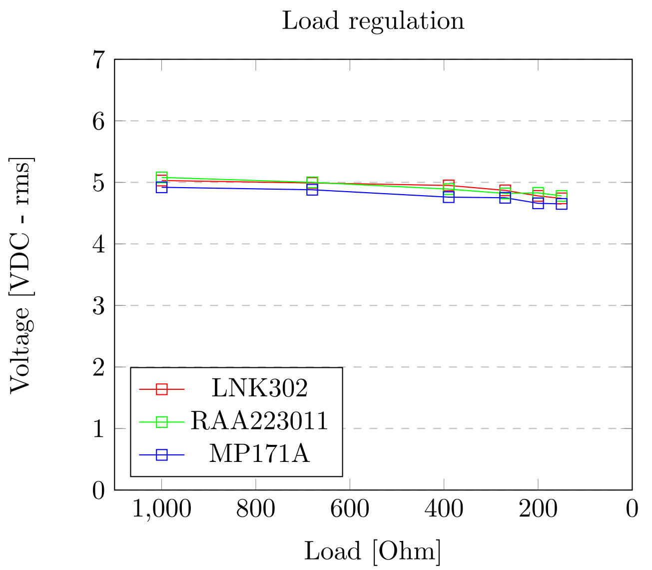
Voltage Regulation The following tests are performed with a variac that has a AC voltage range from 0V to 260V. All chips are tested from their minimal working voltage to the maximum of the variac. A chip is marked as working when a constant output voltage is obtained and the chip is not shutting down due to too less voltage.



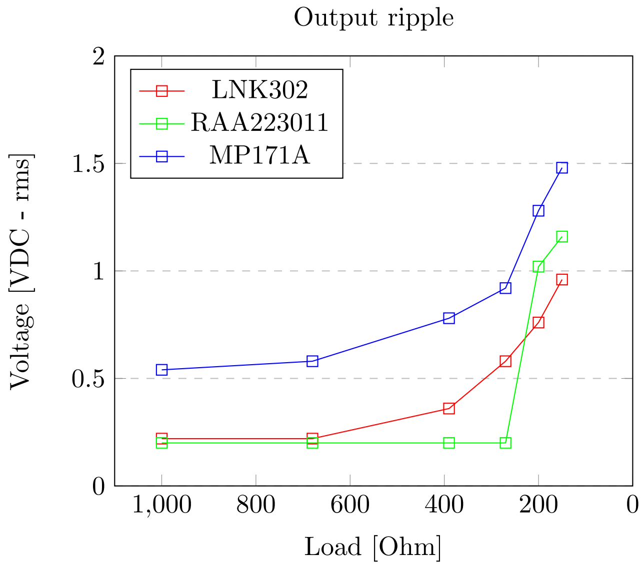




Load regulation This test is done with a constant input voltage of 230V AC and a varying resistance. The resistor values vary from 1kΩto 150Ω. The requirement is set to 25mA output current, but with the lowest resistor value also a heavier load can be tested.

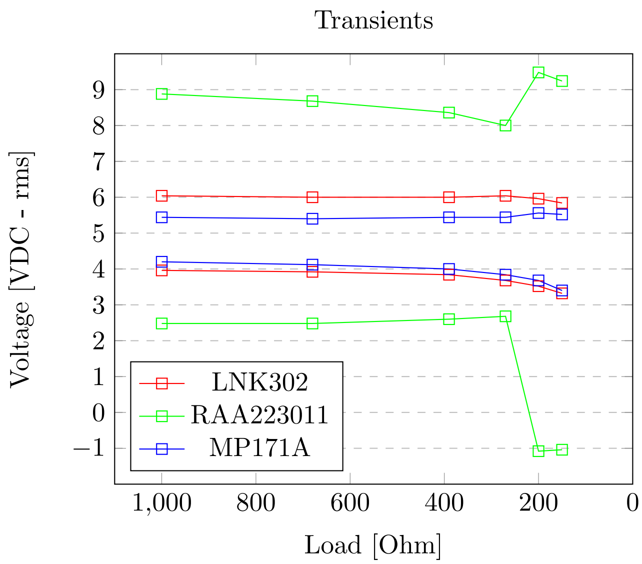


Output ripple The output ripple is measured with a 230V AC input voltage and different resistors. This test has the focus on the continuous ripple on the output. In other words, due to the feedback and the time constant of the regulator a sine or triangle waveform can appear on the output. The total output ripple voltage is measured from the lowest continuous voltage to the highest. This voltage is plotted down below.



For the MP171A and the LNK302 the output voltage ripple mainly has a frequency of around 1 to 2 kHz.

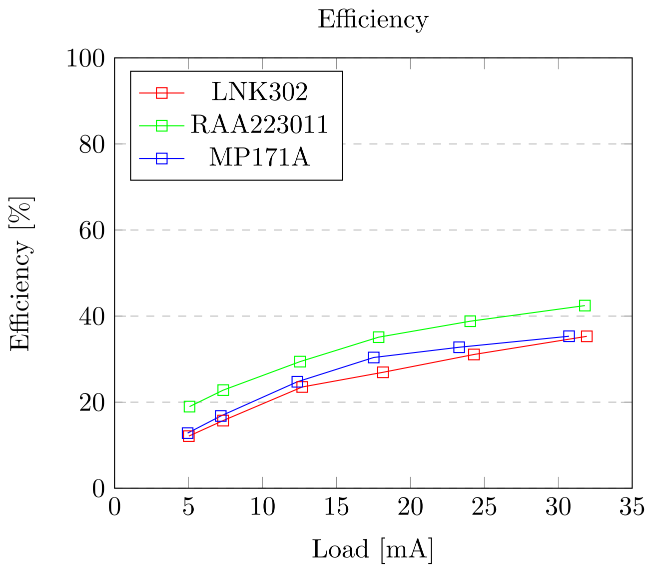
Transients In contrast to the previous test, this test focuses on the non-continuous wave forms. So rapidly changing spikes are captured in this test. The input voltage is a 230V AC voltage and the load resistance will vary. This test is done with a trigger set on falling or rising edge. A positive voltage spike (relative to the rms voltage) can get measured by setting the trigger to rising edge, setting the trigger to a high voltage and slowly decreasing the voltage. When trigger gets triggered, a voltage spike has been detected and that voltage will be written down as the maximum voltage spike. The same process will be done inverted with a negative voltage spike.



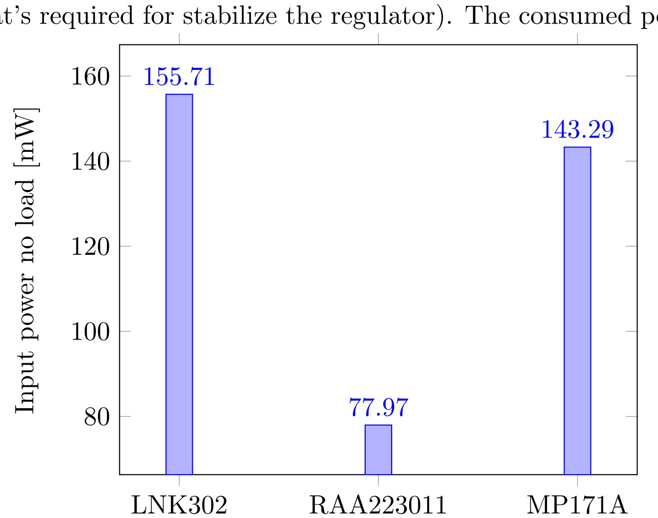
For extra insight the largest spikes are measured down below. The amount of energy a voltage spike has says something about how easy the spike can be eliminated. The energy is calculated by integrating the voltage over the given time period. For this calculation an assumption is made that each spike has the waveform of a perfect triangle.

Part	Voltage	Time	Energy
LNK302	1.4V	8 ns	39.2 pJ
RAA223011	6V	10 ns	900 pJ
MP171A	1V	7 ns	17.5 pJ

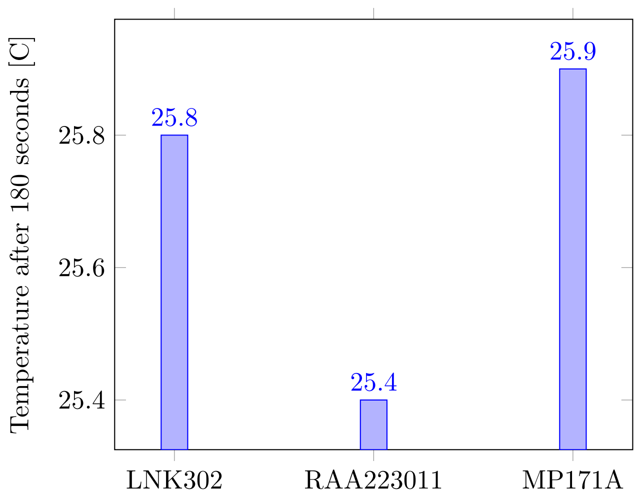
Efficiency This test is done with a input voltage of 230V AC and varying output resistors. By measuring the input and output current with a multi meter, the efficiency can be determined.



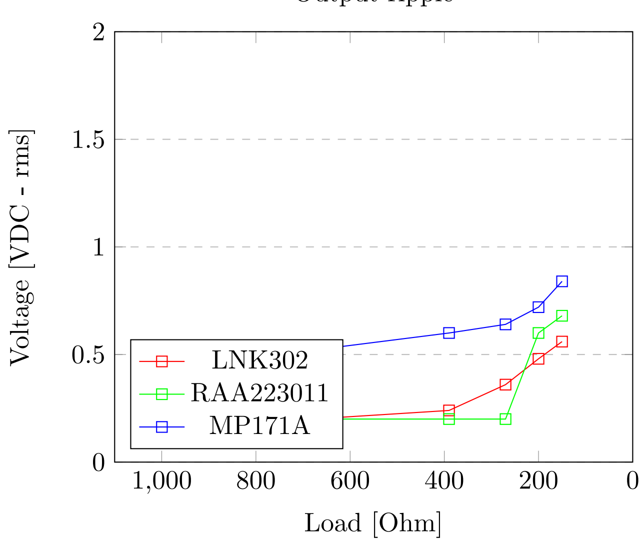
No load power This test is done with a input voltage of 230V AC and no output load (only the load that's required for stabilize the regulator). The consumed power is measured by a multi meter a the input.

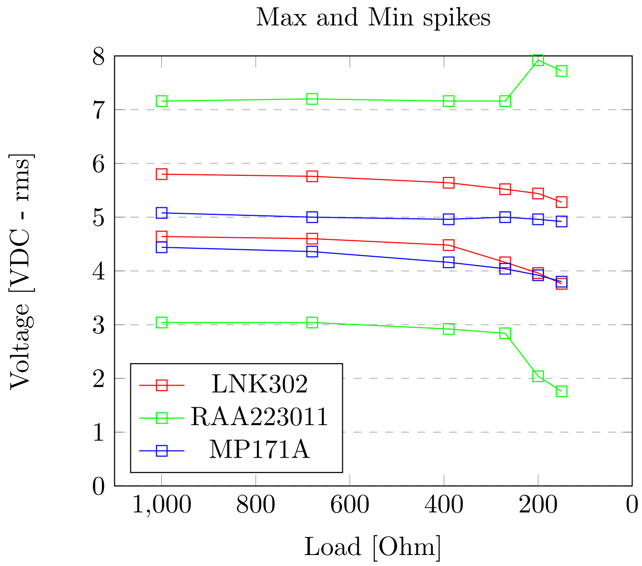


Temperature The temperature of the chips is tested with a IR temperature meter. The input voltage of the chips is 230V AC and a heavy load of 150 Ohms is chosen for testing. After a period of 180 seconds (or 3 minutes) the total temperature is measured. The highest temperature measured is documented in the figure below. The room temperature during testing was around 23.8 degrees.



Testing with a LC filter An important aspect is how easy it is to filter the signal. With a LC filter at 1.59kHz is measured what the performance improvement is. This is done only fore the ripple and transients measurements because they have the biggest advantage of a output filter. The components chosen are a 1mH inductor and a 10uF capacitor.





Max and Min spikes
Voltage [VDC - rms]
Load [Ohm]
0
1
2
3
4
5
6
7
8
1,000
800
600
400
200
0
LNK302
RAA223011
MP171A

C Unit requirement verification

Test 1

Requirements	**REQ-PSU1** The output voltage must be 3.3 V with a maximum deviation of 5 percent. **REQ-PSU2** The chip must be able to deliver a current of 25 mA.
Conditions	Use test setup 1 for this test. In addition to that connect to the output of the power supply a resistor of 120 Ωwith a power capability of 100 mW. Connect a oscilloscope to this output to measure the output signal.
Input	An AC voltage from the variac.
Output	A scope image on the oscilloscope.
Criteria	When measuring with the oscilloscope the values should not raise or drop outside the given boundaries. The boundaries are set on 3.135 V and 3.465 V, when exceeding these values the test did not pass. This applies to the average voltage, the minima and maxima given by the oscilloscope and transients. To be sure the the power supply is stable, the test has to take at least 15 seconds.
Procedure	Perform the following test procedure: 1. Set the variac on a voltage of 0V AC and turn it on. 2. Increase the voltage to 230 V AC. 3. Look at the oscilloscope carefully. 4. Do this for at least 15 seconds.
Results	The figure below shows the test result on the oscilloscope.
Passed	yes

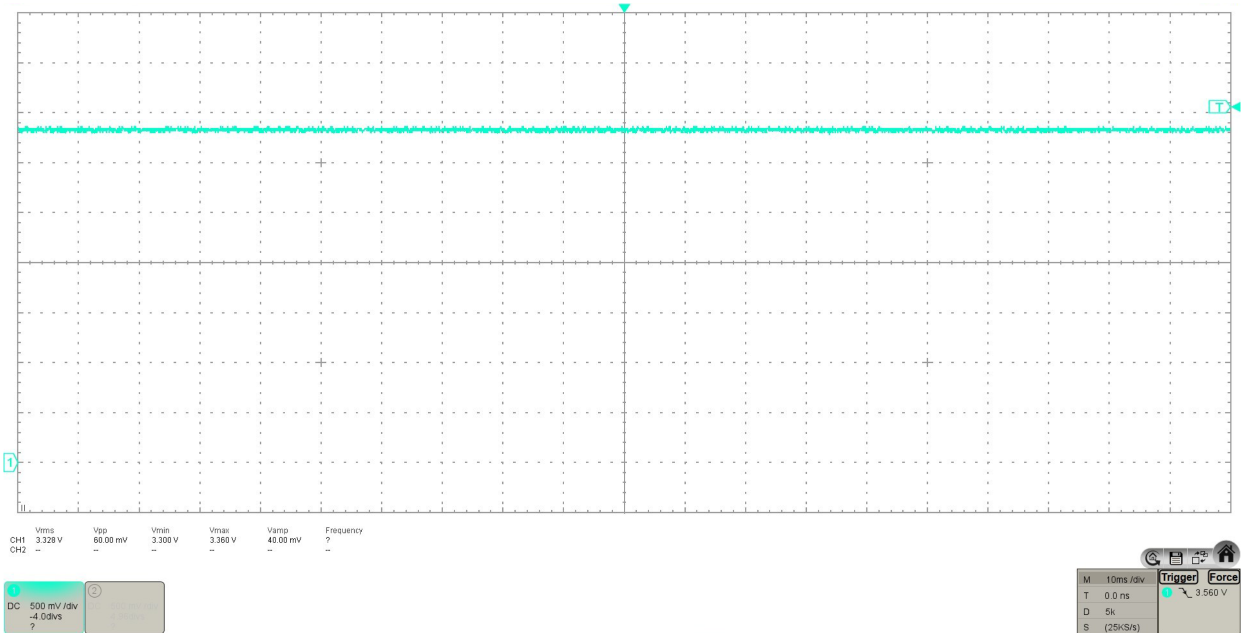


Figure 38: Power supply unit test

Test 2

Requirements	**REQ-PSU3** The power supply must have a minimum absolute rating of 600 volts.
Conditions	The datasheets of the relevant components are required.
Input	None
Output	The maximum voltage rating of the component.
Criteria	All the components at the primary side of the voltage converter (including the converter itself) need to have a voltage rating of at least 600 V, if not the test did not pass.
Procedure	Perform the following test procedure: 1. Search for the datasheets of the components. (The names can be found in the BOM, appendix E).
Results	The diodes at the input have a voltage rating of 1000 V, the input capacitors have a rating of 630 V and the off line regulator have a rating of 700 V.
Passed	yes

Test 3

Requirements	**REQ-AMP1** The device has to measure the current of a connected outlet plug inductively with currents higher than 10A, this is only for pure resistive loads. **REQ-AMP2** The device has to measure the current of a connected outlet plug inductively with currents higher than 1A, this is only for pure resistive loads. **REQ-AMP3** The device has to measure the current of a connected outlet plug inductively with currents higher than 100 mA, this is only for pure resistive loads.
Conditions	Use test setup 2 for this test. Also a power supply is needed at 3.3 V to supply the circuit. The power supply can be connected to the ground and 3.3 V as can bee seen in figure 34. Als a oscilloscope is needed to measure on the output of the opamp, U2 pin 1.
Input	3.3 V and a current from the rogowski coil.
Output	An fft on a oscilloscope.
Criteria	When the system is on first the noise floor has to be determined. When this is set up and while a current is flowing to the coil and the FFT will peak on 50 Hz above the noise floor value the test has passed. To analyse if there will be a peak above the noise floor analyse the FFT for 15 seconds with every test.
Procedure	Perform the following test procedure: 1. Turn on the network analyser. 2. Configure the analyser to display the S11 parameters. 3. Read the values.

Results	
Passed	Yes

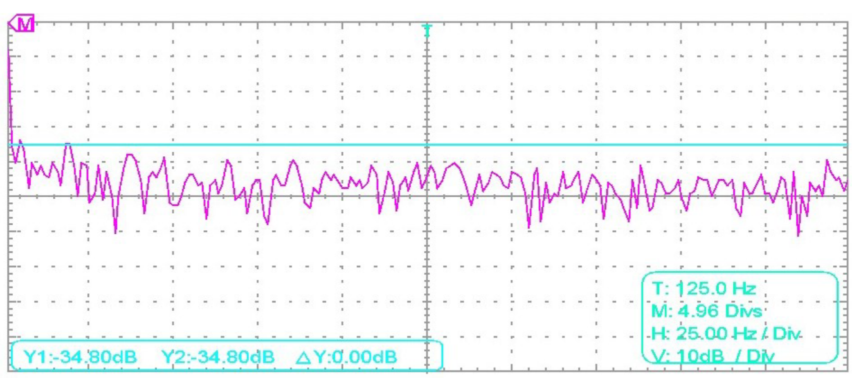


Figure 39: Measurement circuit unit test 0.11 A

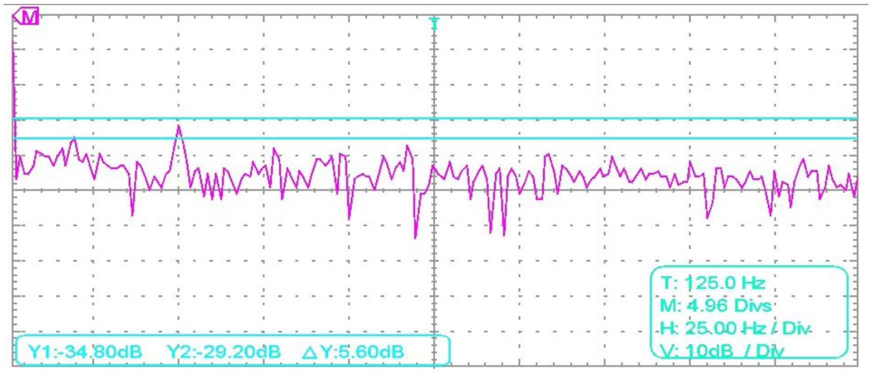


Figure 40: Measurement circuit unit test 0.90 A

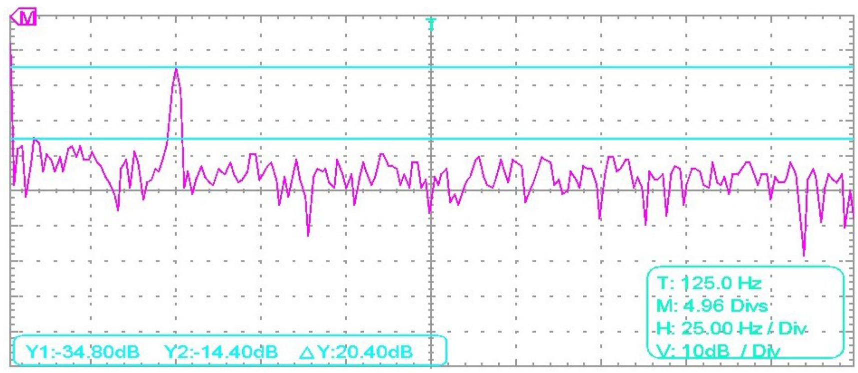


Figure 41: Measurement circuit unit test 9.19 A

Test 4

Requirements	**REQ-ANT1** 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-ANT2** The VSWR or return loss needs to be less than 2.5 dB within the frequency range of the Bluetooth communicating protocol (2.4000GHz to 2.4835GHz).
Conditions	This test needs a network analyser, the 50 Ohm cable has to be soldered between the feed point and the PI-filter.
Input	None
Output	S11 parameters on the screen of the network analyser
Criteria	Between 2.4GHz to 2.4835GHz the S11 parameter has to be -10dB or lower. When even one peak falls above this value the test did no pass. The same is for the VSWR.
Procedure	Perform the following test procedure: 1. Turn on the network analyser. 2. Configure the analyser to display the S11 parameters. 3. Read the values.
Results	The results are show in the figure below. Point 1 and 2 are respectivly -18.8 and -19.0 dBm for the magnitude and 1.26 and 1.25 for the VSWR.
Passed	Yes

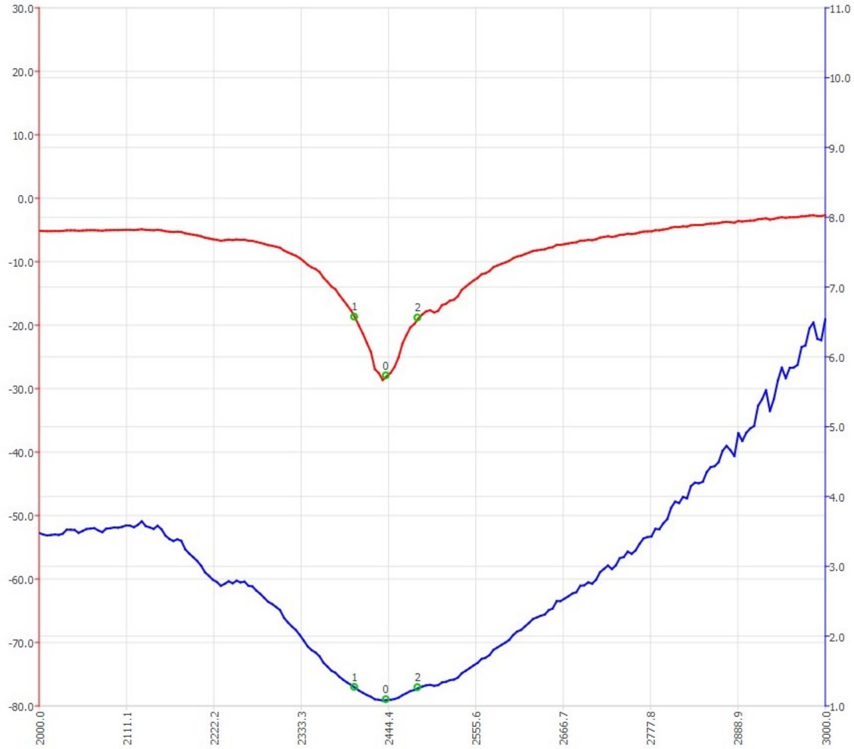


Figure 42: Antenna S11 unit test

D Requirement verification

Test 1

Requirements	**REQ-F1** [MH] The device can be powered directly from a 207V - 253V AC power source.
Conditions	Use test setup 1 for this test.
Input	An AC voltage from the variac.
Output	Connectivity with the Smart Outlet Tag in the Crownstone app.
Criteria	The test did pass when the Crownstone app is able to established a connection with the Smart Outlet Tag. Within the whole voltage range (207V - 253V AC) the Smart Outlet Tag must be available in the app. Between switching voltages wait 10 seconds so the app can verify the connection.
Procedure	Perform the following test procedure: 1. Set the variac on a voltage of 0 V AC and turn it on. 2. Increase the voltage to 207V AC. 3. Wait for 10 seconds. 4. Check the app if a connection is active. 5. Repeat step 2-4 with voltages of 230V and 253V AC.
Results	The app returns a positive connection for all the voltages. When the test hasn't started yet the Crownstone app looks like figure 43 and when the variac is turned on after a few seconds figure 44 showed up.
Passed	Yes

Figure 43: Crownstone app with no connection

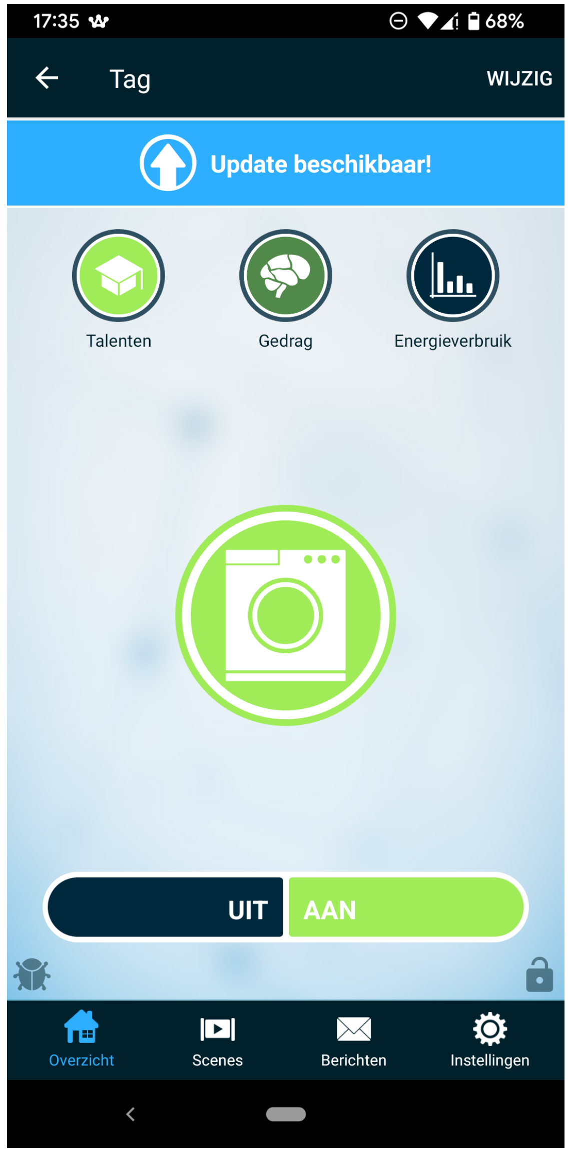


Figure 44: Crownstone app with connection

Test 2

Requirements	**REQ-F2** [MH] The product has to have Bluetooth communication that can send data over 20 meter. The receiving device has to pick up at least -100dBm.
Conditions	Use test setup 1 for this test. Additionally there are multiple smartphones to validate the test results.
Input	An AC voltage from the variac.
Output	Connectivity in the Bluetooth intensity app.
Criteria	When measured on a given distance the app must give a dBm value higher than -100. With every measurement wait 5 seconds so the connection can be verified, then the test has passed.
Procedure	Perform the following test procedure: 1. Set the variac on a voltage of 0 V AC and turn it on. 2. Increase the voltage to 230V AC. 3. Walk in a straight line away from the Smart Outlet Tag. 4. Verify each few meters the connection with the Bluetooth intensity app. 5. While checking the app, wait 5 seconds before reading out the values. 6. When the point is found where the Bluetooth range stops, measure the distance from that point to the Smart Outlet Tag.
Results	This test is done with a Google Pixel 3a and a Samsung galaxy fold Z. The test results are respectively 25 and 27 meters. Note that there where no obstacles such as glass or walls. The minimum detected signal strength was -97dBm. See figure 45.
Passed	Yes

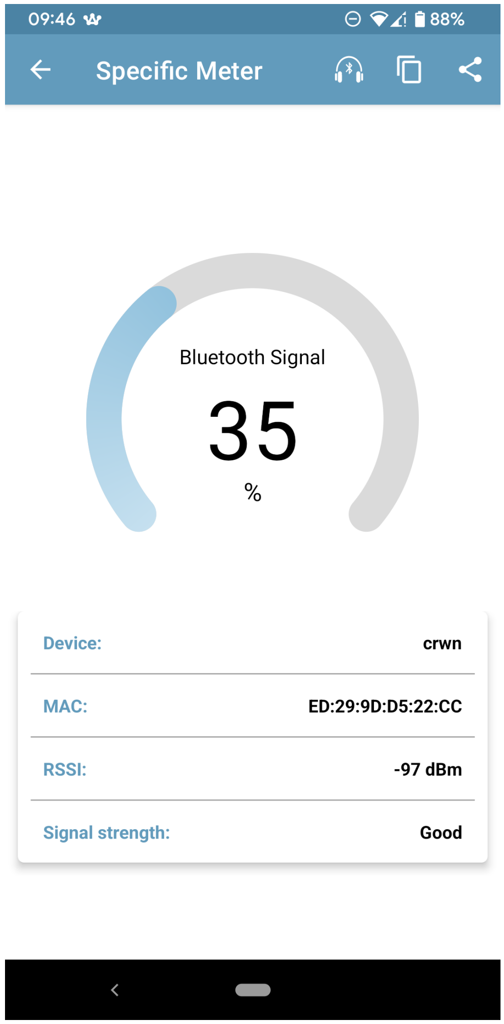


Figure 45: Bluetooth Intensity app

Test 3

Requirements	**REQ-F3** [MH] The device has to measure the current of a connected outlet plug inductively with currents higher than 10A (10 percent), this is only for pure resistive loads. **REQ-F4** [SH] The device has to measure the current of a connected outlet plug inductively with currents higher than 1A (10 percent), this is only for pure resistive loads. **REQ-F5** [CH] The device has to measure the current of a connected outlet plug inductively with currents higher than 0.1A (10 percent), this is only for pure resistive loads.
Conditions	Use test setup 1 and 2 for this test.
Input	An AC voltage from the variac and a current through the coil.
Output	A graph of the current flow in the Crownstone app.
Criteria	When a current is generated this waveform can be read in the Crownstone app. The app displays a time period of 20 ms so if one cycle of a sine is visible in the app and the amplitude is high enough to confirm there is a signal the test has passed.
Procedure	Perform the following test procedure: 1. Set the variac on a voltage of 0V AC and turn it on. 2. Increase the voltage to 230V AC. 3. Generate a current of 0.1, 1 and 10 A with the available devices in different configurations. 4. When a specific current is generated request in the Crownstone app the ADC buffer. 5. Check if there is a signal visible of 50 Hz. 6. Do this for all the currents.
Results	The results can be seen in figure 46. The currents in the case of this test are 0.11, 0.90 and 9.20 A. Note that the signals are not in phase.
Passed	Currently there is no function like a fft build into the firmware, when implemented even lower currents can be read. For now only requirement F3 did pass and F4 is on the edge of being called an AC signal. Requirement F5 did not pass.

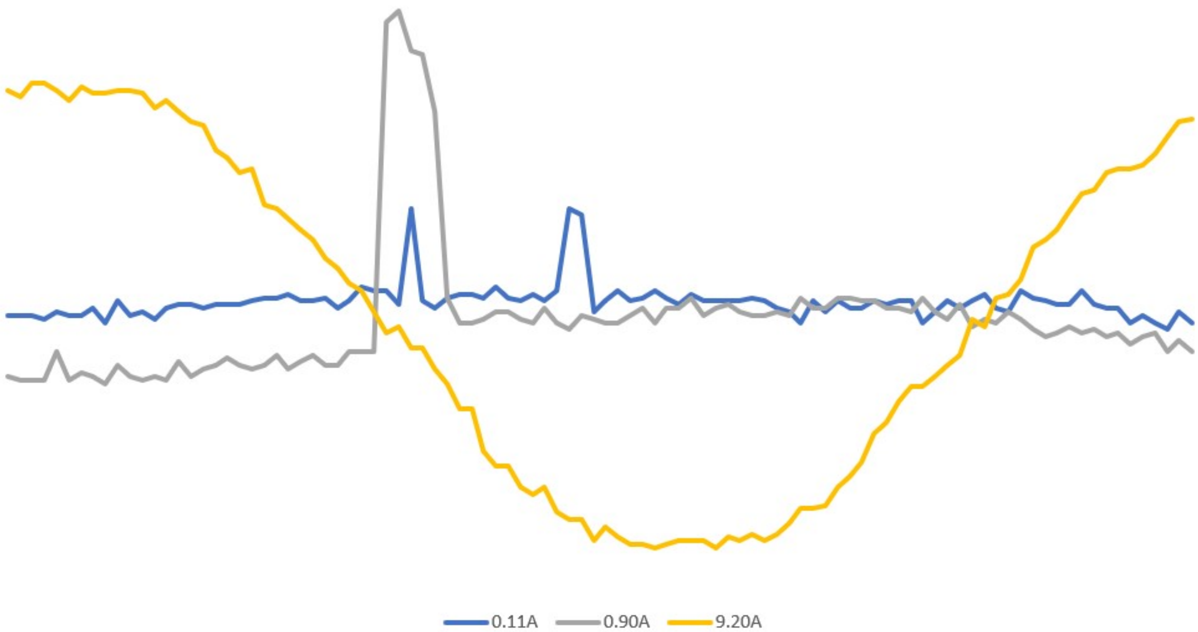


Figure 46: ADC values

Test 4

Requirements	**REQ-NF1** [MH] The microcontroller has to be the nRF52832 or nRF52840 from Nordic Semiconductor.
Conditions	Only the Smart Outlet Tag is needed.
Input	None
Output	The text on top of the microcontroller.
Criteria	Only when the text on the microcontroller matches N52840 the test has passed.
Procedure	Perform the following test procedure: 1. Look at the top of the microcontroller and note the text on it. 2. Compare this text with the text in the criteria.
Results	The text on top of the microcontroller stated N52840 as can be seen in figure 47.
Passed	Yes

Figure 47: nRF52840 package

Test 5

Requirements	**REQ-NF2** [MH] The components on the PCB can't have a thickness more than 1.3mm but preferably 1.1mm on its maximum.
Conditions	The Smart Outlet Tag and a digital caliper are needed.
Input	None
Output	The height measured with a digital caliper
Criteria	Only when the largest component on the board is smaller than 1.3mm the test has passed.
Procedure	Perform the following test procedure: 1. First measure the thickness of the board. 2. Then measure the thickness of the board on the thickest point. 3. Subtract these values and the thickness of the thickest component is known.
Results	The PCB has a thickness of 1.52mm and the thickest part on the board with component has a thickness of 3.38mm. So the thickness of the thickest component (the power inductor) is 1.86mm. The second thickest part has a thickness of 2.75mm what results in a thickness of 1.23mm.
Passed	The test has not passed but the inductor that was chosen for this device wasn't on stock. The footprint does match so later on the smaller inductor can be swapped with the current one. So the test has passed if this is done.

Test 6

Requirements	**REQ-NF3** [MH] The diameter of the PCB has to be 0.5mm smaller than a outlet plug (CEE7/4), this results in a maximum diameter of 35.5mm
Conditions	The Smart Outlet Tag and a digital caliper are needed.
Input	None
Output	The length measured with a digital caliper
Criteria	When the measured diameter of the Smart Outlet Tag is smaller or equal to 35.5mm the test has passed.
Procedure	Perform the following test procedure: 1. Measure the diameter of the Smart Outlet Tag on its largest part.
Results	The measured diameter is 35.42mm.
Passed	Yes

Test 7

Requirements	**REQ-NF4** [MH] The device can be programmed with a J-Link programmer.
Conditions	Use test setup 1 for this test. Also the J-Link Commander software is needed for this test (it can be downloaded from www.segger.com). A J-Link programmer is needed and needs to be connected to the pins on the PCB and a computer. Be sure there is one common ground for all the devices. See figure 34 for the pin mapping on the Smart Outlet tag.
Input	An AC voltage from the variac and signals from the J-Link commander terminal.
Output	An output in the J-Link Commander software.
Criteria	Only when the software states that a connection has been established the test has passed. Messages such as "Core found" or "Cortex-M4 identified" imply that there is a connection. This test can be performed only one time otherwise the test will not pass.
Procedure	Perform the following test procedure: 1. Set the variac on a voltage of 0V AC and turn it on. 2. Increase the voltage to 230V AC. 3. Open up J-Link Commander. 4. Type "connect" 5. Type "NRF52840XXAA" 6. Type "SWD" 7. Type "4000" 8. When a messages pops up prompting to unlock the device, accept it.
Results	The results are shown in figure 48.
Passed	Yes

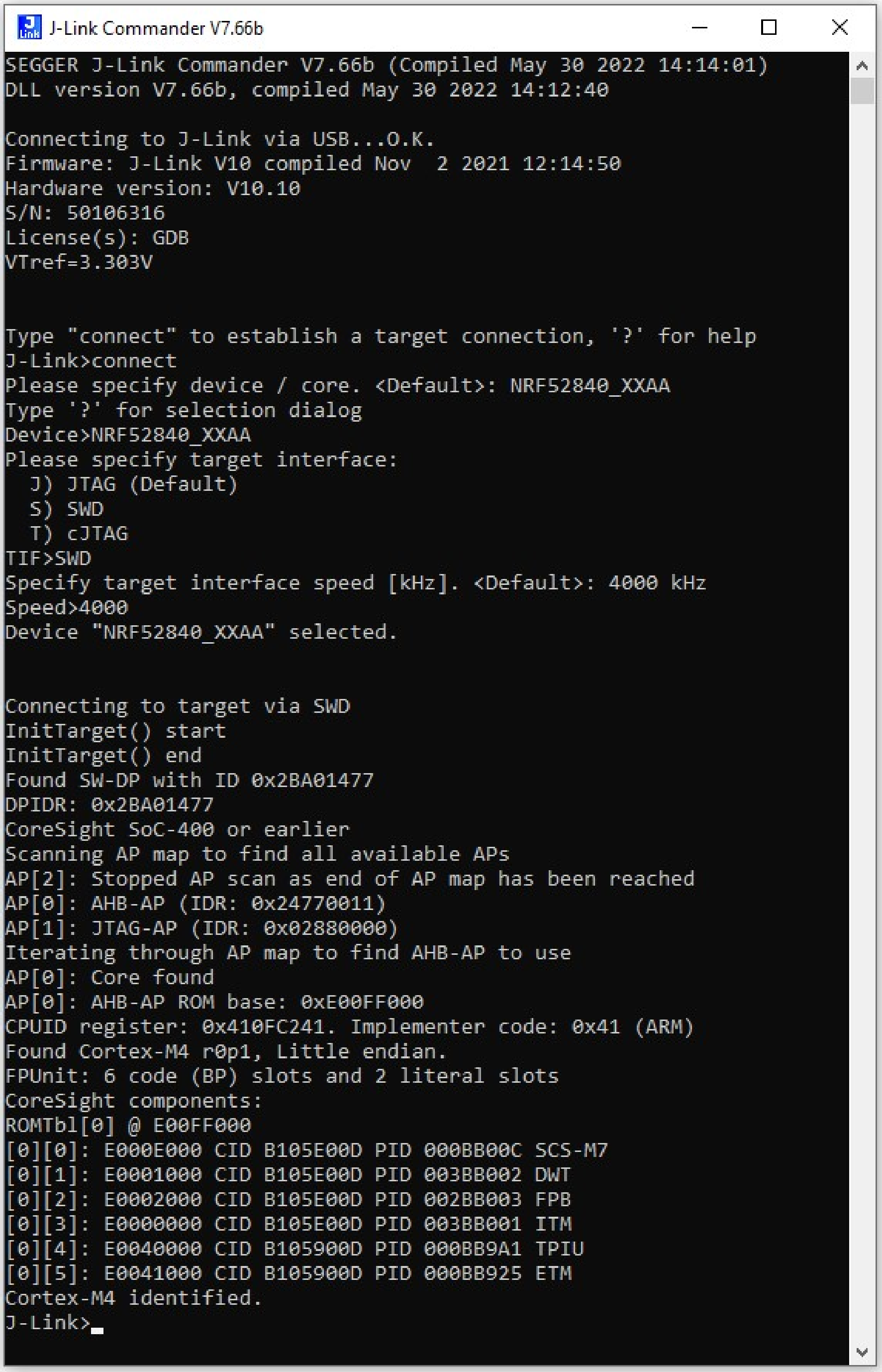


Figure 48: J-Link Commander

Test 8

Requirements	**REQ-NF5** [SH] The device can communicate using UART on a baudrate of 230.400kb/s.
Conditions	Use test setup 1 for this test. Also an UART to USB converter is needed for this test. Connect the TX and RX pins to the connection on the Smart Outlet Tag and the other end into the computer. Don't forget to also connect the grounds to a common ground. Also terminal software like TeraTerm must be available. See figure 34 for the pin mapping on the Smart Outlet tag.
Input	An AC voltage from the variac and signals from the UART.
Output	An output in a terminal.
Criteria	When the device is outputting messages in the terminal the test has passed. When the device boots up there must be characters visible on the screen.
Procedure	Perform the following test procedure: 1. Open up a terminal program. 2. Use a connection of 230.400kb/s. 3. Set the variac on a voltage of 0V AC and turn it on. 4. Increase the voltage to 230V AC. 5. View the terminal program for messages.
Results	The program puts out messages when the device boots up or when values are being requested in the Crownstone app.
Passed	Yes

Figure 49: ADC values

Test 10

Requirements	**REQ-NF6** [SH] The price of the design should be no higher than 9 euros.
Conditions	The BOM (Bill Of Material) needs to be present.
Input	The BOM generated from the project files.
Output	The prices of the components.
Criteria	Only if all the prices are combined less then 9 euros the test has passed. For all the components the quantity will be set on 1000 pieces.
Procedure	Perform the following test procedure: 1. Look at the BOM and look at the prices. 2. Also add the price of the PCB.
Results	See the BOM in attachment E. The price for the components is 7.54 EUR and a rigid PCB costs 1.34 EUR. The total price is 8.88 EUR.
Passed	Yes

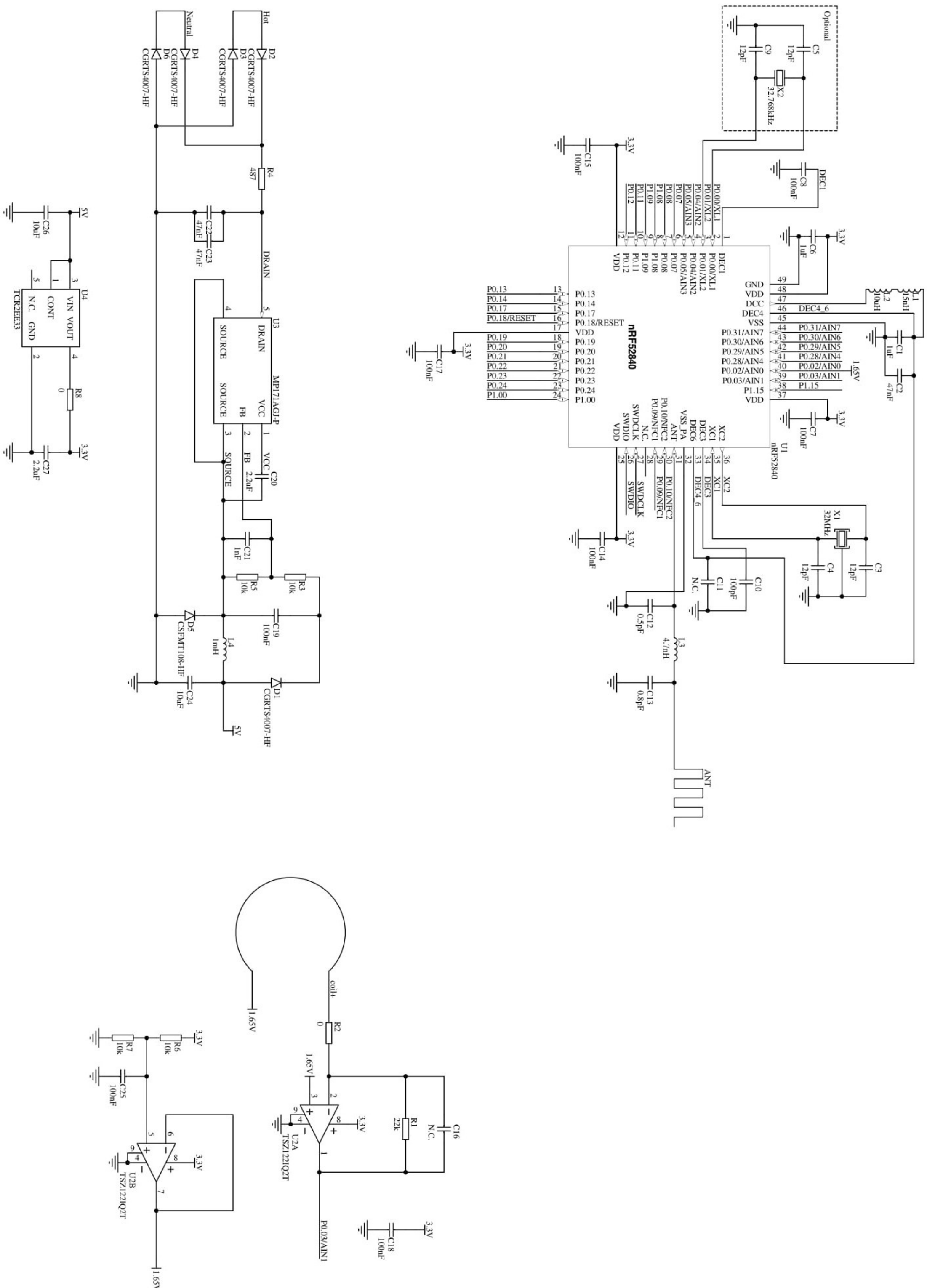
E Bill Of Material

Name	Description	Designator	Quantity	Manufacturer 1
1uF	Capacitor, 1uF, X5R, ±5%, 6.3V	C1, C6	2	Murata
47nF	Capacitor, 47nF, X5R, ±10%	C2	1	Murata
12pF	Capacitor, 12pF, NP0, ±2%, 50V	C3, C4, C5, C9	4	Murata
100nF	Capacitor, 100nF, X5R, ±10%, 25V	C7, C8, C14, C15, C17, C18, C19, C25	8	Samsung
100pF	Capacitor, 100pF, NP0, ±5%	C10	1	Murata
N.C.	Not mounted	C11, C16		
0.5pF	Capacitor, 0.5pF, NP0, ±0.05pF, 50V	C12	1	Murata
0.8pF	Capacitor, 0.8pF, NP0, ±5%, 50V	C13	1	Murata
2.2uF	Capacitor, 2.2uF, X5R, ±10%, 25V	C20, C27	2	Yageo
1nF	Capacitor, 1nF, X5R, ±10%, 25V	C21	1	Murata
47nF	Capacitor, 47nF, X7R, ±10%, 1kV, 1812	C22, C23	2	KEMET
10uF	Capacitor, 10uF, X5R, ±10%, 25V, 0603	C24, C26	2	Murata
CGRTS4007-HF	General Purpose Rectifier	D1, D2, D3, D4, D6	5	Comchip
CSFMT108-HF	Super Fast Recovery Rectifier	D5	1	Comchip
15nH	Inductor, 15nF, 320mA, ±5%	L1	1	Murata
10uH	Inductor, 250mA, ±20%, 1.05ohm. -55°C ~	L2	1	Taiyo Yuden
4.7nH	High frequency chip inductor, 4.7nF, 160m	L3	1	Murata
1mH	Inductor, 1mH, 110mA, 28 Ohm	L4	1	Coilcraft
22k	Resistor, 22k Ohm, ±0.1%	R1	1	Yageo
0	Resistor, 0 Ohm	R2, R8	2	Yageo
10k	Resistor, 10k Ohm, ±0.5%	R3, R5, R6, R7	4	Yageo
487	Resistor, 487 Ohm, ±0.5%	R4	1	Yageo
nRF52840	Multi-protocol Bluetooth Low Energy, IEEE	U1	1	Nordic Semiconductor
TSZ122IQ2T	Operational Amplifier	U2	1	STMicroelectronics
MP171AGJ-P	Offline regulator	U3	1	Monolithic Power Systems
TCR2EE33	LDO 3.3V	U4	1	Toshiba
32MHz	XTAL SMD 2016, 32MHz, Cl=8pF, Total Tol	X1	1	Murata
32.768kHz	XTAL SMD 2012, 32.768kHz, Cl=9pF, Total	X2	1	Seiko

Manufacturer Part Number 1	Manufacturer Lifecycle 1	Supplier 1	Supplier Part Number 1	Supplier Unit Price 1	Supplier Subtotal 1
GRM155R61E105KA12D	Volume Production	Mouser	81-GRM155R61E105KA2D	0,01919	38,37
GRM155R71E473KA88D	Volume Production	Mouser	81-GRM155R71E473KA88	0,01247	12,47
GJM1555C1H120FB01D	Volume Production	Mouser	81-GJM1555C1H120FB1D	0,03549	141,97
CL05A104KA5NNNC	Volume Production	Mouser	187-CL05A104KA5NNNC	0,00192	19,19
GRM1555C1H101GA01D	Unknown	Mouser	81-GRM1555C1H101GA1D	0,04892	48,92
GJM1555C1HR50RB12D	Unknown	Mouser	81-GJM1555C1HR50RB2D	0,059	59
GJM1555C1HR80WB01D	Volume Production	Mouser	81-GJM1555C1HR80WB1D	0,04029	40,29
CC0402KRX5R8BB225	Unknown	Mouser	603-CC0402KRX5R8B225	0,03645	72,9
GRM155R61E102KA01D	Unknown	Mouser	81-GRM155R61E102KA1D	0,00671	6,71
C1812V473KDRACTU	Volume Production	Mouser	80-C1812V473KDR	0,27722	554,45
GRM188R61E106KA73D	Unknown	Mouser	81-GRM188R61E106KA3D	0,07003	140,05
CGRTS4007-HF	Unknown	Mouser	750-CGRTS4007-HF	0,076	380
CSFMT108-HF	Unknown	Mouser	750-CSFMT108-HF	0,16403	164,03
LQG15HS15NG02D	Unknown	Mouser	81-LQG15HS15NG02D	0,03933	39,33
LBMF1608T100K	Volume Production	Mouser	963-LBMF1608T100K	0,09976	99,76
LQP03TN4N7H02D	Volume Production	Mouser	81-LQP03TN4N7H02D	0,02206	22,06
LPZ5010-105MRC	Volume Production	Farnell	2476221	0,772	77,2
RT0402BRD0722KL	Volume Production	Mouser	603-RT0402BRD0722KL	0,05564	55,64
AC0402FR-070RL	Volume Production	Mouser	603-AC0402FR-070RL	0,00384	7,67
RT0402DRE0710KL	Volume Production	Mouser	603-RT0402DRE0710KL	0,02686	107,44
RT0805FRE07487RL	Volume Production	Mouser	603-RT0805FRE07487RL	0,01343	13,43
NRF52840-QFAA-R	Unknown	Digi-Key	1490-NRF52840-QFAA-RTR-ND	2,5	2500
TSZ122IQ2T	Volume Production	Mouser	511-TSZ122IQ2T	1,05	1045,58
MP173AGJ-P	Unknown	Mouser	946-MP173AGJ-P	1,13	1131,92
TCR2EE33,LM(CT	Volume Production	Mouser	757-TCR2EE33LM(CT	0,08154	81,54
XRCGB32M000F1H01R0	Unknown	Mouser	81-XRCGB32M000F1H01R	0,26379	263,79
SC20S-9PF20PPM	Unknown	Mouser	628-SC20S-9PF20PPM	0,41152	411,52

Total (1000 pieces) 7535,23
Total per board 7,53523

F Altium circuit



G Plan of action

Smart Outlet Tag

Plan van Aanpak

Stagiair	:	Ies Verhage
Begeleider	:	Anne van Rossum
Docent	:	Joris Straver
Datum van uitgifte	:	23 maart 2022

Inhoudsopgave

Versiehistorie

Versie	**Datum**	**Wijzingen**	**Auteur**
0.1	01-02-2022	Eerste versie	Ies Verhage
0.2	07-02-2022	Feedback verwerken	Ies Verhage
0.3	09-02-2022	Kleine verbeteringen	Ies Verhage
0.4	11-02-2022	Projectwijziging naar scrum	Ies Verhage
0.5	23-03-2022	Update risico’s	Ies Verhage

1 Achtergronden

Crownstone, gevestigd in Rotterdam, is een fabrikant van slimme stekkers en connectoren. Het boegbeeld van dit bedrijf is een alles in één kastje dat achter een stopcontact of lamp geplaatst kan worden. Denk hierbij aan functionaliteiten als een 16A schakelaar, LED dimmer, vermogensmeter, soft-fuse, standby-killer en aanwezigheidssensor. Het doel van dit product is om gebruiksgemak aan de eindgebruiker te verlenen en om onnodig energieverbruik tegen te gaan.

Kenmerkend aan de Crownstone apparatuur is de positiebepaling van smartphones en wearables. Door het opvangen van Bluetooth signalen kan bepaald worden waar een apparaat zich in een ruimte bevindt. Hierdoor wordt het mogelijk om bepaalde zaken te automatiseren, denk aan het aan/uit schakelen van verlichting of verwarming. Verder is er ook interesse uit de zorgindustrie om deze techniek te implementeren. Zo zou in een ziekenhuis bepaald kunnen worden waar een patiënt zich bevindt. Ook kan dit in huizen/kamers met hulpbehoevende mensen, denk bijvoorbeeld aan dementie. Door het monitoren van activiteit en locatie van de bewoner kan dit waardevolle informatie geven over zijn of haar toestand.

2 Projectresultaat

2.1 Probleemstelling

Crownstone heeft behoefte aan een nieuw product en wil daarmee het product assortiment verder uitbreiden. De huidige module kan achter een stopcontact of lamp geplaatst worden maar in geval dat enkel positiebepaling nodig is kan deze stap bewerkelijk zijn, zeker voor een niet technisch onderlegd individu. Het zou een toevoeging zijn om een simpele module te ontwikkelen die eenvoudig in een stopcontact gestoken kan worden.

Extra gunstig is als deze module de form factor heeft van een stopcontactbeveiliger. In dat scenario zou de positie bepaald kunnen worden en is het stopcontact nog beschikbaar voor gebruik. Een bijkomend voordeel is dat deze oplossing zeer minimalistisch is en amper zal doen opvallen. Echter is tot op heden onduidelijk in hoeverre dit mogelijk is waardoor dit project leven is ingeblazen.

2.2 Doelstelling

Het doel van dit project is een module ontwikkelen die het formaat heeft van een stopcontactbeveiliger en Bluetooth functionaliteiten heeft. De modules zullen in een zogenaamd mesh-netwerk functioneren zodat verschillende modules samen één groot systeem maken. De uitdaging zal hem voornamelijk zitten in het maken van een compact/dun ontwerp en het voeden. Om dit te verwezenlijken moet goed afgewogen worden welke componenten gebruikt gaan worden en is het gebruik van een flex-PCB waarschijnlijk onvermijdelijk.

Extra toevoegingen aan het systeem zijn zaken als het inductief stroom meten van het aangesloten apparaat. Eventuele andere uitbreidingen omvatten het gebruik van Ultra-Wideband (UWB) of NFC. Dit kan leiden tot het nauwkeuriger bepaling van de locatie, of het uitlezen van stekkers met ingebouwde NFC tag. Echter komen deze uitbreidingen enkel aan de orde wanneer een eerste prototype vervaardigd is. Uiteraard moet BOM optimalisatie in het achterhoofd gehouden worden voor zowel een compact ontwerp als een goedkoop ontwerp.

3 Projectactiviteiten

Voor het volbrengen van dit project zijn enkele stappen nodig. Deze zijn onderverdeeld in verschillende fasen die achtereenvolgens uitgevoerd zullen worden. Deze stappen zijn hoofdzakelijk opgesteld volgens scrum. Hoe dit zich zal vormgeven staan in onderstaande alinea's uitgelegd.

Het project zal starten bij de definitiefase om het project kleur te geven. Zo zal met de stagebegeleider overlegd worden wat de wensen zijn en zal na analyse de eisen worden opgesteld. Naarmate het project vordert is het mogelijk dat sommige eisen nog aangepast kunnen worden.

Het doel van het project is iteratief te werken, dus dat betekend veel iteraties van een product maken. Door het testen van deze iteraties haal je snel feedback uit de schakeling om dat weer toe te passen in het volgende ontwerp. Het project zelf zal opgesplitst worden in delen, deze units worden los van elkaar getest en geoptimaliseerd.

Elke iteratie begint met het kijken naar de unit eisen en werkt deze zo nodig bij. Daarna wordt er een klein onderzoekje gedaan naar de verschillende chips die potentie hebben. Bij deze chips wordt er een schakeling ontworpen en worden de benodigde componenten besteld. Mocht het van toepassing zijn wordt er ook een PCB besteld, anders gebeurt het testen op een breadboard. In de tijd dat componenten besteld worden kan er eventueel verder gegaan worden met een andere iteratie. Zodra de componenten binnen zijn worden deze opgebouwd op een PCB of breadboard en worden ze stuk voor stuk getest op de eisen. Uit de resultaten zal blijken dat sommige chips niet voldoen of nadelen hebben. Door het praktisch inzien wat sommige nadelen kunnen zijn kunnen de eisen hierdoor aangevuld of aangepast worden. De kennis die is opgedaan in deze iteratie bepaald het verloop van de volgende.

Als na verloop van tijd blijkt dat de units van dermate hoog niveau zijn zullen deze geïntegreerd worden tot één PCB. Tijdens deze integratie zal blijken of de eisen die in het begin (en door de loop van het project heen) opgesteld zijn behaald worden.

Bovengenoemde stappen behoren tot de kern van het project maar vanzelfsprekend kent het project meerdere kanten. Zodra er tijd genoeg is zal ook aandacht besteed worden aan het programmeren van de microcontroller of wordt er onderzoek gedaan naar een mogelijk bevestigingsmechanisme.

4 Projectgrenzen

Dit project omvat het analyseren van het probleem, het ontwerpen van schakelingen en het realiseren daarvan. Aan het einde van de periode wordt verwacht minimaal één prototype vervaardigd te hebben (op een PCB). De tijdsduur die voor deze opdracht geschreven staat is 840 uur en zal ingaan op 31 januari 2022 met als einddatum 8 juli 2022, het project moet voor deze datum afgerond zijn. Met de einddatum is rekening gehouden met eventueel verzuim (10 dagen). Verder zal tijdens dit project hoofdzakelijk het elektrotechnische gedeelte afgeleverd worden. Er zal ook geprogrammeerd worden maar dit wordt enkel gedaan om de hardware te testen. Algoritmes over positiebepaling vallen buiten dit project. Een eventueel prototype van het bevestigingssysteem zal ook niet vervaardigd worden omdat daar te weinig kennis over is. Het opdoen van deze kennis zal te veel tijd in beslag nemen.

5 Tussenresultaten

De deelproducten die tijdens dit project opgeleverd moeten worden zijn als volgt.

- *Programma van Eisen*
  De eisen die op basis van de wensen van de klant zijn opgesteld.
- *Onderzoeksrapport*
  Een praktisch onderzoek naar de verschillende schakelingen.
- *Prototypes van schakelingen*
  Verschillende iteraties van schakelingen waarbij steeds verbeteringen worden doorgevoerd.
- *Prototype op PCB*
  Een test PCB op schaal om te integreren en de werking te kunnen testen.
- *Conceptverslag*
  Een tussentijds verslag voor feedback.
- *Eindverslag*
  Het in te leveren verslag met daarin het volledige proces van idee tot realisatie. Tevens staan hier ook de testresultaten beschreven.
- *Github repository*
  Een online repository waar documentatie, planning, schema's, code en projectbestanden opgeslagen worden.
- *Testrapport*
  Een uiteindelijke test om aan te tonen dat het eindproduct werkt.

6 Kwaliteit

Door het regelmatig terugkoppelen aan de stagebegeleider en de stagedocent kan de algehele voortgang van het project bewaakt worden. Ontwerp keuzes zullen daarom ook altijd door gekoppeld worden naar de stagebegeleider. Elke maandag zal aan de stagebegeleider teruggekoppeld worden wat de planning is en of er eventuele obstakels zijn. Om de kwaliteit van het op te leveren product te garanderen zal uitvoerig getest worden. Voor het realiseren van het PCB zal gebruikgemaakt worden van Altium Designer 2022.

Het uiteindelijke verslag zal gemaakt worden in LaTeX en geschreven in het Engels. Het verslag zal volgens scrum opgebouwd worden. Dit om te voldoen aan de standaarden van Crownstone. Bronnen zullen zoveel mogelijk van betrouwbare plaatsen komen of zullen zelf worden geverifieerd. Voor het beheren van documenten en projectbestanden zal een eigen Github repository gebruikt worden. Deze is te vinden middels de volgende link:

https://github.com/iesverhage/crownstone-smart-outlet-tag

7 Projectorganisatie

Naam	Functie	Email
Ies Verhage	Stagiair	iesverhage@gmail.com
Anne van Rossum	Stagebegeleider	anne@crownstone.rocks
Peet van Tooren	Ondersteunend begeleider	peet@crownstone.rocks
Joris Straver	Stagedocent	j.g.straver@hr.nl
Stefan Groot Nibbelink	Afstudeercoördinator	s.groot.nibbelink@hr.nl

8 Planning

De globale planning staat hieronder weergeven. De stage zal starten in week 5 en zal eindigen in week 27. Een meer gedetailleerde planning op weekbasis is te vinden in de Github repository, deze zal over verloop van tijd bijgewerkt worden.

Weeknummer	Te voltooien
6	PvA *(deadline)*
7	Programma van Eisen
15	Iteraties afronden
17	Ontwerp PCB 1
19	Testen PCB 1
4 weken voor afstudeerzitting	Conceptverslag *(deadline)*
2 weken voor afstudeerzitting	Eindverslag *(deadline)*
Onbekend	Afstudeerzitting
27	Product opleveren *(deadline)*

9 Kosten en baten

Voor dit project zijn de enige vaste kosten de vergoeding van de stagiair. De variabele kosten zullen voornamelijk de kosten zijn aan componenten en het produceren van het eindproduct. Verder zijn er voor de kosten geen vaste bedragen maar ter indicatie wordt als bedrag €300,- genoemd. Om deze kosten zo laag mogelijk te houden zal de componentkeuze daarop afgesteld worden.

De baten liggen beide bij Crownstone en de klanten. Door de ontwikkeling van de module kan Crownstone een nieuw goedkoper product aanbieden. Daarbij komt kijken dat de uiteindelijke klant ook gebaat gaat bij de ontwikkeling doordat de aanschaf van locatiebepaling goedkoper wordt. Mocht dit product in de zorg gebruikt gaan worden zal een hele grote groep mensen baat hebben. Aan de andere kant van het spectrum zal de stagiair kennis en ervaring opdoen.

10 Risico's

In onderstaande tabel zullen de risico's die betrekking hebben tot dit project benoemd worden. De risico's worden met een cijfer beoordeeld zodat duidelijk zichtbaar is welke zaken aandacht nodig hebben. Op basis van een cijfer tussen de 1 en 5 (= waarbij 1 niet ernstig/onwaarschijnlijk is en 5 zeer ernstig/waarschijnlijk is) zal bepaald worden wat het risico is. De risico's zijn vrij algemeen opgesteld maar dat zorgt ervoor dat de meeste problemen naar deze punten terug te herleiden zijn.

	Bruto				*Netto*		
Risico's	**Kans**	**Gevolg**	**Risico**	**Maatregelen**	**Kans**	**Gevolg**	**Risico**
Verzuim door corona.	2	2	4	**Voorkomen:** Met gezond verstand afwegen of thuiswerken nodig is.	1	2	2
Fouten of problemen aan het PCB ontwerp.	3	4	12	**Voorkomen, corrigeren, detecteren:** Hulp inschakelen zodra nodig en werk laten controleren, anders met een 2e versie de fout herstellen.	2	4	8
Problemen met levering of beschikbaarheid van componenten.	4	4	16	**Voorkomen, accepteren:** Het op tijd bestellen van componenten en rekening houden tijdens ontwerpen.	3	3	9
Onvoldoende kennis over onderwerpen.	3	2	6	**Corrigeren, overdragen:** Verdiepen in de onderwerpen en waar nodig om hulp vragen.	3	1	3
Het project komt in tijdnood.	3	4	12	**Voorkomen, detecteren:** Regelmatig met de stakeholders communiceren en deadlines instellen.	2	4	8
Onduidelijkheid over de projectgrenzen.	2	3	6	**Voorkomen:** Tijdens de eerste weken heel duidelijk bespreken welke zaken belangrijk zijn en vastleggen.	1	2	2
De complexiteit van het eindverslag is niet hoog genoeg.	2	5	10	**Voorkomen, detecteren:** In contact blijven met de stakeholders en deze regelmatig om feed-	1	4	4

				back vragen.			
De scrum methode is de student nog niet eigen.	3	4	9	**Corrigeren, detecteren:** In contact blijven met de opdrachtgever en diegene op de hoogte houden van de planning.	3	3	9
Componenten zijn dikker dan de gestelde eis.	3	4	12	**Voorkomen, accepteren:** Kijken naar alternatieven, anders met de begeleider in gesprek om de wensen bij te stellen.	2	3	6
Design van een Rogowski coil is te ingewikkeld of suboptimaal.	2	4	8	**Corrigeren, overdragen, accepteren:** Samen met begeleider het ontwerp optimaliseren. Anders accepteren of een nieuwe topologie zoeken.	2	3	6
Door het toedoen van externe factoren achterlopen op de planning	2	3	6	**Voorkomen: Z**o min mogelijk afhankelijk zijn van anderen en daar dan ook niet op vertrouwen.	1	3	3

H Reflection

Als ik terugkijk naar mijn project aanpak bleek ik nog best wat moeite te hebben om te wennen aan de Scrum methode. Deels vanwege mijn eigen precisie en wat we op school hebben geleerd viel ik soms toch terug in het V-model. Ik ben blij dat ik ervaring op heb kunnen doen met deze methode maar ik maakte het mezelf hierdoor niet makkelijker. Het gevaar van het terugvallen is dat soms langer de tijd genomen wordt voor een onderwerp om dit te perfectioneren wat soms ten ongunste van de planning kon zijn.

Het punt waar ik het meest op moet focussen in de toekomst is communicatie. Samen met mijn stagebegeleider hebben we het hier ook over gehad en zijn tot de conclusie gekomen dat zeker in een Scrum project dit erg van belang kan zijn. Een van de redenen hoe dit zo gekomen is is mijn zelfstandigheid; Ik vond het namelijk erg uitdagend om dingen zelf te onderzoeken en er achter te komen hoe iets zit. Leergierigheid is goed maar het nadeel is dat dit ook veel extra tijd gaat kosten (wat er eigenlijk niet is).

Het voordeel is dat hierdoor het technisch niveau soms ietsje verder gaat en dat het geleverde werk op niveau is. Op de gedane onderwerpen heb ik veel extra kennis vergaard.

Tijdens deze stage ben ik het documenteren wat gestructureerder gaan doen. Vooral het werken met verscheidene Excel sheets hielpen zaken georganiseerd te houden en formules bij elkaar te houden.

Dagelijks werd er binnen het bedrijf een stand-up gehouden om te vertellen waar je mee bezig bent en waar je tegen aanloopt. Het grote voordeel hiervan is dat je je zelf ook bewust maakt van wat je aan het doen bent en hoe productief je bent. Om er voor te zorgen dat de opdrachtgever op de hoogte wordt gehouden werd deze Wekelijks voorzien van een korte update. Dit houdt in dat er een korte terugblik op de afgelopen week geven werd en dat er duidelijk gemaakt werd wat er op mijn takenlijst staat.

I Competency accountability

Analyseren

Aan het begin van het project is met de opdrachtgever overlegt welke eisen hij heeft. Deze eisen zijn opgesomd en ieder onderzocht op haalbaarheid en het concretiseren. Alle eisen zijn concreet geformuleerd met een onderbouwing waar bepaalde waarden vandaan komen of waarom de eisen een bepaalde prioriteit heeft. De eisen zijn een technische vertaling van de wensen van de klant en zijn zo concreet mogelijk opgesteld. Tijdens het project is er op essentiële momenten een afweging gemaakt welke keuze gemaakt moet worden.

Ontwerpen

Tijdens dit project is er veel diepgang in verscheidene onderwerpen. Zo is bij het versterkingscircuit rekening gehouden met menig aspecten van een opamp. Bij de voeding zijn veel potentiële chips met elkaar vergeleken. Daarnaast is bij de voeding en versterkingscircuit rekening gehouden met veelvoorkomende footprints, eventuele fouten kunnen zo potentieel verholpen worden door een chip te vervangen. Bij de units zijn de belangrijkste keuzes onderbouwd en het ontwerp is op een gestructureerde manier opgebouwd.

Realiseren

Tijdens het gehele project is er meermaals getest. Zo is er tijdens het onderzoek getest of de Rogowski coil naar verwachting presteert. De voeding van de Smart Outlet Tag heeft meerdere iteraties gehad en er is daardoor ook met meerdere chips getest (in totaal met 5 verschillende). De antenne is aan de hand van voorbeeldschakelingen in het design opgenomen maar is aan de hand van het uitvoeren van testen goed gematcht aan de uitgang van de nRF52840. Aan het einde van het project is het gehele product testbaar en is er getest of het aan de gestelde requirements voldoet.

Beheren

De documentatie staat opgeslagen op een Github pagina. Het plan van aanpak en de planning is hierop meermaals geüpdate Het volledige eindverslag is gemaakt in Overleaf. Laatstgenoemde heeft een ingebouwde functie voor versiebeheer zodat eerdere versies teruggehaald kunnen worden. Overleaf is een programma dat documenten in LaTeX laat schrijven, dit is een geldende standaard voor het bedrijf hoe zaken gedocumenteerd moeten worden. Ook is een eerste versie van het PCB geback-upt zodat deze eventueel nog teruggehaald kan worden.

Managen

Tijdens het project is in tegenstelling tot het V-model gebruik gemaakt van Scrum. Dit is een gehanteerde standaard binnen Crownstone. In het begin is er een globale planning van het project opgezet in de vorm van een Gantt chart. Deze zorgde voor de algemene structuur, voor het opstellen van aparte taken is Trello dat als takenlijstje gebruikt kan worden. Daarnaast is Trello een veelgebruikt onderdeel binnen de Scrum methode. Het plan van aanpak is gedocumenteerd met relevante risico's die tussentijds zijn geëvalueerd.

Adviseren

Voor de Rogowski coil zijn adviezen gegeven voor hoe de coil potentieel nog verbeterd kan worden. Daarnaast is aan het einde een advies opgesteld voor wat er aan het product toegevoegd kan worden of wat er nog veranderd kan worden om het eindproduct beter te maken. Deze adviezen zijn onderbouwd en geven aan wat het nut daarvan is.

Onderzoeken

Het onderzoek van de Rogowski coil bevat een validatie van de formules door twee verschillende varianten te gebruiken en deze uitkomsten te vergelijken met de praktijk. Meermaals is uit literatuur informatie gehaald om tekst te onderbouwen daarnaast is er ook een onderzoeksvraag geformuleerd met bijbehorende deelvragen. Ook de methode van het onderzoek is beschreven.

Professionaliseren

Ondanks de nog niet aanwezige ervaring met Scrum is toch voor deze ontwerpmethodologie gekozen. Weliswaar niet makkelijk als je gewend bent aan het V-model maar wel handig om alvast wat ervaring te hebben op de arbeidsmarkt. Daarnaast is tijdens het onderzoek naar de dikte van de componenten en het PCB contact opgenomen met mensen via LinkedIn en bedrijven. Als leek op het gebied van mechanica zou het veel tijd kosten om in hierin te verdiepen terwijl in de praktijk vaak ook het expertise van buitenaf wordt geraadpleegd. Ook is het verslag in het Engels getypt, zeker bij grotere bedrijven is dat vaak een vereiste. Ook was ik vrij zelfstandig tijdens dit project en zorgde ik er zelf voor dat ik aan de benodigde informatie kwam. Ook is er een reflectie aanwezig die terugblikt op de afgelopen periode.

J Feedback student

Beoordelingsadvies afstuderen door de bedrijfsbegeleider

Instituut voor Engineering en Applied Science

Elektrotechniek

Naam student: Ies Verhage

Bedrijf: Crownstone

Bedrijfsbegeleider: dr. ir. A.C. van Rossum

A. KENNIS / PRAKTISCHE EN VAARDIGHEDEN

	Uitstekend	Goed	Voldoende	Zwak
1) De student pakte de opdracht systematisch aan	X			
2) en houdt rekening met maatschappelijke aspecten		X		
3) De student heeft een bruikbaar ontwerp gemaakt		X		
4) De student heeft de benodigde kennis (verzameld)	X			
5) De student maakt gebruik van passende methoden		X		
6) De student volbracht de afstudeeropdracht	X			
7) Het resultaat is bruikbaar en bedrijfsrelevant	X			
8) De technische complexiteit is op gewenst~~e~~ niveau	X			

B. BEROEPSHOUDING EN SOCIALE COMMUNICATIEVE VAARDIGHEDEN

	Uitstekend	Goed	Voldoende	Zwak
9) De student kan zelfstandig werken	X			
10) De~~e~~ student is verantwoordelijk	X			
11) De student is initiatiefrijk		X		
12) De student koppelt geregeld terug		X		
13) Schriftelijke vaardigheden van de student	X			
14) De student onderbouwt zijn keuzes/conclusies		X		
15) De student heeft inzicht in het beroepsveld		X		
16) De student past zich aan de bedrijfscultuur aan	X			
17) De student kan doeltreffend communiceren			X	

C. ALGEMEEN

18) Wat is uw algemene indruk van de student en zijn afstudeerwerk?

Autodidactisch, goed werk afgeleverd! Zeer goed

19) Welk eindcijfer zou u de student willen geven?

1	2	3	4	5	6	7	8	9	10

Totaal aantal dagen van afwezigheid: 1

Reden: 1 dag ziek

Datum: 9 juni 2022 **Handtekening:**