Three-Phase Power Monitoring

Internship Report

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1 Summary

This document will walk the reader through the design process of a Three-Phase Power Meter. The necessary research that has been done in order to design the product will be documented. Furthermore, this document shall feature information about the design and integration of the several units that together make up the power meter. A PCB shall be designed for this project, which will also be documented in this report, together with the various performed tests.

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2 Three-Phase Power Monitor

2.1 Introduction

2.1.1 Problem Definition

Crownstone is developing a product that can measure currents running through a three-phase cable in a non-intrusive manner. This will be useful for applications such as an elevator or in a hospital. Not having to interrupt the circuit in order to carry out a current measurement is crucial for these applications.

There are a number of non-intrusive current measurement devices on the market already, however these do not function well for a three-phase cable. The reason for this being the fact that with those devices, the user would be measuring the current on all three phases at once.

2.1.2 Aim of This Project

The aim of this project is to design and realise a product that is capable of measuring the current per phase in a three-phase installation in a non-intrusive manner. This device shall also feature the nRF52832 or nRF52840 micro controller, in order to output the data over Bluetooth.

At the end of the project, a PCB shall be designed and realised and the necessary software to read the sensors shall be written.

3 Research

This research document shall detail the research and experiments that shall be done in support of the three phase power monitoring project. In order to determine suitable requirements, experiments shall be done on magnetic sensors. The chosen sensors for these experiments are:

- Rogowski Coils
- Hall Effect Sensors
- Magnetoresistive Sensors

An amplifier circuit shall be designed and produced for the Rogowski coil. The procedures and calculations will be detailed in this report. To test the hall effect sensor, a hall effect module shall be connected to an Arduino Uno and the outputs will be read through a PC running an Arduino serial monitor. The magnetoresistive sensors will be mounted to a PCB and will also be read through a PC and Arduino software.

3.1 Rogowski Coils

3.1.1 Theory

Rogowski coils have been used for current measuring since 1912. [1] Traditionally, Rogowski coils have only been considered when other methods were unsuitable. Starting in 1965, the CEGB laboratories at Harrogate began investigating Rogowski coils for use in the power industry and developed the technology to produce high-accuracy and reliable measuring systems using Rogowski coils. [2]

Rogowski coils are toroidal windings placed around the conductor from which they will be measuring the current of. This way, the coil will pick up the electromagnetic field (EMF). The output of the winding is an EMF proportional to the rate of change of current. This is where the Rogowski coil differs from a current transformer, as a current transformer outputs the current that is being measured. The coils are designed to reject external magnetic fields, so that they may provide accurate measurements. The coil can be wound on a rigid former or it can be wound on a flexible former.

In order to monitor the current, the output of the Rogowski Coil has to be integrated. This is because the output of the coil is proportional to the rate of change of current. For this experiment, however, this shall not be necessary, since we are only interested in how sensitive a Rogowski coil is.

The output of a Rogowski coil is very low however, it can be as low as 40 microvolts per amp. [1] For this reason, an amplifier must be used in order to produce a reliable signal.

By choosing correct values for the amplifier, a single coil could theoretically be used to measure an extremely wide range of currents. The coil itself could also be wound more tightly, in order to increase the number of turns and therefore increasing its sensitivity.

One of the advantageous features of the Rogowski coil is that it is linear, because of this the coil could be used to measure a wide range of currents. Instead of having to change the coil when switching systems, the gain of the amplifier could be adjusted instead.

3.1.2 TL074 Amplifier

Two proposed circuits will be discussed in this section. The goal of the circuits shall be to amplify the output of the Rogowski coil so that it may be interpreted by a micro controller or observed through an oscilloscope. The output of the Rogowski coils are extremely low, that's why the signal must be amplified. An op amp amplifier circuit shall be utilized for this. See figure 1 for a schematic of the amplifier using the TL074 op amp. The gain can be tuned by adjusting the value of R4. We can calculate the gain using this simple formula. 1.

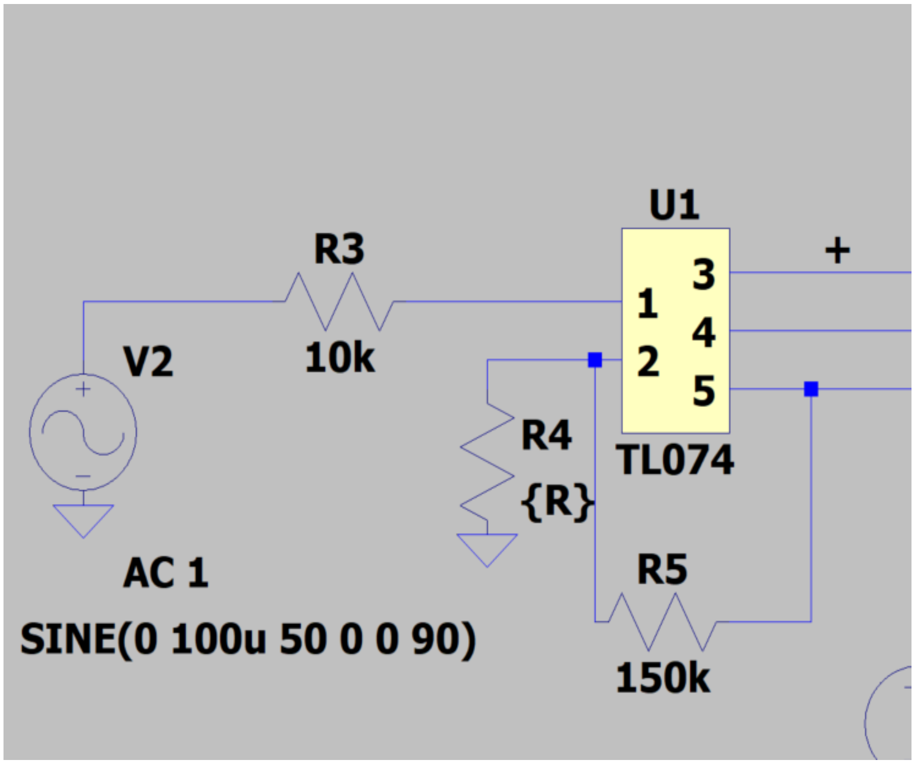


Figure 1: Amplifier using a TL074 op amp.

$$GAIN_{non-inv} = \frac{V_{Out_{max}} - V_{out_{min}}}{V_{In_{Max}} - V_{In_{Min}}} = 1 + \frac{R5}{R4} \tag{1}$$

The output of a Rogowski Coil is not suitable for the input of an ADC. The ADC of an Arduino cannot read signals below -0.3V. Therefore, if we wish to observe the output through an Arduino, we will have to implement a level shifter circuit.

With a reference voltage of 2.5V, our signal will swing from that point rather than from 0V. This will prevent our signal from going below 0v, thus making it readable by an Arduino.

The gain for the level shifter can be calculated using formula 2.

$$\begin{aligned} GAIN &= \frac{R7}{R9} * \frac{R9 + R8}{R6 + R7} \\ If R9 &= R6, then: \\ GAIN &= \frac{R7}{R9} \end{aligned} \tag{2}$$

3.1.3 OPA2342

A circuit for the Rogowski coil using an OPA2342 shall now be discussed. This op amp features a few improvements over the TL074. Firstly, the op amp is a rail-to-rail amplifier. Unlike the TL074, input signals can swing all the way up to the level of the supply voltage. Secondly, a single supply voltage is sufficient to properly amplify the signal correctly. This makes a level shifter redundant as well, since the single (positive) supply voltage makes it so that the amplified signal stays in the positive range.

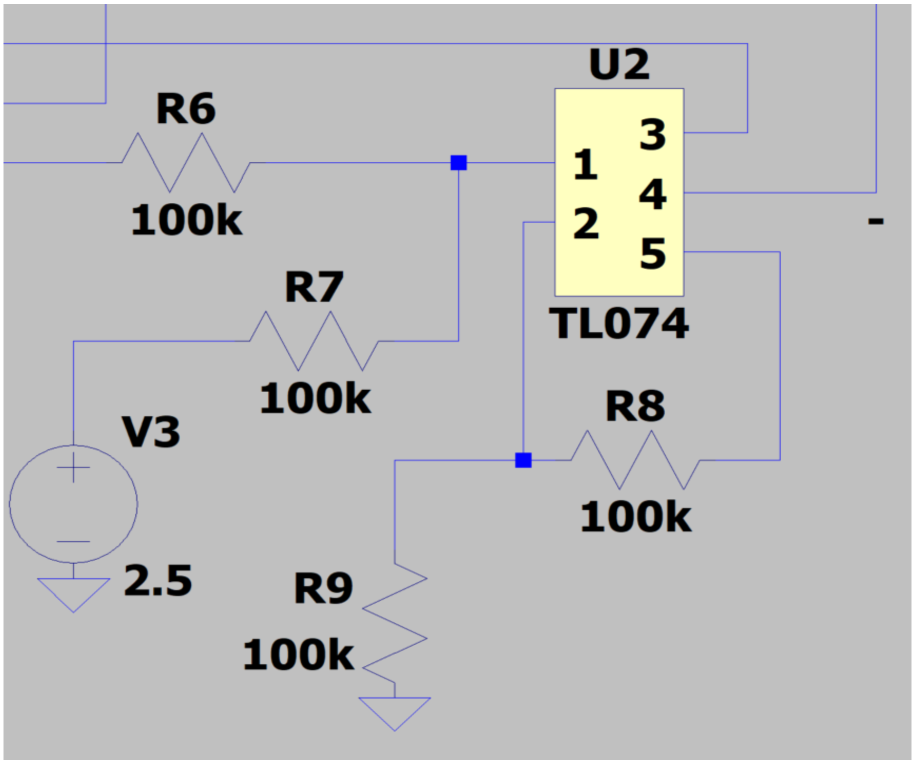


Figure 2: Level shifter using a TL074 op amp.

See figure 3 for the circuit. The gain for this amplifier can be calculated using the same formula as the gain formula for the TL074, formula 1, by plugging the values for R3 and R2 in R5 and R4 respectively.

In this section, the results of the simulations will be discussed. Multiple sweeps have been performed, including temperature sweeps, AC frequency sweeps and resistance sweeps.

3.1.4 TL074 Simulations

The first simulation will be a resistance sweep on R4. This will be done to simulate a potentiometer, so that the gain may be adjusted on the fly. See figure 4 for the results. As expected, the higher the resistance goes the weaker the signal becomes because of the lowered gain.

Next, a temperature sweep shall be run to monitor the performance of the amplifier circuit through a certain range of temperatures. A sweep running from 0 degrees celsius to 100 degrees celsius has been selected. Notice how much the offset varies once the temperature starts to rise above 70 degrees celsius. See figure 5 for the results.

Lastly, an AC frequency sweep shall be performed. With this sweep we will simulate the frequency response of the circuit and we will be able to see the cut off frequency. See figure 6 for the results.

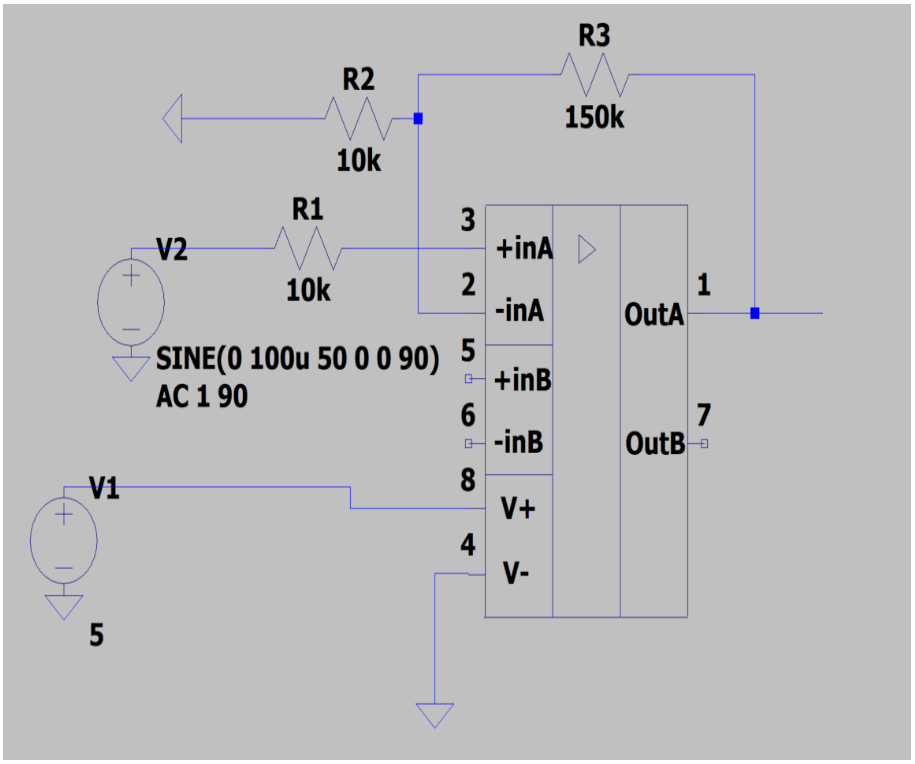


Figure 3: Amplifier using OPA2342 op amp.

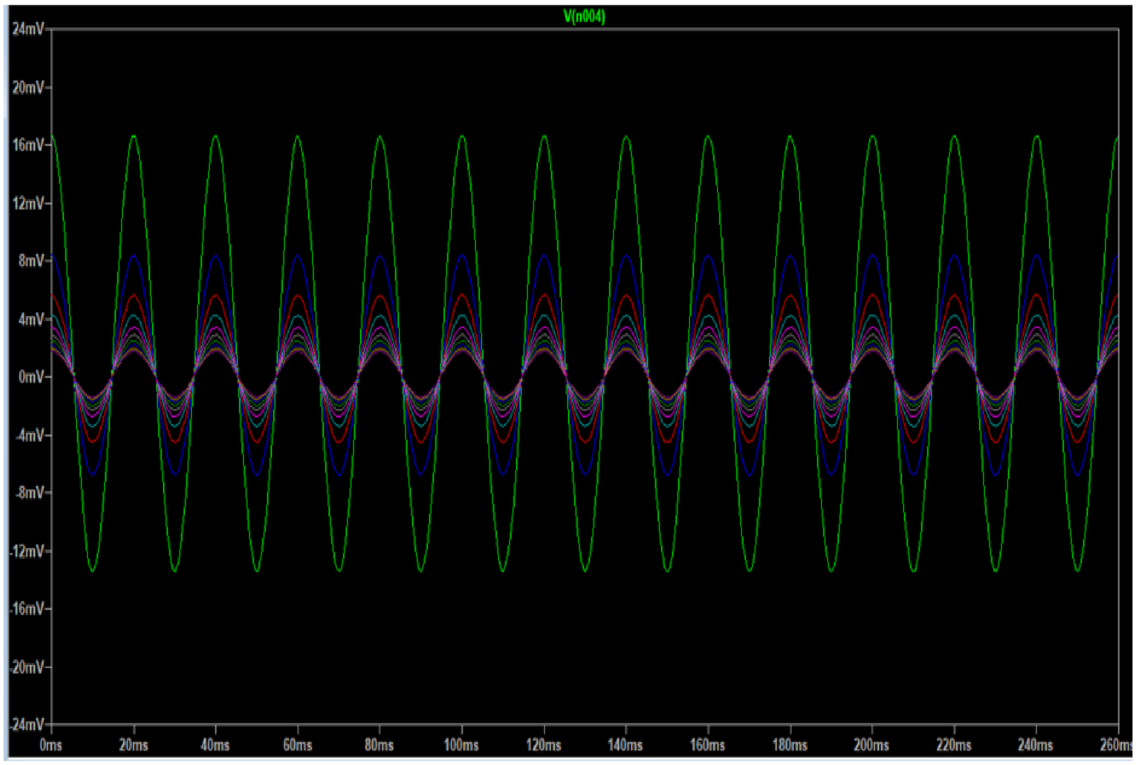


Figure 4: TL074 resistance sweep

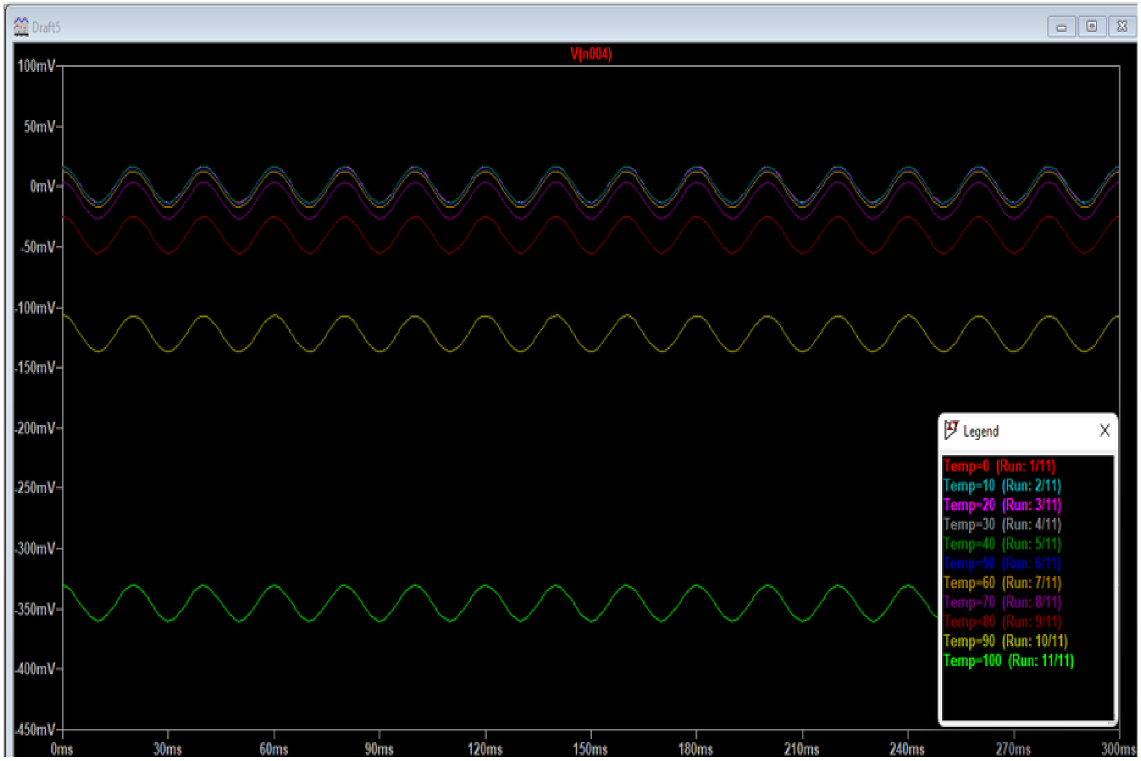


Figure 5: TL074 temperature sweep

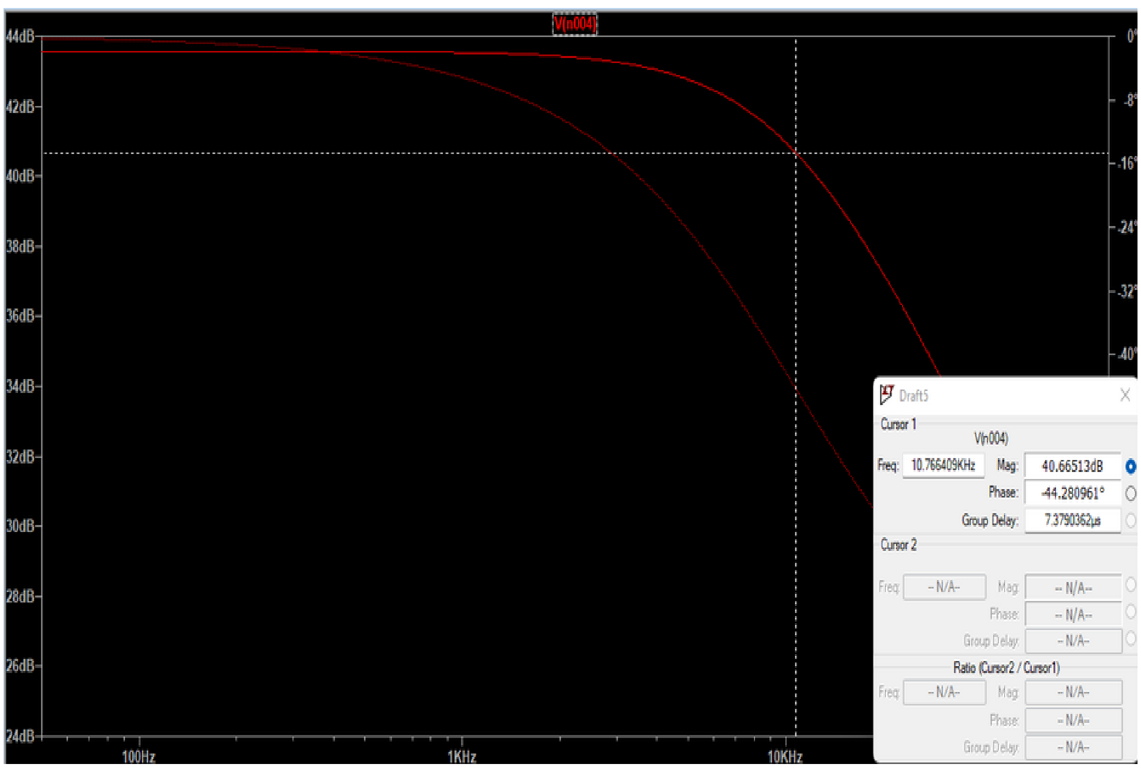


Figure 6: TL074 frequency sweep

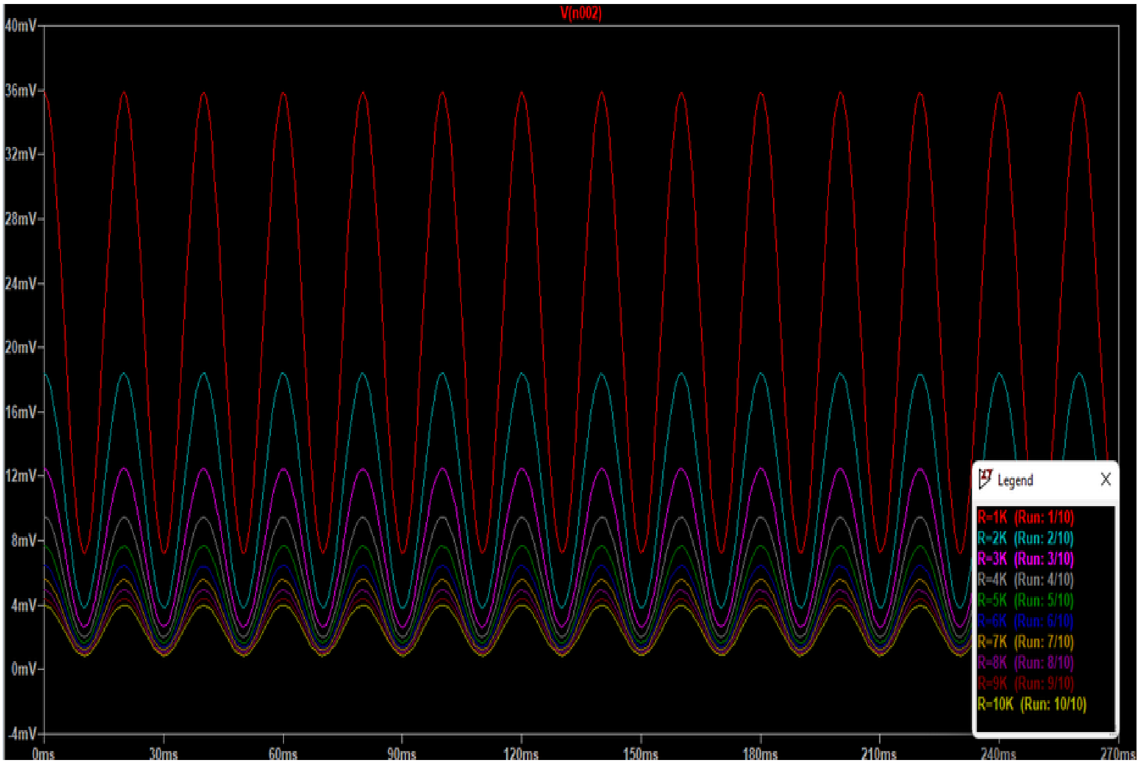


Figure 7: OPA2342 Resistance sweep.

3.1.5 OPA2342 Simulations

In this section we will discuss the simulations performed on the OPA2342 circuits. Just like with the TL074, multiple sweeps were performed to monitor the behaviour of the circuit based on temperature, frequency and resistance.

The first simulation will be the resistance sweep. Here, R2 (3) will be simulated with varying values, to simulate a potentiometer. See figure 7 for the results. Once again, the gain lowers as the resistance increases.

Next up is the temperature sweep. A temperature range of 0 degrees Celsius up to 100 degrees Celsius has been selected. See figure 8 for the results. Note how temperature affects this circuit much less than the TL074 circuit. In fact, it appears that temperature barely affects the circuit at all.

Finally, we have the frequency sweep. The sweep ran from 50Hz up to 100KHz. We can see in figure 9 that the cut off frequency is at 10KHz.

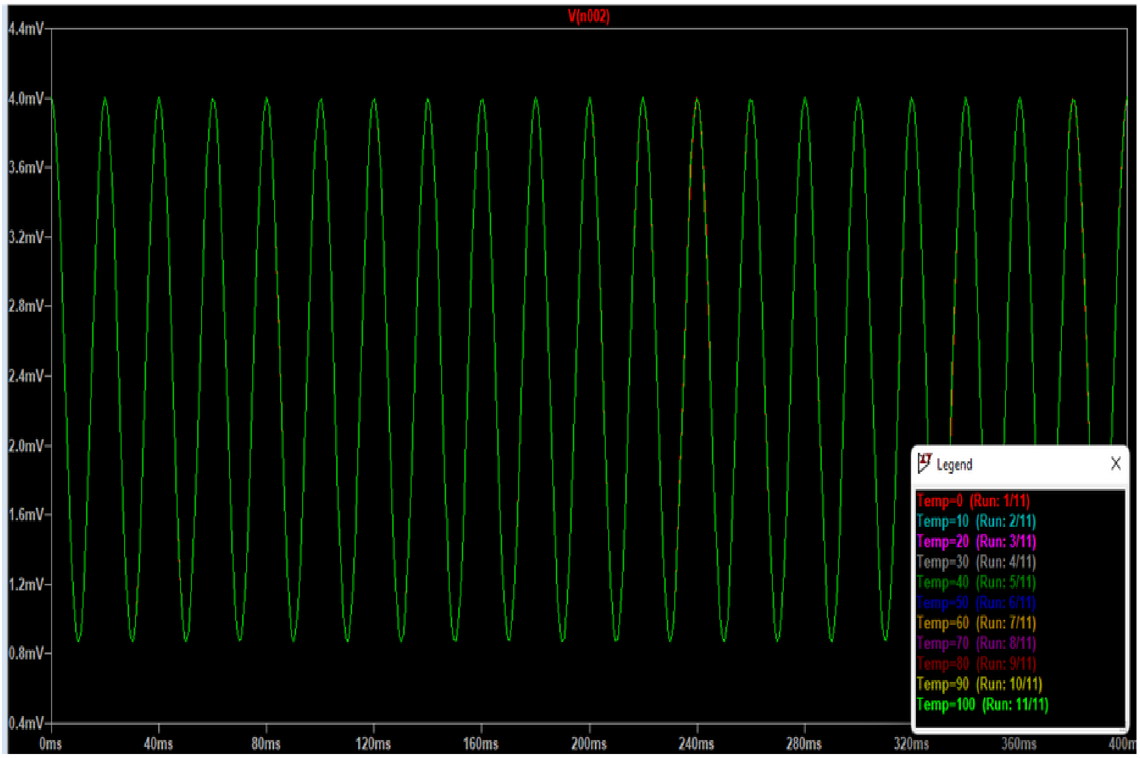


Figure 8: OPA2342 Temperature sweep

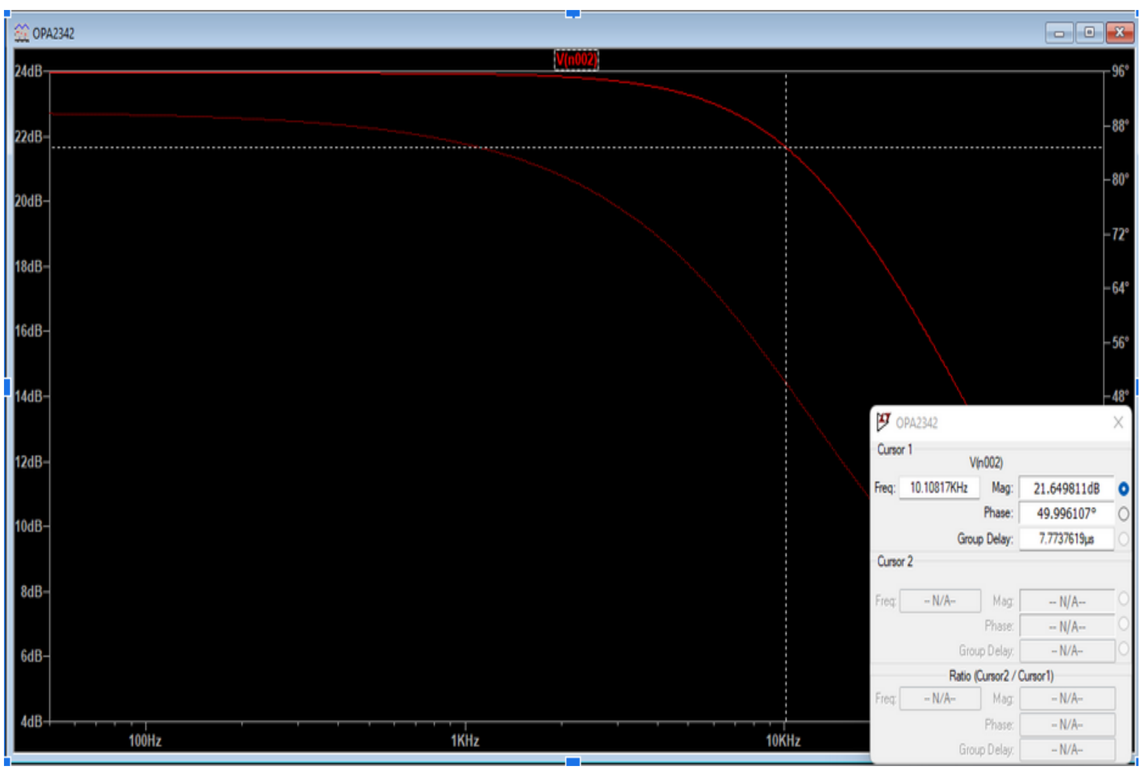


Figure 9: OPA2342 frequency sweep

3.2 Hall Effect Sensors

3.2.1 Theory

The hall effect sensor is named after American physicist Edwin Hall. Hall discovered that objects can be moved by electricity and magnetism. Hall effect sensors used that principle to convert magnetically encoded information into electrical signals.

Hall effect sensors have a vast range of applications, including several uses in the automotive industry such as position sensing, speed and distance sensing etc.

When a current flows through any material, the electrons in the current move in a straight line. The electricity creates its own magnetic field. If this electrically charged material is placed between the poles of a permanent magnet, the electrons will move with a curved path instead. This is because their own magnetic fields react to the magnet's magnetic field. As a result of this, more electrons will be present at one side of the material than the other. Because of this a potential difference, voltage, appears across the material. [3]

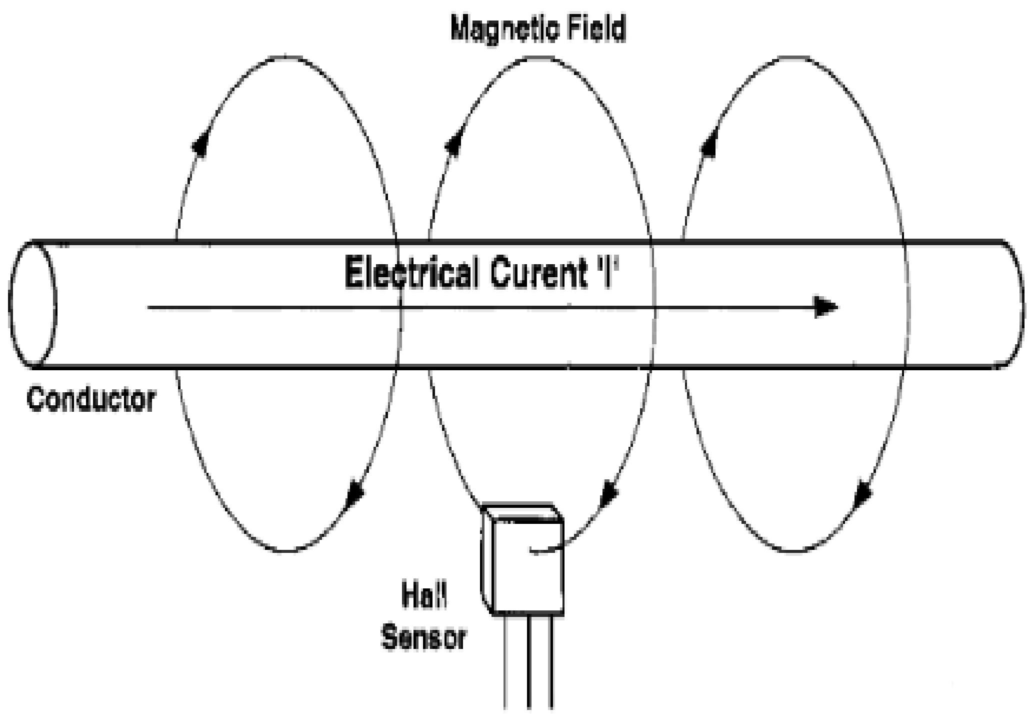
Hall effect sensors will measure the changing voltage across this material. With this method, the sensor can detect that is in a magnetic field.

Hall effect sensors are activated by an external magnetic field. The two most important characteristics of a magnetic field are flux density (B) and polarity (north and south).

The output of a Hall effect sensor is the function of the magnetic field density around the sensor. When the external magnetic flux density around the sensor exceeds a certain threshold, the sensor will output a voltage called the Hall voltage, V_h.[4]

Hall effect sensors are usually utilized to detect proximity, position or speed of mechanical targets. They can, however, also be used as current sensors. The way this is achieved is by measuring the magnetic field that is generated by the current.

In theory, to create a current sensor a hall effect sensor could be placed close to a conductor that is carrying a current. The sensor has to be placed in such a way that the magnetic flux lines can be detected, see figure [x].



Assuming that there is only empty space surrounding the conductor and the conductor has a circular cross-section, the magnitude of the magnetic field can be calculated by the following equation:

$$B = \frac{\mu_0 I}{2\pi r} \tag{3}$$

R in this equation is the distance to the center of the conductor in meters.

While this would be an ideal setup, in reality this introduces several problems. Firstly, the generated magnetic field will not be substantial. For example, a 10 amp current will only generate about 2 Gauss at a distance of 1 cm.

$$\frac{4\pi * 10^{-7} * 10}{2\pi * 0.01} = 0.0002T\, or\, 2\, Gauss \tag{4}$$

By this logic, the sensor will be influenced by external fields. One example of a field that could influence the readings would be the magnetic field of Earth. Earth has a magnetic field of about $\frac{1}{2}Gauss$. The generated error would be 2.5 amps. From this we could draw the conclusion that in this configuration the hall effect sensor would only be suitable for measuring extremely large currents. If this would be applied for systems with less current, the measuring error would relatively be much higher.

$$\frac{2\pi * 0.01 * 0.00005}{4\pi * 10^{-7}} = 2.5A \tag{5}$$

The second challenge would be the difficulty of correctly placing the sensor. To make the sensor effective, it is very important to place the hall effect sensor in the correct spot.

Thirdly, the calculations above assume an infinitely long and straight cable. In reality, however, cables are not infinitely long and there is a chance of the cable flexing and bending. The flexing and bending will have a major impact on the sensor's sensitivity.

3.3 Magnetoresistive sensors

3.3.1 Theory

Magnetoresistive sensors (MR sensors) are linear magnetic field transducers. A MR sensor uses the fact that the electrical resistance in a thin magnetic film alloy is changed through an external magnetic field. Materials such as iron and nickel are commonly used for this alloy. MR sensors are very small and highly efficient, using very little current to operate. [5] An MR sensor can be used for multiple applications, such as:

- Angle measurement
- Magnetic field sensing
- Used as switches
- Current measurements

A simply way to explain the working of the sensors would be as follows: When the sensor comes into contact with a magnetic field, the electrical resistance changes. This also makes it possible to detect at what angle the external object is located. The magnetic field also makes it possible to determine the distance.

Technology has advanced to the point where researchers were able to create nanostructured multilayer devices with succesively larger giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) effects. Together with anisotropic magnetoreistance (AMR), these three types of sensors are currently in use.

A way to calculate the maximum obtainable signal from the sensor would be as follows:

$$MR\% = \frac{R_{max} - R_{min}}{R_{min}} \tag{6}$$

As mentioned earlier, the three types of MR sensors that will be discussed in this research are:

- AMR Sensors
- GMR Sensors
- TMR Sensors

3.3.2 Anisotropic magnetoresistance

AMR, or anisotropic magnetoresistance, sensors depend on the angle between the electric current and the magnetization direction. The AMR effect is a change in the paths of the electrons. The magnetic field distorts these paths. The change is maximum when the magnetic field is parallel to the sensor.

The resistance of the material of the sensor can be given by the following formula:

$$R = R_0 + \Delta R \tag{7}$$

4 System Analysis

Requirements will be set up and discussed with the stakeholder to insure the end product will be satisfactory. The requirements will also be used as a means to formulate various tests to test the functionality of the product.

Multiple illustrations shall be provided in this document to visualise the working of the product. With the help of a data context diagram (DCD) and a data flow diagram (DFD) the reader of this document will be able to get a clear picture of the inputs and outputs of the product, as well as the various subsystem and the connections between these subsystems.

4.1 Requirements

4.1.1 Functional Requirements:

REQ-1: The product will be able to measure current from a three-phase cable with up to 5 cores in a non-intrusive manner.
One of the most essential requirements of this project. The goal is to sense current from the aforementioned cable type without having to break the circuit. A possible scenario in which this product might be used is in a hospital. In this case, having to break the circuit to measure current would rather be avoided.

REQ-2: The product will be able to measure current from a cable while attached in a fixed position.
A must have for this product is the ability to sense current when the device is installed in a pre-determined location. Placing it in a random position, with the core positions unknown, is considerably more difficult and shall be treated as a 'nice to have' feature.

REQ-3: The product will be able to measure current at a sample rate of 5KHz.
European AC voltage runs at a frequency of 50Hz. By sampling at a sample rate of 5KHz, 100 waveforms can be captured in a single second. With this data, the reactive power can be measured as well.

REQ-4: The product will be able to perform measurements on a 400V cable.
The standard phase voltage for Dutch three-phase cables is 400V.

REQ-5: The product will contain either a nRF52832 or nRF52840 micro controller.
These are the stakeholder's and company's requested micro controllers. Crownstone has already developed products using the nRF52832. Therefore, they have adopted the nRF chips into their ecosystem and have written a substantial amount of firmware for it.

REQ-6: The product will be able to output data over a USB connection.
Since the product will be powered over a USB connection, a USB data connection is also desired.

REQ-7: The product will be able to output data over a Bluetooth connection.
With a Bluetooth connection, the product will not be solely depending on a USB host device in order to output its data. This also makes the device more portable, as it won't have to be tethered to, for example, a laptop or dekstop pc.

REQ-8: The product will be powered via USB.
In order to be perform measurements over a long period of time (i.e. for anomaly detection) it is much more reliable to have the device mainly powered by a non-battery solution.

REQ-10: The product should have a battery power supply.
If the product would feature a battery power supply as well, then it would make the product much more portable. Not only does it eliminate the need to be tethered to a USB device or charger, but because of the Bluetooth functionality the device can operate completely wirelessly.

REQ-11: The product could feature rechargeable batteries.
This would be a nice feature, it saves the user the frustration of having to switch out batteries and it's a more economical and environmentally friendly approach than using disposable batteries.

REQ-12: The product could measure currents while attached to a cable in a random position. As mentioned earlier, it would be nice for the product to have this feature included. This, however, is a considerably more difficult requirement due to the fact that the distance between the sensors and the cores will have to be calculated.

4.1.2 Non-Functional Requirements:

NFREQ-1: The product could feature a 3D-printed enclosure.
The intern currently does not have any experience designing and 3D-printing enclosures. However, if there is time to spare at the end of the project, the intern would attempt to design and create an enclosure.

NFREQ-2: TBD: Cores and Shielding of the cables.

NFREQ-3: Lifespan of product.

NFREQ-4: The product should feature a redundancy of sensors, so it may continue to function in the event of a sensor failure.
It would be beneficial to feature a redundant amount of sensor, so that the entire device does not need to be replaced in the event a non-critical amount of sensors cease to function.

NFREQ-5: The device could have the ability to measure currents while being held by the user. Having someone hold the device while trying to measure current introduces constant tiny movements. Because of this, the distance to the cores needs to be calculated constantly.

NFREQ-6: The device should be completely level when two pcb's are connected.
It is important for the device to be level when fitted around a cable. If it is not level, the angles from the sensors to the cable will not be constant, which would affect the calculations.

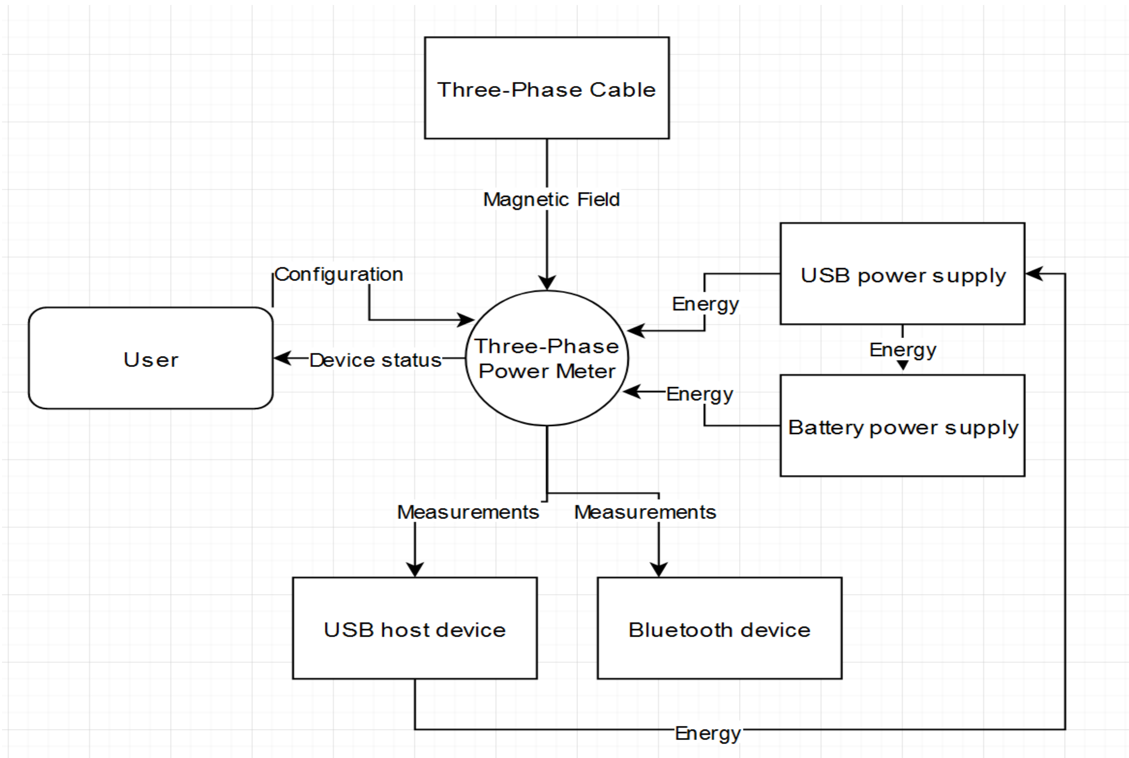


Figure 10: A Data Context Diagram of the system.

4.2 Data Context Diagram

A DCD has been drawn to illustrate the inputs and outputs of the device. The DCD can be seen in figure 10. The magnetic field gets picked up by the power meter and the device calculates the current running through the phases. This data will then be carried over USB or Bluetooth so that the user may read the data. The meter is powered by either a USB or battery power supply. In the event REQ-11 is implemented, this USB connection will also recharge the batteries.

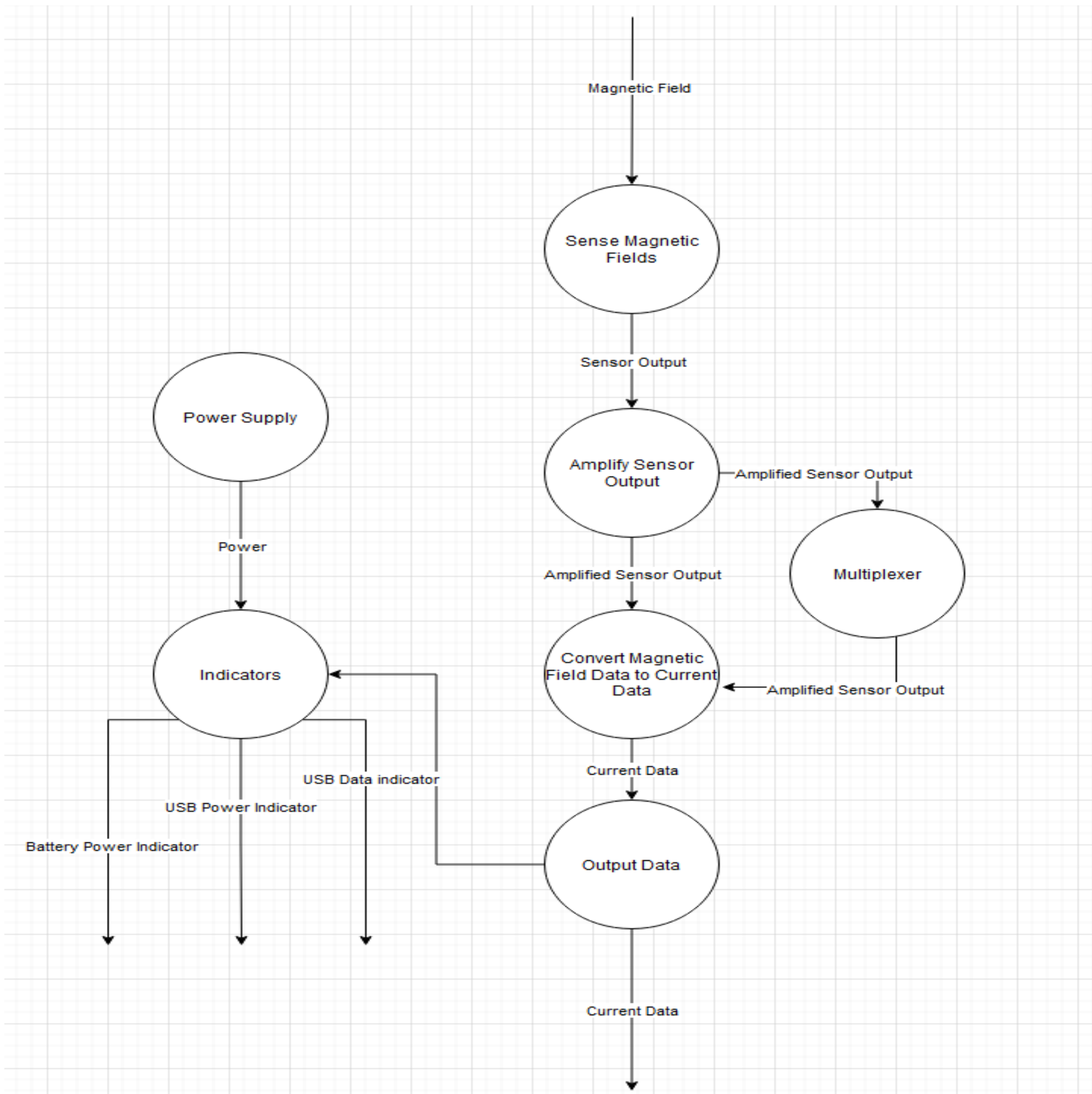


Figure 11: A Data Flow Diagram of the system.

4.3 Data Flow Diagram

A DFD has been drawn to illustrate the connections between the subsystems that comprise the system. This DFD can be seen in figure 11. The DFD illustrates the incoming magnetic field, after which it gets picked up by the sensors and proceeds to get amplified. This amplification is necessary since most magnetic field sensors have a very low output voltage-wise. After this step the designer has the choice to either send the data straight to the ADC of the micro controller, or send it through a multiplexer first. A multiplexer will allow the micro controller to receive data of a greater amount of sensors, since the micro controller has a limited amount of analog inputs. The micro controller will then convert this data to current data, which then will be sent over either USB or Bluetooth.

4.4 Acceptance Tests

Requirements	REQ-1, 2, 3, 4, 6, 8
Equipment	The three-phase power monitor USB host device (laptop) Three-phase cable
Test procedure	- Position the product around the three-phase cable. - Connect the product to the host device via USB. - Verify the connection between the product and the host device. - Verify if the product is measuring data. - Verify if the measured data matches the expected output.
Conditions	Test is considered successful if the product manages to measure current with an accuracy of +-10% and output the data over USB.

Table 1: Acceptance test 1.

Requirements	REQ-1, 2, 3, 4, 7, 8
Equipment	The three-phase power monitor Bluetooth device (phone) Three-phase cable USB power supply
Test procedure	- Position the product around the three-phase cable. - Connect the product to the host device via Bluetooth. - Verify the connection between the product and the host device. - Verify if the product is measuring data. - Verify if the measured data matches the expected output.
Conditions	Test is considered successful if the product manages to measure current with an accuracy of +-10% and output the data over Bluetooth.

Table 2: Acceptance test 2.

Requirements	NFREQ-4, 6
Equipment	The three-phase power monitor A level
Test procedure	- Visually inspect the product and notice the amount of sensors installed. - Connect two pcb's together. - Use the level to verify if the pcb's are level while connected to each other.
Conditions	Test is considered successful if the product features multiple redundant sensors and if it is level while two pcb's are connected.

Table 3: Acceptance test 3.

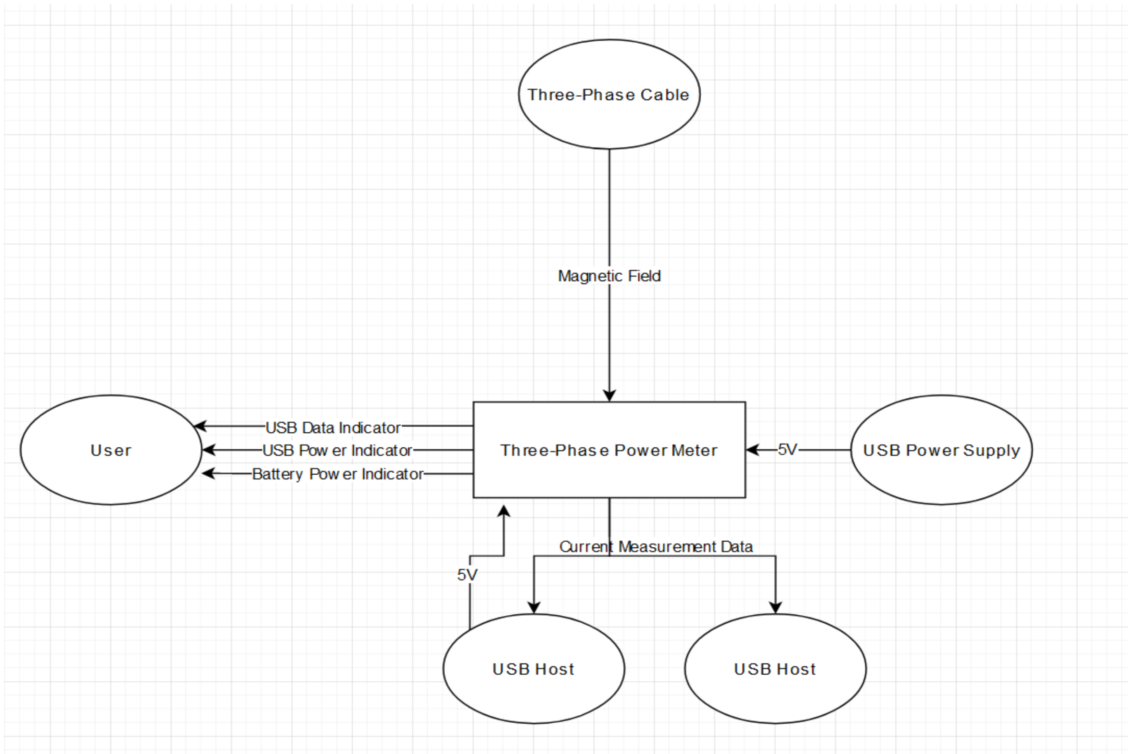


Figure 12: An ACD Describing the inputs and outputs of the system.

5 Architecture

This section will focus on the architecture phase. The connections to and from the device and various subsystems within the system will be highlighted. An Architecture Context Diagram has been drawn to illustrate the connections between and can be seen in figure 12. This section will also highlight the various design choices. These choices will be made for the following units:

- Magnetic Sensors
- Amplifier
- Micro Controller
- Multiplexer
- USB
- Board Connectors

5.1 Magnetic Sensors

For this unit it is essential that the sensor can detect a magnetic field from a suitable distance. This means the magnetic sensor has to be a contactless magnetic field sensor. The most ideal sensor for this would be a linear magnetic sensor, so that the current from a given magnetic field can be accurately calculated.

There are various ways to sense magnetic field. The methods that will be discussed now are:

- Rogowski Coils
- Hall effect Sensors

- Magnetoresistance Sensors

5.1.1 Rogowski Coils

Rogowski coils are usually the preferred current sensors due to their host of positive features. They feature no magnetic saturation, they cannot overheat and they suffer no losses due to hysteresis. They are also linear which means they can be utilized in many different systems with varying currents. At most, the amplifier and/or the amplifier's gain will need to be adjusted to suit the output of the system.
Despite these positive features, a Rogowski coil would not be a suitable choice for the product, multiple coils would need to be deployed around the three-phase cable. This would drive up manufacturing costs and would completely eliminate the possibility of being able to find the location of the cores of the cable through measuring. Basically, the measurements would only be possible if the user knows the locations of the cores beforehand.

5.1.2 Hall effect Sensors

Hall effect sensors are used in applications such as proximity sensing, speed sensing etc. They can, however, also be used to measure current. Hall effect sensors are very sensitive to changes in distance and angle. Therefore, a magnetic flux concentrator is usually used for accurate measurements. This cannot be used for a three-phase current sensing solution, because putting a magnetic flux concentrator around an entire three-phase cable would result in a magnetic field of zero being read by the sensor.

5.1.3 Magnetoresistance Sensors

The last candidate for the product are magnetoresistance sensors. These sensors can measure a magnetic field using the principle of magnetoresistance. When applying a magnetic field to a resistor, its resistance changes and by applying a voltage across the resistors, the magnetic field can be measured. These sensors can also be used to measure the angle and the distance to the conductor. These sensors require no external components, like a magnetic flux concentrator, and are relatively small. This means that multiple sensors can be placed around a three-phase cable and can be used to both measure and locate the multiple cores.

5.1.4 Conclusion

Considering the positive and negative attributes of these types of sensors, the product shall feature **Magnetoresistance sensors.** These sensors will be able to measure the individual magnetic fields generated by the conductors accurately without disturbing the other magnetic fields. Multiple of these sensors will be able to be implemented in order to dynamically locate the conductors in a three-phase cable.

5.2 Amplifier

The output of the magnetic sensor needs to be amplified. This is because the outputs of these sensors typically range in the low millivolts. Therefore, amplifying these signals will make it possible to detect lower currents as well, also will it provide more accurate readings due to the analog to digital converter (ADC) of the micro controller.

Operational amplifiers (opamps) will be utilized in order to provide the necessary amplification for these output signals. The necessary gain and opamp configuration will be determined based on the selected sensor. Based on this data, a suitable opamp shall also be chosen later on in this document.

5.3 Micro controller

Crownstone has requested the use of either the nRF52832 or the nRF52840 micro controller. Crownstone has developed products with these Nordic chips in the past and thus are very familiar with them. They have written firmware for these chips in the past, firmware that will remain usable if newer products are developed using these chips.

It is essential for the product to feature bluetooth connectivity. For this product, a USB connection is also desired. the nRF chips feature both of these connections, therefore this request will not cause any conflicts with the design.

An ADC is also required, since magnetic sensors output an analog signal, this analog signal will need to be translated into a digital signal so that it maybe be output over bluetooth to a smartphone or other bluetooth enabled devices, or via usb.

5.4 Multiplexer

A multiplexer can be soldered on the PCB to ensure the micro controller can handle a large (more than 8) amount of sensors. This large amount of sensors is needed in order to detect the location of the conductors.

A multiplexer can take multiple inputs but only output one of them. This is done through an internal switching circuitry, and the signal can be selected through the use of a few selection pins, the amount of selection pins depends on the amount of possible in- and outputs.

Multiplexers with multiple outputs and different input configurations do exist, however they are not relevant for this product. For this product, multiplexers with multiple inputs and a single output will be used.

For a multiplexer it is crucial that it features a relatively low resistance, in order not to distort the signal too much and cause an inaccurate reading.

5.5 USB

This device shall be mainly USB-powered. Meaning, the input voltage shall be 5V and because it will utilize the USB 2.0 protocol, a maximum current of 500mA will be able to be drawn.

A USB connection is desired for this product. To act as the main power supply and to transmit data. A comparison between a few different connector types shall be made later in this document to determine which connector will be used.

5.6 Board Connectors

The device will be able to be clamped around a three-phase cable, this way, all the magnetic fields around the three-phase cable may be analyzed. In order for this to happen, there needs to be some sort of connection between the two halves. This prototype will not rely on an enclosure as a connection between two halves, it will instead use connectors on the pcb itself. These connectors will provide both a mechanical connection and an electrical connection between the two.

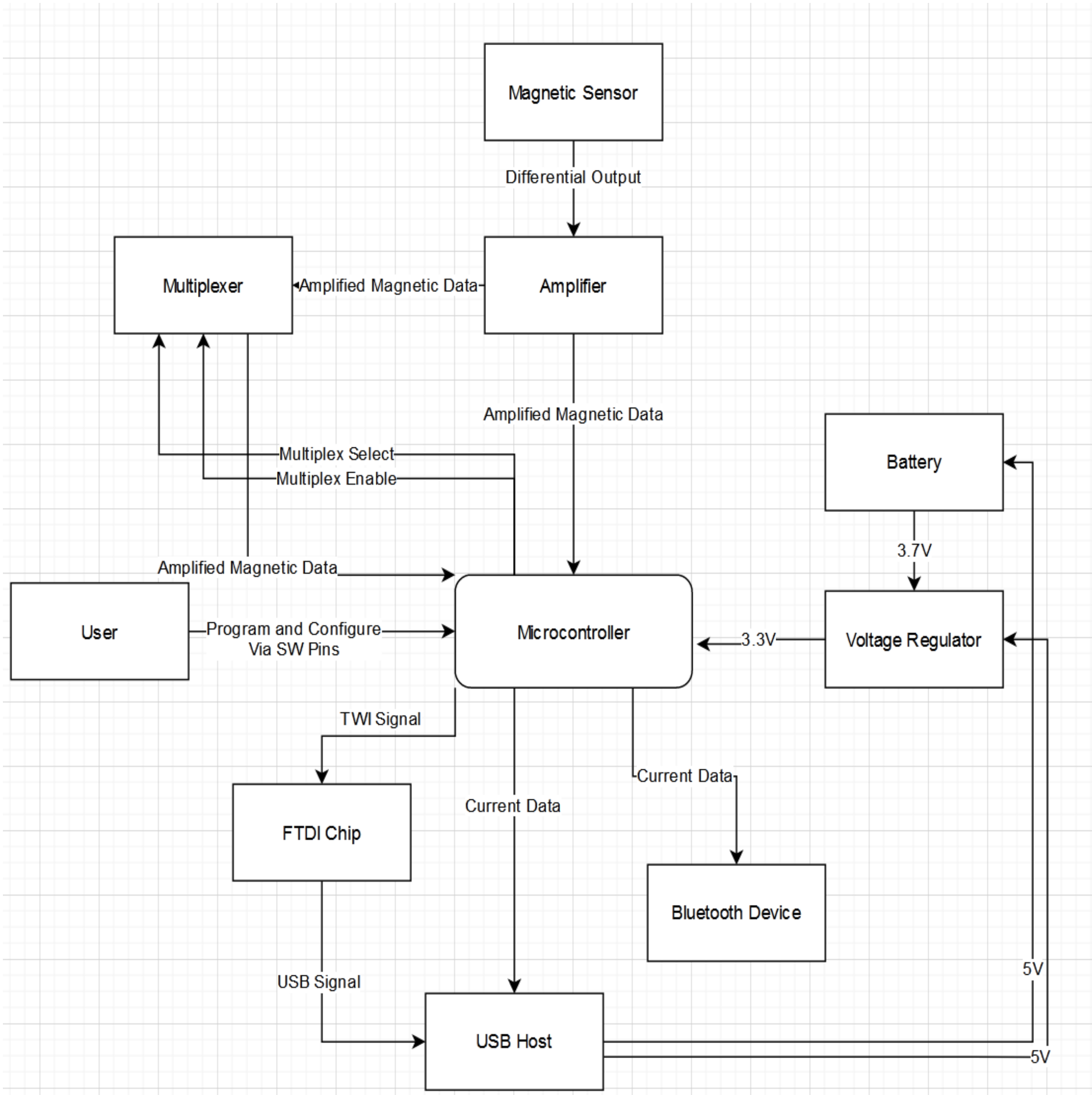


Figure 13: An AID showcasing the connections between units.

5.7 Architecture Interconnect Diagram

Now that the design choices have been made, an architecture interconnect diagram (AID) can be set up. This AID will help illustrate the connections between the units of this system. It also shows the type of connection these units share. The AID can be seen in figure 18.

5.8 Integration Tests

Units	Magnetic sensors & Amplifiers
Equipment	Oscilloscope Oscilloscope probes 5V power supply
Test procedure	- Turn the oscilloscope on - Connect the oscilloscope probes - Connect the product to a 5V power supply - Position the sensors near an alternating magnetic field - Probe the Sensor and corresponding Mux_x testpoints - Verify that the signal is being amplified with a gain of 16 - Repeat this test for every sensor on the board
Conditions	Test is declared successful if all sensor outputs are being amplified with the correct gain of 16.

Units	USB & Magnetic sensors/ Amplifier/ Board connector/ Micro controller
Equipment	USB power supply
Test procedure	- Connect the board to a USB power supply - Use corresponding test points to determine if each unit is receiving power through the USB connection.
Conditions	Test is declared successful if every unit is receiving 5V +-10% from the USB connection.

Units	USB & Micro controller
Equipment	USB host device (laptop) The product
Test procedure	- Connect the board to a USB host device - Verify through the USB host device if the product is connected
Conditions	Test is declared successful if the micro controller is able to be detected by the USB host device.

Units	Board Connector & Magnetic sensors/ Amplifier
Equipment	5V power supply Multimeter in volt mode
Test procedure	- Connect two pcb's together via the edge connectors. - Connect the main pcb (the pcb with the nRF52840 module) to a 5V power supply. - Put the multimeter in volt mode - Use the multimeter to check the supply voltages of each unit.
Conditions	Test is declared successful if the multimeter reads 5V +-10% on every unit.

Unit	Component	Reason
Magnetic Sensor	CT100	Continuous output Accurate differential output
Amplifier	OPA4342	Rail-to-rail in- and output Low input offset
USB Connector	USB Type C	Future-proof Robust connector Better user experience
Micro Controller	IMM-NRF52840 Module	Module for ease of installation This module is relatively easy to implement compared to others No compromises
Board Connector	2058703-1	Suitable edge connector designed to connect multiple pcb's Only one type of connector has to be ordered

6 Design

6.1 Component Selection

This section features a table filled with the chosen components for the design. These components shall be discussed further in the coming sections.

6.2 Magnetic Sensors

Suitable sensors have been found, the RR111 TMR sensor and the CT100 TMR sensor. Both of these sensors feature a linear output and can detect a magnetic field remotely. While the RR111 is cheap and arguably easier to implement, it has obtained the 'obsolete' status, meaning no more new sensors of this type will be produced. The successor to this sensor, the RR112 TMR sensor, only has a maximum sample rate of 100Hz. This is far too low for this project, therefore the RR112 will not be utilized in this project. The CT100 on the other hand features a continuous output. The main difference with the output, however, is that the CT100 features a differential output. Meaning, the actual value of the magnetic field is the difference between the X2 and the X1 pins. See figure 15 for a schematic representation of this sensor. Since the difference between the two pins has to be calculated and amplified, since the output can be in the very low millivolts, a differential amplifier shall be utilized. The amplifier shall be discussed in the next section.

A simple RC high-pass filter will be implemented and both output pins of the sensor shall be connected to these filters. The filter features a cut-off frequency of:

$$Fc = \frac{1}{2 * \pi * 150k * 0.1u} = 10.6Hz \tag{8}$$

This filter is being implemented in order to filter out the DC component of the signals. Figure 14 for a functional block diagram of the sensor. The sensor features a voltage divider, in which the resistance of the resistors change based on the applied magnetic field. This means that there will always be a DC-voltage present on the outputs. Therefore, the outputs shall be connected to RC filters to filter out this DC-voltage.

Another reason the filters are being applied is to filter out the Earth's magnetic field. The Earth has a constant magnetic field in the range of 25 to 65 μT. In order for this magnetic field to not interfere with the current readings, it shall be filtered out.

Conclusion: The CT100 will be used in this design. Its accuracy and sample rate capability make it worth the price.

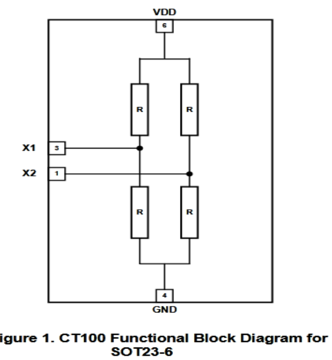


Figure 14: Block diagram of the ct100 sensor.

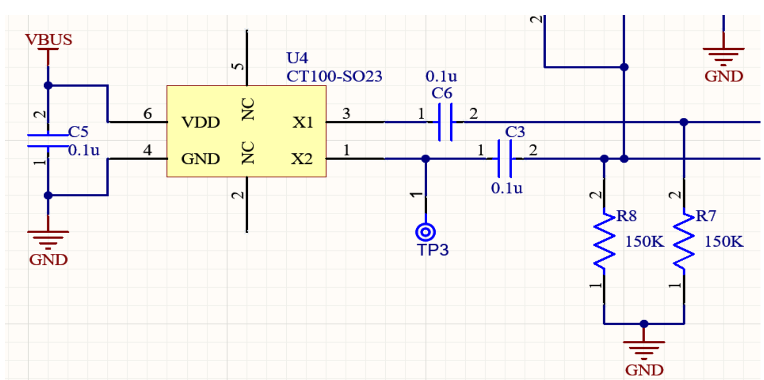


Figure 15: Schematic symbol and connections of the CT100 sensor.

Sensor	Pros	Cons
RR111	Easy to implement Cheap	Obsolete
RR112	Easy to implement Cheap	Sample rate is too low
CT100	Accurate differential output Continuous output	Slightly more difficult to implement Slightly more expensive

Table 4: Design Considerations for the magnetic sensors.

6.3 Amplifier

A differential amplifier has to be utilized in this design. This is for the aforementioned magnetic sensors. For these amplifiers, it is important for them to be single-supply compatible. This is because the micro controller does not accept negative voltages on its analog inputs. Because the sensor's outputs are in the millivolts range, feeding the amplifier with 5V will suffice. With a supply voltage this low, however, it would be desirable for the amplifier to be a so-called rail-to-rail output opamp. Meaning, the amplifier can amplify signals up to (or very near to) its supply voltage. An opamp with this particular feature, and low input offset has been selected: The OPA342 series. Figure 14 shows this opamp in the schematic and its connections.

In order for the micro controller to be able to measure negative currents as well, an offset shall be applied to the amplifier. A reference voltage will be applied to the non-inverting input of the opamp. This reference voltage shall be:

$$Vref = 5V * \frac{1125K}{2000K + 1125K} = 1.8V \tag{9}$$

This means, that if the micro controller reads a value below 1.8V, it shall be treated as a negative value. Vice versa, if the value is above 1.8V, then it shall be treated as a positive value. This all is necessary due to the micro controller not tolerating negative voltages below -0.3V

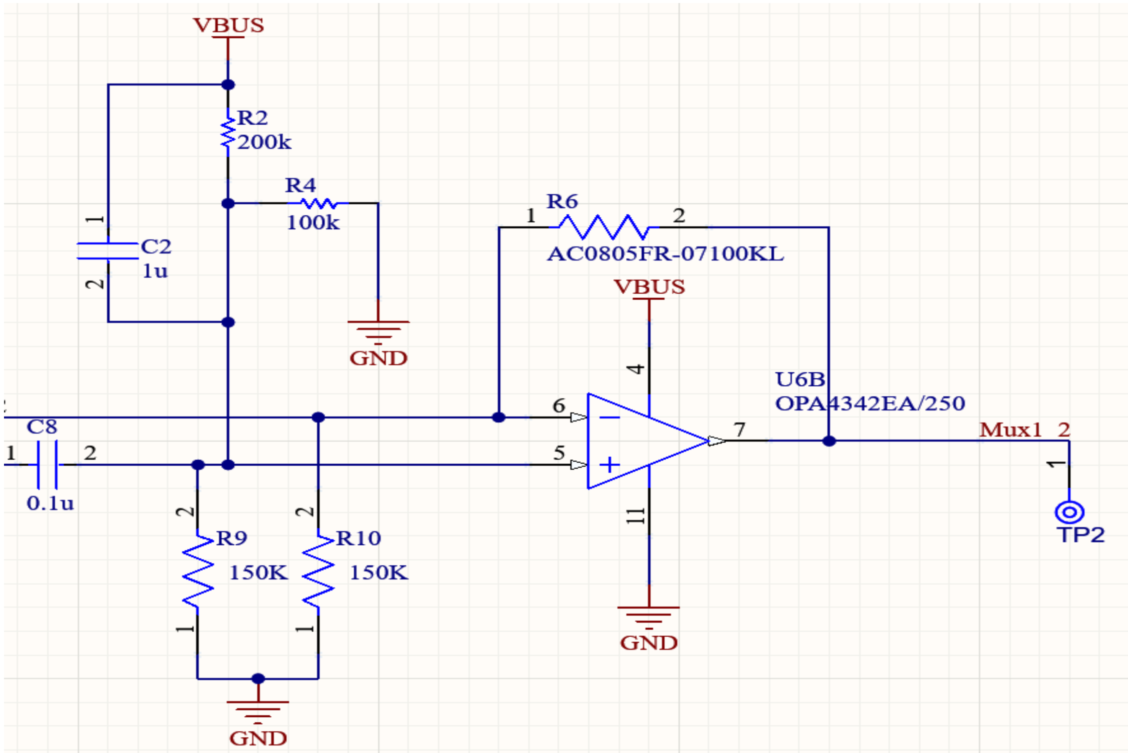


Figure 16: OPA4342 Amplifier in the schematic.

6.4 USB

In this section, a USB connector shall be chosen and then added to the complete circuit of the product. Considering the product will run the USB specification USB 2.0, many different connectors will be able to support the product. For this project, the comparison will be made between these three connectors:

- Mini-USB
- Micro-USB
- USB-C

In table 2, a quick comparison has been made with some pros and cons of each connector. For this product, the USB type C connector has been chosen. It is much more robust than the older generations of USB connectors. Most newer electronic devices that feature USB connectivity are implementing USB type C as well. Although it is slightly harder to implement compared to mini and micro, it is a necessary step in order to, ideally, only need one type of cable in the future. Therefore, picking USB type C can be seen as the most environmental friendly option. Because it can be plugged in both orientations, it is also seen as the most user friendly connector of the three.

The specific connector that has been picked is the USB4110-GF-A. This connector is relatively easy to hand-solder, compared to other USB type C connectors, as this connector features only one row of pins. Figure 17 shows the connector in the circuit.

R67 and R68 are connected to the configuration pins. If the host device detects a current through either of the 5.1k resistors, the host device can figure out the orientation of the cable and consequently turn on the correct VBUS line. F1 Is a fuse that has been added for protection, a maximum current of 500mA has been chosen as that is the maximum current draw of the USB 2.0 specification. C24 has been added for stability, and a ferrite bead has been added as well to filter out unwanted frequencies and provide cleaner power.

Connector	Pros	Cons
Mini-USB	Easy to implement Cheap	Fragile Outdated
Micro-USB	Easy to implement Cheap	Fragile On its way out
USB-C	Robust Better user experience Environmentally friendly compared to other options	Difficult to implement Slightly more expensive

Table 5: A table comparing three USB connectors.

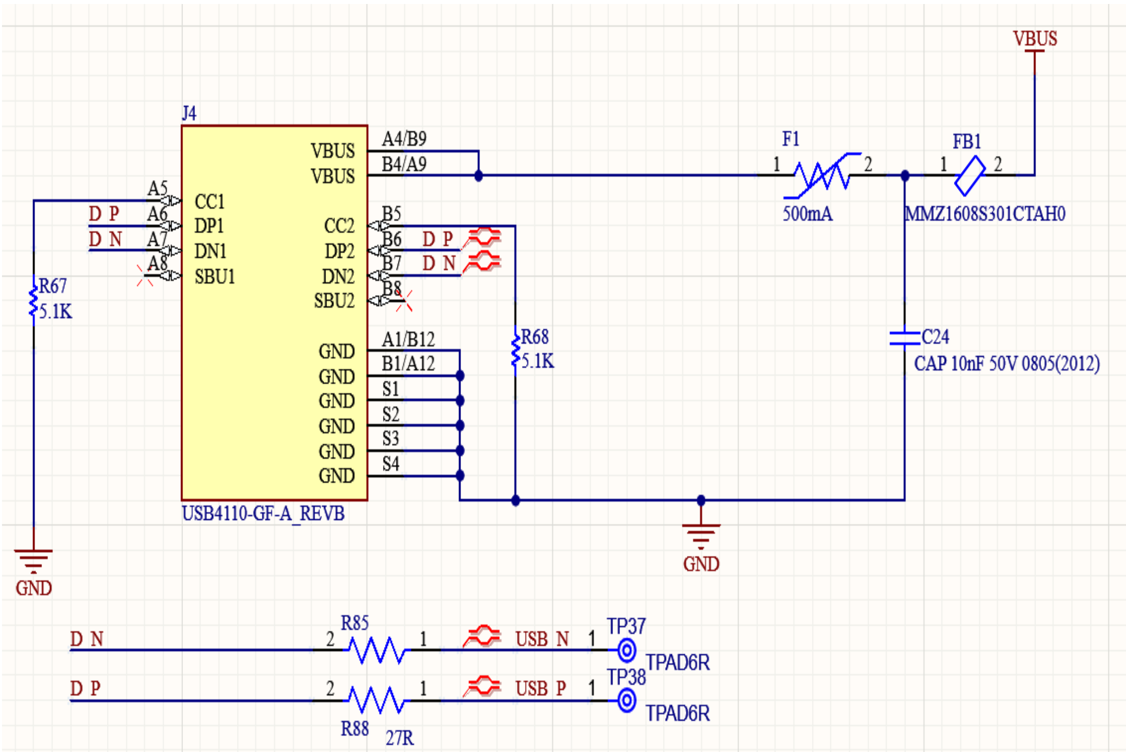


Figure 17: USB type C connector

6.5 Board Connectors

To connect multiple pcb's together, the 2058703-1 has been chosen. This is a hermaphroditic connector specifically designed to connect multiple pcb's together. In order to only need one nRF52840 module, these edge connectors will deliver power to the second pcb. The board will also feature three-pin JST connectors in order to share the magnetic sensor data. Figure 18 shows the power connectors in the circuit and figure 19 shows the data connector.

6.6 Micro Controller

The selected nRF52840 module is the IMM-NRF52840 made by i-syst. This module features all the desired functions for this product. It is also relatively easily to hand-solder when compared to similar modules on the market.

For programming and debugging, the product will feature a j-link connector. This is a 20-pin connector with 2x10 rows of header pins. The pins have been wired according to the diagram on the j-link device itself.

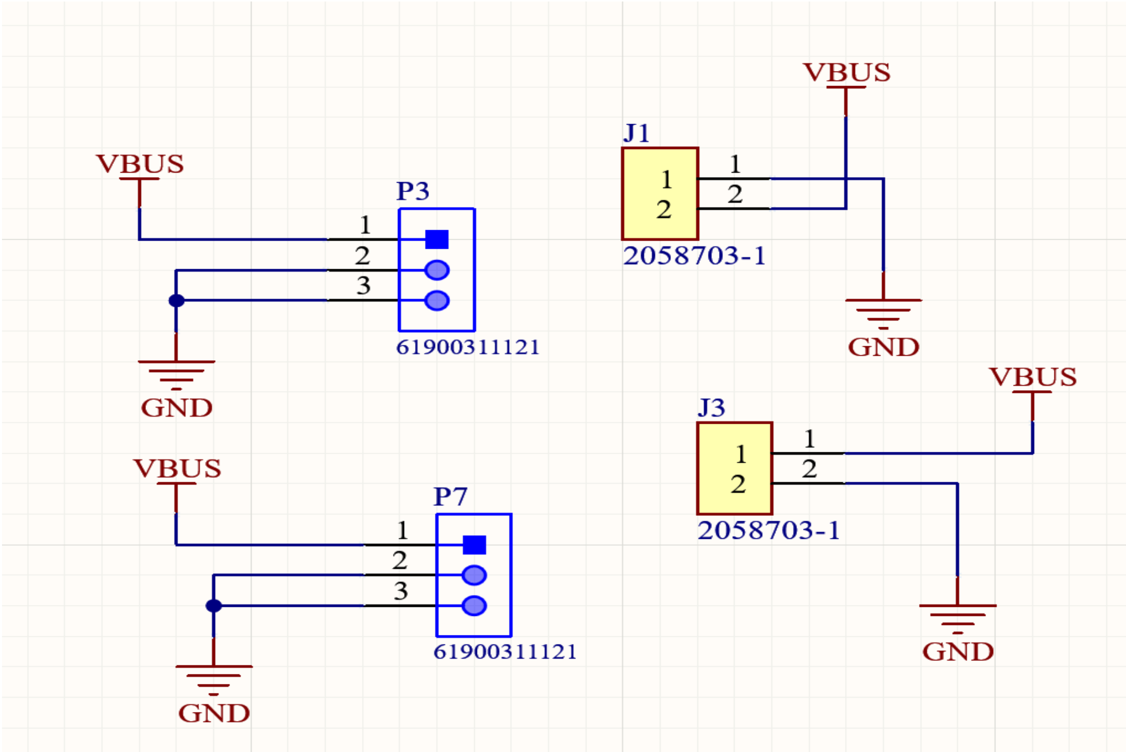


Figure 18: Power Connectors featured on the pcb.

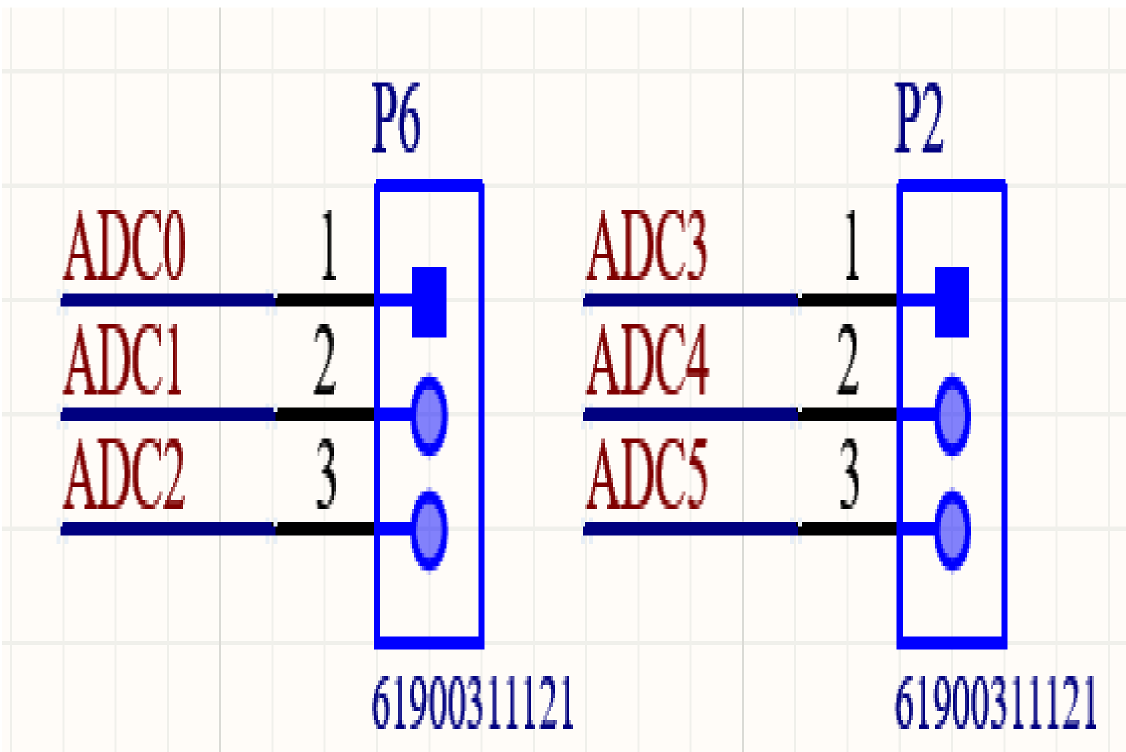


Figure 19: Data connectors featured on the pcb.

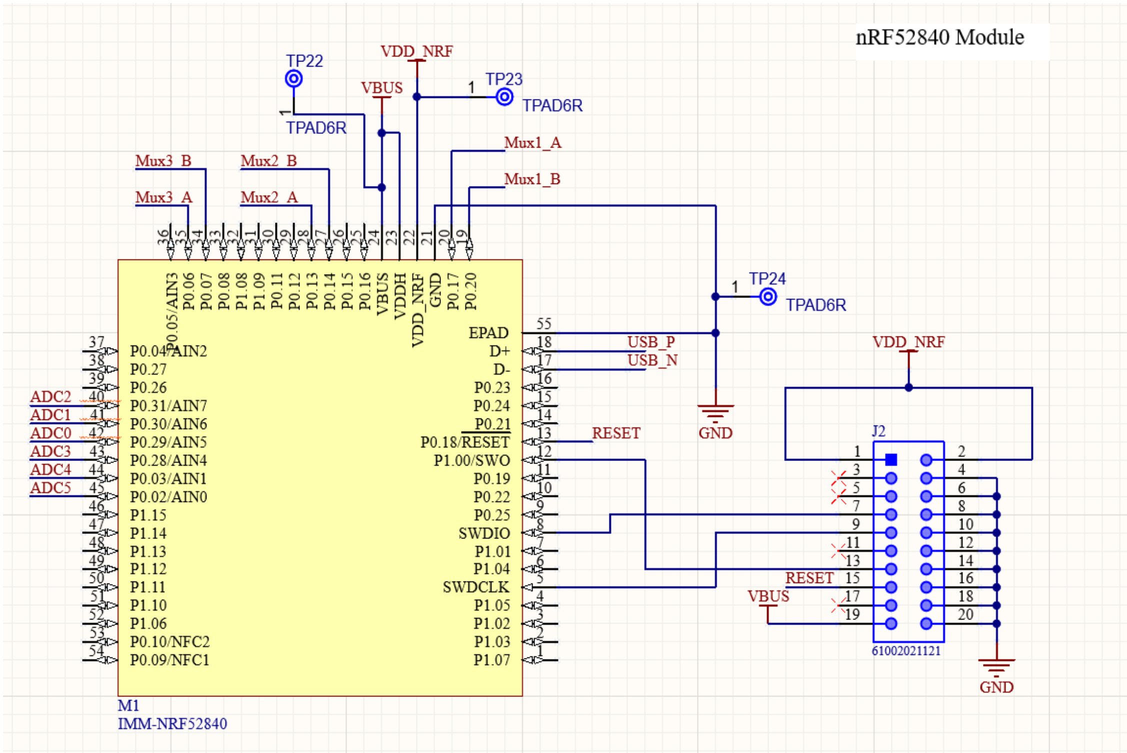


Figure 20: IMM-NRF52840 module in the schematic.

The module has been wired according to the schematic in figure 20. The outputs of the multiplexers have been wired to the AINx input pins of the nRF52840. The multiplexer signal selection pins have been wired to available GPIO pins.

6.7 Unit tests

Unit	Magnetic sensors
Equipment	Lab bench power supply set to 5V Multimeter in volt mode
Test procedure	- Turn on the lab bench power supply and set it to an output of +5V and limit it to 10mA. - Connect the lab bench power supply to the +5V and GND pins on the board. - Put the multimeter probes on the Sensor test point closest to the sensor and put the negative probe on a GND test point. - Confirm the DC voltage across the magnetic sensor. - Repeat this test for every magnetic sensor on the board.
Conditions	Test is declared successful if the multimeter reads 2.5V across every magnetic sensor, indicating that there is a DC voltage across the internal voltage divider of the sensors.

Unit	Magnetic sensor
Equipment	Lab bench power supply Oscilloscope Magnetic source
Test procedure	- Set the lab bench power supply to 5V and limit the current to 20mA. - Connect the power supply to the +5V and GND pins on the board. - Hold a probe to the Sensor test point near the sensor that is being tested. - Put the magnetic source near the sensor. - On the oscilloscope, verify that the sensor is indeed detecting a magnetic field. - Repeat this test for every sensor present on the board.
Conditions	Test is declared successful if every sensor on the board is able to detect a magnetic field.

Unit	Amplifier
Equipment	Lab bench power supply set to 5V Oscilloscope Magnetic source Function generator
Test procedure	- Turn on the lab bench power supply and set it to an output of +5V and limit it to 10mA. - Connect the lab bench power supply to the +5V and GND pins on the board. - Turn on the oscilloscope and connect the probes. - Turn on the function generator and connect the probes. - Put the function generator channel 1 on Sine wave mode, with a Vpp of 100mV and frequency of 50Hz. - Put the function generator channel 2 on Sine wave mode, with a Vpp of 110mV and frequency of 50Hz. - Connect the output of both function generator channels to the inputs of the amplifier. channel 1 to the non-inverting input and channel 2 to the inverting input. - Connect the oscilloscope probe to the output of the amplifier and the ground clip to a GND pin on the board. - Verify the output of the amplifier on the oscilloscope. - Verify that the amplifier is correctly working as a differential amplifier and that the output is the difference of the two signals amplified by 16. - Repeat this test for all the amplifiers present on the board.
Conditions	Test is declared successful if every amplifier correctly amplifies the difference of 10mV by 16, resulting in a signal with a Vpp of 160mV.

Unit	USB
Equipment	Multimeter Multimeter probes with thin tips USB power supply
Test procedure	- Ensure the multimeter is set to continuity mode. - Probe the USB type C connector pins with the corresponding test points (USB_N and USB_P) and listen for the audible beep. - Repeat this procedure for the VBUS pins and the GND pins. - Sweep the pins looking for possible shorts. - Connect the board to a USB power supply. - Switch the multimeter to volt mode. - Measure the voltage across the USB connector.
Conditions	Test is declared successful if: - There is continuity in the aforementioned pins and test points. - No shorts between the USB type C connector pins. - A voltage of +5V +-10% is present across the connector.

Unit	Board connector
Equipment	Lab bench power supplyMultimeter
Test procedure	- Set the lab bench power supply to 5V and limit the current to 20mA. - Put the multimeter in continuity mode - Probe the edge connectors (J1 and J3) and check for continuity on the +5V and GND pins. - Connect the lab bench power supply to the +5V and GND pins on the board. - Put the multimeter in volt mode and check the voltage across each connector.
Conditions	Test is declared successful if there is continuity on the 5V and GND connections and if a voltage of 5V is measured across both connectors.

Unit	Micro controller
Equipment	Multimeter Lab bench power supply
Test procedure	- Put the multimeter in continuity mode. - Using the test points located around the module on the board, check for continuity to ensure the module is soldered properly, these test points are: 1. NRF_GND 2. USB_N and USB_P 3. NRF_VBUS 4. VDD_nRF - Set the lab bench power supply to +5V and limit the current to 50mA. - Using test points NRF_VBUS and NRF_GND, measure the voltage across the module.
Conditions	Test is declared successful if continuity is detected and if the voltage across the module reads +5V +-10%

Unit	Micro controller
Equipment	A desktop pc or laptop J-link programmer
Test procedure	- Connect the J-link device to the board and the pc or laptop. - Run nRF Connect on the computer. - Select an example code file for this test. - Upload example code to the nRF52840.
Conditions	Test is declared successful if the nRF52840 module is programmed successfully.

6.8 Schematic

Figure 21 shows the complete schematic.

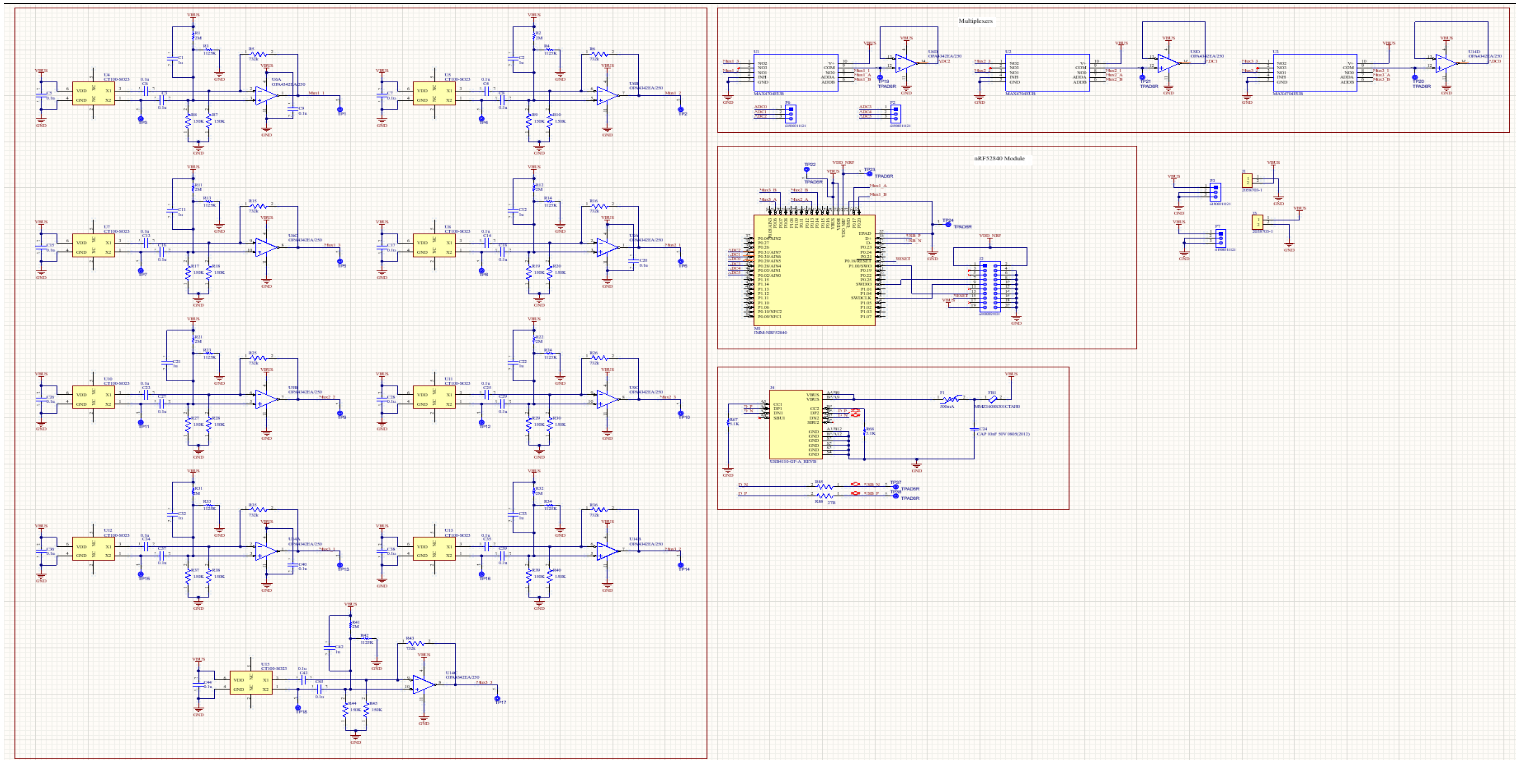


Figure 21: Complete schematic.

6.9 PCB

Figure 22 shows the pcb that has been designed.

7 Test Results

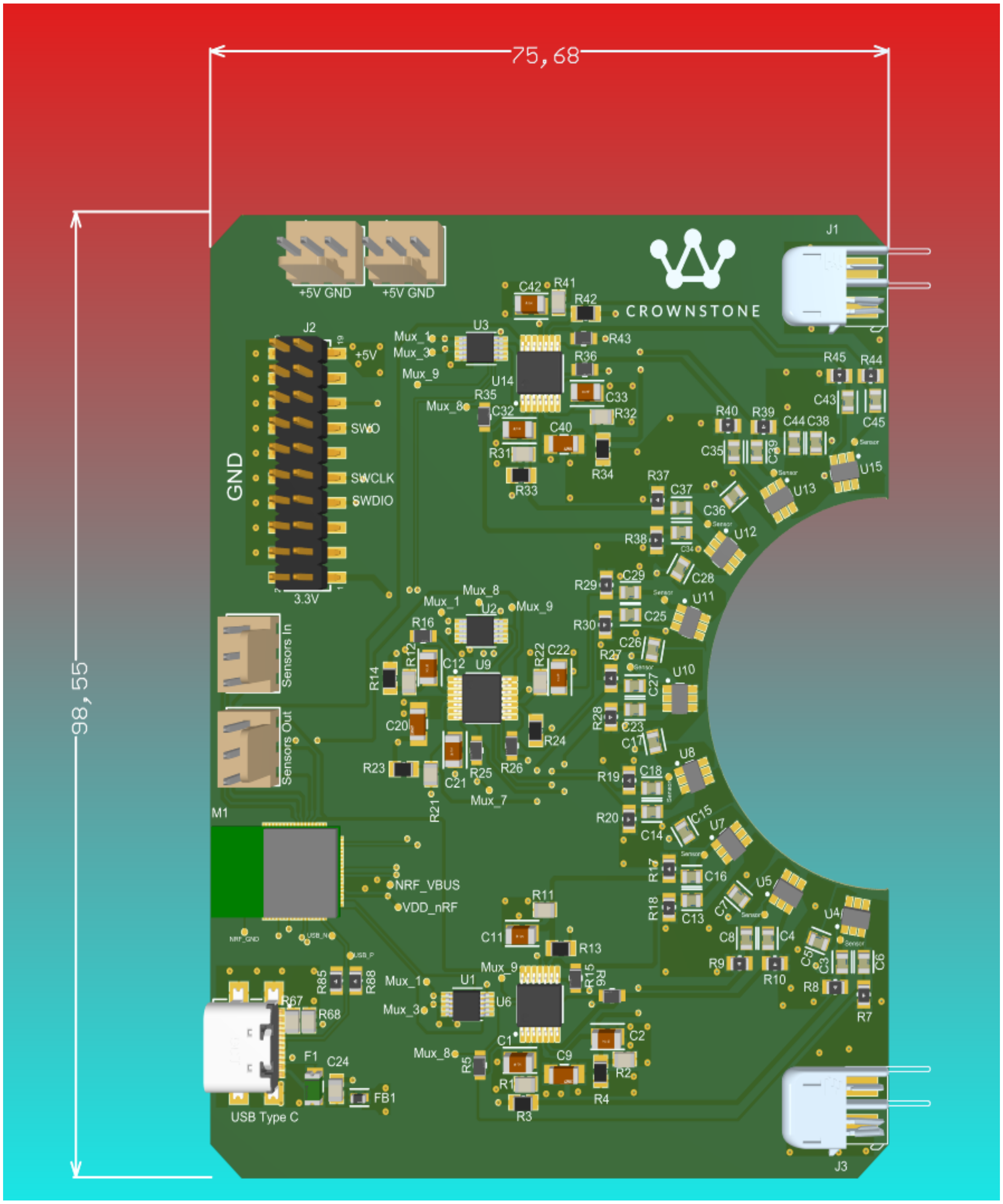


Figure 22: The PCB.

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