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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2.1 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 circuit 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 of this simple using formula 1.

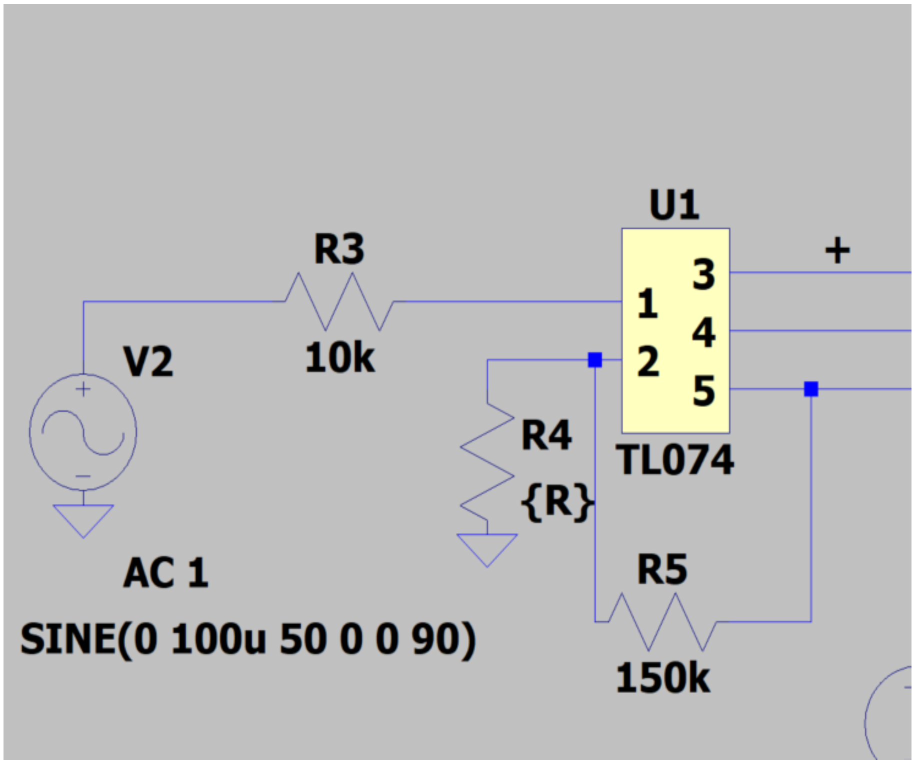


Figure 1: Amplifier using a TL074 op amp.

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

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.

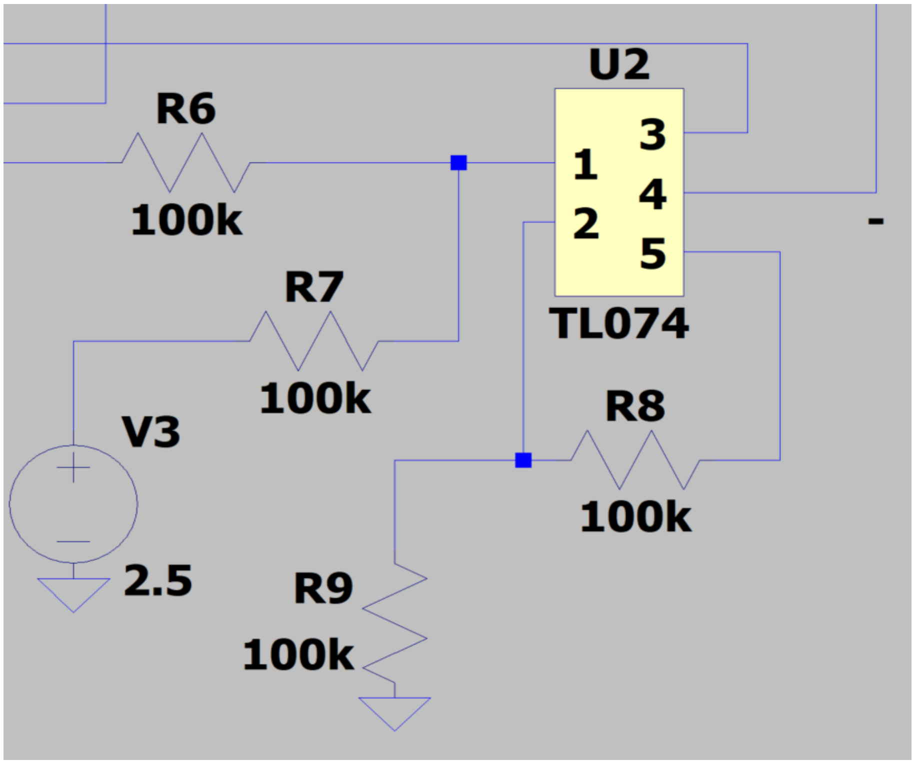


Figure 2: Level shifter using a TL074 op amp.

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.

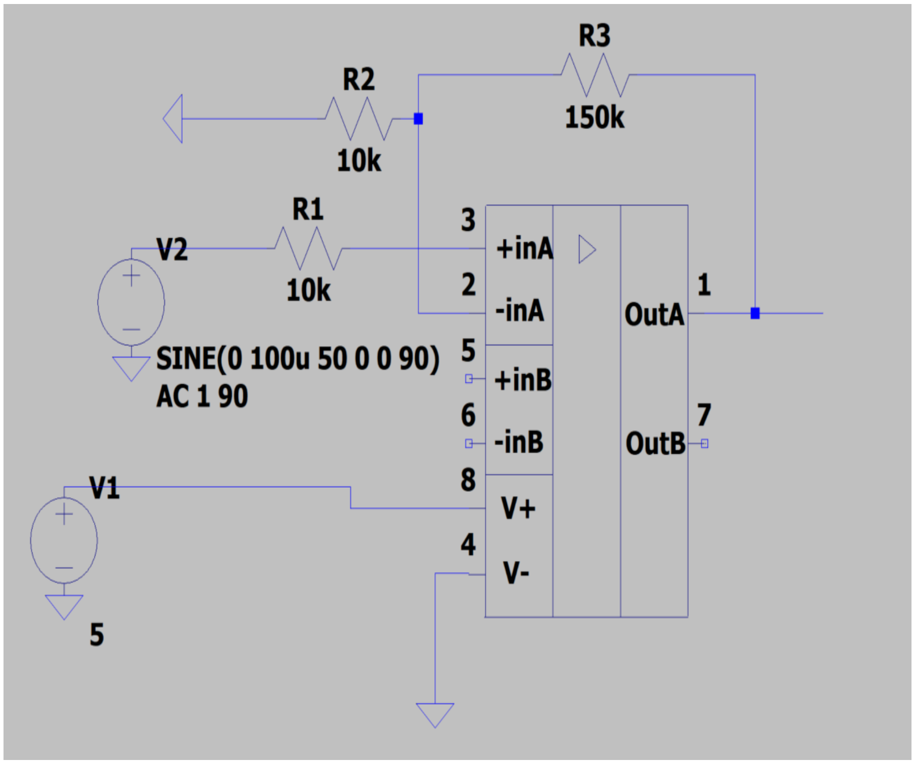


Figure 3: Amplifier using OPA2342 op amp.

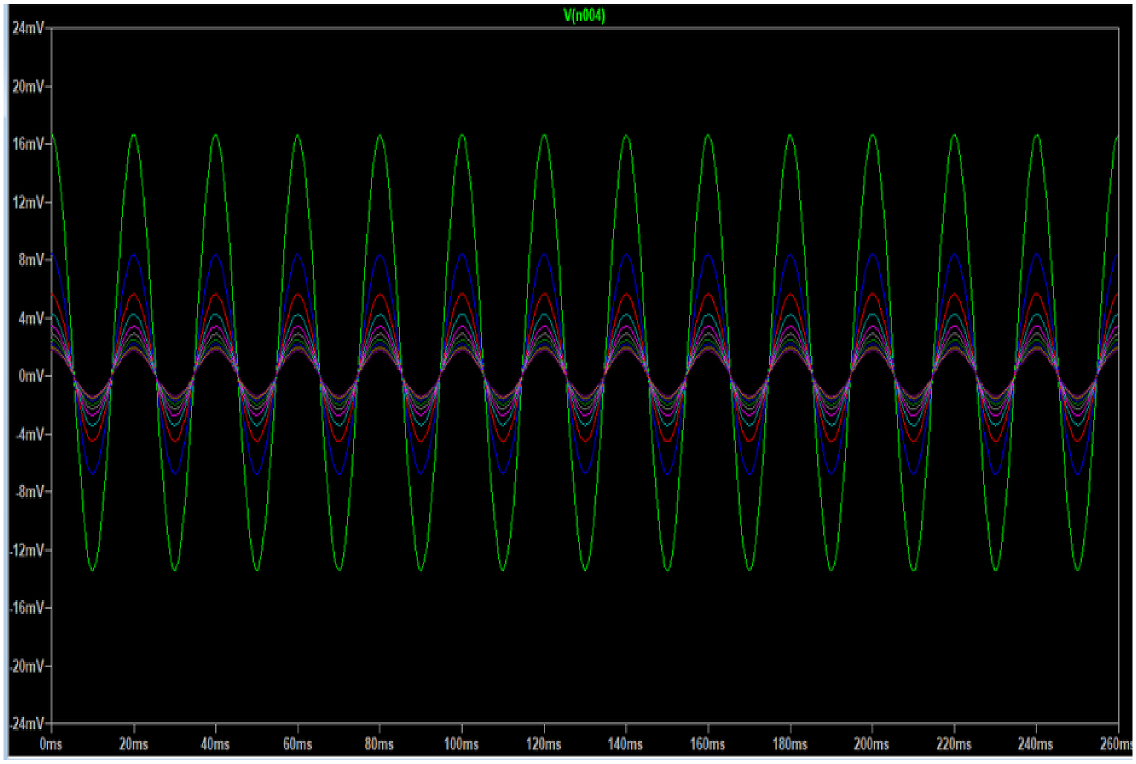


Figure 4: TL074 resistance sweep

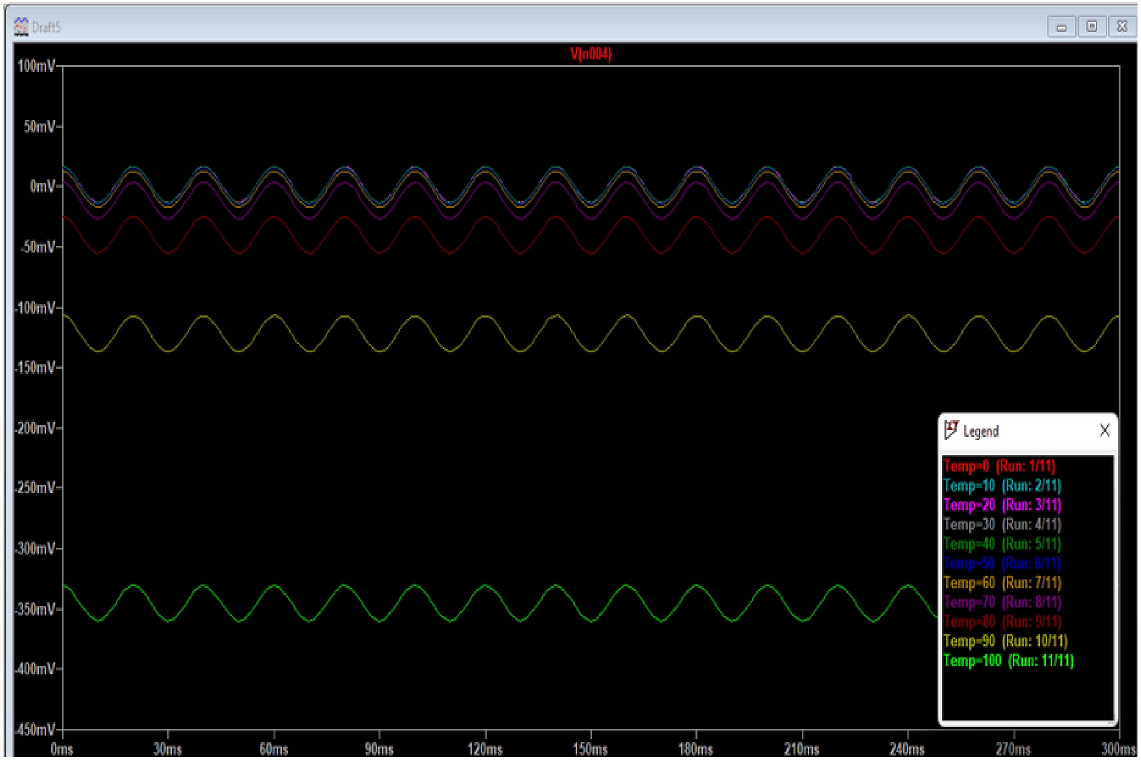


Figure 5: TL074 temperature sweep

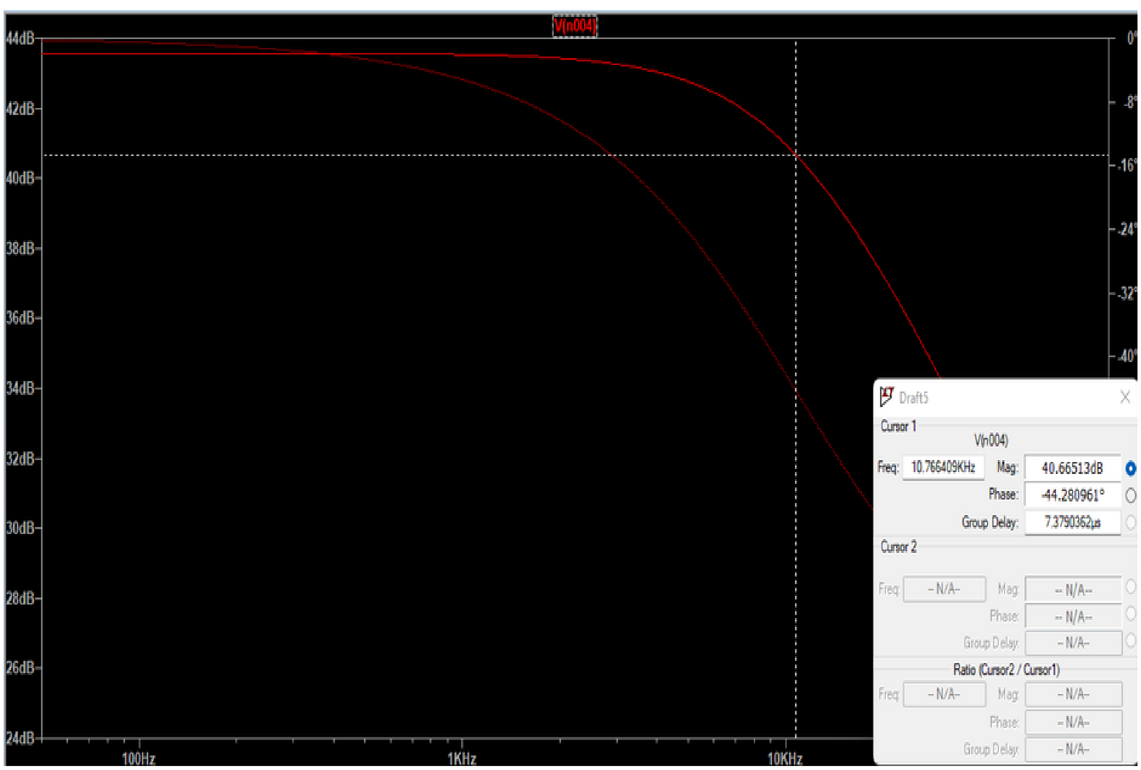


Figure 6: TL074 frequency sweep

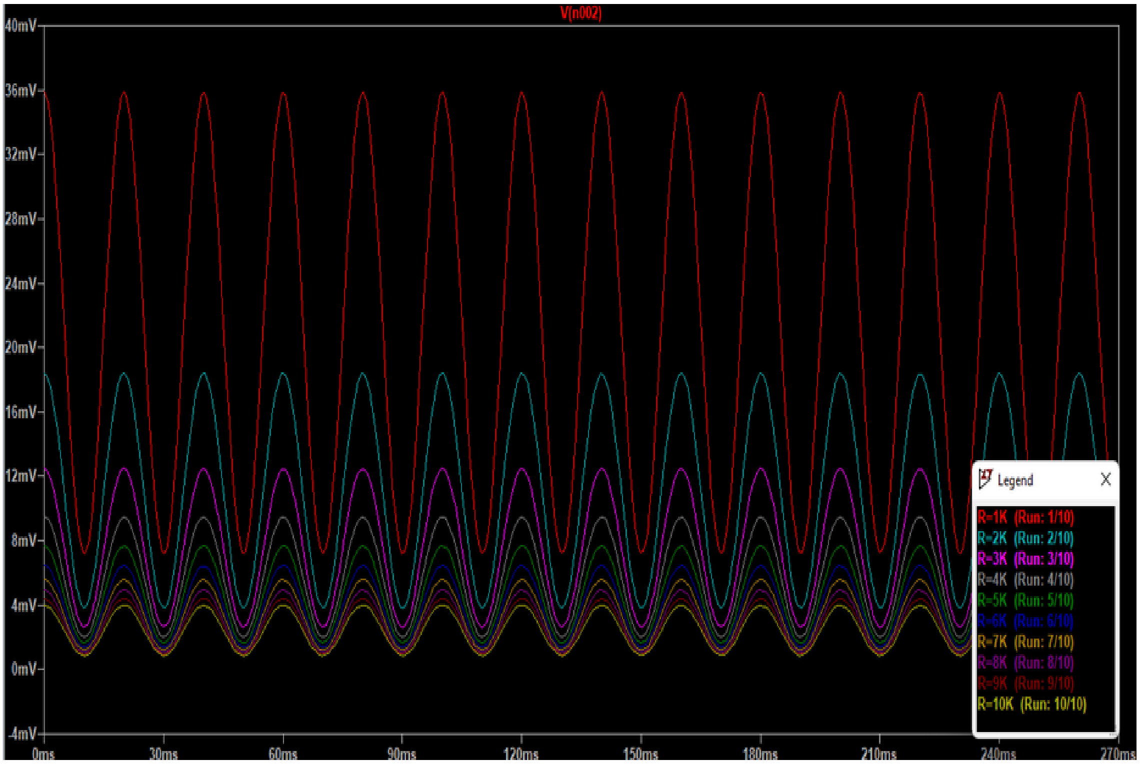


Figure 7: OPA2342 Resistance sweep.

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.

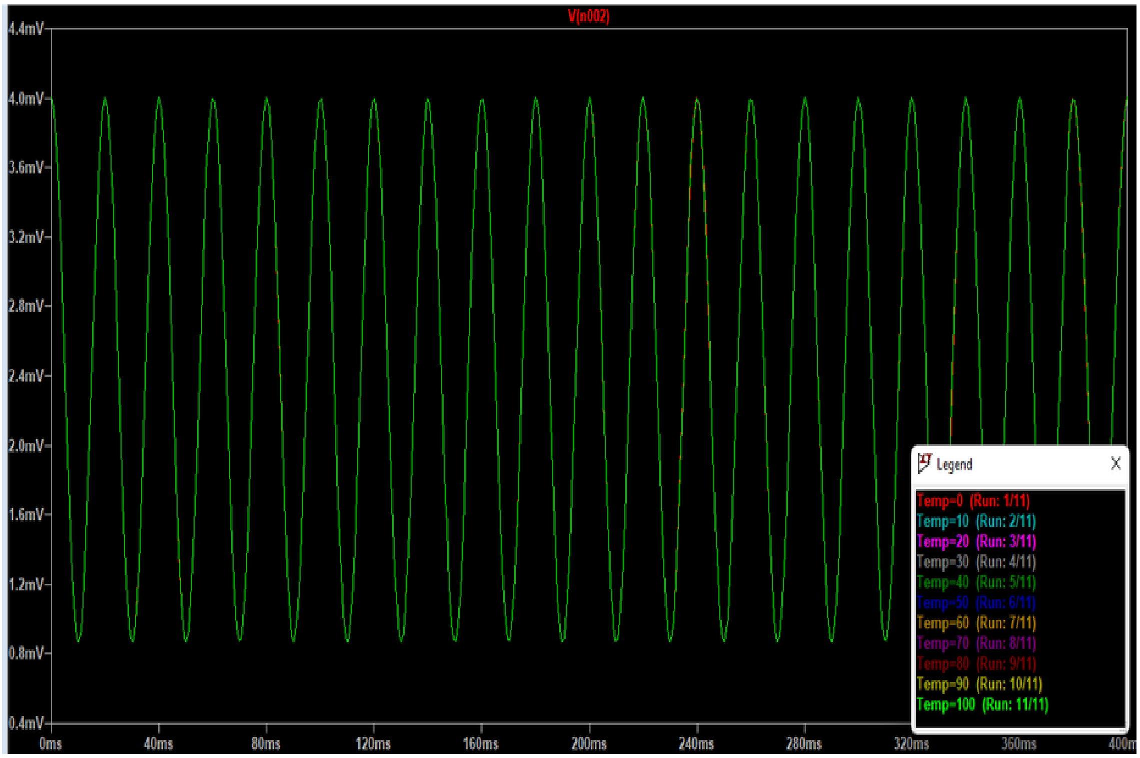


Figure 8: OPA2342 Temperature sweep

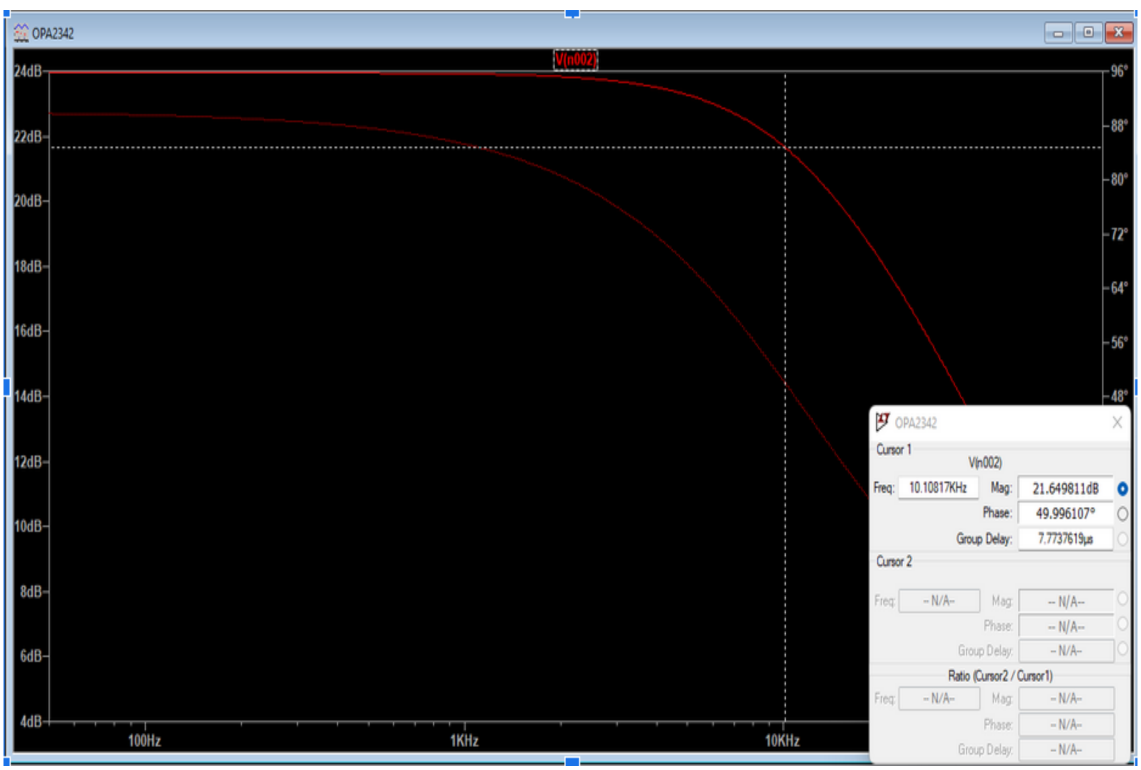


Figure 9: OPA2342 frequency sweep

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]

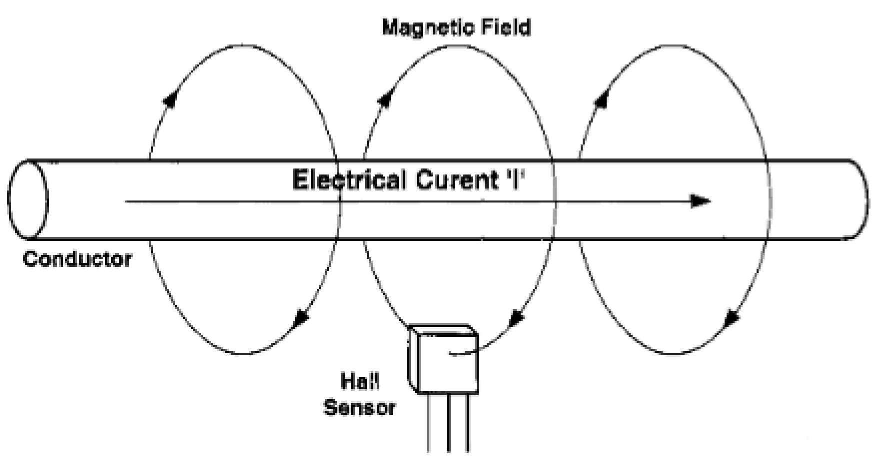
Hall effect sensors will measure the changing voltage across this material. With this method, the sensor can detect that is in a magnetic field.

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.

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, together with the fact that the nRF has Bluetooth functionality, Crownstone has a strong preference for these chips.

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.

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-9: 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.

REQ-10: The product should have a back-up battery power supply.
In case the main power supply ceases to supply the necessary power to the product, for example because of a temporary disconnect, the product would be able to continue measuring current while running on a back-up power supply.

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:

REQ-13: 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.

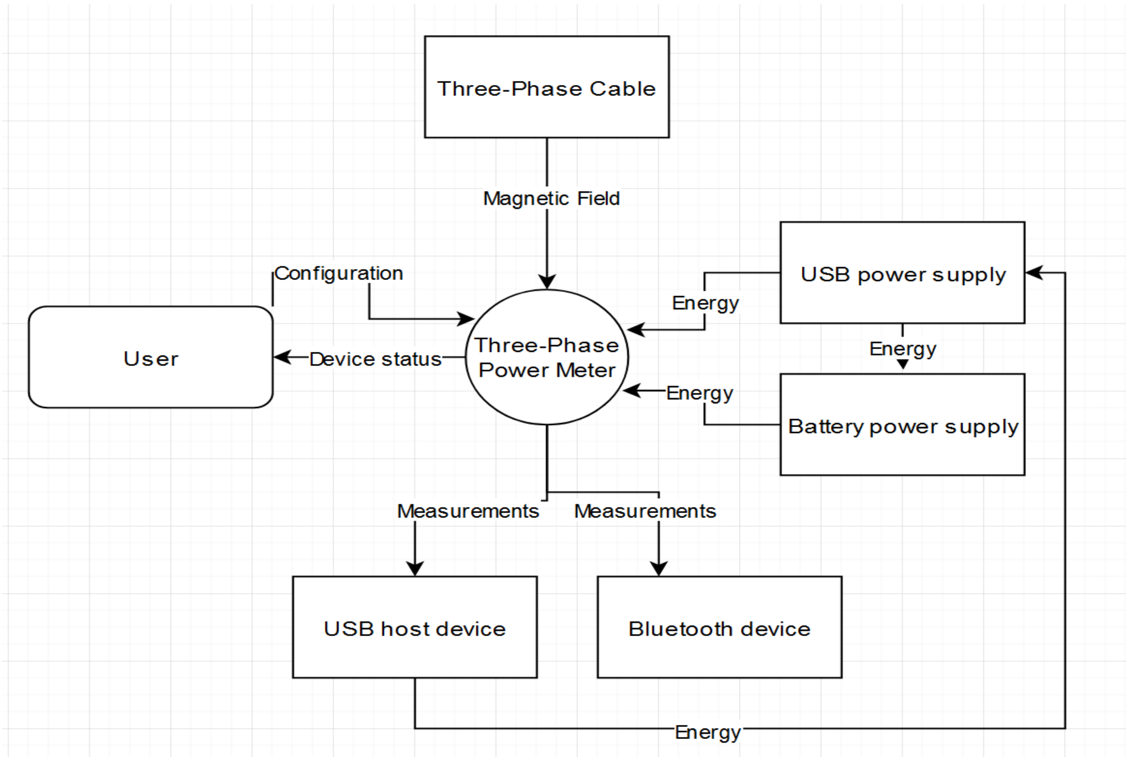


Figure 10: A Data Context Diagram of the system.

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.

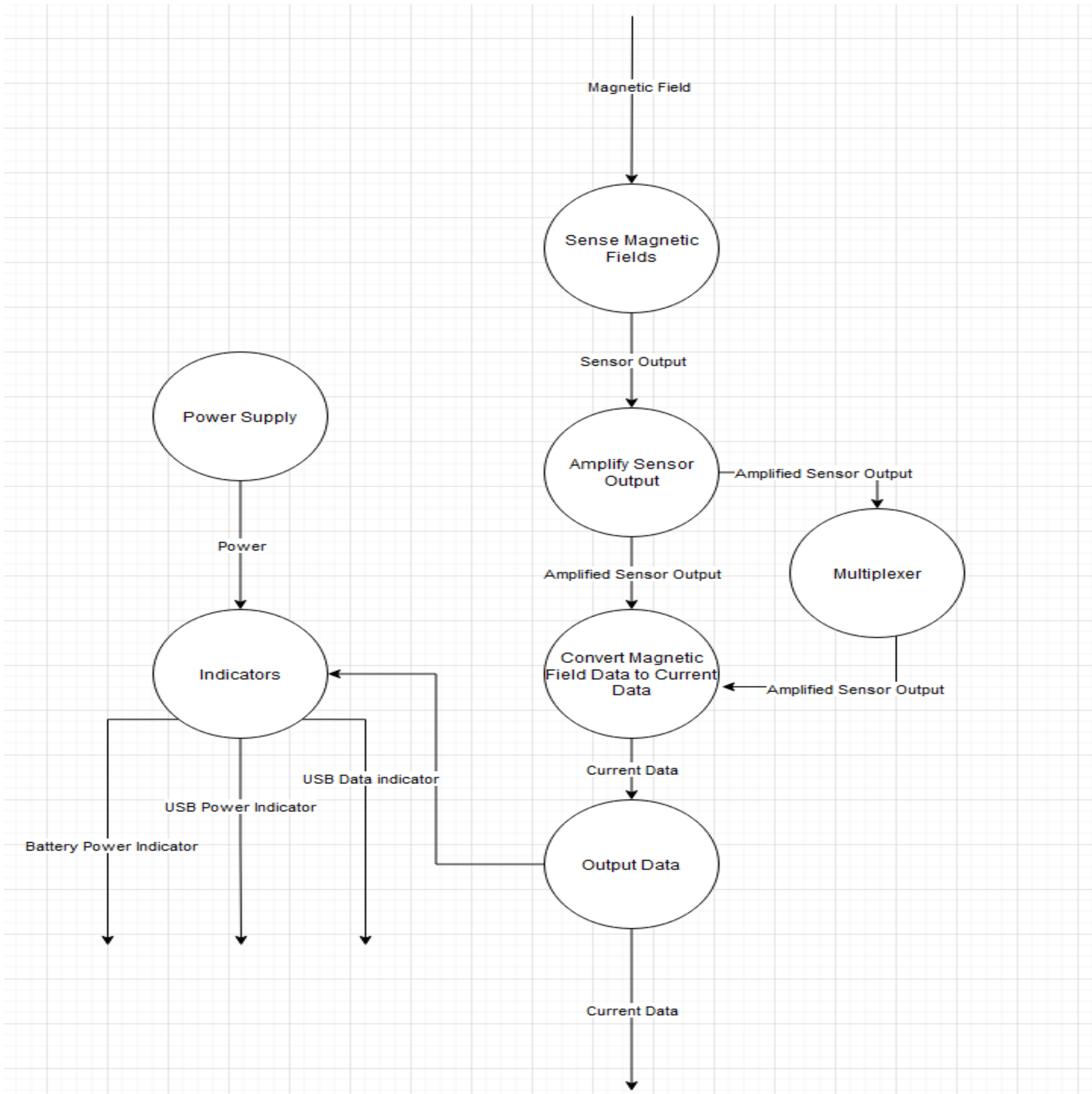


Figure 11: A Data Flow Diagram of the system.

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.

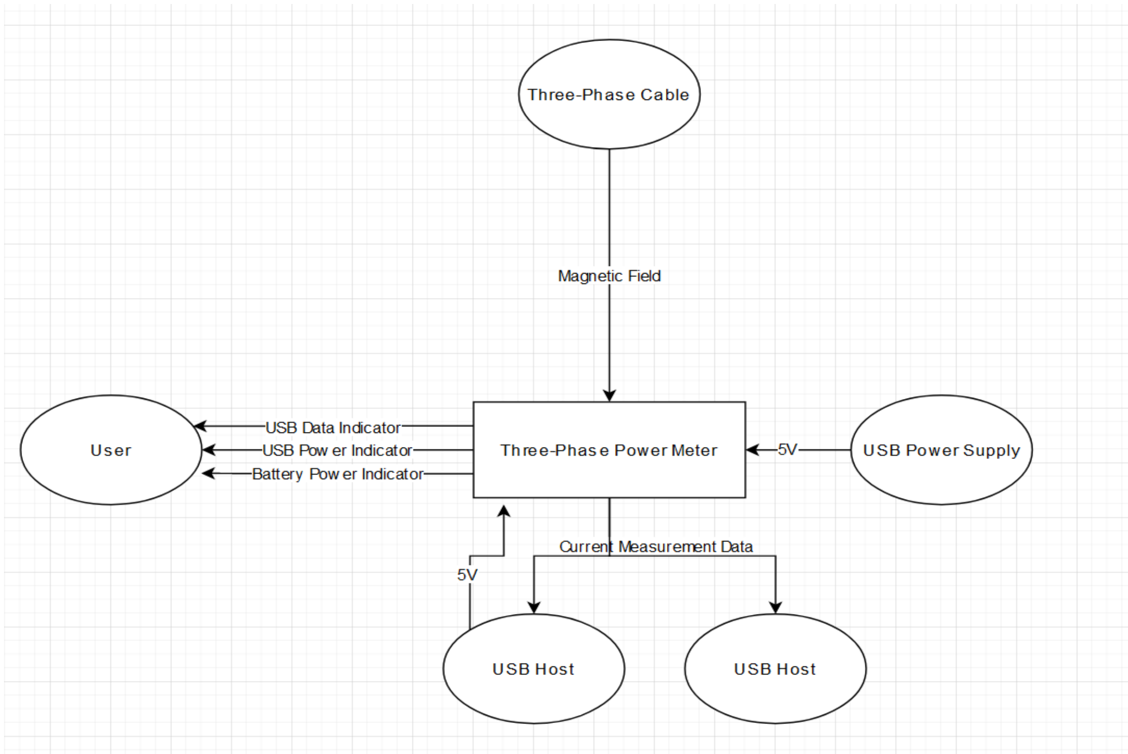


Figure 12: An ACD Describing the inputs and outputs of the system.

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
- Power Supply
- USB

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. 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

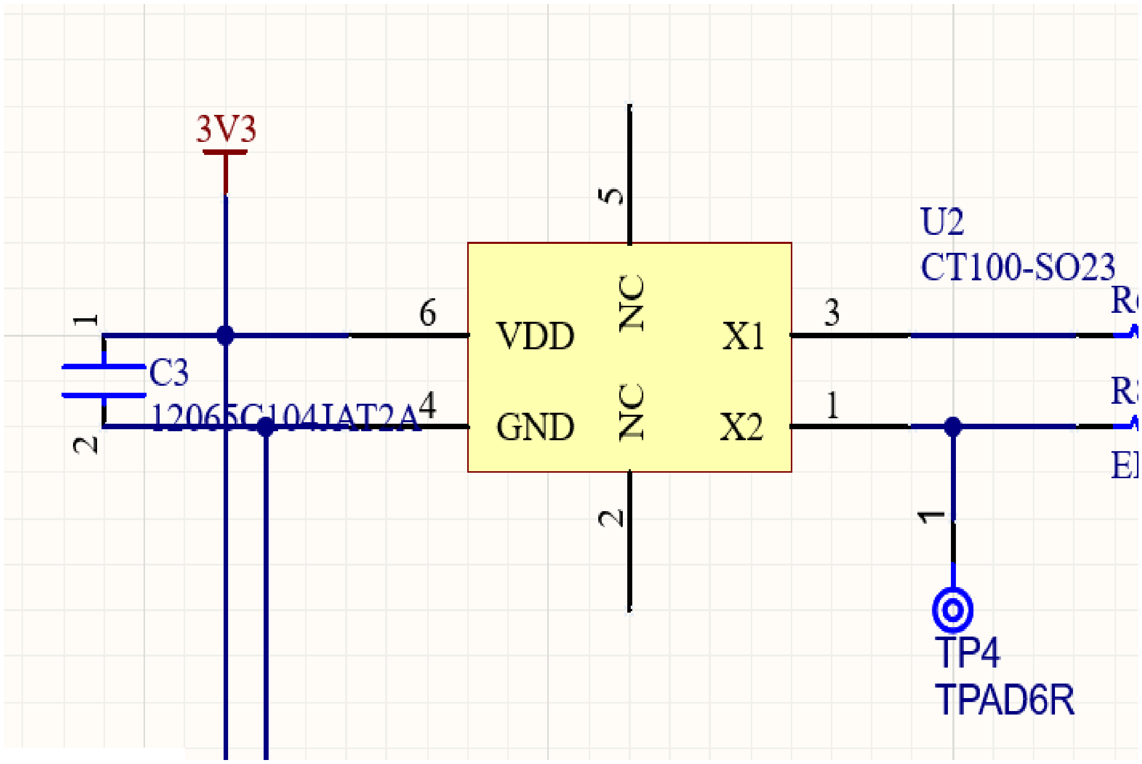


Figure 13: Schematic symbol and connections of the CT100 sensor.

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 13 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.

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

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 1: Design Considerations for the magnetic sensors.

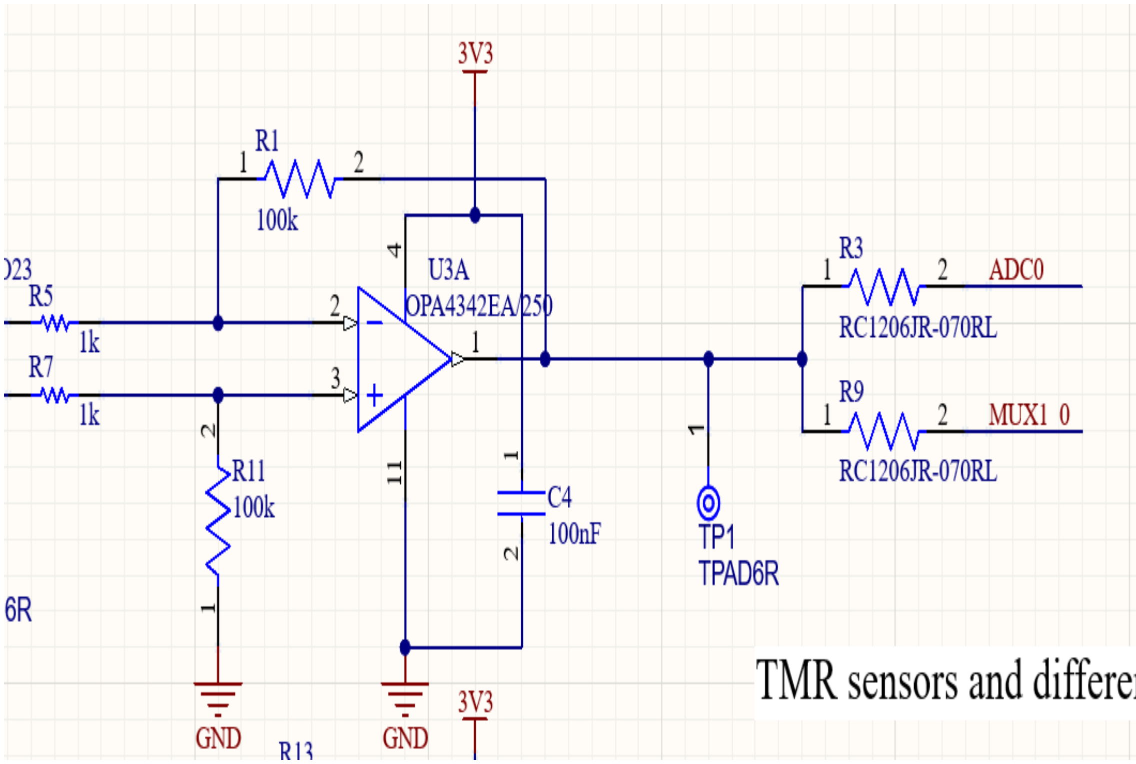


Figure 14: OPA4342 Amplifier in the schematic.

5.2 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 3.3V should suffice. With a supply voltage this low, however, it would be desirable for the amplifier to be a so-called rail-to-rail 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. Similar values have been chosen for R1 and R11, and the same applies to R5 and R7. Because of this, the gain can be very easily calculated as such:

$$Gain = \frac{R1}{R5} \tag{8}$$

So according to this formula, the selected gain of this amplifier is 100. Considering the very low outputs of the CT100, this is a suitable gain.

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. However, it became apparent that they are approaching the limits of the nRF52832's memory. So a slightly stronger preference was given for the nRF52840. To add to this, the nRF52832 does not support USB in any of its packages. Considering this, the nRF52840 micro controller shall be used.

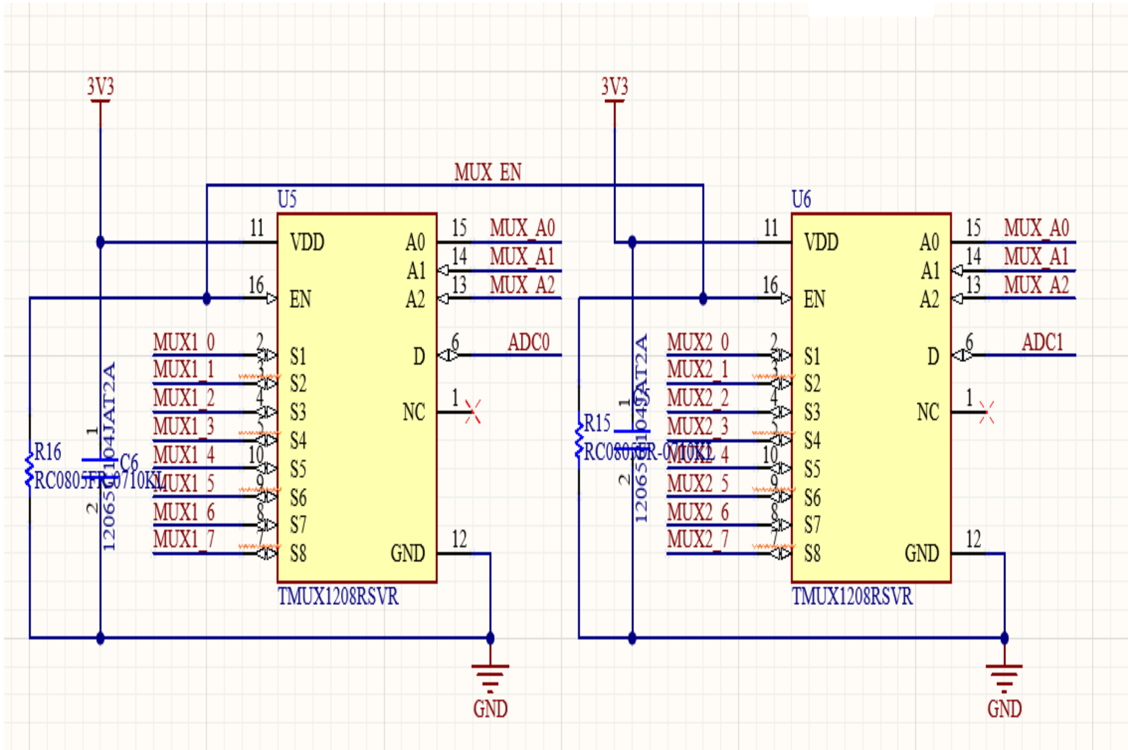


Figure 15: TMUX1208 multiplexer in the circuit's schematic.

However, another choice remains to be made. The stakeholder has made it clear that a module may be used to ease the design process. Since there are no size restrictions, both methods (module and own micro controller circuit) will be able to be utilized in this product. Also, for creating a micro controller circuit, the QFN48 package shall be used instead of the aQFN73 or WLCSP packages. This is not only for the sake of easier soldering, but also for manufacturing. The latter packages require a much more expensive manufacturing process due to via's hidden under the system-on-chip (SoC).

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. It is important to select a multiplexer featuring low resistance, in order to not distort the incoming analog signal so much that it differs vastly from the original signal. A 8:1 1-channel multiplexer with a low on-resistance of 5 ohms has been selected. This multiplexer also features a tiny supply current of 10nA. Furthermore, just like the amplifier, it features Rail to Rail operation. The selected multiplexer is the TMUX1208 by Texas Instruments. Figure 15 shows the multiplexer in the circuit's schematics.

5.5 Power Supply

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 maxium current of 500mA. The nRF52840 QFN48, however, does not accept 5V on its input. Thus, a 3V3 regulator must be used in order to satisfy the power supply needs of the SoC. The chosen chip for this will be the MCP1602. This is a chip with high efficiency (over 90%) and output current up to 500mA, which matches the USB 2.0 spec. It features a fixed output voltage of 3.3V and several safety features which shall be beneficial to this product. The chip has been connected to the circuit following the datasheet's recommended application. The circuit can be seen in figure 16.

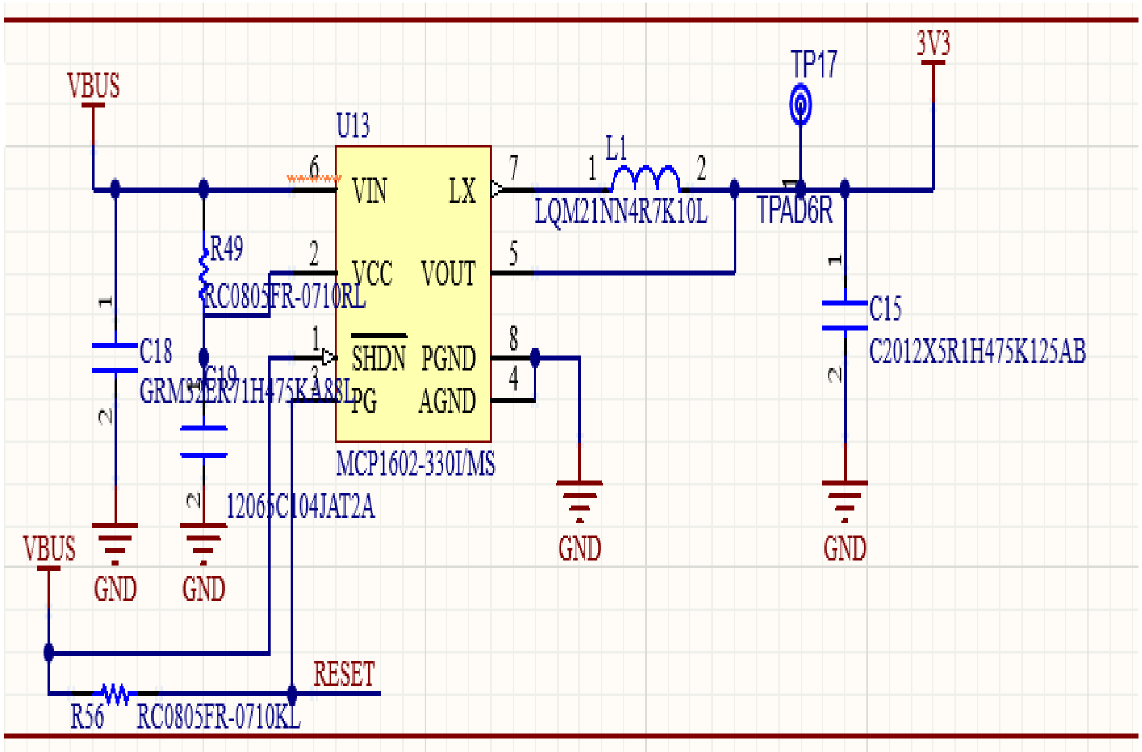


Figure 16: 3V3 Regulator Circuit

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 2: A table comparing three USB connectors.

5.6 USB

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 to determine which connector will be used.

In conclusion, for the USB connector, USB-C shall be utilized. The positives outweigh the negatives for this design choice.

When utilizing an nRF52840 circuit instead of a module, an FTDI chip has to be used as well. This is because the nRF52840 QFN48 package does not natively support USB. Therefore, an FTDI chip is needed to convert the serial data to data that is usable by the SoC. The FT201XS-U shall be utilized in this design. This is a chip that can be powered by the USB VBUS power, and has its own 3.3V/1.8V LDO converters for its own I/O. This chip converts USB data to I2C data, and since the nRF52840 features TWI capability, the data can be sent to the SoC. Also, no external clock is required as this chip has its own internal crystal.

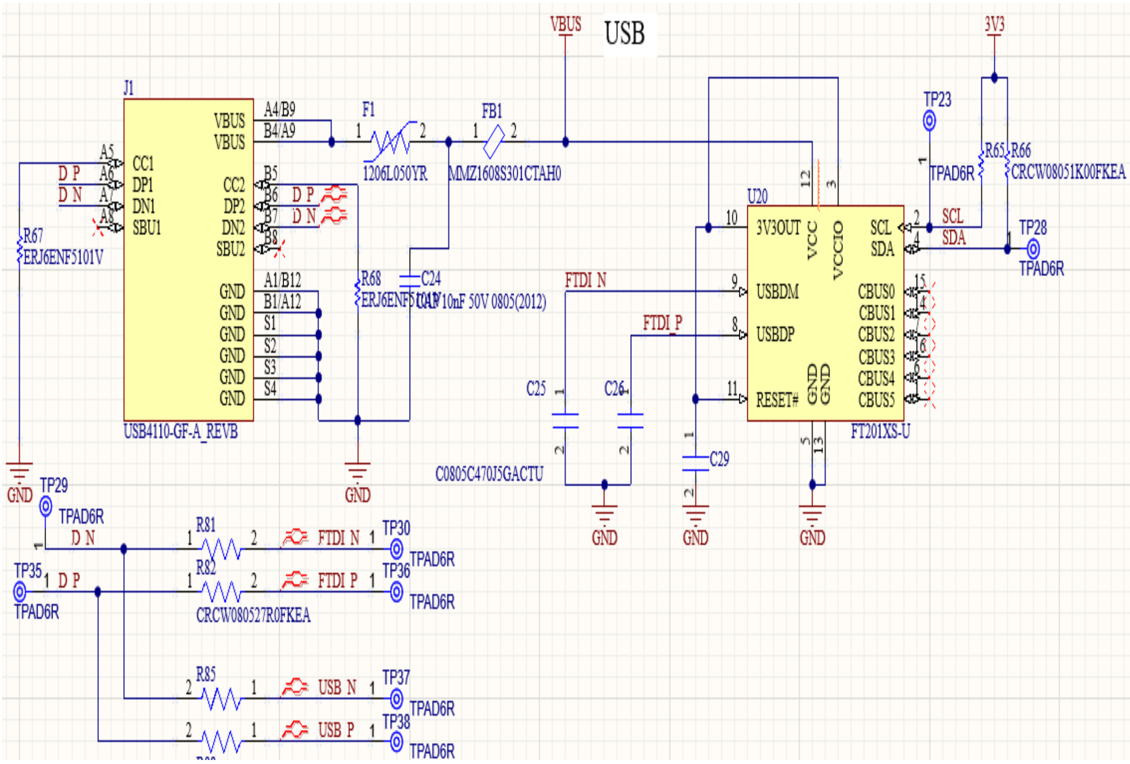


Figure 17: The USB connector and the FTDI chip.

A low supply current also makes this a very suitable chip.

Figure 17 shows the chip integrated into the circuit. The chip has been connected according to the datasheet's specifications and recommended applications. It also shows the USB-C connector. This has also been wired according to USB 2.0 specifications, with the CC pins acting as configuration pins, so that the host device may detect the orientation of the cable.

References

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