Research

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February 2022

1 Introduction

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.

2 Rogowski Coils

2.1 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.

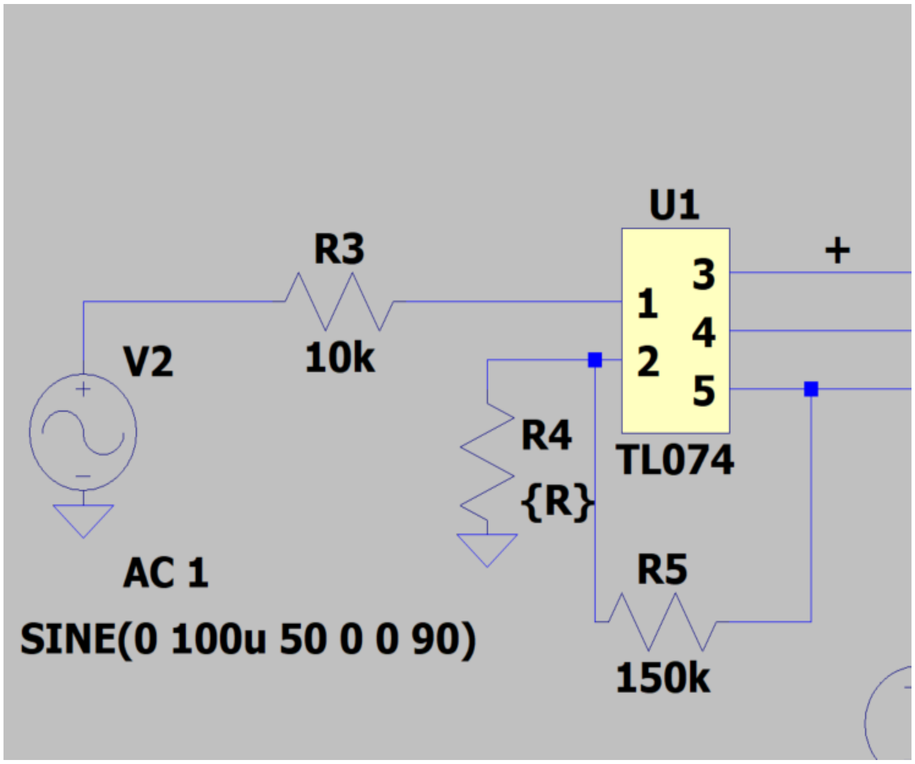


Figure 1: Amplifier using a TL074 op amp.

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.

2.2 Circuits

2.2.1 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.

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

2.2.2 TL074 Level Shifter

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.

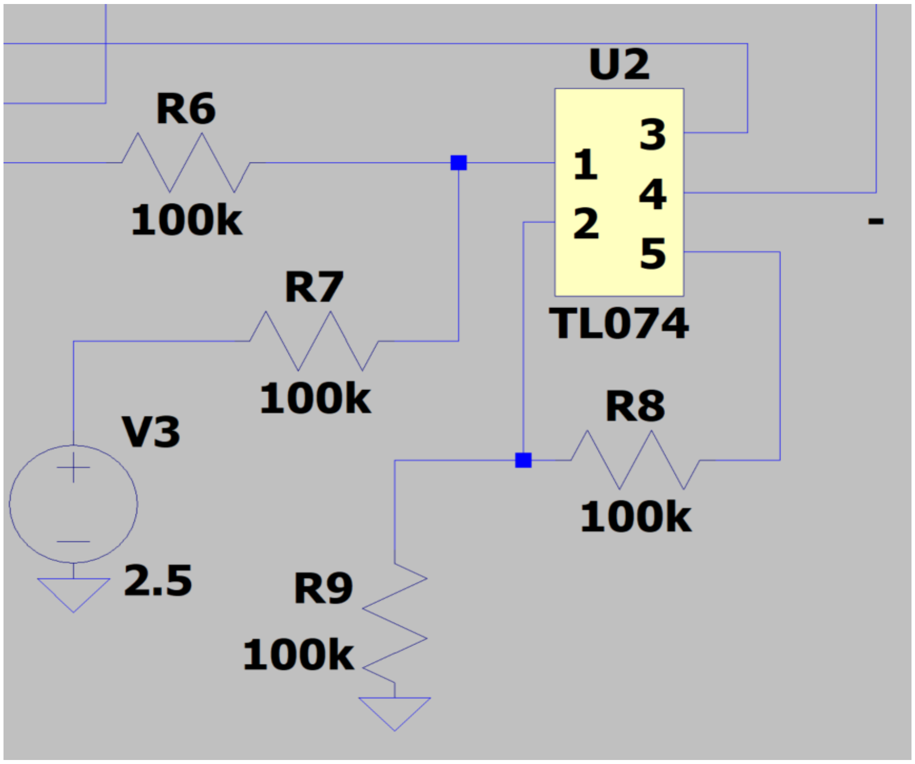


Figure 2: Level shifter using a TL074 op amp.

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

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

2.2.3 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.

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.

2.3 Simulations

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.

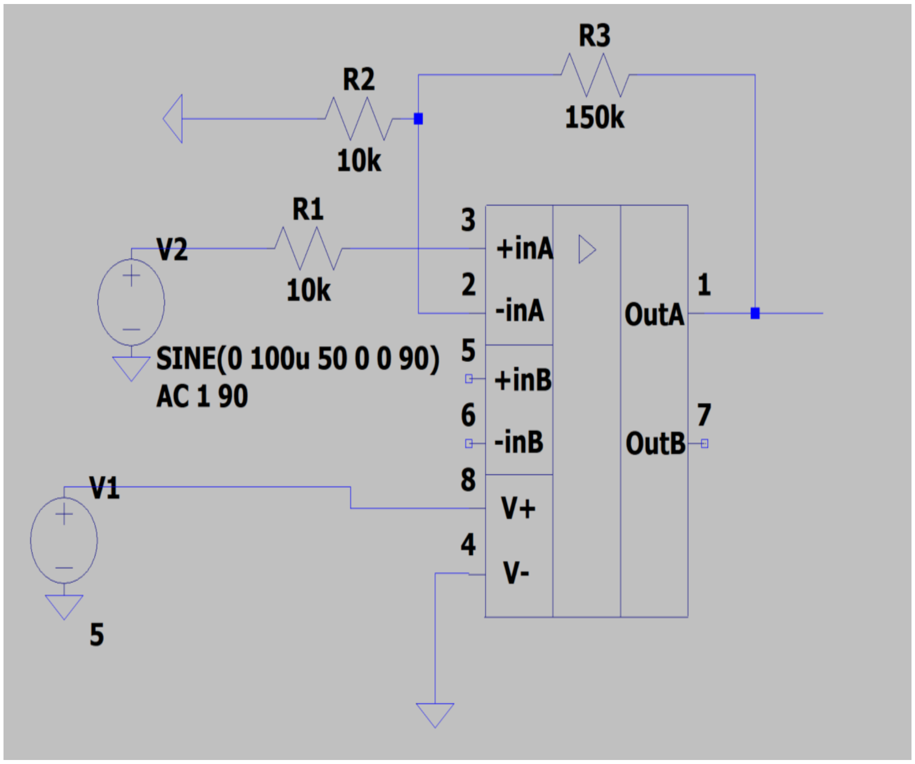


Figure 3: Amplifier using OPA2342 op amp.

2.3.1 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.

2.3.2 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.

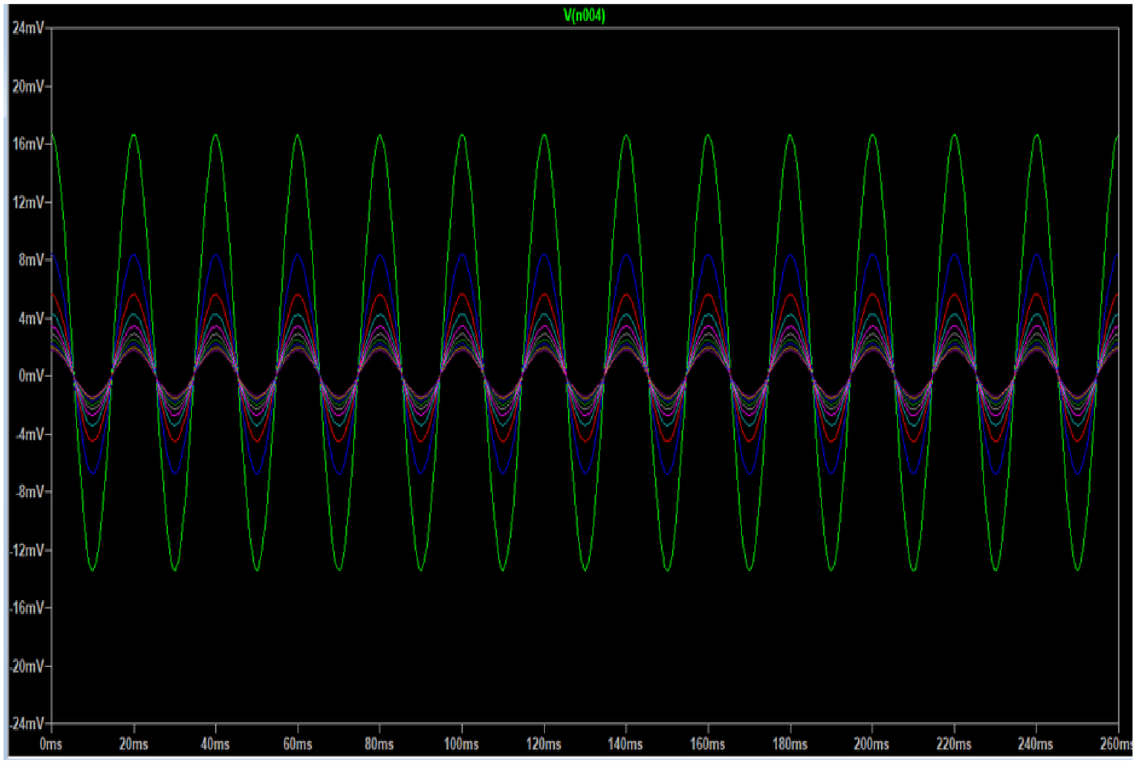


Figure 4: TL074 resistance sweep

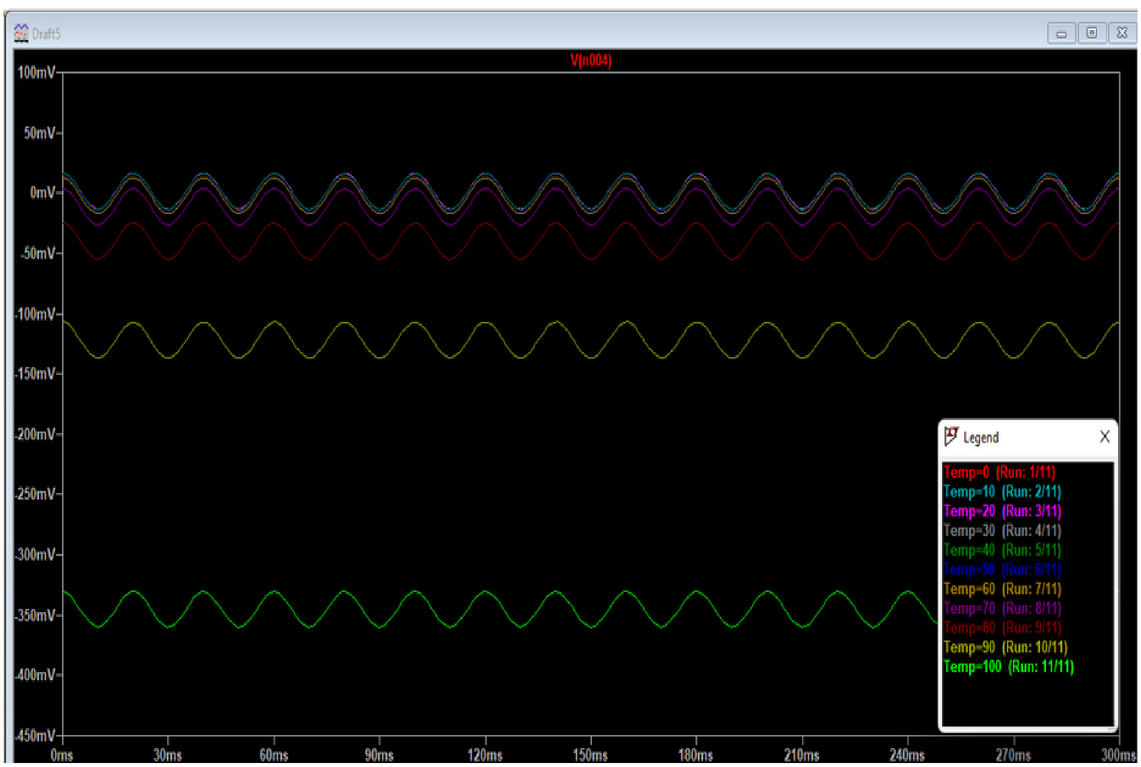


Figure 5: TL074 temperature sweep

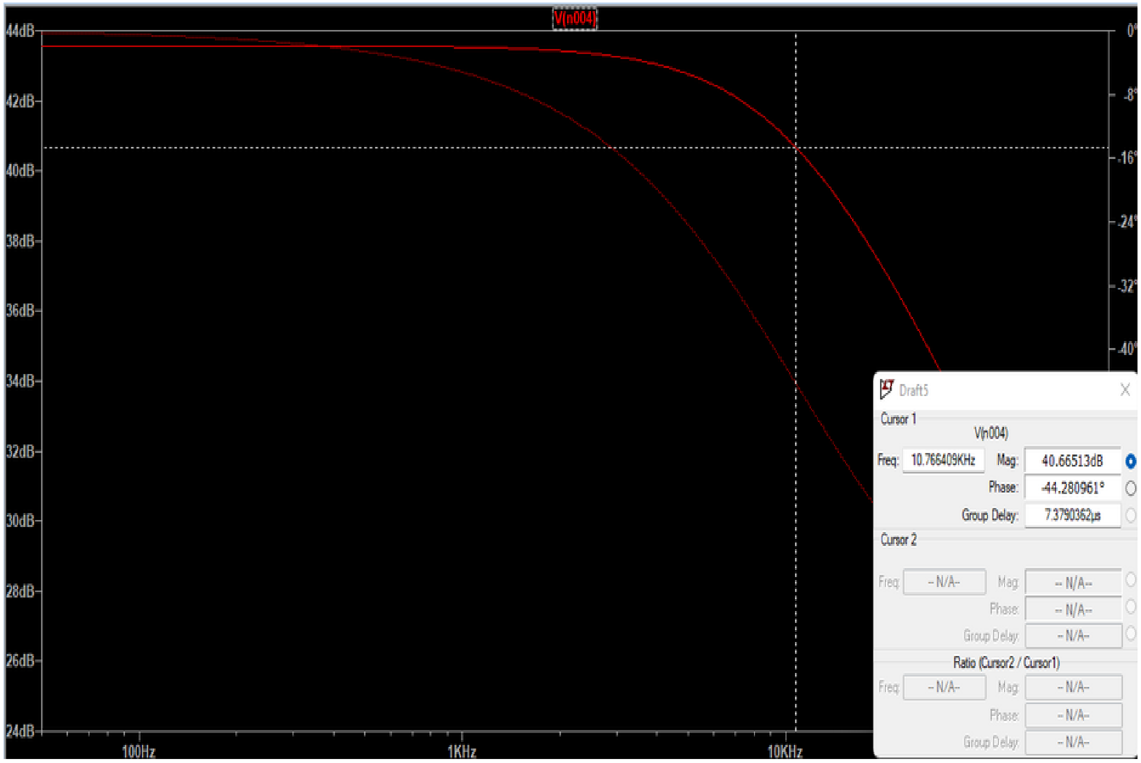


Figure 6: TL074 frequency sweep

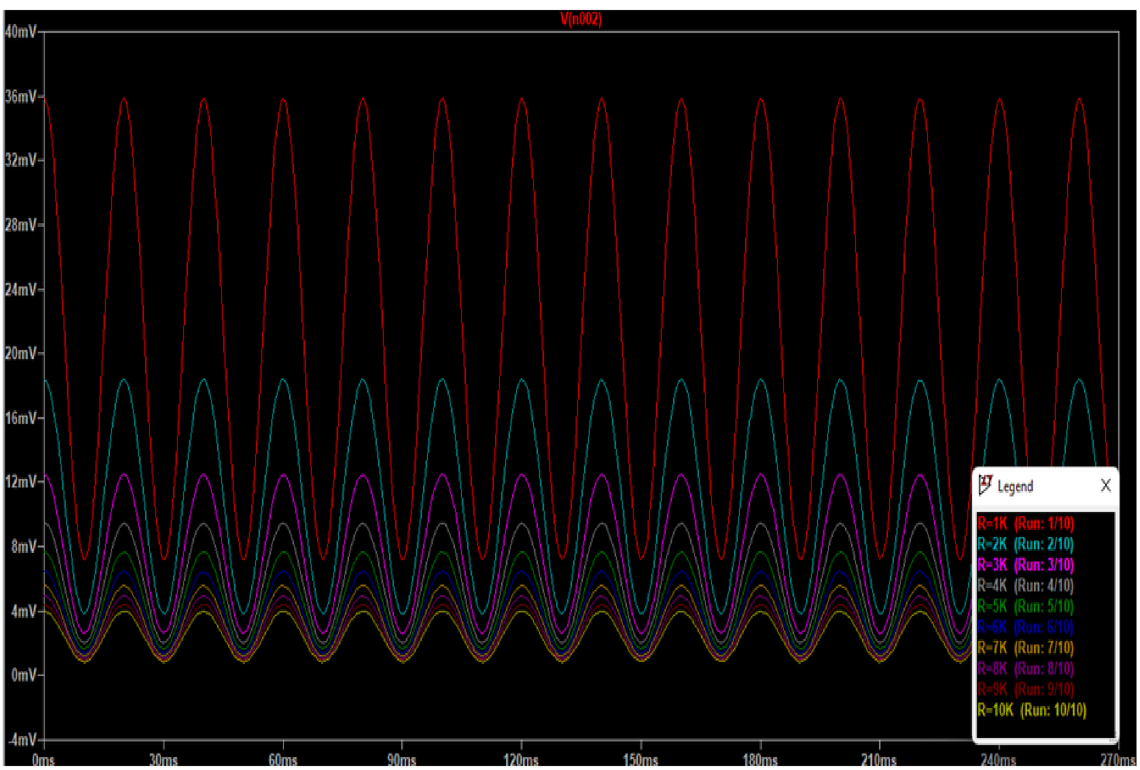


Figure 7: OPA2342 Resistance sweep.

Figure 8: OPA2342 Temperature sweep

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.

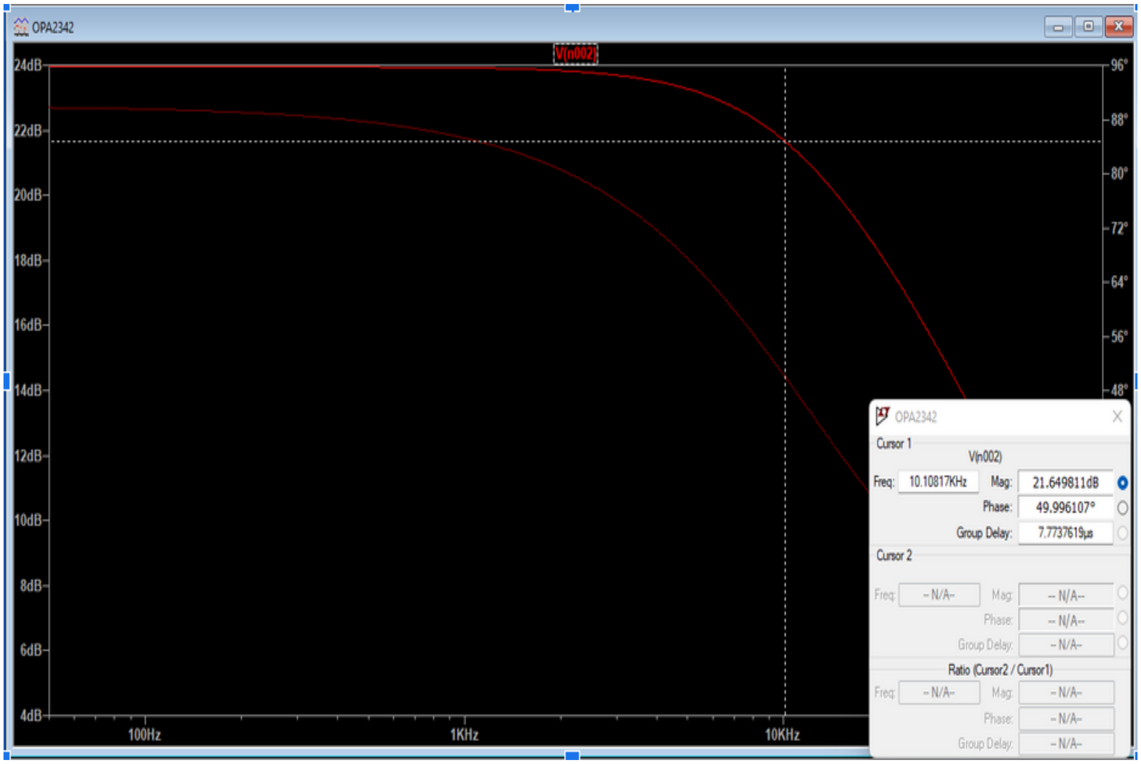


Figure 9: OPA2342 frequency sweep

3 Hall Effect Sensors

3.1 Theory

3.1.1 Background

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.

3.1.2 How do Hall effect sensors work?

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.

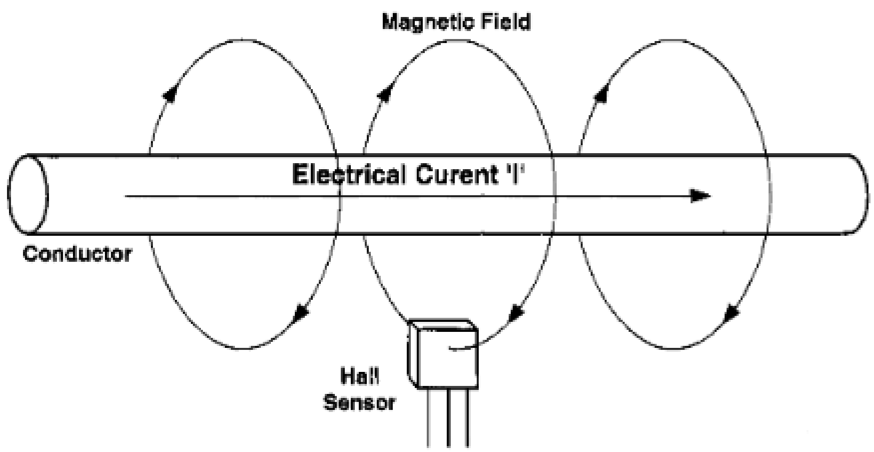
Hall effect sensors are activated by an external magnetic field. The two most important characteristics of a magnetic field are flux density (B) and polarity (north and south).

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]

3.1.3 Current-sensing techniques

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.

4 Magnetoresistive sensors

4.1 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

4.2 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:

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

References

[1] V. Fehlberg, "How rogowski coils work."

[2] D. Ward, "Measurement of current using rogowski coils."

[3] R. Ltd., "Everything you need to know about hall effect sensors." [Online]. Available: https://ie.rs-online.com/web/generalDisplay.html?id=ideas-and-advice/hall-effect-sensors-guide

[4] E. tutorial, "Hall effect sensor." [Online]. Available: https://www.electronics-tutorials.ws/electromagnetism/hall-effect.html

[5] S. C. P P Freitas, R Ferreira and F. Cardoso, “Magnetoresistive sensors,” 2007.