



**COMILLAS**

UNIVERSIDAD PONTIFICIA

**ICAI**

# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

**Sensor de voltaje con aislamiento galvánico**

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Madrid



Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Sensor de voltaje con aislamiento galvánico

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2022/23 es de mi autoría, original e inédito y

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El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

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EL DIRECTOR DEL PROYECTO



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**Isolated voltage sensor**

Autor: Laureano Salcines Cubría

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# SENSOR DE VOLTAJE AISLADO GALVANICAMENTE

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Entidad Colaboradora: University of Illinois at Urbana-Champaign

## RESUMEN DEL PROYECTO

A lo largo del proyecto, se ha diseñado, construido y calibrado un sensor de voltaje aislado galvánicamente, con la capacidad de medir altos voltajes con gran precisión y frecuencia de muestreo. Inicialmente, se diseñó el circuito y se seleccionó los componentes adecuados. Posteriormente, se procedió a la implementación y montaje de todos los elementos en una placa de pruebas, con el objetivo de evaluar y verificar su funcionamiento.

Palabras clave: Aislamiento, voltaje y medidas.

## Introducción

La electrónica de potencia es un campo de la ingeniería eléctrica que se enfoca en la conversión y control de la energía eléctrica. El objetivo principal de la electrónica de potencia es regular el voltaje, la frecuencia o la forma de onda de la energía eléctrica.

En este campo de la electrónica de potencia, es siempre necesario utilizar dispositivos de medición para comprobar que el circuito está funcionando de manera óptima. Estos dispositivos no pueden conectarse directamente al circuito de potencia debido a las altas tensiones en los circuitos de potencia, las cuales, si se conectaran directamente mediante cables, podrían dañar los circuitos de control digitales, que funcionan con tensiones mucho más bajas. Otro grave problema es que el usuario podría recibir una descarga eléctrica. Sin embargo, las barreras de aislamiento galvánico impiden las conexiones directas al circuito de potencia, lo que hace posible la medición directa de los voltajes.[1]

Con este proyecto, el objetivo es crear un sensor de voltaje aislado galvánicamente que pueda medir con precisión el voltaje en un circuito de alta potencia. Para lograr una alta precisión y estabilidad, el sensor se construirá utilizando las dos principales tecnologías de aislamiento, basadas en transformadores y en aislamiento óptico.

## Objetivos

El sensor tendrá unos requisitos principales que verificar al final del proyecto.

- **Voltaje:** El sensor debe ser capaz de medir voltajes de hasta  $\pm 100$  voltios, con una tolerancia de 100 milivoltios, lo que implica un error del 0.1% del valor real.
- **Impedancia:** Para no afectar demasiado a los circuitos de potencia, la impedancia de entrada debe ser al menos de 10 mega ohmios.
- **Frecuencia de muestreo:** Para proporcionar una medición precisa en cualquier momento, el sensor debe muestrear al menos 10 kilo muestras por segundo.



## Descripción del modelo

### Diagrama de bloques

Se ha dividido el diseño en 5 subsistemas que se pueden observar en el diagrama de bloques de la Ilustración 1.

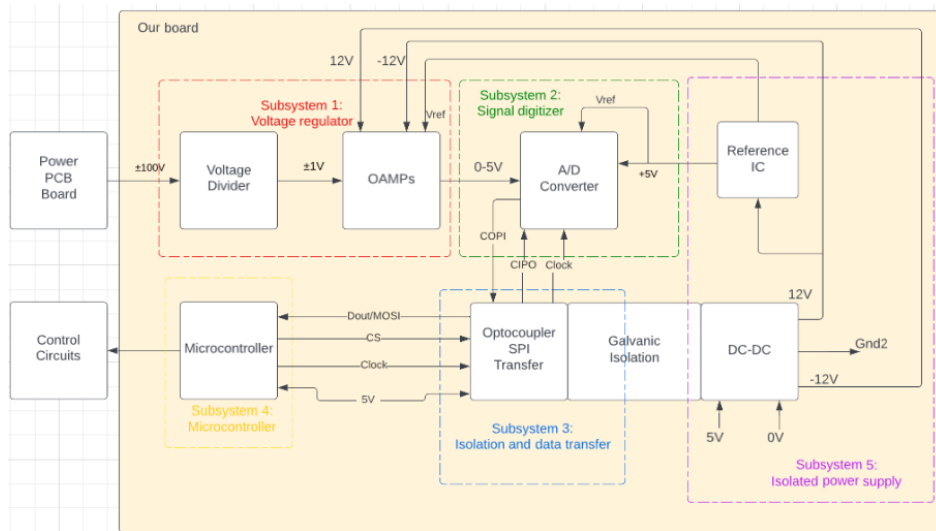


Ilustración 1 – Diagrama de bloques del sistema [2]

Descripción de los subsistemas.

1. Regulador de voltaje: Regula el voltaje desde el rango de entrada de  $\pm 100V$  a una señal de 0 a 5 voltios utilizando un divisor de voltaje y dos amplificadores operacionales (OP-AMPS).
2. Digitalizador de señales: Un convertidor analógico a digital (ADC) convierte la señal de entrada analógica en una señal digital de 8 bits, con una frecuencia de muestreo lo suficientemente alta.
3. Aislamiento y transferencia de datos: Aísla galvánicamente la salida digital del ADC y transfiere los datos al microcontrolador utilizando un aislador digital implementado con optoacopladores.
4. Microcontrolador: El microcontrolador enviará/recibirá señales hacia/desde el ADC, y realizará los cálculos necesarios para obtener una medida legible. La salida se graficará utilizando el código de Arduino visto en el Apéndice D. [3]
5. Fuente de alimentación aislada: Suministra energía y una referencia de voltaje a los OP-AMPS y al ADC a través de un convertidor DC-DC y un circuito implementado de referencia de voltaje (RIC).

## PCB

Se desarrolló una placa de circuito impreso (PCB) usando la aplicación Ki-Kad[4] para la integración de los diversos subsistemas del sensor. En las figuras 2 y 3 se pueden observar el esquema y la disposición de la PCB, respectivamente.

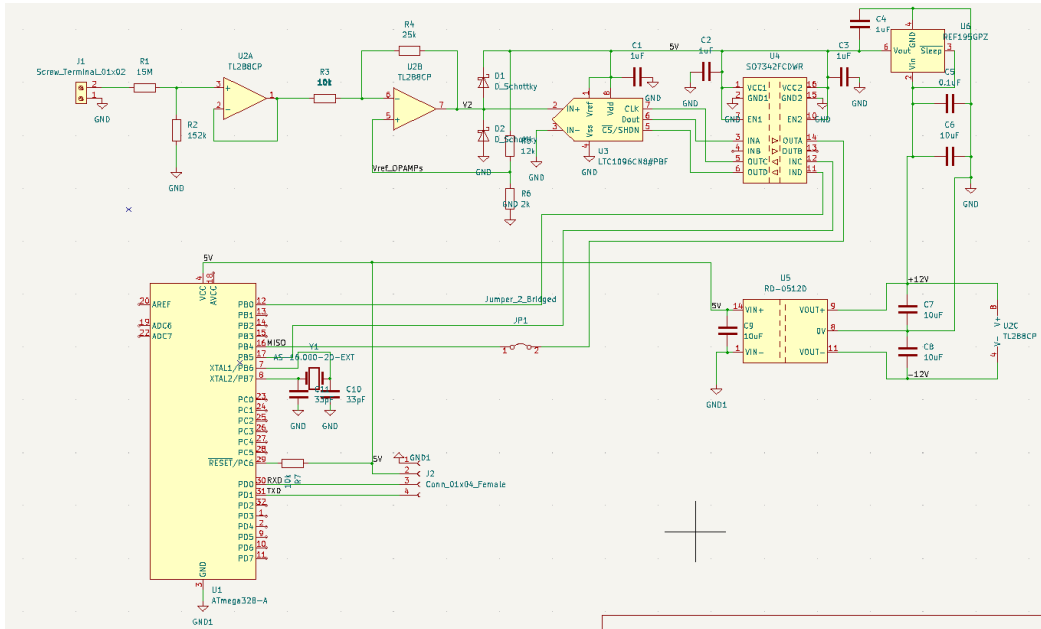


Ilustración 2 – Esquema de la PCB

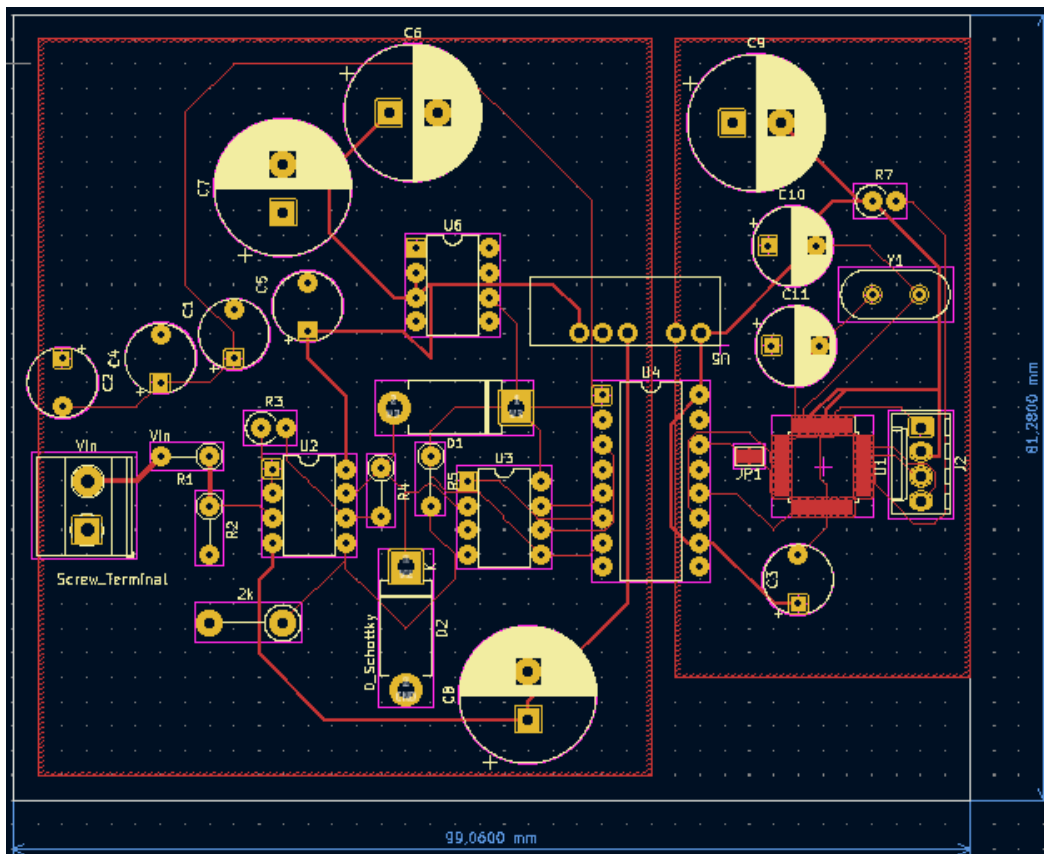
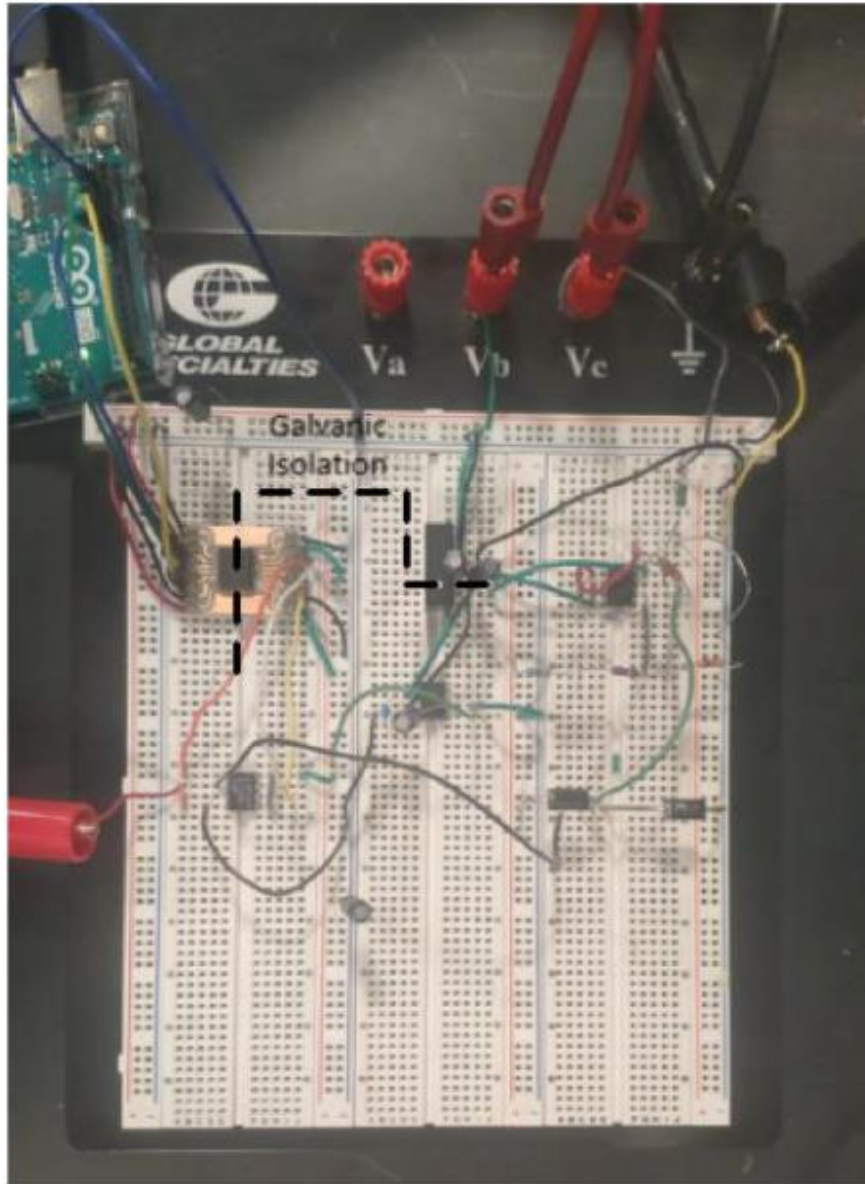


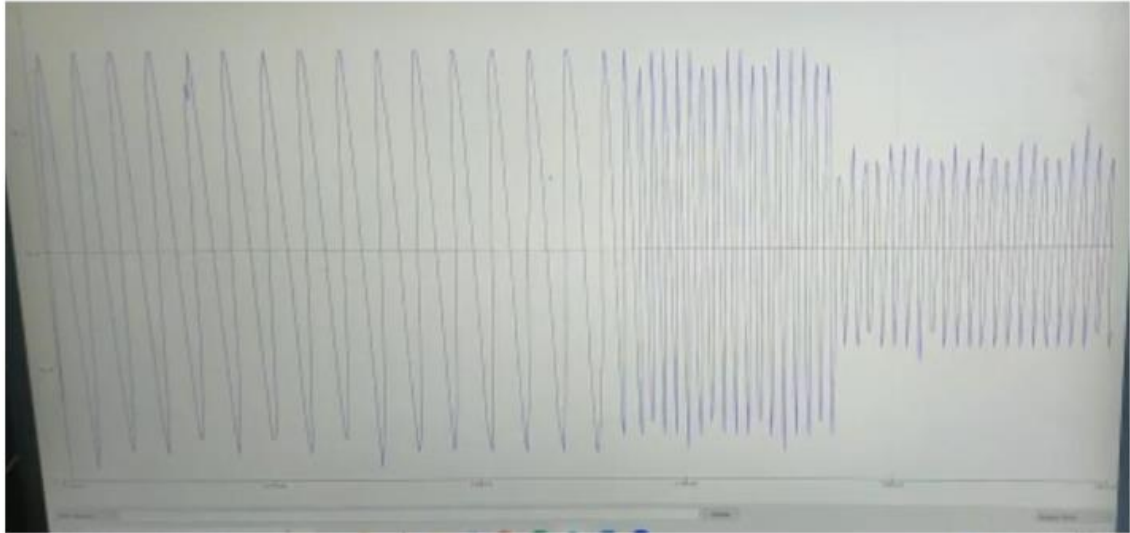
Ilustración 3 – Disposición de la PCB

## Resultados

Al final del proyecto este es el resultado en la placa de pruebas, con todos los componentes conectados como se ve en la Ilustración 4.



*Ilustración 4 – Placa de pruebas del sistema*



*Ilustración 5 – Placa de pruebas del sistema*

Una vez se conectan los componentes, se representa gráficamente la señal medida por el sistema y se observa si la medición sigue la señal de entrada con la precisión y velocidad requeridas. En la Ilustración 5, se puede apreciar cómo la gráfica de salida se ajusta inicialmente a una señal de 10 Vpp y 1 Hz, para luego modificar la entrada a una señal de 5 Vpp y 3 Hz, tal como se muestra en la Ilustración 5 el sistema sigue correctamente la señal de entrada. En consecuencia, se constata que el sistema sigue la señal de entrada de acuerdo con los parámetros necesarios.

## **Conclusiones**

En conclusión, el proyecto del sensor de voltaje aislado fue un éxito, ya que cumplió con la mayoría de los requisitos principales previamente establecidos (ver apéndice C). Además, el proyecto proporcionó una importante oportunidad de aprendizaje, ya que fue desarrollado desde cero.

Al examinar el enfoque general de nuestro proyecto, este tiene varias aplicaciones importantes. En primer lugar, aborda un problema de seguridad del usuario, lo cual siempre es un asunto relevante. Además, desde el punto de vista ambiental, es indispensable reducir el consumo de componentes al reutilizar los componentes electrónicos, y con nuestro proyecto también se protege los componentes electrónicos de posibles.

## Referencias

- [1] Horowitz, P., & Hill, W. The Art of Electronics. Third edition. Cambridge University Press. 2015. New York
- [2] Block diagram maker, Lucid app. [https://lucid.app/lucidchart/8268570b-8a52-4e64-96e5-f640a08b56c5/edit?page=0\\_0#](https://lucid.app/lucidchart/8268570b-8a52-4e64-96e5-f640a08b56c5/edit?page=0_0#). [Accessed: 20-Mar-2023]
- [3] Arduino web page. <https://www.arduino.cc/>.
- [4] Ki-Kad web page. <https://www.kicad.org/>.

# GALVANICALLY ISOLATED VOLTAGE SENSOR

**Author: Salcines Cubría, Laureano.**

Supervisor: Gruev, Viktor.

Collaborating Entity: University of Illinois at Urbana-Champaign

## PROJECT SUMMARY

### Abstract

Throughout the project, a galvanically isolated voltage sensor capable of measuring high voltages with great precision and sampling frequency has been designed, built, and calibrated. Initially, the circuit was designed, and suitable components were selected. Subsequently, all the elements were implemented and assembled on a test board to evaluate and verify their functionality.

Key words: Aisolation, voltage and measures.

### Introduction

Power electronics is a field of electrical engineering that focuses on the conversion and control of electrical energy. The main objective of power electronics is to regulate the voltage, frequency, or waveform of electrical energy.

In this field of power electronics, it is always necessary to use measurement devices to ensure that the circuit is operating optimally. However, these devices cannot be directly connected to the power circuit due to the high voltages involved. Direct connections could potentially damage the low-voltage digital control circuits. Furthermore, there is a serious safety concern regarding the risk of electric shock. However, galvanic isolation barriers prevent direct connections to the power circuit, enabling direct voltage measurement.[1]

With this project, our aim is to create a galvanically isolated voltage sensor that can accurately measure voltage in a high-power circuit. To achieve high precision and stability, the sensor will be constructed using the two main isolation technologies: transformer-based isolation and optical isolation.

### Objectives

The sensor will have several key requirements to be verified at the end of the project.

- **Voltage:** The sensor must be capable of measuring voltages up to  $\pm 100$  volts with a tolerance of 100 millivolts, resulting in an error of 0.1% from the actual value.
- **Impedance:** To minimize the impact of load currents, the input impedance must be at least 10 megaohms.
- **Sampling rate:** To provide accurate measurements at any given time, the sensor must sample at least 10 kilo samples per second.

# Model Description

## Block Diagram

The design has been divided into 5 subsystems, which can be observed in the block diagram in Illustration 1.

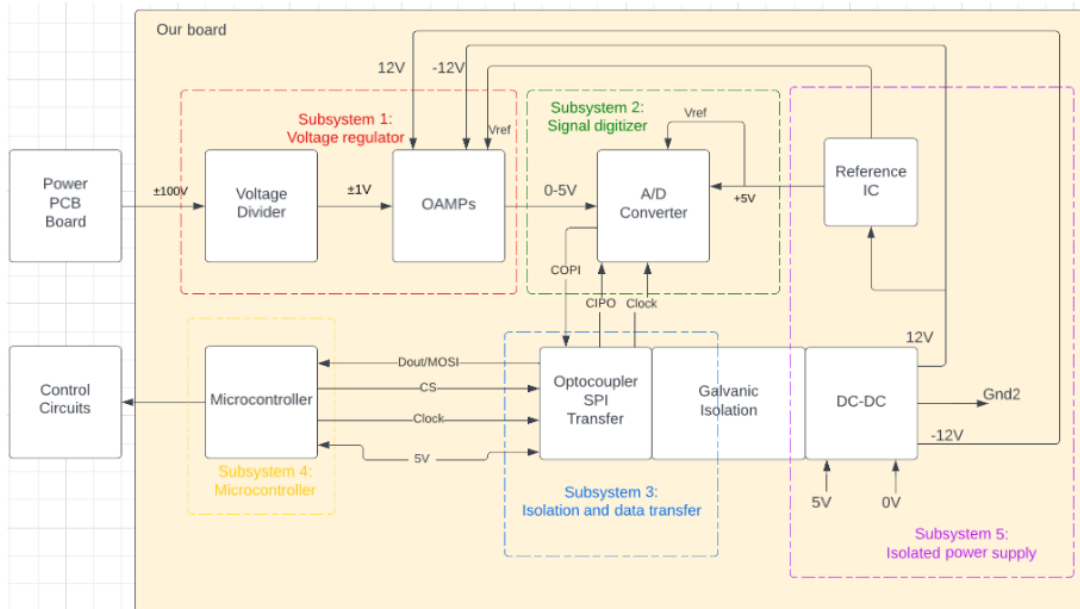


Figure 1 – System block diagram [2]

## Subsystem Description.

1. Voltage Regulator: Regulates the voltage from the input range of  $\pm 100V$  to a 0-to-5 volt signal using a voltage divider and two operational amplifiers (OP-AMPS).
2. Digitizer: An analog-to-digital converter (ADC) converts the analog input signal into an 8-bit digital signal, with a sufficiently high sampling frequency.
3. Isolation and Data Transfer: Galvanically isolates the digital output from the ADC and transfers the data to the microcontroller using a digital isolator implemented with optocouplers.
4. Microcontroller: The microcontroller will send/receive signals to/from the ADC and perform the necessary calculations to obtain a readable measurement. The output will be graphed using the Arduino code seen in Appendix D. [3]
5. Isolated Power Supply: Provides power and a voltage reference to the OP-AMPS and the ADC through a DC-DC converter and an implemented voltage reference circuit (VRIC).

# PCB

A printed circuit board (PCB) was developed using the Ki-Cad application [4] for integrating the various subsystems of the sensor. Figures 2 and 3 show the schematic and layout of the PCB, respectively.

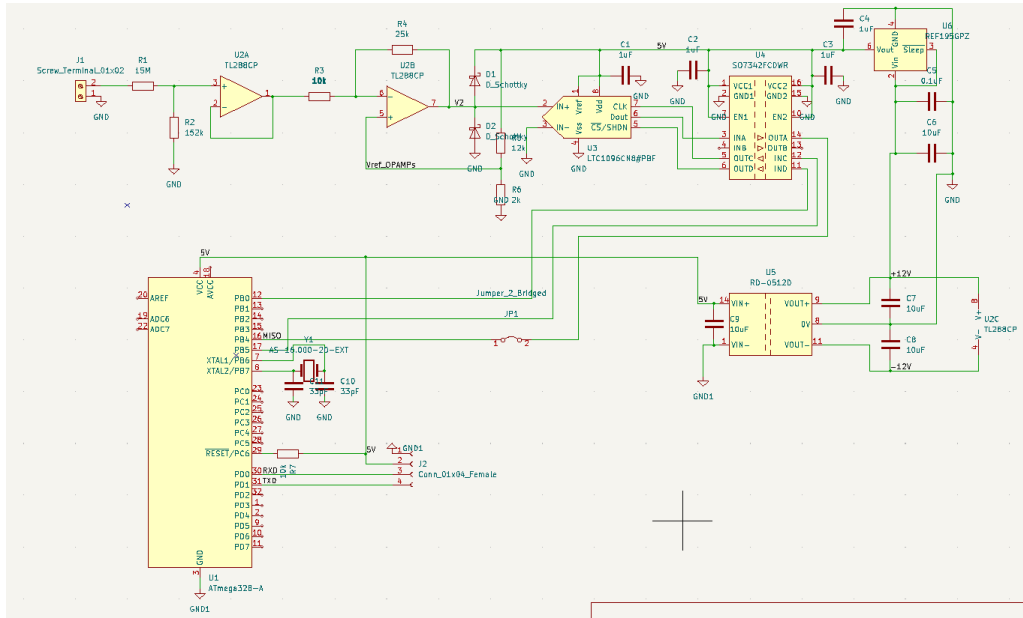


Figure 2 –PCB schematic

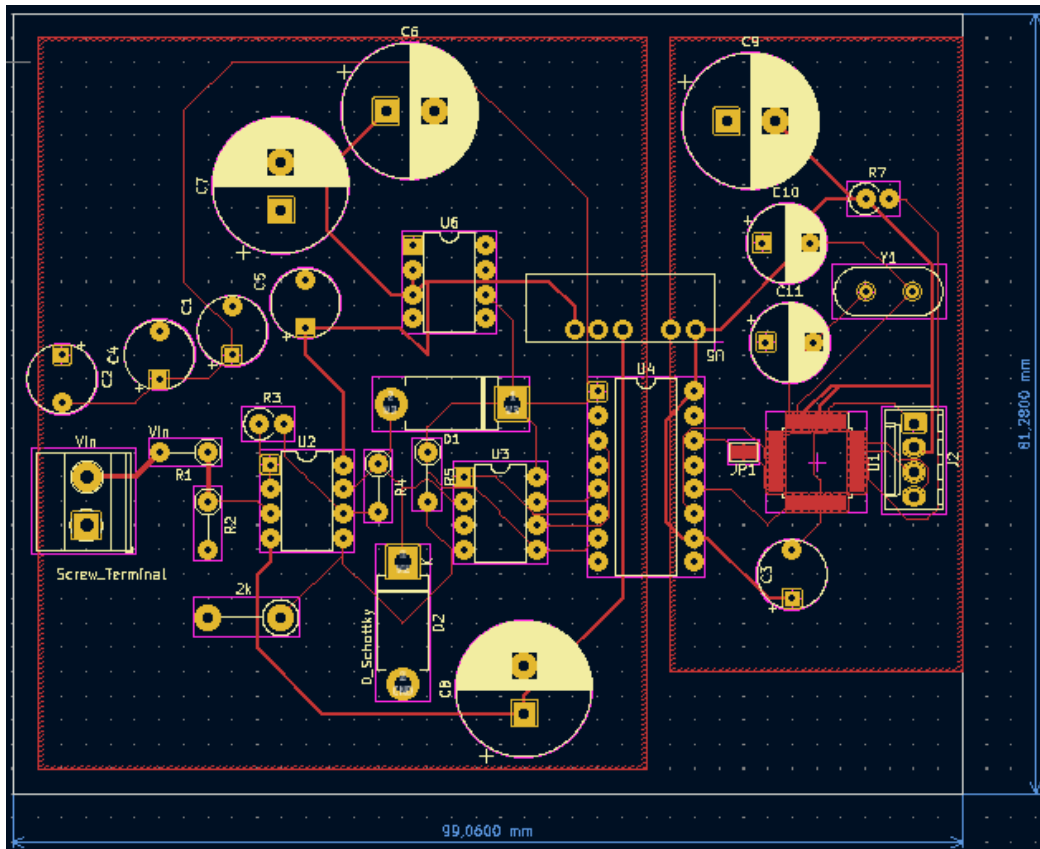
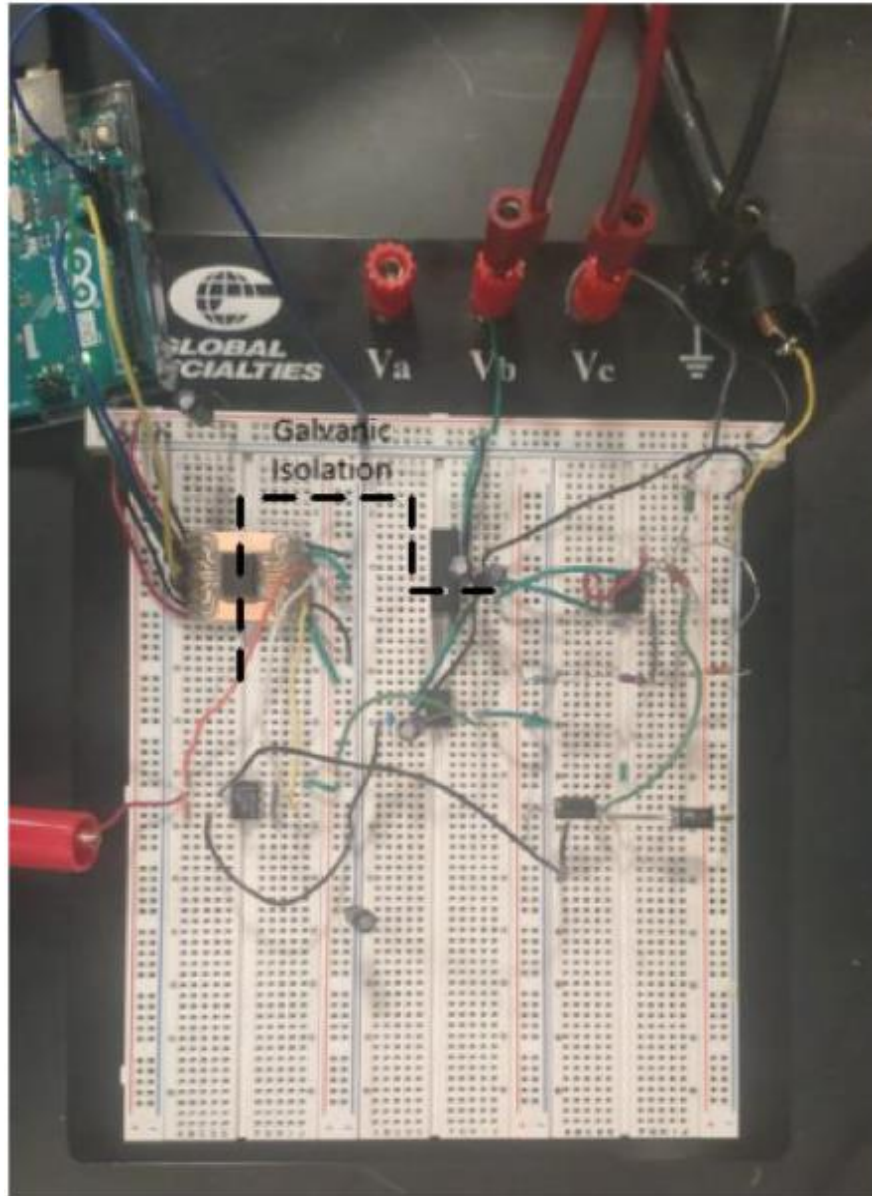


Figure 3 – PCB distribution



## Results

At the end of the project, this is the final breadboard, with all the components connected as seen in Figure 4.



*Figure 4 – System breadboard*



*Figure 5 – Final results*

Once the components are connected, the measured signal by the system is graphically represented, and it is observed if the measurement follows the input signal with the required accuracy and speed. In Figure 5, it can be seen how the output graph initially follows a 10 Vpp and 1 Hz signal, and after modifying the input to a 5 Vpp and 3 Hz signal it can be observed how the output follows the input, as shown in Figure 5. The system accurately measures the input signal. Consequently, the system is working as required.

## **Conclusions**

In conclusion, the isolated voltage sensor project was a success as it fulfilled most of the previously established key requirements (see Appendix B). Additionally, the project provided a significant learning opportunity as it was developed from scratch.

Upon examining the overall approach of our project, it has several important applications. Firstly, it addresses a user safety issue, which is always a relevant concern. Moreover, from an environmental standpoint, it is crucial to reduce component consumption by reusing electronic components, and our project also safeguards electronic components from potential damage.

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## **Abstract**

This study introduces an isolated voltage sensor that provides galvanic isolation to safeguard the measurement taking and the measurement equipment from potentially dangerous voltages while correctly measuring the voltage across a high-voltage source. The suggested sensor is built on the combination of a high-precision voltage regulator, an ADC, and both transformer and light-based isolation. The voltage regulator lowers the voltage to a level that the ADC can precisely detect, while a DC-DC converter and some optocouplers provide the required isolation. The sensor's design is discussed, and simulations and experiments are used to assess the sensor's performance. The objective is that the sensor can measure voltages up to  $\pm 100\text{V}$  correctly with a maximum error of 0.1%. Making it suitable for use in a wide range of industrial and laboratory applications.

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# 1. INTRODUCTION

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Power electronics is a field of Electrical engineering that focuses on converting and controlling electrical power. Power electronics' major goal is to efficiently transform electrical power from one form to another while maintaining high reliability and efficiency. Meaning that it is used to regulate the voltage, frequency, or waveform of electrical power.

Renewable energy systems, electric vehicles, aerospace, medical equipment, industrial machinery, and many more fields where power conversion and control are essential depend on power electronics technology. [1]

In this power electronics field, it is always necessary to use measurement devices to test if the circuit is working optimally and meeting requirements. These devices cannot be directly connected to the power circuit due to the high voltages in the power circuits, which, if connected by wires, can fry digital circuits, which run on much lower voltages. However, galvanic isolation barriers prevent direct connections to the power circuit, making direct measurement possible.

With this project, our hope is to create a galvanically isolated voltage sensor that can precisely measure the voltage in a high-power circuit. To achieve high accuracy and stability, the sensor will be built on the two main isolation technologies, transformer-based and optical isolation.

The project will involve designing the sensor circuitry, selecting the appropriate components, and assembling the sensor. To make sure the sensor satisfies the necessary accuracy requirements, we will also test and calibrate it. The project's ultimate output will be a dependable and accurate galvanic isolated voltage sensor that may be employed in a range of high-voltage or high-power applications.



## 2. OUTLINE OF SUBJECT MATTER

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The development of the first real galvanic isolated voltage sensors took place in the middle of the 20th century, scientists at Bell Laboratories [2] and other organizations in the United States were instrumental in furthering the development of transformer-based isolation technology. Companies like Siemens [3] and ABB [4] were early innovators in Europe when it came to creating isolation technology and its use in electrical systems. This happened as electronics started to become increasingly prevalent in commercial and consumer applications. Once this isolation technology was tested the first sensors started to appear. These sensors were employed in a variety of applications, such as power systems, telecommunications, and scientific instruments.

The contributions of countless researchers and engineers have led to galvanic isolated voltage sensors development along with technological advancements. The development of novel materials and design strategies has resulted in sensors that are smaller, lighter, and more efficient than ever before, while the usage of advanced isolation techniques, including optical isolation, has increased recently.

In many contemporary electronic systems with high voltage or high-power applications, galvanic isolated voltage sensors have become crucial parts. These sensors offer a way to precisely measure voltage while keeping the measuring circuitry and the measured voltage electrically isolated. Because it stops harmful currents from flowing from the measured circuit to the measuring circuit, this isolation is essential for maintaining the safety of people and equipment.

Galvanic isolated voltage sensors have been developed as a result of the demand for higher precision, stability, and safety in high voltage and high-power applications. These sensors are now used more and more in emerging technologies like electric vehicles, renewable energy systems, and other fields that need reliable and effective power control.

For example, in a renewable energy system, power electronics technology is used to convert DC power generated by solar panels or wind turbines into AC power that can be used by homes or businesses. In this case, power electronic devices such as inverters are used to convert DC power into AC power. To track the voltages through this key system for modern life, the isolated voltage sensors to be designed are vital.

There are several isolation technologies that can be implemented into the voltage sensor, the first popular isolation method used in galvanic isolated voltage sensors was transformer-based isolation. Through the use of a transformer, energy can be transferred from one circuit to another without there being any direct electrical connections, completely isolating the two circuits in the process. In comparison to other isolation approaches, transformer-based isolation has a number of benefits, including high isolation levels, high common-mode rejection ratios, and low input capacitance.[5][6]

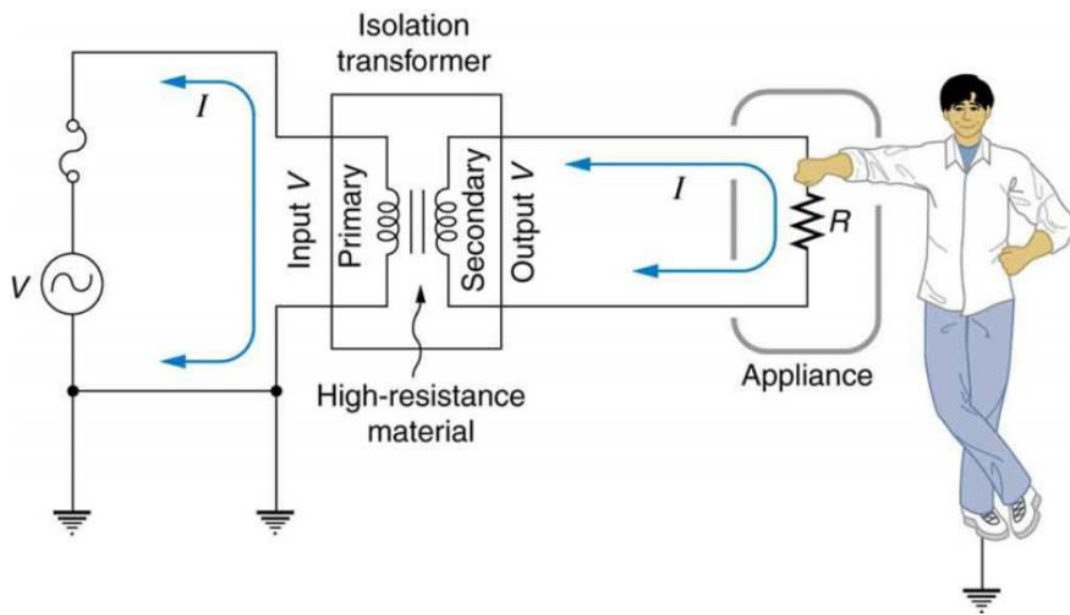


Figure 1: Transformer-based isolation.[7]

Another popular isolation method that was used later on was optical isolation. Using an optocoupler, this method uses light to transmit electrical impulses between two circuits. While optical isolation offers superior noise immunity and isolation levels, it can be more expensive than transformer-based isolation, but the information transfer is more accurate and faster.

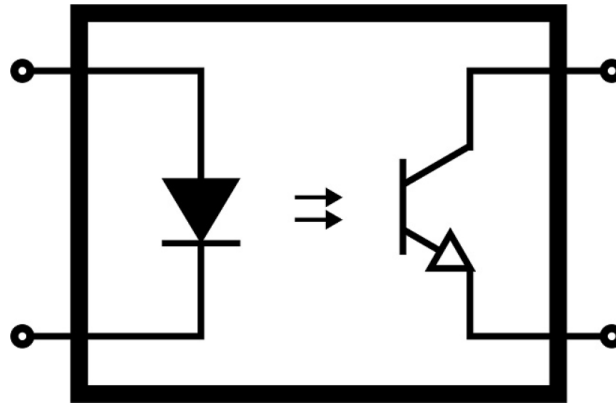


Figure 2: Optical isolation.[8]

In the voltage sensor to be constructed both isolations will play a key part. Firstly, transformer-based isolation (seen in Figure 1) will be used to isolate the subsystem that will give power to our electronic components like OP-AMPs or the Analog to Digital Converter. Secondly, optical isolation (seen in Figure 2) will be used to isolate the digital signal that comes from the ADC and transfers to the microcontroller.

Looking into the future galvanic isolated voltage sensor technology has recently made improvements with an emphasis on increasing the effectiveness and dependability of these sensors. The use of new materials and design strategies to minimize the size and weight of these sensors has been one area of research, making them more useful for use in portable and wearable electronic systems.

The employment of sophisticated sensing technologies, such as microcontrollers and digital signal processing, to increase the precision and stability of galvanic isolated voltage sensors is another field of study. In high voltage and high-power applications, these technologies enable real-time monitoring and control of the sensor output, enhancing accuracy and dependability.[9]

All of this research has the objective to keep improving the devices, this is because these devices are used in many fields on the rise, the solar electricity field has already been discussed but there are other high-importance fields to be aware of.

Electric car applications are in rising demand. The voltage levels of the battery pack and the electric motor could be checked using isolated voltage sensors. By doing so, the system would be functioning within the intended voltage range and the batteries would not be overcharged or undercharged. Additionally, independent voltage sensors might be employed to keep an eye on the charging system's voltage levels and make sure the vehicle is charged effectively and safely.[10]

Other renewable energy systems, such as wind and hydroelectric power systems, could also use isolated voltage sensors. Voltage sensors could be employed in these systems to keep track of the voltage levels of the generators, batteries, and other energy storage units.[11]

Overall, the need for isolated voltage sensors is expected to rise as clean energy and electric vehicles gain popularity. These sensors will be crucial in assuring the effectiveness and safety of these systems as well as in facilitating the move toward a more sustainable future.

### 3. DESIGN

#### DESIGN OVERVIEW

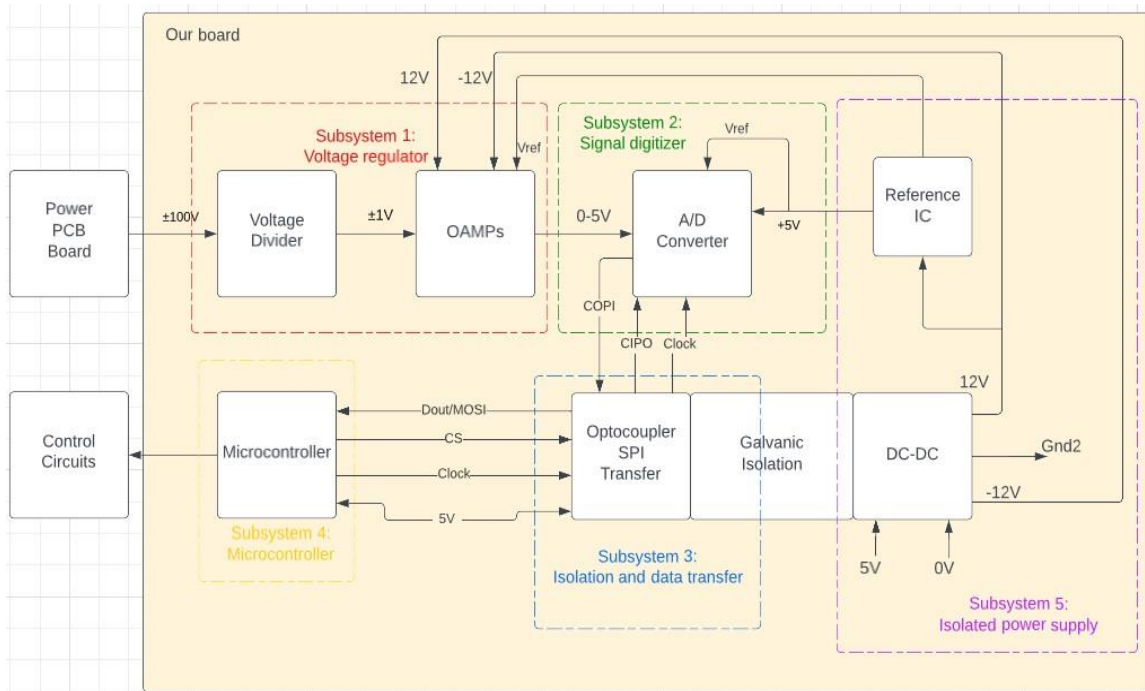


Figure 3. Block diagram. [12]

The galvanic isolated voltage sensor function is to measure an AC or DC voltage signal accurately while providing a galvanic isolation barrier from the high voltages. We have divided the design into 5 subsystems which can be seen in the Figure 1 block diagram.

## Subsystems description.

1. Voltage regulator: This will regulate the voltage from our input range of  $\pm 100\text{V}$  to a signal of 0 to 5 volts using a voltage divider and two operational amplifiers (OP-AMPS).
2. Signal digitizer: An Analog to Digital Converter converts the analog input signal to an 8-bit digital signal, with a high enough sampling rate.
3. Isolation and data transfer: Galvanically isolate the digital output of the ADC and transfer the data to the microcontroller, using a digital isolator implemented with optocouplers.
4. Microcontroller: The microcontroller will send/receive signals to/from the ADC, and it will make the calculations needed to have a readable measurement.
5. Isolated power supply: It will supply power and a voltage reference to the OP-AMPS and the ADC via a DC-DC converter, and a voltage reference implemented circuit (IC).

## ***DESIGN PROCEDURE***

In the design and development of the proposed system, we implemented several subsystems to achieve the desired functionality.

In subsystem 1, voltage regulation was required with a  $1/40$  gain, and an offset voltage to enable the signal to range from 0 to the maximum value the ADC could handle. To accomplish this, we utilized a voltage divider and an OP-AMP. Although an IC could have been used for the voltage divider, we selected two resistors to enable easier modification in the event of an error. Furthermore, the  $\pm 100V$  could not be directly input into the OP-AMPs due to the limited tolerance of most OP-AMPs, including the chosen  $\pm 15V$  OP-AMPs. Thus, the voltage had to be first reduced to meet the OP-AMP's input voltage requirements.

Subsequently, subsystem 2 required an analog-to-digital converter (ADC) with a high accuracy of 12 or 16 bits. However, such a high-precision ADC was challenging to obtain and could have reduced the sample rate. Therefore, we selected an 8-bit ADC for subsystem 2.

In subsystem 3, we needed a low-delay data transfer, with at least three communication channels to transfer and isolate the selected chip, clock, and digital output signals. Optocouplers with light-based isolation were used to achieve digital isolation. Nonetheless, the unavailability of a through-hole digital isolator made necessary a breakout board.

Subsystem 4 employed an ATmega328 microcontroller since it was pre-installed on Arduino, and it operated at a frequency of 16Mhz, which exceeded the required speed.

Finally, subsystem 5 utilized a DC-DC converter and an IC voltage reference. While we could have powered everything directly from the output of the DC-DC converter, we employed a voltage reference to get high precision on the voltage reference of the OP-AMPs and ADC.

## *DESIGN DETAILS*

### **3.1.1 VOLTAGE REGULATOR:**

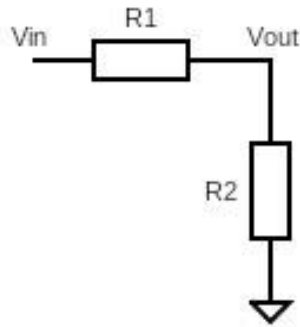


Figure 4. Voltage Divider. [13]

*Voltage divider:*

The input voltage is way too high for normal electronic components, so we reduced the input voltage using a simple voltage divider. Our objective is to divide it by at least one hundred, making this the ratio between the resistors used.

(1.1)

$$V_{out} = \frac{R_2}{R_1 + R_2} \cdot V_{in}$$

The primary objective was to step down the voltage from  $\pm 100$  V to  $\pm 1$  V, with an input impedance of at least 10 megaohms. To achieve this, the implementation was accomplished using two resistances as shown in Figure 2, and Equation (1.1) was utilized to determine the necessary ratio between resistances, which was  $R_1 = 99 \cdot R_2$ . We selected the resistances  $R_1 = 15$  M $\Omega$  and  $R_2 = 152$  K $\Omega$  to meet the requirements.



### Back-to-back OP-AMPs:

The operational amplifiers (OP-AMPs) in this study were utilized to regulate the input signal to enable its reading by the Analog to Digital Converter (ADC). The primary goal of this subsystem was to output a voltage that ranged from 0 to the voltage reference of the ADC.

Moreover, we employed a unity gain buffer to minimize the load currents and ideally reduce them to zero, theoretically isolating the voltage divider from the ADC. By doing so, it enabled accurate and stable voltage measurements and ensured the integrity of the data acquired by the ADC.

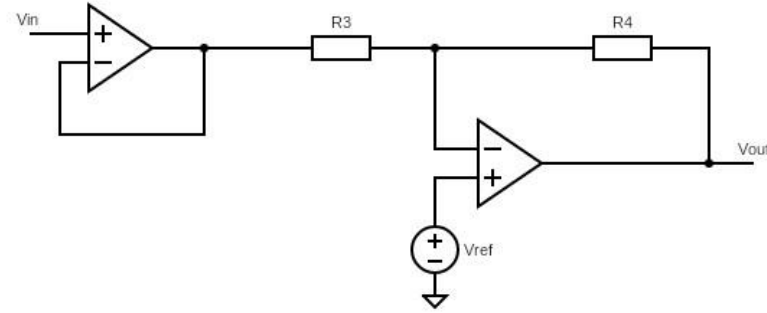


Figure 5. Operational amplifiers.

After the unity gain buffer, we used the second OP-AMP to regulate the voltage as required following the Figure 3 schematic.

$$Gain = \frac{V_{out,max} - V_{out,min}}{V_{in,max} - V_{in,min}} = \frac{R_4}{R_3} \quad (2.1)$$

$$V_{ref} = \frac{V_{out,min} + V_{in,max} \cdot \left(\frac{R_4}{R_3}\right)}{V_{in,max} - V_{in,min}} \quad (2.2)$$

The reference voltage and resistance sizing were done in concordance with Equations (2.1) and (2.2), having in mind that  $V_{out,max} = 5 \text{ V}$ ,  $V_{out,min} = 0 \text{ V}$ ,  $V_{in,max} = 1 \text{ V}$ ,  $V_{out,max} = -1 \text{ V}$  the results were  $\text{Gain} = 2.5$  and  $V_{ref} = \frac{5}{7} \text{ V}$ . To meet these specifications, we selected the resistances  $R_3 = 10 \text{ K}\Omega$  and  $R_4 = 25 \text{ K}\Omega$ . The voltage reference of the OP-AMP will be supplied by applying a voltage divider with a  $\frac{1}{7}$  gain to the 5 V reference, the resistances of this voltage divider can be chosen using Figure 2 and Equation (1) and the ones we choose were  $R_1 = 12 \text{ K}\Omega$  and  $R_2 = 2 \text{ K}\Omega$ .

$$V_{out} = V_{in} \cdot \frac{-R_4}{R_3} + V_{ref} \cdot \left(1 + \frac{R_4}{R_3}\right) \quad (2.3)$$

To see what the expected output of the OP-AMPs is, Equation (2.3) can be applied.

### 3.1.2 SIGNAL DIGITIZER

To digitalize the analog signal, we used an 8-bit serial output Analog to Digital Converter. This 8-bit signal will then be transferred to the microcontroller using a Serial Peripheral Interface (SPI) interface. This ADC uses the 5 V output from the IC voltage reference as a power supply and as a voltage reference, this means that the maximum input voltage that it can stand is 5 V. To make sure these 5 volts weren't surpassed we used two Schottky diodes. We chose these Schottky diodes because they have higher switching speed than normal ones.

$$D_{output} = V_{input} \cdot \frac{2^{n-bits}}{\text{Input voltage range}} \quad (3.1)$$

We can use Equation (3.1) to calculate the expected  $D_{output}$  from the ADC.

### 3.1.3 ISOLATED DATA TRANSFER

For subsystem 3 we wanted to isolate the communications signals from/to the microcontroller to/from the ADC. For this we needed a low-delay data transfer, with at least three communication channels to transfer and isolate the selected chip, clock, and digital output signals.

To achieve this isolation, the digital isolator has 4 internal optocouplers which are devices that use a light-based isolation. As seen in Figure 3 they use a light emitting diode to send a light signal to a transistor, usually a Bipolar Junction Transistor (BJT), that turns on and off depending on the light received, transmitting the digital signal while providing galvanic isolation.

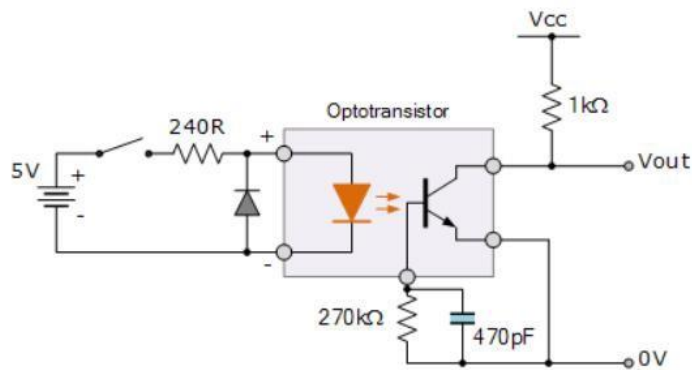


Figure 6. Optocoupler schematic.[14]

### 3.1.4 MICROCONTROLLER

The microcontroller that we selected was an ATmega328 because it was already implemented in the Arduino, we also needed a crystal oscillator to give the 16Mhz frequency in which the microcontroller usually operates. The function of this microcontroller was to, via a SPI transfer, send the slave select and clock signals to the ADC, being the slave select the one that resets the ADC. Its other function is to receive the digital output signal from the ADC and after executing an Arduino program, if everything functioned correctly, display the voltage input signal.

### 3.1.5 POWER SUBSYSTEM

#### *DC-DC converter*

The DC-DC converter will take a 5 V input from the isolated side, and without breaching the isolation barrier output three voltage signals, a  $\pm 12\text{V}$  and a second ground for the non-isolated side. The  $\pm 12\text{V}$  will give power to the OP-AMPS and to an IC voltage reference, while the ground output is a key factor in our design, as the grounds from the two sides cannot be connected under any circumstances because if this is the case the isolation barrier would be broken.

#### *Implemented Circuit voltage reference.*

The IC voltage reference will have the 12 V output signal from the DC-DC converter as its input and it will output a very accurate 5 V output signal which will be used to give power to the ADC and to give a voltage reference to both the OP-AMPS and the ADC. This voltage reference has a sleep pin that is also connected to the 12 V, so the component is always on, when the DC-DC converter is on.

## *DESIGN ALTERNATIVES*

As in every design many options could have been used to achieve the same result. In this section we study these alternatives that could have been used in our design in respect to the ones we have chosen.

Firstly, in the voltage divider design an implemented voltage divider could have been used with two resistances already in the component, but this design was not chosen because two separate resistances are easier to get (from the university shop), and they are easier to change in case of failure or a wrong result.

Secondly, the back to back OP-AMP was not implemented at first as it didn't seem necessary knowing that the resistances already made the load currents significantly low, but after further discussion the idea of reducing these currents to an ideally zero value creating a first ideal isolation seemed to be the best decision, so the buffer was implemented, as for the voltage regulator OP-AMP the design used was the easiest and most precise for the application wanted.

Thirdly, the analog to digital CONVERTER was chosen looking at voltage, precision and speed specifications. At first a 12-bit converter was chosen but it couldn't be found on the online store and the 16-bit converter was too expensive, this meant that we used the 8-bit converter which reduced the precision of the measurement but increased speed and made it cheaper.

Lastly, in the power subsystem at first the implemented circuit voltage reference was not an option looked at, but after testing and the acknowledgement of how the voltage from the DC-DC converter peaked this solution had to be put into the system to make the reference of the ADC of high precision as to make the digital output precise as well.

## 4. VERIFICATION

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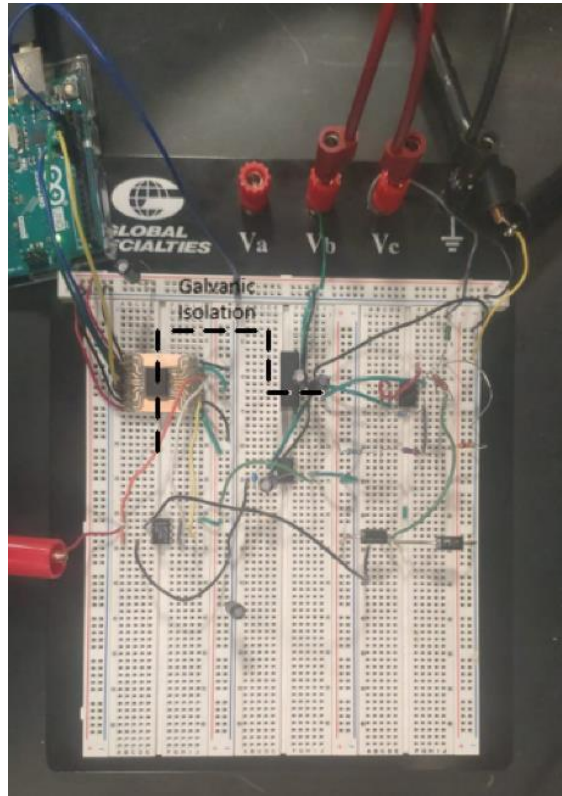


Figure 7. Project breadboard.

After we implemented all these components as explained in the 2.2 section of this paper, we had to take measurements and verify that all the subsystems were well connected and that the design was working as desired, to do this we implemented all the components in a breadboard as shown in Figure 5 and made some examination of the achieved results.

To ensure the success of the entire project, the initial priority was to address the issue of isolation. A critical first step was to perform a thorough verification of the isolation, which was accomplished using resistance measurements between the isolated and non-isolated sides. As indicated in Figure 6, the measured resistance was found to be infinite, confirming that the isolation was functioning as intended.



Figure 8. Isolation verification.

Secondly, there we could check the high impedance high-level requirement by measuring the input resistance of our system. After doing so we measured an input impedance of 15.1 M $\Omega$  as seen in Figure 7, which was greater than the required 10 M $\Omega$  resistance.



Figure 9. Input impedance verification.

Once these initial evaluations were made, we wanted to analyze if the output from subsystem 1 was outputting the right signal before moving on to the digital conversion. To do this we gave an AC voltage input and connected an oscilloscope to the voltage regulator output.

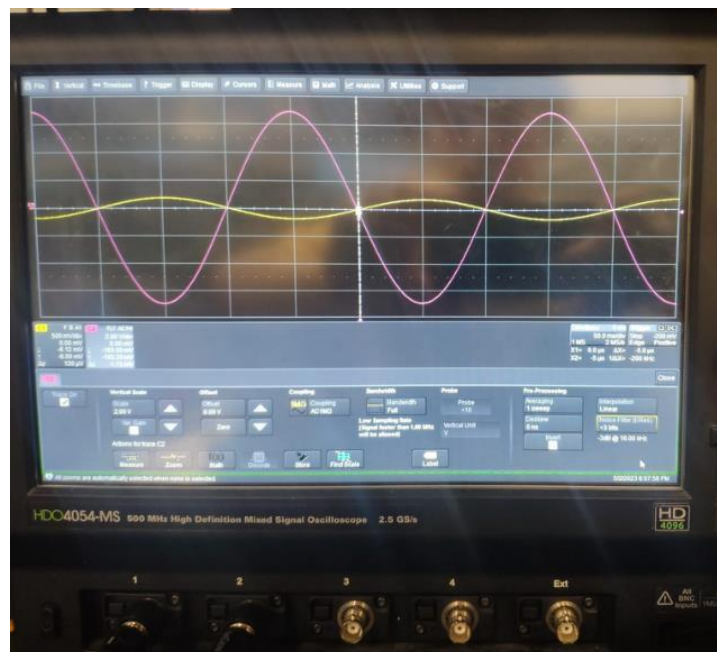


Figure 10. Subsystem 1 output signal.

The results of this testing can be seen in Figure 6, being the purple signal the input voltage and the yellow signal the output voltage. It can be appreciated how the signal has been attenuated and there is  $180^\circ$  phase shift due to our amplifier being an inverting amplifier. This meant that subsystem 1 was working as required and could measure high frequency voltages.

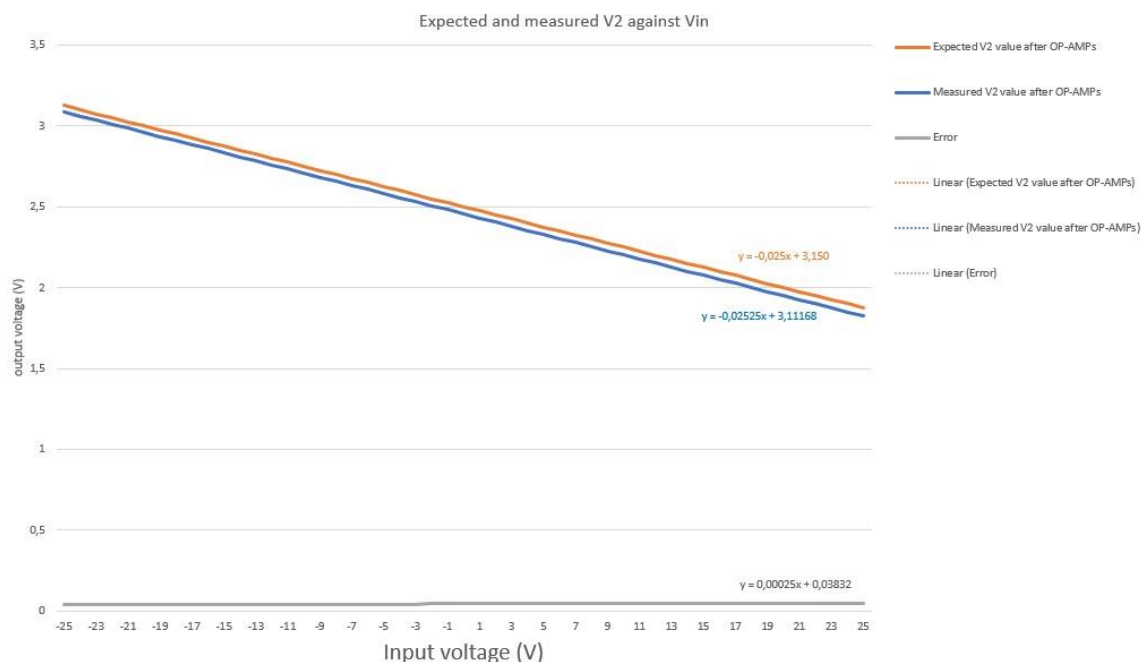


Figure 11. Excel regression graph.

Secondly, we wanted to see if the accuracy of subsystem 1 was as good as expected, to do this we took 50 measurements from a  $\pm 25$  V source, we did not take more measurements because in the lab this because in the lab this  $\pm 25$  V DC signal was the maximum voltage that the signal generators could output. After taking these measurements, as shown in Figure 7, we made a graph on excel of the expected and measured output voltages from subsystem 1 against the input voltage.

Once the graphing was done, we applied some regression to the measured values, we realized that the measured value had a small offset compared to the expected value, this wasn't worrying because we could easily eliminate that offset in the Arduino code, and that's what we later did.



After verifying the functionality of the analog side, the digital side needed to be tested.

We started to graph the output in our computer via Arduino code and after examining the output, it was noticed that two bits from the ADC were missing, this meant our resolution was only 6-bits and our error was hugely increased. After further investigation of the datasheet, we discovered that the ADC SPI transfer protocol had a weird functioning, it initially outputs a zero and null bit before transmitting the actual significant bits. Consequently, only the 6 least significant bits were being received in the microcontroller. To resolve this issue, the SPI transfer function was run twice in Arduino to obtain two variables. The first variable contained the first two null bits and then the two most significant bits of our desired signal, while the second variable contained the two least significant bits of the desired signal first and then 6 null bits. By using appropriate code, the significant bits were extracted from the two variables, resulting in the correct output value.

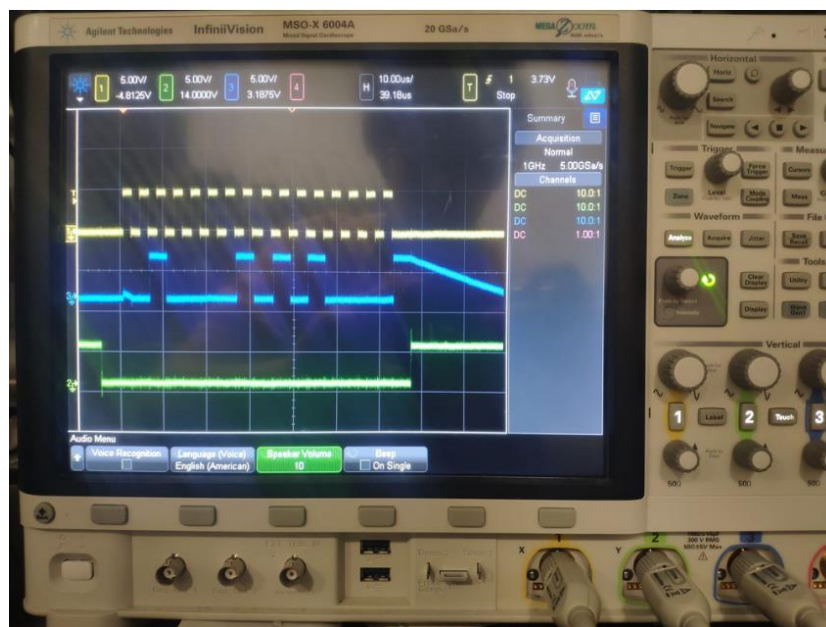


Figure 12. ADC signaling.

We wanted to be able to see this process in an actual oscilloscope, so the transfer data process was recorded in an oscilloscope, the results are shown in Figure 9. The blue signal being the chip select, the yellow signal the clock and the blue signal the digital output from the ADC. As we can see the clock runs 16 times to get the full signal and the first time the clock runs the bit the digital output is always a zero and in the second clock cycle the ADC outputs an insignificant bit. Then the next 8 clock cycles the microcontroller does record the significant bits and the last 6 clock cycles another 6 insignificant bits.

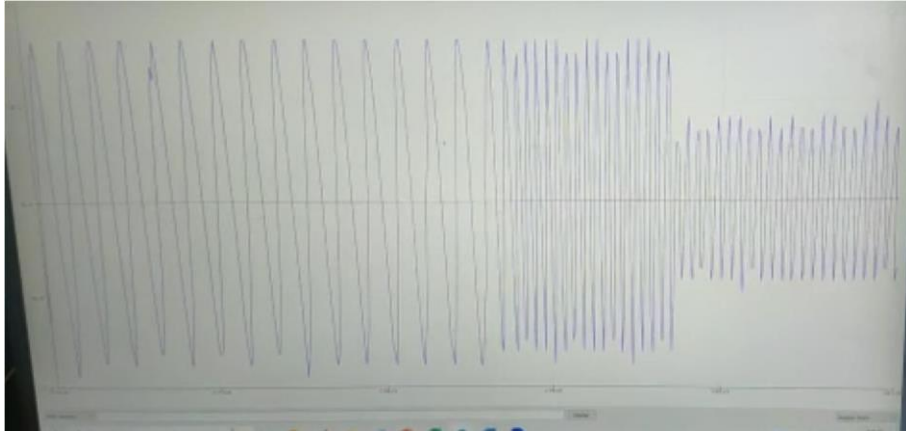


Figure 13. Final output.

Once everything was in order it was time to graph the actual signal and test if the output was following the input signal with the required accuracy and speed. In Figure 9 we can see how the output graph is following first a 10 Vpp, 1 Hz signal and then we changed the input to a 10 Vpp, 3 Hz signal, as shown in Figure 9 the system is following the input as required.

We encountered a problem when raising the frequencies as the expected output was not being displayed on the graph. Upon testing the code and using the `micros()` function at certain points, we discovered that the sampling rate was being limited by the Arduino's graphing function. To address this, we will need to explore alternative methods of graphing, potentially by using a different program.

## 5. COSTS

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In this section we will study the total cost of making our voltage sensor.

To begin with we have the labor cost, which is the money we, as team members, would be earning if we worked the same amount of hours we are spending on the project. The average salary of an ECE graduate is \$96,461/year [5]. A person usually works 2100 hours a year, so the salary is \$45.93/hour. Our team members expect to work around 10 hours per week for ten weeks so the labor cost having in mind we are 2 team members:

$$2 \cdot \text{members} \cdot 10 \cdot \frac{\text{hours}}{\text{week} \cdot \text{member}} \cdot 10 \text{ weeks} \cdot 45.93 \cdot \frac{\$}{\text{hour}} = \$9186 \quad (4.1)$$

Also, the part cost to the project has to be added, cost of all the parts was approximately 72\$ (see Appendix A), this means the total cost of the project has been 9258\$ mainly due to labor cost. For making the project there needs to be also considered the cost of apparatus that the university has provided for free.

## 6. CONCLUSIONS AND FUTURE WORK

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In conclusion, the isolated voltage sensor project was a success as it most of the main requirements set for it (See appendix B). The project also provided a significant learning opportunity as it was developed from scratch, and this is in our opinion the best way to learn.

Regarding ethics, we will have to show integrity with ourselves and with the university. Section 7.6 of the IEEE Code of Ethics I.5 states, “to seek, accept, and offer honest criticism of technical work...and to credit properly the contributions of others” [1]. The project is a challenge but one that we have sought so we look forward to using any constructive criticism that comes up through the process. As our project is not the first isolated voltage sensor, we ensure to credit any sources from previous projects and credit any resources we build upon.

Looking at the broader approach to our project, it has several mayor applications, first it covers a safety issue which is always an important matter. Also, environmentally it is indispensable to reduce the consumption of components by reusing the electronic components, and with our project the isolated voltage sensor we also protect electronic components from burning.

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## 8. APPENDIXES

### *APPENDIX I: SUSTAINABLE AND DEVELOPMENT GOALS*

This project contributes to goals 3 (health and wellbeing), 9 (Industry, Innovation, and Infrastructure) and 12 (Responsible Production and Consumption) of the Sustainable Development Goals [13]. According to the Global E-waste Monitor 2020 [14], approximately 56.7 million metric tons of electronic waste were generated worldwide in 2022. The total global e-waste generated in 2014 was 41.8 million metric tons. This indicates a significant rise in electronic waste generation within a span of eight years. The increasing trend is expected to continue unless effective measures are taken to promote responsible consumption, recycling, and proper disposal of electronic waste.

First off, it makes it possible to measure voltage accurately and dependably in electronic systems without the use of direct electrical connections. The sensor guarantees the security of both the user and the apparatus by cutting off the measuring circuitry from the main power source.

This isolation function is especially important for extending the lifespan of electronic gadgets. Voltage spikes or transients are a frequent reason for early failure in electronic systems because they can harm delicate components. Potential dangers brought on by voltage fluctuations can be reduced, increasing the device's operational life, by including an isolated voltage sensor in the design. As a result, there is less electronic waste generated because gadget replacements happen less frequently.

**APPENDIX II: PART COST.**

Part	Manufacturer	Part Number	Quantity	Extended Cost
152Kohms Resistor	Vishay Sfernice	RCMS0215202FHA22	1	4\$
15Mohms Resistor	Stackpole Electronics Inc	RNV14FAL15M0	1	0.24\$
10Kohms Resistor	YAGEO	MFR-12FTF52-10K	2	2*0.1\$
25Kohms Resistor	Vishay Dale	RN55D2502FB14	1	0.69\$
OP-AMPS	Texas instruments	TL288CP	1	4.31\$
A/D Converter	Analog Devices Inc.	LTC1096CN8#PBF	1	8.86\$
Digital Isolator	Texas instruments	SO7342FCDWR	1	\$5.12
Microcontroller	Microchip Technology	ATmega328	1	\$2.76
Reference-IC	Analog Devices	REF195GPZ	1	\$6.77
DC-DC Converter	Recom Power	RD-0512D	1	8.68\$
1 uF Capacitor	KEMET	R82DC4100DQ60J	4	0.60*4\$
0.1 uF Capacitor	KEMET	MMK5104K50J01L16.5TA18	1	1*0.46\$
2Kohms Resistor	Stackpole Electronics Inc	RNF14FTD2K00	1	0.1\$
12Kohms Resistor	Stackpole Electronics Inc	RNMF14FTC12K0	1	0.1\$
Schottky diode	Diodes Incorporated	SB5100-T	2	2*0.7\$
Crystal Oscilator	Raltron Electronics	AS-16.000-20-EXT	1	0.18\$
33pF capacitance	WIMA	FKP20100331D00KSSD	2	0.57*2\$
4Pin_Socket	MOLEX	WM18592-ND	1	2.75\$
2_Pin_ScrewTerminal	Phoenix Contact	277-1258-ND	1	1.61\$
2_Pin_Jumper	Harwin Inc.	952-1728-ND	1	0.43\$



Breakout board	Aries Electronics	LCQT-SOIC16	1	5.2\$
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**TABLE 1: CHECKING OF INITIAL REQUIREMENTS.**

**Subsystem 1:**

<b>Requirement</b>	<b>Verification</b>	<b>Status</b>
Able to regulate the input voltage from $\pm 100$ V to 0-5V.	Connect a voltmeter to the output of the signal regulator and adjust the input voltage while measuring the output. Check that for all the $\pm 100$ V spectrum the output moves in the 0-5V.	Achieved
The impedance of the combined subsystem should be at least 10 megohms	Connect an ohmmeter to the input and ground and check the input impedance	Achieved
Precision: The voltage after regulation must meet a certain level of accuracy With respect to the expected value. We want an accuracy of at least 0.5%	Measure the output voltage of the subsystem for a range of voltage inputs	Not achieved

## Subsystem 2:

Requirement	Verification	Status
From an accepted input of 0 - 5volts, output a digital sequence of bits into the COPI corresponding to that measurement.	<ul style="list-style-type: none"><li>- Connect the input of the signal digitizer to a voltage supply. Then, select ten roughly evenly-spaced values within the 0 - 5 volts range as test values. Record the values.</li><li>- Connect the output to a signal analyzer, take a snapshot that covers at least 20 cycles, and check if the binary cycle displayed has any correspondence with the actual input value</li></ul>	Achieved

### Subsystem 3:

Requirement	Verification	Status
Good galvanic isolation of the circuit.	Check the resistance: Use an ohmmeter to check the resistance between the two sides of the isolation. There should be an infinite resistance reading, indicating that there is no electrical continuity between the two circuits.	Achieved
Transfer the data with at most 1us delay.	Connect an oscilloscope to the digital signal on the input and output of the digital isolator and measure the delay.	Achieved

## Subsystem 4:

Requirement	Verification	Status
The microcontroller shall convert the analog voltage level into a digital signal that can be displayed on the output display for the user to read the measured value.	When changing the voltage input check that the output is displayed on the serial monitor.	Achieved
To provide an accurate measurement at any time, the sensor needs to sample at least 10-kilo samples per second	When applying an AC voltage input check that the output follows the signal correctly up to 10 kHz.	Achieved

### Subsystem 5:

Requirement	Verification	Status
Supply the 12 and -12 Volts to the OP-AMPSs and the IC reference when connected to VCC and ground.	Give power to the DC-DC converter and measure the voltage outputs.  Measure the Voltage output of the IC reference. It should be exactly 5V.	Achieved

### *APPENDIX III: ARDUINO CODE*

```
#include <SPI.h>

const int csPin = 10; // chip select pin

void setup() {
  Serial.begin(9600);
  SPI.begin();
  SPI.setBitOrder(MSBFIRST); // set SPI bit order to MSB first
  SPI.setClockDivider(SPI_CLOCK_DIV32); // set SPI clock divider to 32 for a clock
  frequency of 500 KHz
  pinMode(csPin, OUTPUT);
  digitalWrite(csPin, HIGH); // set chip select pin to high to disable the ADC
}

void loop() {
  uint16_t time1 = micros();
  digitalWrite(csPin, LOW); // enable ADC
  delay(0.01); //giving a wakeup time to the ADC
  uint8_t adcVal1 = SPI.transfer(0); // transfer first 8-bits
  uint8_t adcVal2 = SPI.transfer(0); // transfer second 8-bits
  uint8_t adcVal_fin;
  digitalWrite(csPin, HIGH); // disable ADC
  uint16_t time3 = micros();

  //Code to output the required 8 bit signal
  adcVal1 = adcVal1 & 0B00111111;
  adcVal1 = adcVal1 << 2;
  adcVal2 = adcVal2 & 0B11000000;
  adcVal2 = adcVal2 >> 6;
  adcVal_fin = adcVal1 | adcVal2;

  //Final calculation
  float adcVal_fin2 = float(adcVal_fin);
  float voltage_input = 96.5 - adcVal_fin2 * (float(200)/float(256)); // convert ADC value
  to voltage

  uint16_t time4 = micros();

  //DC
  // Serial.print(" Voltage_input = ");
  // Serial.println(voltage_input);
```

```
// delay(500);

//AC
Serial.println("#LABEL Time (s),voltage_input");
Serial.println("#SCALEX 0.000001"); //10Khz=0.0001 ; 5Khz=0.02 ; 1Khz=0.000001
Serial.println(voltage_input);

//Sample rate
// uint16_t time2 = micros();
//
// uint16_t time_tot=time2-time1;
// uint16_t time_adc=time3-time1;
// uint16_t time_calculations=time4-time3;
// uint16_t time_printing=time2-time4;
//
// uint16_t Sample_rate=1/time_tot;
// Serial.print("time_adc = ");
// Serial.println(time_adc); //prints time the adc takes
// Serial.print("total_time = ");
// Serial.println(time_tot); //prints the time all process took
// Serial.print("time_calculations = ");
// Serial.println(time_calculations); //prints time the adc takes
// Serial.print("total_print = ");
// Serial.println(time_printing); //prints the time all process took

// delay(1000); //wait a second to see the result
}
```