Galvanic Isolated Voltage Sensor

By

Team 74

Laureano Salcines Cubría

And

Jevin Liu

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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 ±100V correctly with a maximum error of 0.1%. Making it suitable for use in a wide range of industrial and laboratory applications.

Contents

1. Introduction

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

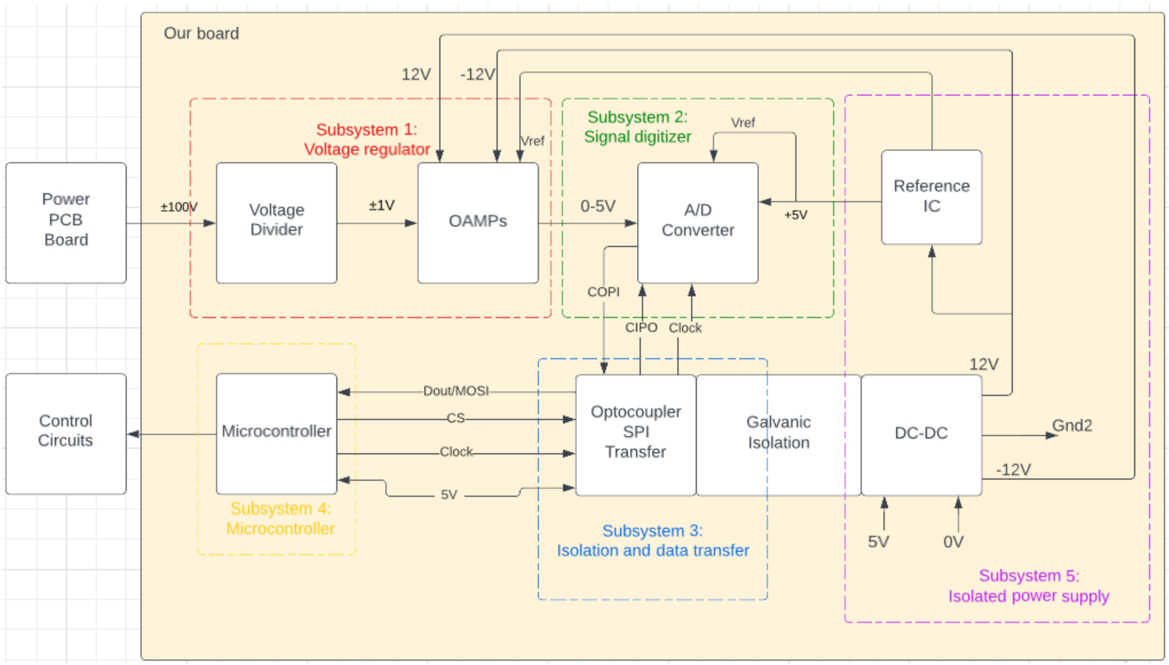

Figure 1. Block diagram. [1]

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 ±100V 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).

3. Design

3.1 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 ±100V could not be directly input into the OP-AMPs due to the limited tolerance of most OP-AMPs, including the chosen ±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[X], 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.

3.2 Design details

Voltage regulator:

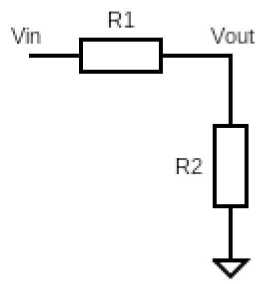

Figure 2. Voltage Divider. [2]

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.

$$V_{out} = \frac{R2}{R1+R2} \cdot V_{in} \tag{1}$$

The primary objective was to step down the voltage from ±100 V to ±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) was utilized to determine the necessary ratio between resistances, which was $R_1 = 99 \cdot R_2$. We selected the resistances R_1 = 15 MΩ and R_2 = 152 KΩ 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.

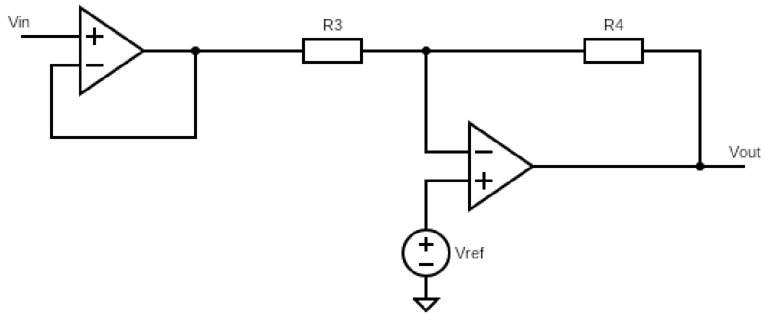

Figure 3. Operational amplifiers.

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

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

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

The reference voltage and resistance sizing were done in concordance with Equations (2.1) and (2.2), having in mind that $V_{out,max} = 5$ V, $V_{out,min} = 0$ V, $V_{in,max} = 1$ V, $V_{out,max} = -1$ V the results were Gain = 2.5 and $V_{ref} = \frac{5}{7}\ V$. To meet these specifications we selected the resistances R_3 = 10 KΩ and R_4 = 25 KΩ. 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 KΩ and R_2 = 2 KΩ.

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

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

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 form 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.

$$D_{output} = V_{input} \cdot \frac{2^{n-bits}}{Inout\ voltage\ range} \tag{3}$$

We can use Equation (3) to calculate the expected D_{output} from the ADC.

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.

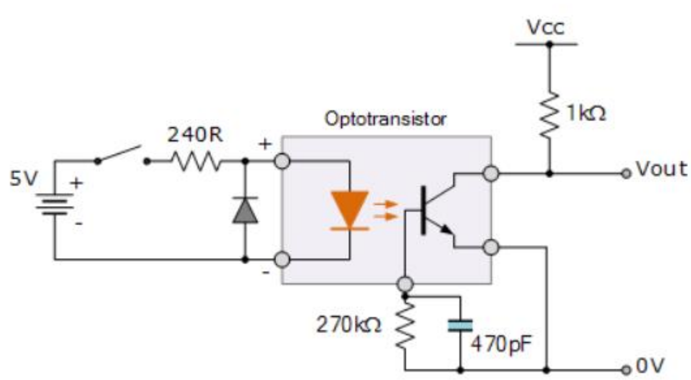

Figure 4. Optocoupler schematic.[11]

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.

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 ±12V and a second ground for the non-isolated side. The ±12V 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.

4. Verification

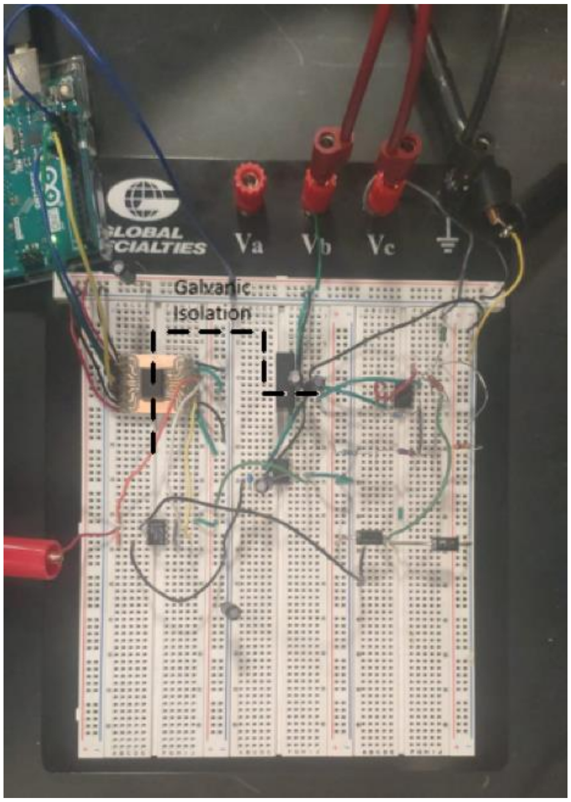

Figure 5. Project breadboard.

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 6. 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 MΩ as seen in Figure 7, which was greater than the required 10 MΩ resistance.

Figure 7. 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.

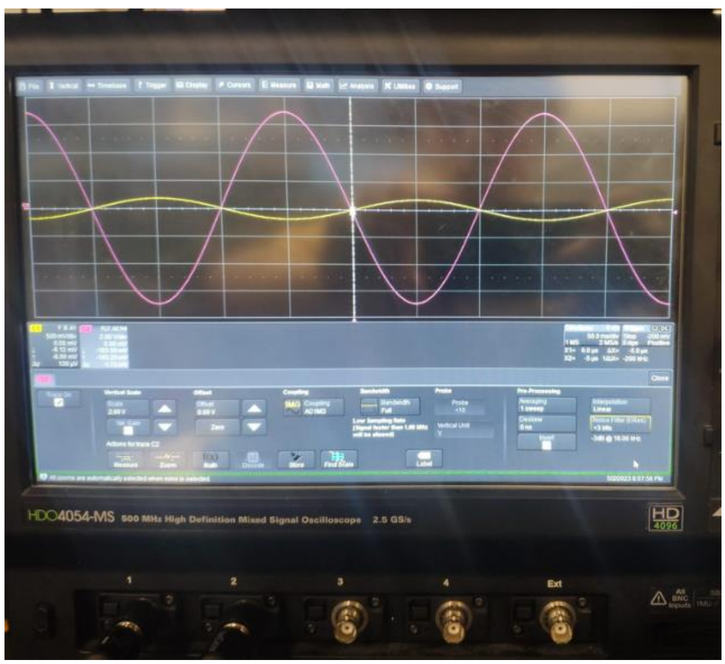

Figure 7. Subsystem 1 output signal.

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 180º 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.

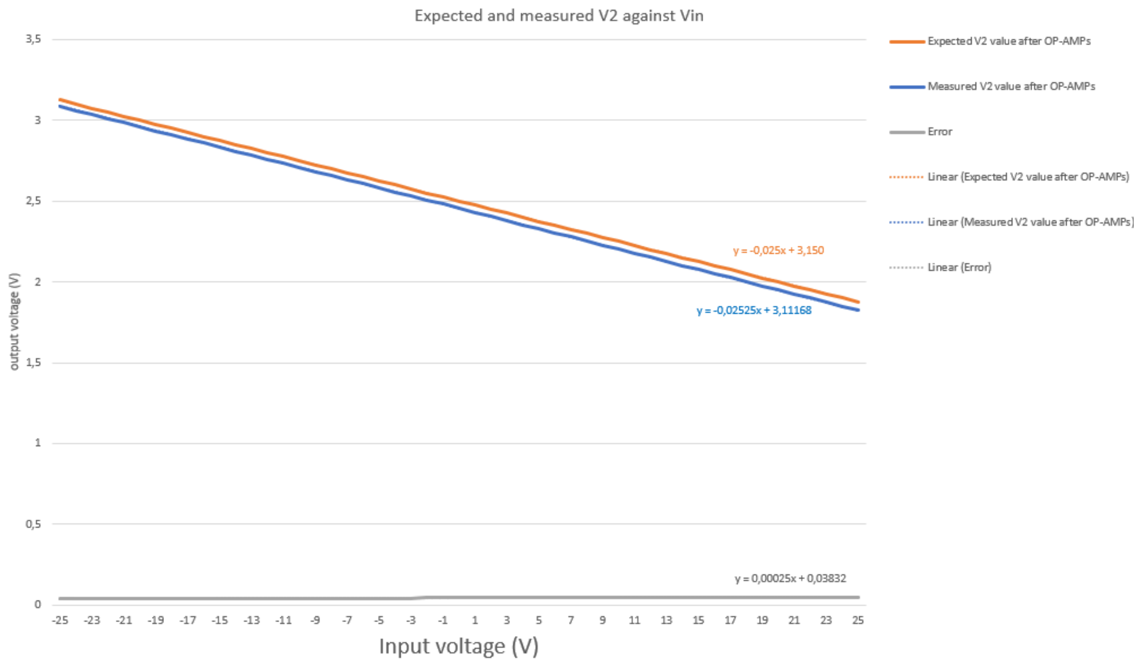

Figure 8. Excel regression graph.

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 ±25 V source, we did not take more measurements because in the lab this because in the lab this ±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.

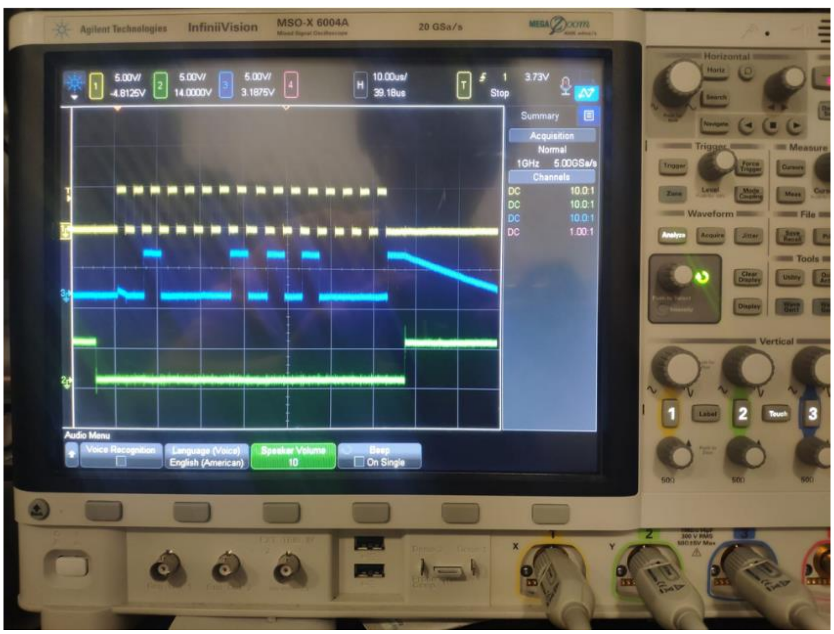

Figure 9. ADC signaling.

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.

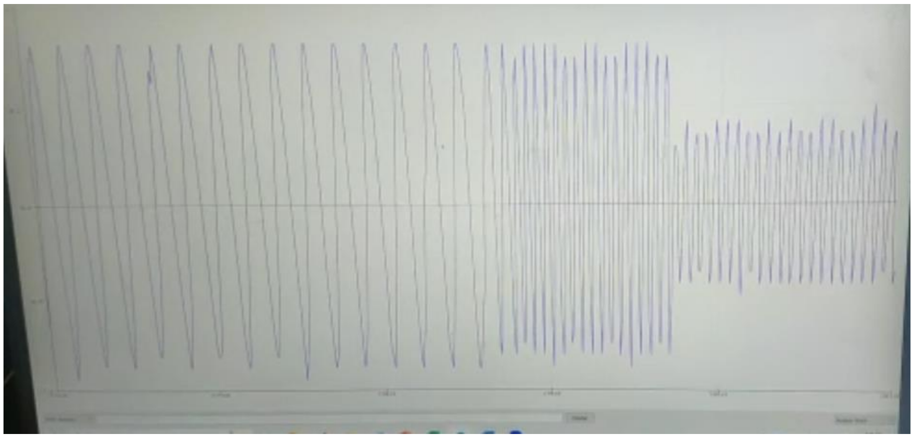

Figure 9. Final output.

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

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:

$$2\ \text{Members}\ \cdot 10\ \frac{\text{hours}}{\text{week}\cdot\text{member}} \cdot 10\ \text{weeks} \cdot 45.93\ \frac{\$}{\text{hour}} = \$9186 \tag{4}$$

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

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.

7. References

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APPENDIX A: Parts 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	FKP2O100331D00KSSD	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$
10 uF Capacitor*	WIMA	MKS2B051001N00JSSD	4	4*3.84$

APPENDIX B: Check requirements.

Subsystem 1:

Requirement	Verification	Status
Able to regulate the input voltage from ±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 ±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 - 5 volts, output a digital sequence of bits into the COPI corresponding to that measurement.	- 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. - 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	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 particular 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