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Implementation of an algorithm for monitoring electrical signals on a STM32 microcontroller

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1 General board layout

As we have mentioned in the introduction (**??**), we need a circuit board to measure triphasic voltage and current,so we need to condition six signals (three for voltage between phases and three for current in each phase) with galvanic isolation for safety reasons, and it has to be able to communicate with the chosen microprocessor. Given the features needed we think that the best way to proceed is a shield card with Arduino^{TM} Uno V3 connectivity support[1].

2 Signal conditioning

As we are treating with high voltage signals, a conditioning circuit is mandatory to archive the low voltage levels used in a microcontroller.

2.1 Voltage measurement

2.1.1 Input side

The development of the sensor board is the same for both the voltage and the current sensor so we are explaining it in depth for the $LV-25P$ voltage transducer.

We can see in the datasheet of the component that the input nominal current is $10mA$ with a maximum of $14mA$ so we need to dimension the input resistor in a way that the peak voltage $380V \times \sqrt{2} = 537.4V$ measured between phases produces around 10mA considering also the internal resistance, which is about 220Ω.

By Ohm law:

$$V_{in} = I_{in}(R_{internal} + R1) \tag{1}$$

$$R_{in} = \frac{V_{in}}{I_{in}} - R_{internal} = \frac{537,4V}{10mA} - 220\Omega = 53,5k\Omega \tag{2}$$

We have to use commercially available resistors so we use a $56k\Omega$ with 1% tolerance .With this resistor, the maximum input voltage that we could have (staying under de 14 mA max current) would be:

$$V_{in_{max}} = I_{max} \times (R_{internal} + R_{in}) = 787V \tag{3}$$

[1] This is one of the connector types supported by our development card

The nominal input power dissipation is:

$$P = I_{in}^2 \times (R_{internal} + R1) = 5.6W \tag{4}$$

In the datasheet we can see that the current consumption is given by:

$$10(@15V)mA + I_s mA \tag{5}$$

Electrical data

I_{PN}	Primary nominal rms current			10		mA
I_{PM}	Primary current, measuring range			0 .. ± 14		mA
R_M	Measuring resistance			$R_{M\,min}$	$R_{M\,max}$	
		with ± 12 V	@ ± 10 mA $_{max}$	30	190	Ω
			@ ± 14 mA $_{max}$	30	100	Ω
		with ± 15 V	@ ± 10 mA $_{max}$	100	350	Ω
			@ ± 14 mA $_{max}$	100	190	Ω
I_{SN}	Secondary nominal rms current			25		mA
K_N	Conversion ratio			2500 : 1000		
U_C	Supply voltage (± 5 %)			± 12 .. 15		V
I_C	Current consumption			10 (@ ± 15 V) + I_S		mA

Figure 1: LV25-P Datasheet

I_s is the nominal output current given a conversion ratio of 2500 : 1000 (k_N) so the current consumption will be arround:

$$10mA + 25mA = 35mA \tag{6}$$

2.1.2 Output side

As we are using a sensor that outputs current, we need a resistor to transform the current to voltage that is what the microprocessor measures. The measuring resistor R_m is limited to a range of values that we can find in the datasheet and depends of the supply voltage of the sensor.

We know that the 12-bits ADC of the STM32 can measure voltages between 0 and 3.3V but we have alternating voltage in the input and current in the output so we need to adapt the amplitude and level of the signal. Half of the input range of the ADC is used for the positive part of the signal and the other half for the negative so the 25mA is transformed into 1.6 V.

For the signal conditioning we chose a combination of a voltage follower and an Op Amp attenuator with level shifting

$$R_m = 200\Omega \implies V_m = \pm 25mA \times 200\Omega = \pm 5V \tag{7}$$

And we transform this alternating signal into a positive value with a suitable range with the following circuit:

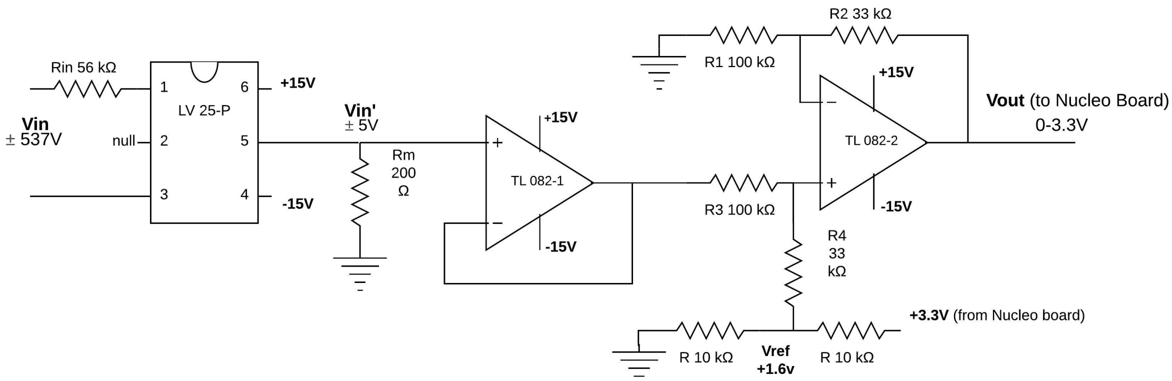


Figure 2: Signal conditioning circuit

To dimension the components of the attenuator circuit, we can start with the basic principles of an Op Amp:

$$V_- = V_+ \;\; \& \;\; I_+ = I_- = 0 \tag{8}$$

The input voltage of the attenuator is the output of the voltage follower and theoretically the same value at the input of it so we call it $V_{in}^{'}$.

Analyzing the non inverter line:

$$\frac{V_{in}^{'} - V_{ref}}{R_3 + R_4} = \frac{V_+ - V_{ref}}{R_4} \tag{9}$$

$$\implies V_+ = (V_{in}^{'} - V_{ref}) \times \frac{R_4}{R_3 + R_4} + V_{ref} \tag{10}$$

And for the inverter line:

$$\frac{V_{out}}{R_1 + R_2} = \frac{V_-}{R_1} \tag{11}$$

$$\implies V_{out} = V_- \times \frac{R_1 + R_2}{R_1} \tag{12}$$

Knowing that $V_+ = V_-$ we can find the relationship between $V_{in}^{'}$ and V_{out}:

$$V_{out} = \left[(V_{in}^{'} - V_{ref}) \times \frac{R4}{R_3 + R_4} + V_{ref}\right] \times \frac{R_1 + R_2}{R_1} \tag{13}$$

And analyzing the equation for the two extreme cases:

If $V_{ref} = 0$:

$$\frac{V_{out}}{V_{in}^{'}} = \frac{R_4}{R_1} \times \frac{R_1 + R_2}{R_3 + R_4} = A \tag{14}$$

Being A the gain of the signal.

If $V_{in} = 0 \rightarrow V_{in}^{'} = 0$:

$$\frac{V_{out}}{V_{ref}} = \frac{R_3}{R_1} \times \frac{R_1 + R_2}{R_3 + R_4} = A_{Vref} \tag{15}$$

Being A_{Vref} the gain of the offset voltage.

We can see here that the relationship $\frac{R_1+R_2}{R_3+R_4}$ is affecting both gains in the same way, and if we choose the resistors values in a way that $\frac{R_1+R_2}{R_3+R_4} = 1$ we can simplify the attenuator transfer equation.

$$V_{out} = V_{in}^{'} \times \frac{R4}{R1} + V_{ref} \times \frac{R_3}{R_1} \tag{16}$$

As we know that the input range is $10V$ and the output must be $0 - 3.3V$, the gain should be:

$$A_v = \frac{33}{100} = \frac{R_4}{R_1} \tag{17}$$

So we will use:

$$R_1 = 100k\Omega, R_4 = 33k\Omega, R_2 = 33k\Omega, R_3 = 100k\Omega$$

With this setup $A_{Vref} = \frac{R_3}{R_1} = 1$ but we don't have a source of +1.6V so we will use a voltage divider and the +3.3V output of the Nucleo board.

2.1.3 Transfer equation

Knowing each part of the circuit and the relationship between the outputs and inputs we can get together the complete transfer equation:

$$
\begin{aligned}
V_{out} &= A_v \times R_m \times K_n \times \frac{V_{in}}{R_{in}} + V_{ref} && (18)\\
&= \frac{R4}{R1} \times R_m \times K_n \times \frac{V_{in}}{R_{in}} + V_{ref} && (19)\\
&= \frac{33 \times 10^3}{100 \times 10^3} \times 200 \times \frac{2500}{1000} \times \frac{V_{in}}{56 \times 10^3 \Omega} + 1.6V && (20)\\
&= \frac{33}{11200} \times V_{in} + 1.6V && (21)
\end{aligned}
$$

2.2 Current measurement

The LA-25P transducer also works as a current source so the only difference in this circuit is the input range of the sensor,being the input nominal current $\pm 25A$.

With a gain $K_N = \frac{1}{1000}$, the nominal output current will be $25mA$ and using the same circuit equations already explained in section 2.1.1 we can obtain the transfer equation.

Electrical data

I_{PN}	Primary nominal rms current			25				A
I_{PM}	Primary current, measuring range			0 .. ± 55				A
R_M	Measuring resistance			T_A = 70 °C		T_A = 85 °C		
				$R_{M\,min}$	$R_{M\,max}$	$R_{M\,min}$	$R_{M\,max}$	
		with ± 12 V	@ ± 25 A $_{max}$	10	280	60	275	Ω
			@ ± 55 A $_{max}$	10	80	60	75	Ω
		with ± 15 V	@ ± 25 A $_{max}$	50	400	135	395	Ω
			@ ± 55 A $_{max}$	50	140	135	135	Ω
I_{SN}	Secondary nominal rms current			25				mA
K_N	Conversion ratio			1 : 1000				
U_C	Supply voltage (± 5 %)			± 12 .. 15				V
I_C	Current consumption			10 (@ ± 15 V) + I_S				mA

Figure 3: LA25-P Datasheet

Following the same procedure as in section 2.1.3, we obtain the following equation:

$$\begin{aligned}
V_{out} &= A_I \times R_m \times K_n \times I_{in} + V_{ref} && (22)\\
&= \frac{R4}{R1} \times R_m \times K_n \times I_{in} + V_{ref} && (23)\\
&= \frac{33 \times 10^3}{100 \times 10^3} \times 200 \times \frac{1}{1000} \times I_{in} + 1.6 && (24)\\
&= \frac{33}{500} \times I_{in} + 1.6 && (25)
\end{aligned}$$

3 Power supply

3.1 Dimensioning

The hole system energy supply will be a 12V battery from which we will generate the different voltage levels needed. As this is a stand-alone system which could be used in a remote location, a battery level monitoring circuit will be included and explained later.

Table 1: Power supply distribution

Power supply distribution			
Voltage (V)	Component	Quantity	Current consumption(mA)
±15	LA 25-P	3	35
	LV 25-P	3	35
	TL082	6	3.6
+15	TL082	1	3.6
+5	STM32 board[1]	1	< 500
+3.3	Vref[1]	1	≈ 0

[1] Obtained from the STM32 board.

We can see that the most power requiring supply is the one of $\pm 15V$ with almost 7 watts needed so we have chosen a Tracopower TEN 8-1223 8W DC-DC converter, and for the 5V supply a TEC 2WI. Both converters are directly connected to the battery. For the 3.3V supply we will use the STM32 voltage output because the power consumption is negligible.

3.2 Battery voltage measurement

If the system is installed in a remote location, a low battery alert sent to the cloud is mandatory to assure continuous monitoring of the network or machinery. For this purpose we are including a simple circuit to measure the battery voltage with an analog input of the microprocessor.

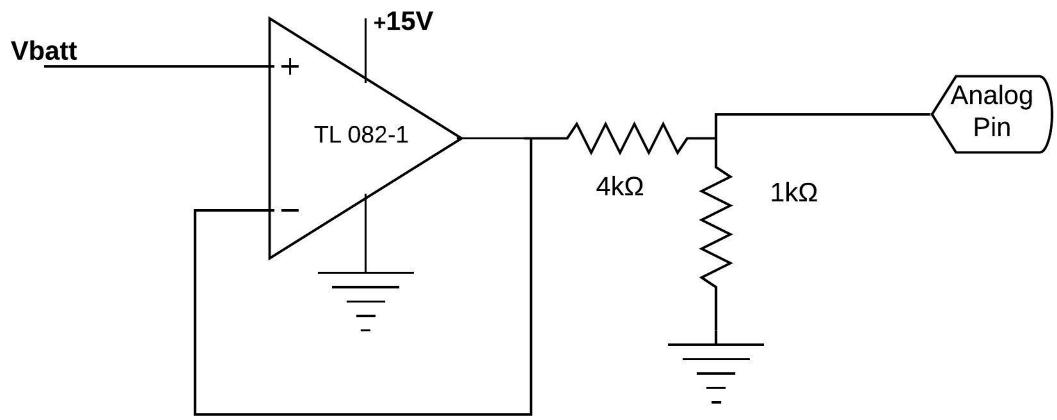


Figure 4: Battery measurement circuit

4 Board manufacturing

For the prototyping process we will be using Eagle PCB design software and UV lithography. The first version of the board had some troubles so we had to make minor changes and try again.

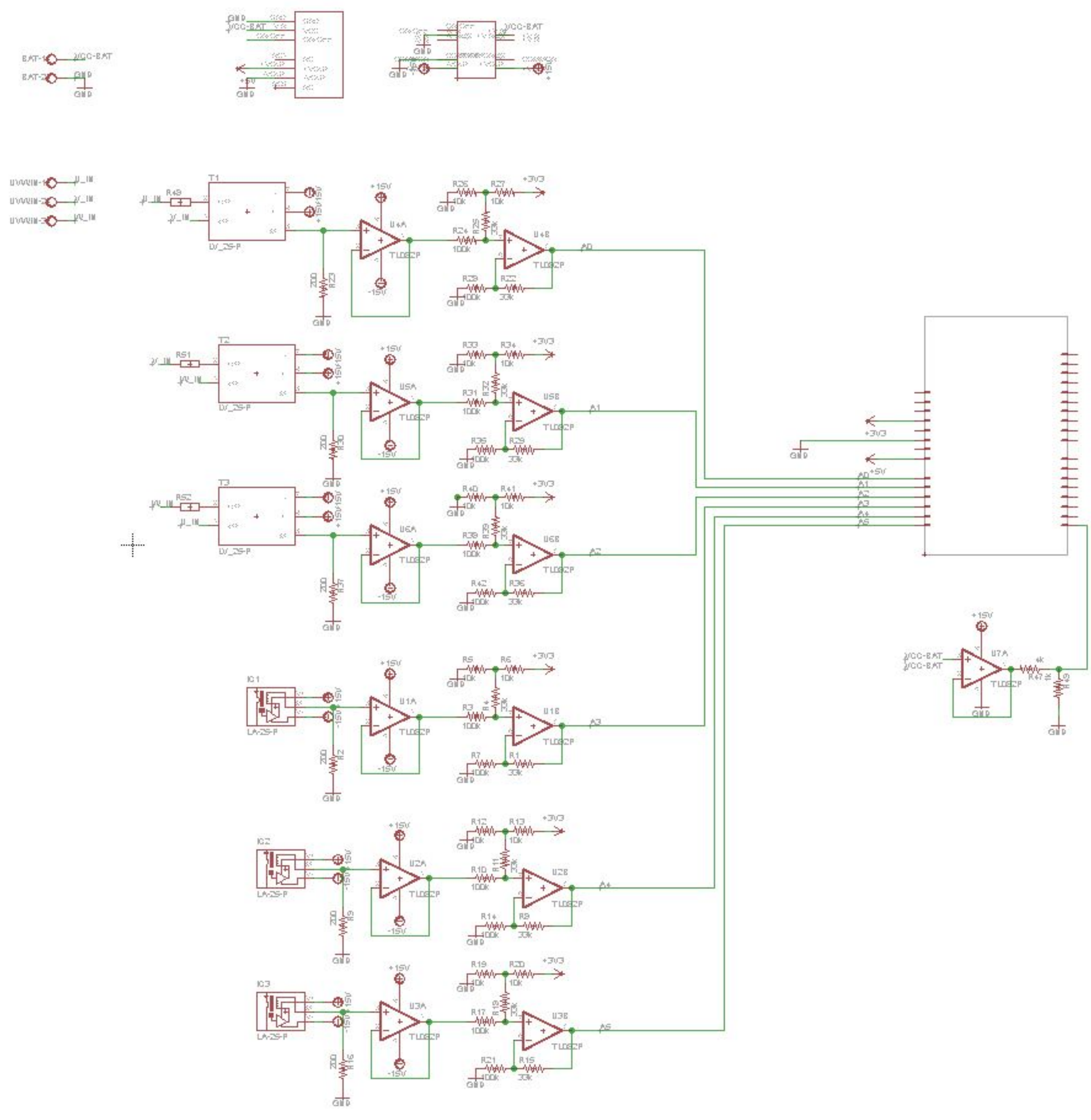
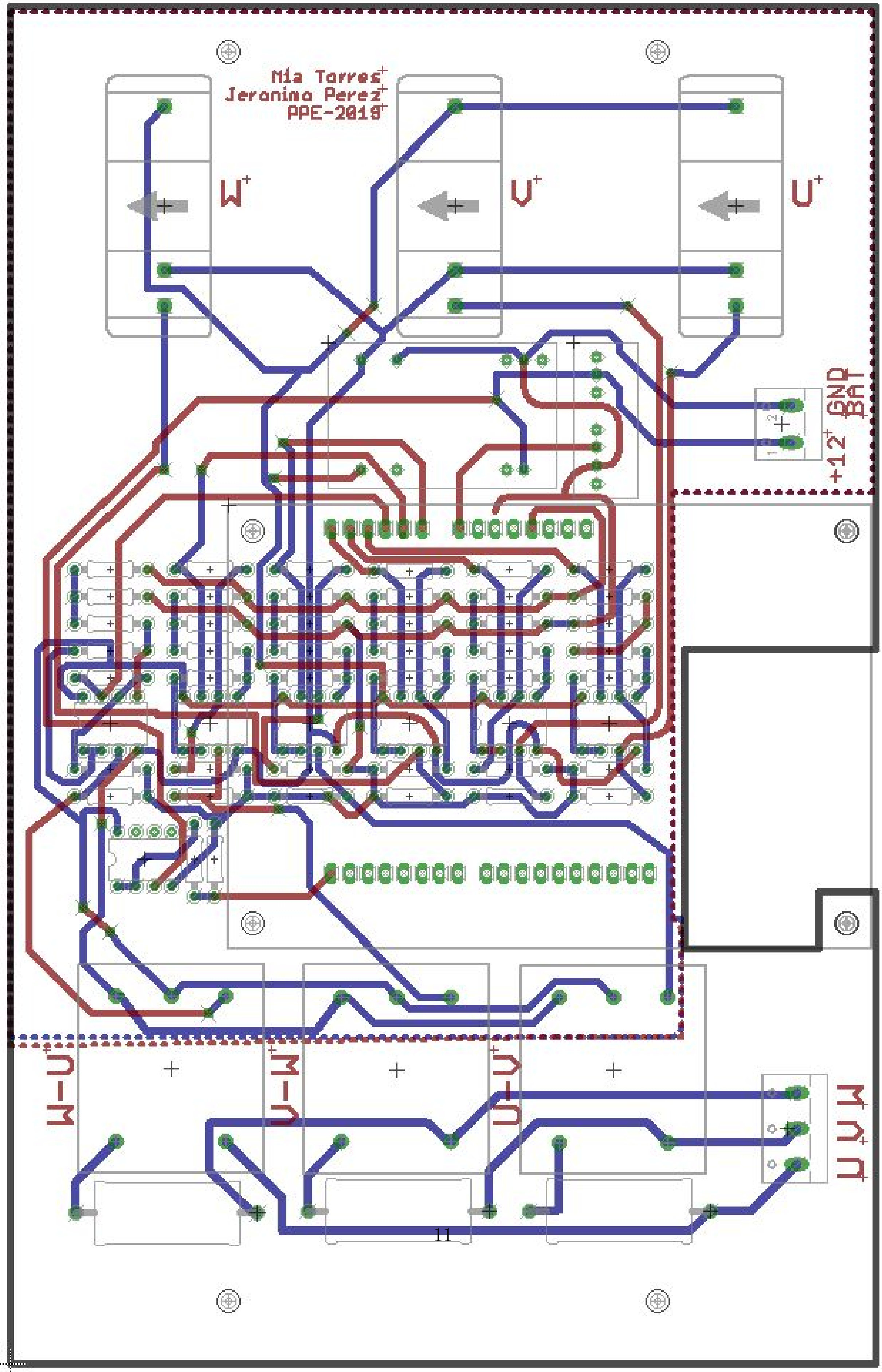


Figure 5: Schematic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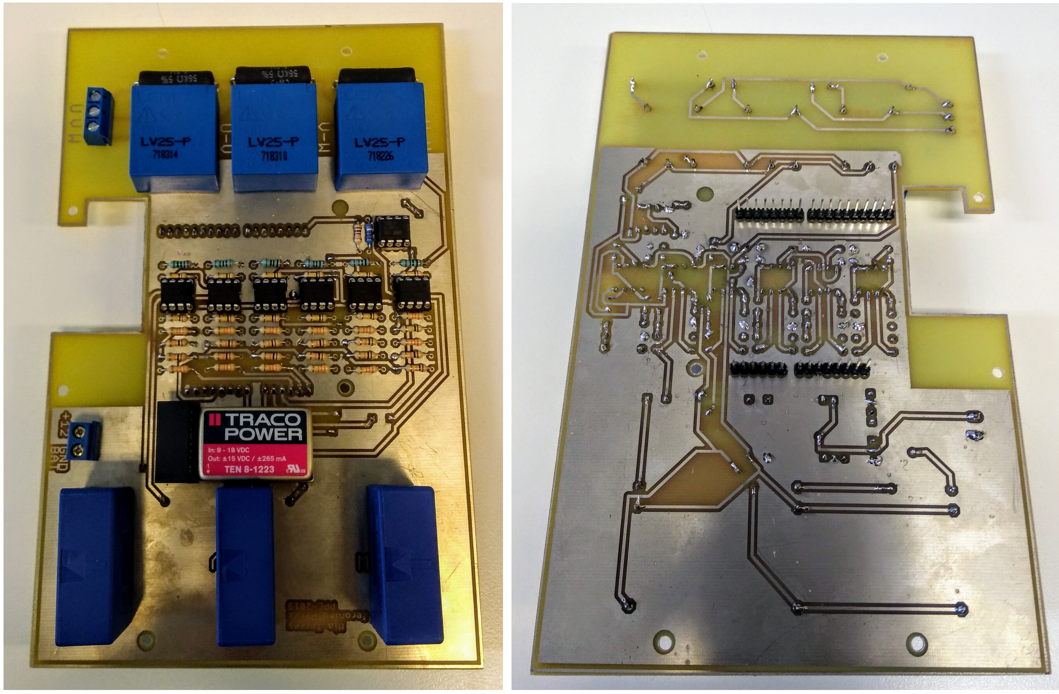


(a) Front side (b) Back side

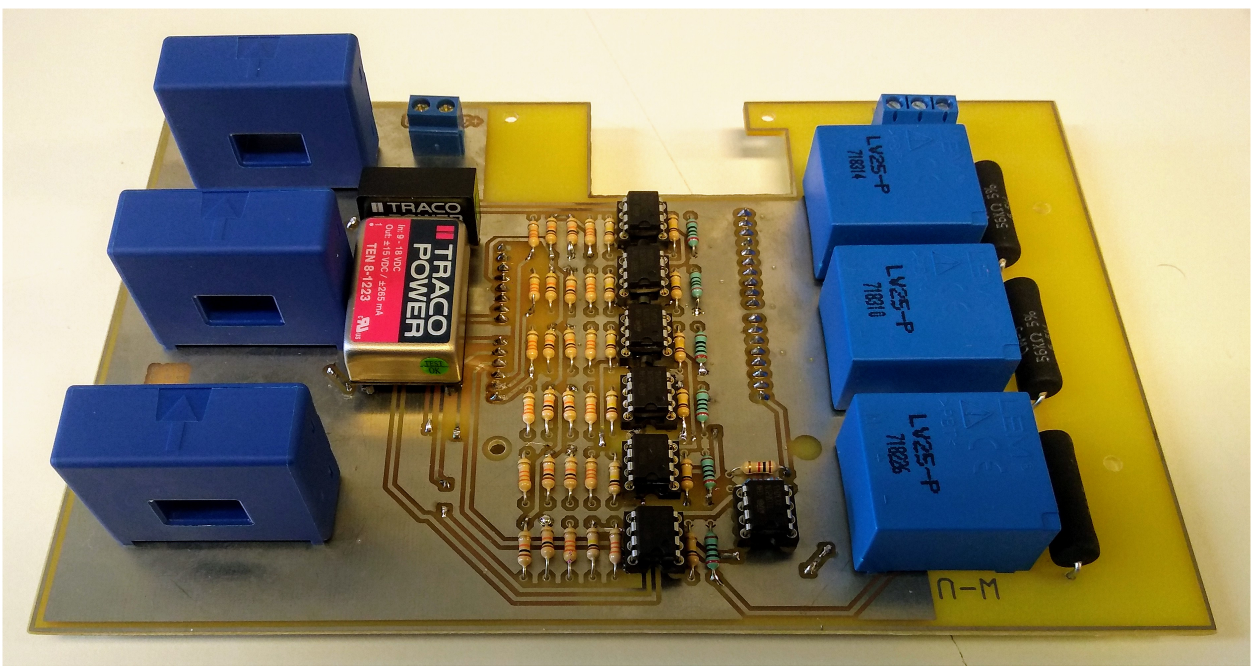


Figure 7: Front side horizontal

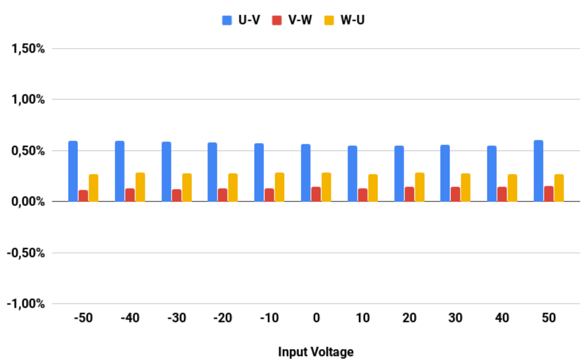
4.1 Board testing

All the tests are made with $V_{ref} = 0$, because this tension is supplied by the STM board which is not connected in the tests for safety reasons[2]. We connect V_{ref} directly to ground.

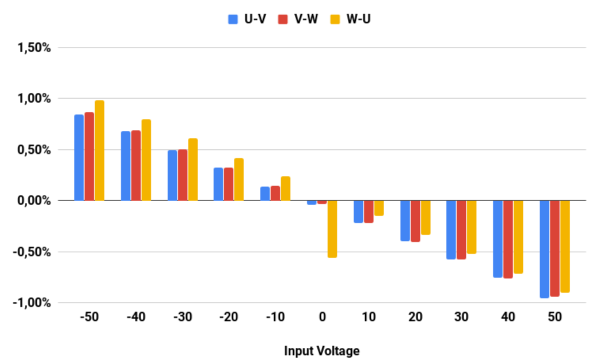
4.1.1 Voltage side

To test the voltage measurement circuit, we use a bench power supply with adjustable voltage and current output. Even when this is not the ideal test scenario given the low voltages used, it's good enough to have an idea of the general performance.

We test each phase with continuous voltage in the range of $\pm 50V$ in 10V steps measuring the sensor output Vin', the voltage follower output $Vfollower$ and the attenuator circuit output $Vout$ to calculate the error percentage (relative to the maximum possible value) between the theoretical and the measured values in each part of the signal conditioning process.



(a) $V_{in}^{'}$ sensor circuit isolated



(b) Signal attenuator circuit isolated.

Figure 9: Error percentage relative to the measurement range in the two main parts of the circuit.

[2]We have to be sure that there are no voltages higher than 3.3V in the board inputs.

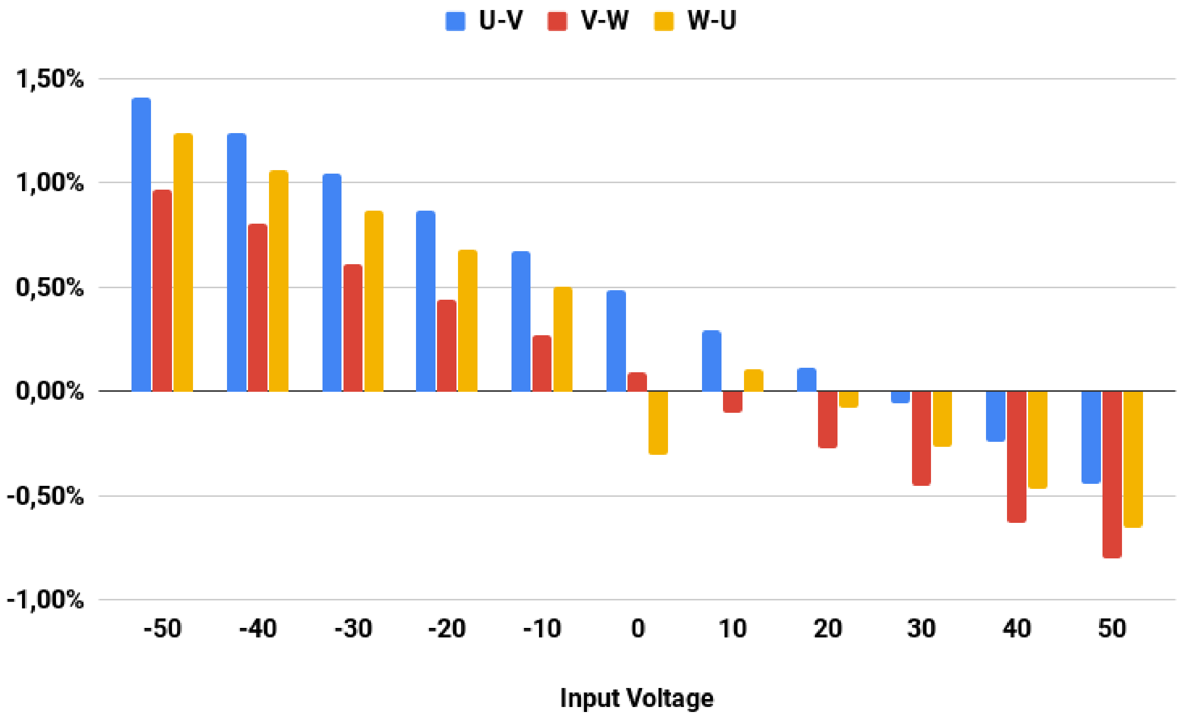


Figure 10: V_{out} error percentage relative to the measurement range

When the two main parts of the circuit are isolated, we can see clearly the error contribution of each one. When added this two graphs (see figure 9a and 9b) and depreciating the voltage follower circuit error which is minimal (see figure 12) we obtain approximately the V_{out} error percentage chart (see figure 10). Here we can see that in some cases error is compensated between each part and in others it is increased, this explains the asymmetry in the V_{out} error percentage chart. This kind of errors are probably caused by differences between resistors values, given that all the resistors used in the board have a 5% tolerance. To test this hypotheses the maximum theoretical error is calculated by taking the worst case scenario of the resistors values variation, calculating with the transfer equation the correspondent theoretical output values and plotting them together with the V_{out} values measured in each phase.

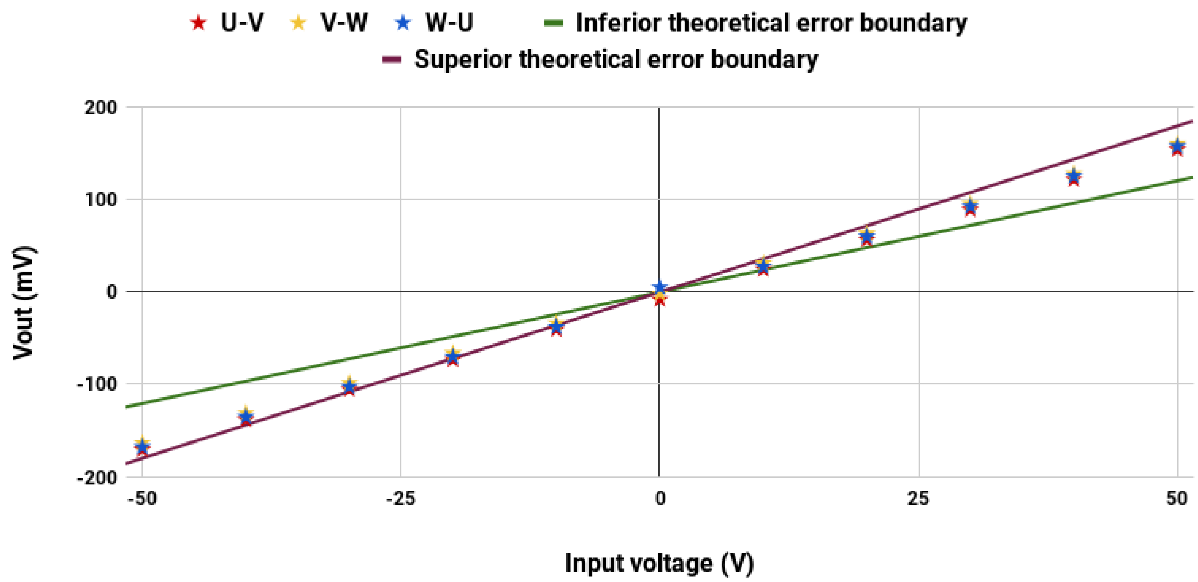


Figure 11: V_{out} Theoretical error boundaries.

We can see that the error is inside the expected values so this part of the circuit behaves as expected and no changes are needed. In future iterations, it will be necessary to evaluate if error values are low enough for signal analysis to work properly.

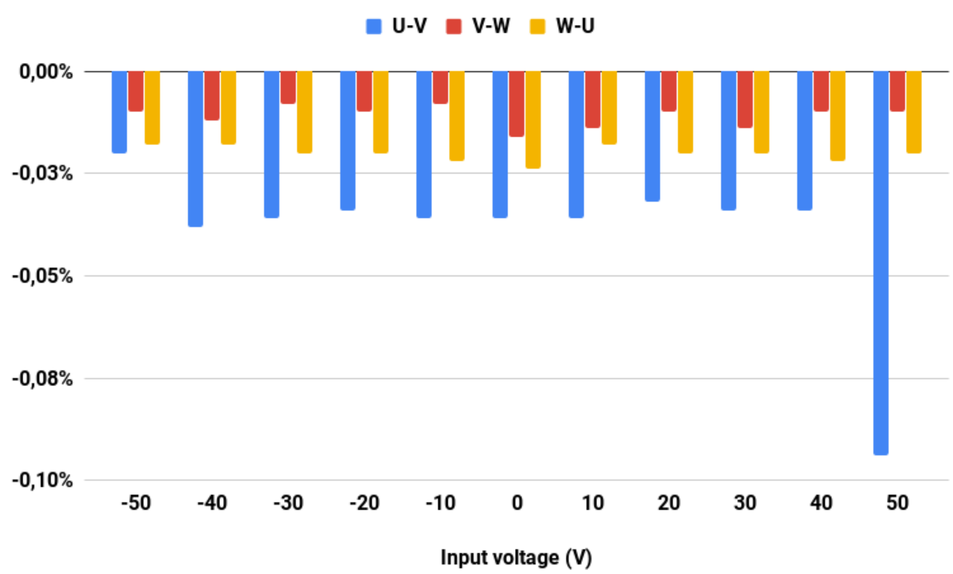


Figure 12: Voltage follower error.

4.1.2 Current side

In this test we use the current control feature of the bench power supply to feed each phase with a continuous current in a range of 0-2.5A with 0.5A steps.

newline

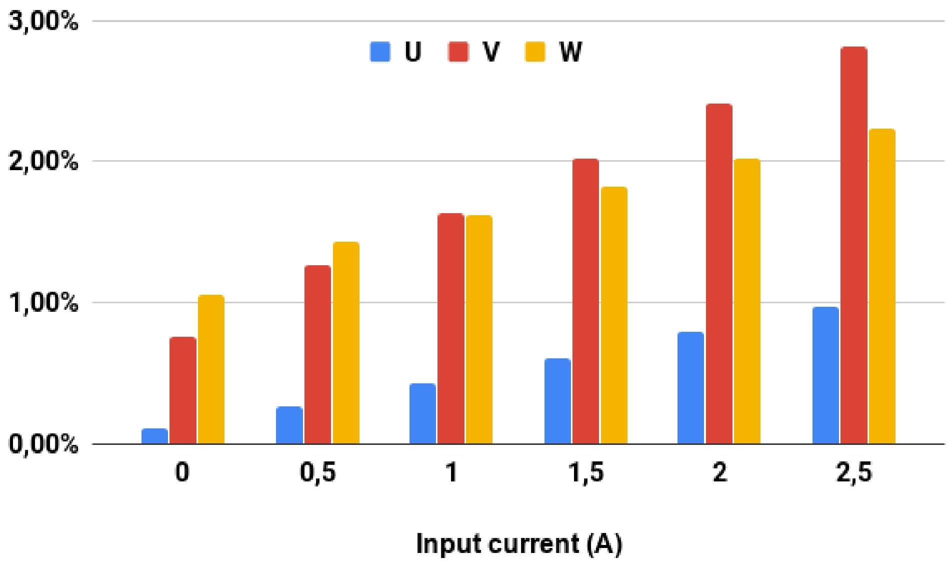
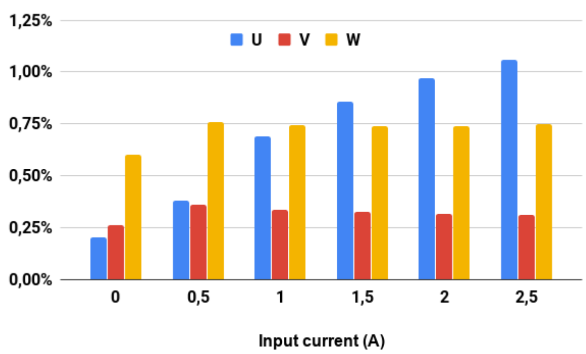
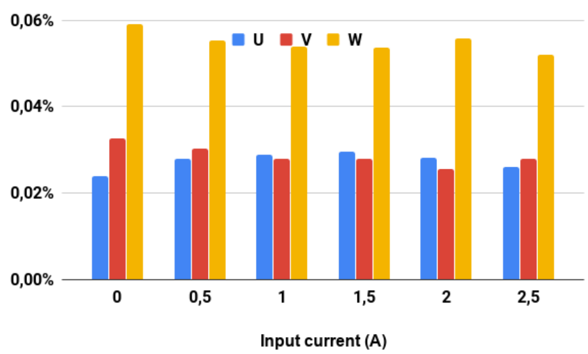


Figure 13: V_{out} error percentage relative to the measurement range



(a)



(b)

Figure 14

With an initial analysis of the results showed in the charts (see figures 13, 14a and 14b we see that the error in the output of the sensor and in the output of the signal conditioning circuit is already much higher than the one in the voltage measurement part, and after revising the circuit design we have come to the conclusion that the range chosen is too big for the available test equipment, so we proceed to make a redesign of this part.

4.2 Current side redesign

After a reevaluation of the circuit, we figured that the $\pm 25A$ measuring range was too high so we change it to a $\pm 5A$ range and redesign the signal conditioning circuit to work with higher voltages, making it less susceptible to noise and errors in the resistors values.

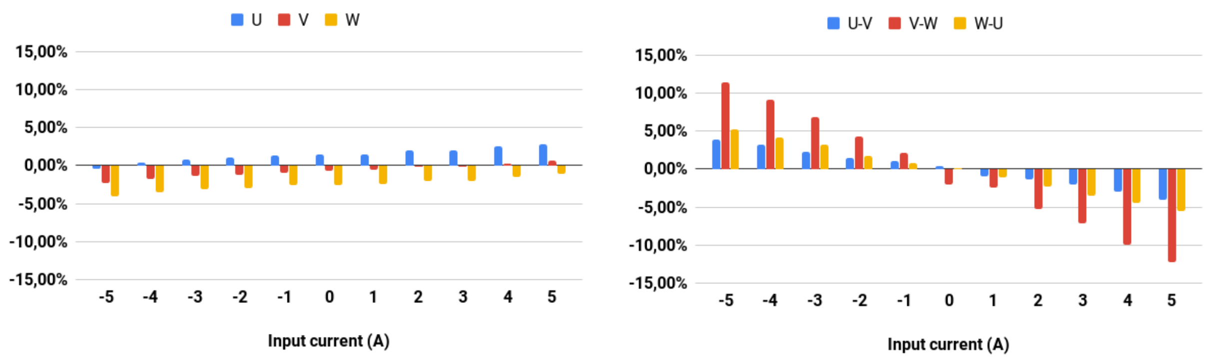
4.2.1 Transfer equation

The equations developed in the section 2.2 are still valid but we are changing some resistors values. As our maximum output current of the sensor is $\pm 5mA$, the measuring resistor R_m is $2k\Omega$. With this configuration the maximum $V_{in}^{'}$ voltage is $\pm 10V$ and as this value is doubled, the gain of the attenuator circuit is halved so we double the R1 and R3 values, being the new transfer equation:

$$
\begin{aligned}
V_{out} &= A_I \times R_m \times K_n \times I_{in} + V_{ref} && (26)\\
&= \frac{R4}{R1} \times R_m \times K_n \times I_{in} + V_{ref} && (27)\\
&= \frac{33 \times 10^3}{200 \times 10^3} \times 2000 \times \frac{1}{1000} \times I_{in} + 1.6 && (28)\\
&= \frac{33}{200} \times I_{in} + 1.6 && (29)
\end{aligned}
$$

4.2.2 Testing

We test each phase with continuous current in the range of $\pm 5A$ with 1A steps measuring the voltage in each section of the board, as in section 4.1.1 and calculate the error percentage (relative to the maximum possible value) between the theoretical and the measured values.



(a) V'_{in} sensor circuit isolated

(b) Signal attenuator circuit isolated.

Figure 15: Error percentage relative to the measurement range in the two main parts of the circuit.

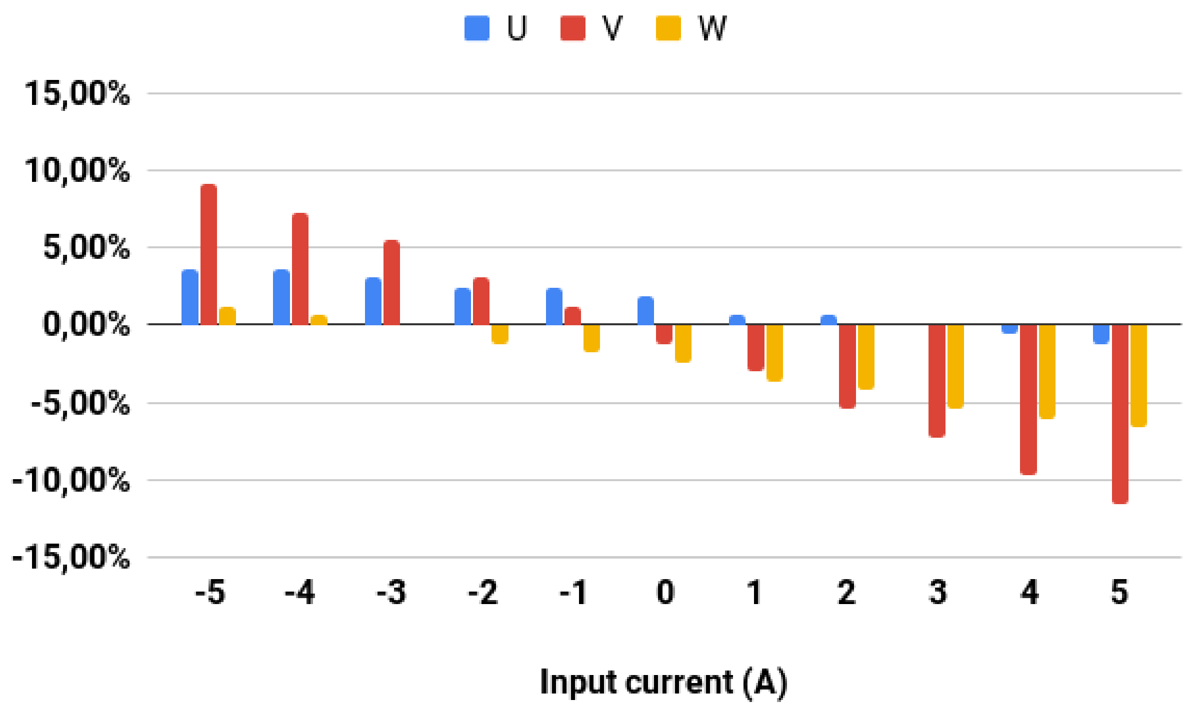


Figure 16: V_{out} error percentage relative to the measurement range

As we saw in section 4.1.1 adding up this two graphs (see figure 15a and 15b) and depreciating the voltage follower circuit error which is even lower than in the first version due to the higher voltages used (see figure 18) we obtain approximately the V_{out} error percentage chart (see figure 16). Following the same procedure that in section 4.1.1 the values corresponding to the maximum theoretical error are calculated and plotted together with the total V_{out} values for each phase.

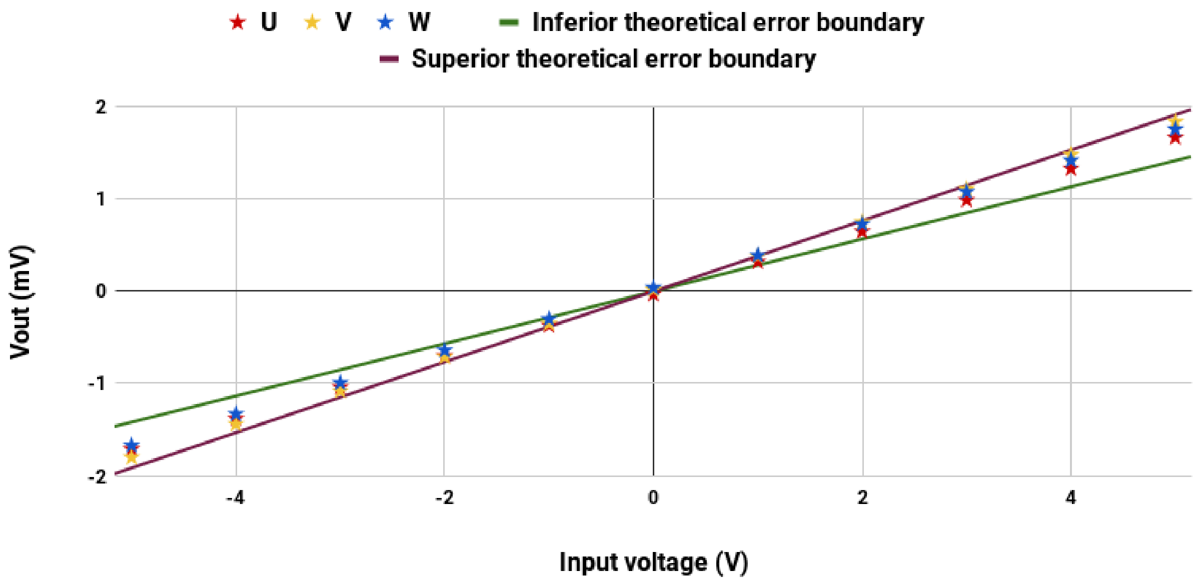


Figure 17: V_{out} Theoretical error boundaries.

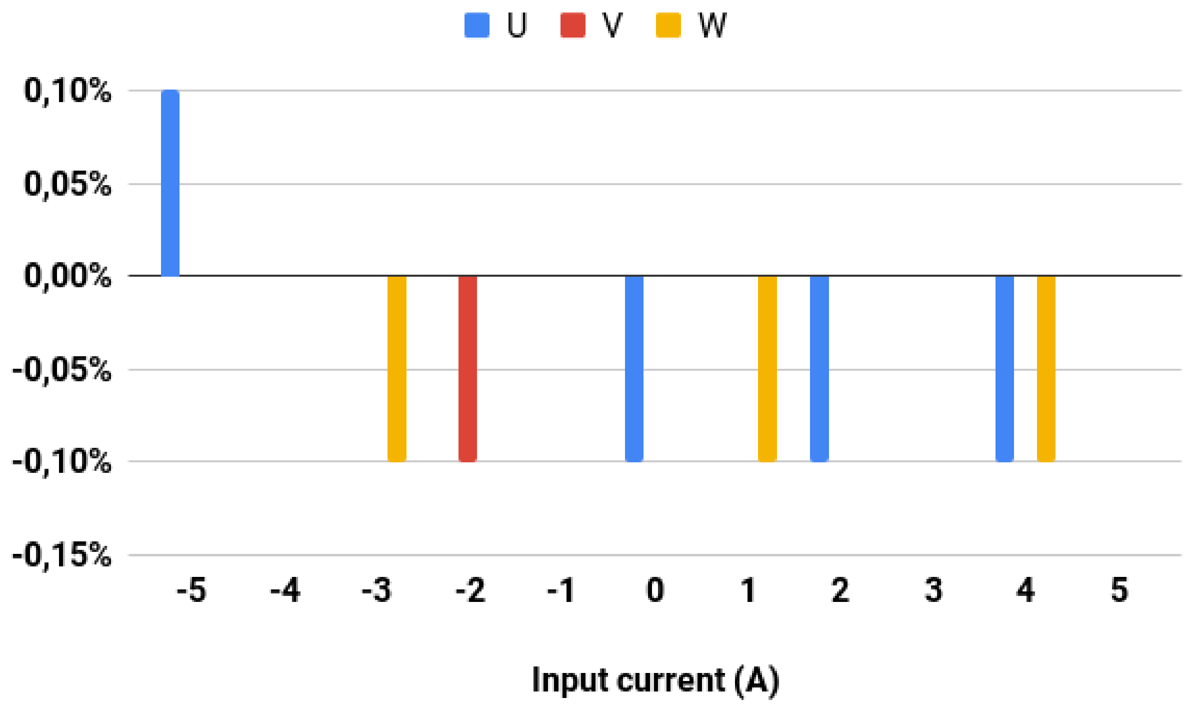


Figure 18: Voltage follower error.

We can see that the error is inside the expected values (see figure 17) so this part of the circuit behaves as expected. Even when the error values seem to be higher, this is the error relative to the maximum value measurable so for example, a 10% error over 5A it's equal to 0.5A, while with the previous design the highest error value was around 3% over 25A which means 0.75A so the circuit behaviour has been indeed improved.

References

[1] ST. *Discovery kit for IoT node, multi-channel communication with STM32L4*. URL: `https://www.st.com/content/ccc/resource/technical/document/user_manual/group0/b1/b8/7a/f2/f7/8d/4b/6b/DM00347848/files/DM00347848.pdf/jcr:content/translations/en.DM00347848.pdf`. (accessed: 03.06.2019).

Appendices

A Simulation parameters

Unless indicated otherwise, the parameters for the simulations in section **??** are:

$a = 2.31466$

$\phi = 0.0409$

$f = 50, 29411$

$N = 100$

$\theta = \{f_{min}, f_{min} + step, f_{min} + 2 * step, ..., f_{max} - 2 * step, f_{max} - step, f_{max}\}$ where $f_{min} = 40.0$, $f_{max} = 60.0Hz$ and $step = 0.01Hz$

B Recurrence

$$\begin{aligned}
cos(2\pi \times f \times \frac{n}{Fs}) &= cos(2\pi \times f \times (\frac{n-1}{Fs} + \frac{1}{Fs})) && (30)\\
&= cos(2\pi \times f \times \frac{n-1}{Fs} + 2\pi \times f \times \frac{1}{Fs}) && (31)\\
&= cos(2\pi \times f \times \frac{n-1}{Fs}) \times cos(2\pi \times \frac{f}{Fs})) - sin(2\pi \times f \times \frac{n-1}{Fs}) \times sin(2\pi \times \frac{f}{Fs})) && (32)
\end{aligned}$$

$$\begin{aligned}
sin(2\pi \times f \times \frac{n}{Fs}) &= sin(2\pi \times f \times (\frac{n-1}{Fs} + \frac{1}{Fs})) && (33)\\
&= sin(2\pi \times f \times \frac{n-1}{Fs} + 2\pi \times f \times \frac{1}{Fs}) && (34)\\
&= cos(2\pi \times f \times \frac{n-1}{Fs}) \times sin(2\pi \times \frac{f}{Fs})) + cos(2\pi \times f \times \frac{n-1}{Fs}) \times sin(2\pi \times \frac{f}{Fs})) && (35)
\end{aligned}$$