Tekhnê
January - June 2019, Vol. 16, No. 1, pp. 57 – 68

ISSN 1692-8407

Operational amplifier performance practices in linear applications

Practicas de desempeño del amplificador operacional en aplicaciones lineales

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In applications that require signal conditioning, i.e., the coupling of electrical signals in which there are no reductions or distortions due to a low impedance circuit, both in analog and digital signals, the operational amplifier (OpAmp, or Op-Amp) is widely used. These integrated circuits are direct-coupled amplifiers with high gain, which in linear applications require feedback through passive elements. This feedback determines the transfer function of the circuit, which is characterized by the elements used and their connection. In this article, we analyze by simulation the theoretical behavior of the OpAmp in basic signal conditioning configurations, including inverting amplifier, non-inverting amplifier, and voltage follower, as well as circuits coupled with these configurations.

Keywords: Feedback, high impedance, operational amplifier, reversing amplifier, signal coupling

En aplicaciones que requieren el acondicionamiento de señales, es decir, el acople de señales eléctricas en las cuales no se presenten reducciones o distorsiones a causa de un circuito de baja impedancia, tanto en señales análogas como digitales, se utiliza ampliamente el amplificador operacional (OpAmp, o Op-Amp). Estos circuitos integrados son amplificadores de acoplamiento directo con alta ganancia, que en aplicaciones lineales requiere realimentación mediante elementos pasivos. Esta realimentación determina la función de transferencia del circuito, la cual está caracterizada por los elementos utilizados y su conexión. En este artículo se analiza mediante simulación el comportamiento teórico del OpAmp en configuraciones básicas de acondicionamiento de señales, incluyendo amplificador inversor, amplificador no inversor, y seguidor de voltaje, así como circuitos acoplados con estas configuraciones.

Palabras clave: Acople de señales, alta impedancia, amplificador inversor, amplificador operacional, realimentación

Article typology: Research

Date manuscript received: December 7, 2018
Date manuscript acceptance: April 19, 2019

Research funded by: Universidad Distrital Francisco José de Caldas (Colombia).

How to cite: Rendón, A. (2019). *Operational amplifier performance practices in linear applications*. Tekhnê, 16(1), 57 -68.

Introduction

The operational amplifier is an active electronic circuit composed of multiple devices that produce a system that can be connected to an electrical circuit, capable of behaving as a high input impedance element, and a transfer function dependent on the passive elements that are connected to its terminals (Martínez, Martinez, & Montiel, 2017; Wang et al., 2010). Without these passive elements, the output of the OpAmp corresponds to the difference of the signal applied to its two inputs multiplied with a gain factor that depends on the construction of the OpAmp, and whose value is of the order of 10^5.

The OpAmp is used as a coupling circuit between circuits due to its high input impedance and signal gain (Montiel, Martínez, & Martínez, 2019). This high input impedance allows connections to be made between circuits, reducing signal loss and distortion. In this type of application, it is normal to control the open-loop gain of the OpAmp using a feedback loop (feedback to the negative terminal of the OpAmp) which, on the one hand, controls the gain of the circuit, and on the other hand, allows the operation of the OpAmp to be linearized, which facilitates the analysis of circuits that contain it (Tammam, Hayatleh, Ben-Esmael, Terzopoulos, & Sebu, 2014). The elements used to feed the OpAmp have stable and known values, so the transfer function of the OpAmp is also stable and known. Much of the work with the OpAmp lies in the design of circuits with certain transfer functions, i.e., the design of the feedback circuit.

Originally the OpAmp was used on analog computers. In these computers, they formed circuits for operations such as sums, derivatives, and integrals. However, these systems required costly and continuous adjustments, and are currently surpassed in performance by digital systems. Currently, they are widely used in instrumentation, specifically in the coupling of circuits (Chi & Cauwenberghs, 2010). It is for this reason that its study and design is fundamental in the programs of Electrical Engineering and related (García et al., 2014). However, for students new to their study, circuit analysis with OpAmp is complex due to its natural non-linear behavior, compared to the rules of linear circuit analysis traditionally taught and used in these programs (Wong & Ng, 2016).

The design strategies of electronic systems, or of those integrated systems that involve electronic circuits are in continuous change (Martinez, Martínez, & Hernandez, 2017; Martínez, Montiel, & Martínez, 2017). However, some basic circuits, such as those implementable with OpAmp, are still critical in most real implementations (Valbuena, Perdomo, & Martinez, 2017). This is the reason for the continuous development of new tools and strategies that support specific training in the design of electronic systems (Martínez, Rendón, & Guevara, 2017).

Inverter amplifier review

For the first study case, we are going to consider the inverse configuration of the operational amplifier with gain (Fig. 1). In this scheme, the OpAmp uses resistance as output feedback to its negative input (R_2). The input signal is fed by the positive input pin through another resistor (R_1). These two resistors are the only necessary passive elements in the circuit, and determine the behavior of the output signal (V_0) to the input voltage (V_{s1}).

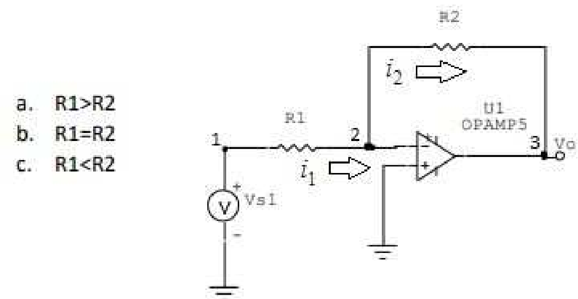

Figure 1. Inverter amplifier with 100 mV input at 1 kHz.

According to the possible values of resistance, the circuit has three possible behaviors determined by the relationship between the magnitudes of the resistors.

- $R_1 > R_2$
- $R_1 = R_2$
- $R_1 < R_2$

Under the inverter amplifier configuration (Fig. 1), the current i_1 is approximately equal to the current i_2 due to the high input impedance of the OpAmp, that is:

$$i_1 \simeq i_2 \tag{1}$$

Therefore, according to the assumed direction of the currents, the following equation can be written to relate these two currents:

$$\frac{v_1 - v_2}{R_1} = \frac{v_2 - v_3}{R_2} \tag{2}$$

As a result of the virtual zero the voltage drop between the two inputs of the OpAmp is zero, ie $V_2 = 0$, so the equation becomes:

$$\frac{v_{s1} - 0}{R_1} = \frac{0 - v_0}{R_2} \tag{3}$$

Or with general circuit input and output expressions:

$$\frac{v_{in} - 0}{R_1} = \frac{0 - v_{out}}{R_2} \tag{4}$$

Clearing the output voltage:

$$\frac{-v_{out}}{R_2} = \frac{v_{in}}{R_1} \tag{5}$$

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$$v_{out} = -v_{in}\frac{R_2}{R_1} \tag{6}$$

As can be seen, the gain at the output is negative (hence the name of the circuit), and depends on the relationship between the two resistors. The three behaviors of the circuit are detailed in table 1.

First case: Inverter voltage follower ($R_1 = R_2$)

To evaluate the performance of the inverter amplifier we will use the following test data:

- v_{in}: 100 mV peak at a frequency of 1 kHz.
- The operational amplifier is supplied with a dual voltage of ±12 V.
- $R_1 = R_2 = 10$ kΩ.
- The ideal model of operational amplifier is used.

According to equation 6, the output voltage is defined as:

$$v_{out}(t) = -0.1\, sin(2\pi f t)\,\frac{10000}{10000}\; V \tag{7}$$

$$v_{out}(t) = -0.1\, sin(2000\pi t)\; V \tag{8}$$

This means that the output voltage is also a sinusoid signal at the same frequency and with the same amplitude, but out of phase concerning the input voltage by 180 degrees. Both signals (v_{in} and v_{out}) have a period $T = 1$ ms, which means that in a 200 μs/Div oscilloscope configuration a period in five horizontal frames would be observed. This behavior is shown in Fig. 2.

Second case: Inverter with voltage amplification ($R_1 < R_2$)

For this second case we will use the following values for the resistors:

- $R_1 = 5$ kΩ.
- $R_2 = 10$ kΩ.

All other test circuit parameters, including the input signal, remain the same. In this case, the output voltage is given by:

$$v_{out}(t) = -0.1\, sin(2\pi f t)\,\frac{10000}{5000}\; V \tag{9}$$

$$v_{out}(t) = -0.2\, sin(2000\pi t)\; V \tag{10}$$

The ratio between the two resistors is $R_2/R_1 = 2$, therefore an amplification in the output voltage equivalent to twice the input signal is expected. All other signal characteristics remain the same, i.e., they are still sinusoidal signals at the same frequency out of phase by 180 degrees. This behavior is shown in Fig. 3.

Third case: Inverter with voltage reduction ($R_1 > R_2$)

In this last case, we will use a voltage reduction ratio of 0.5, therefore the resistors used can be of the following values:

- $R_1 = 10$ kΩ.
- $R_2 = 5$ kΩ.

Once again, all other test circuit parameters, including the input signal, remain the same. In this case, the output voltage is given by:

$$v_{out}(t) = -0.1\, sin(2\pi f t)\,\frac{5000}{10000}\; V \tag{11}$$

$$v_{out}(t) = -0.05\, sin(2000\pi t)\; V \tag{12}$$

That is, the output voltage corresponds to half of the input voltage at all times, again with a negative sign, i.e. a signal 180 degrees off the input. The waveform and its frequency remain the same, only the output amplitude is affected. This behavior is shown in Fig. 4.

Non-inverting amplifier review

The configuration of the OpAmp as a non-inverting amplifier is similar to the configuration as an inverting amplifier. In this circuit again, a resistor is used as output feedback to the OpAmp's negative terminal (R_2), and another resistor R_1 is connected to the same node that allows the circuit current ratios to be defined. However, in this circuit, the input signal (v_{s1}) is not fed to the OpAmp through this resistor but is connected to the positive terminal of the OpAmp (Fig. 5).

Due to the virtual zero between the two terminals of the OpAmp, the voltage at the negative terminal of the OpAmp is the input voltage to the circuit, which radically changes the behavioral equations. As in the inverter amplifier, given the high input impedance of the OpAmp, the two currents indicated in the circuit are practically the same, i.e:

$$i_1 \simeq i_2 \tag{13}$$

Therefore, according to the assumed direction of the currents, the following equation can be written to relate these two currents:

$$\frac{v_1 - v_2}{R_1} = \frac{v_2 - v_3}{R_2} \tag{14}$$

$$\frac{0 - v_{s1}}{R_1} = \frac{v_{s1} - v_0}{R_2} \tag{15}$$

Or with general circuit input and output expressions:

$$\frac{0 - v_{in}}{R_1} = \frac{v_{in} - v_{out}}{R_2} \tag{16}$$

Clearing the output voltage:

Table 1

Possible behavior of the inverter amplifier according to the relationship between the circuit resistors.

$R_1 = R_2$	$R_1 < R_2$	$R_1 > R_2$
$v_{out} = -v_{in}$ The output voltage is equal to the input voltage in magnitude, but with a 180 degree offset.	$1 < \frac{R_2}{R_1}$ The output voltage is equal to R_2/R_1 times the input voltage, but with a 180 degree offset.	$0 < \frac{R_2}{R_1} < 1$ The output voltage is equal to a proportion of the input voltage given by R_2/R_1, but with a 180 degree offset.

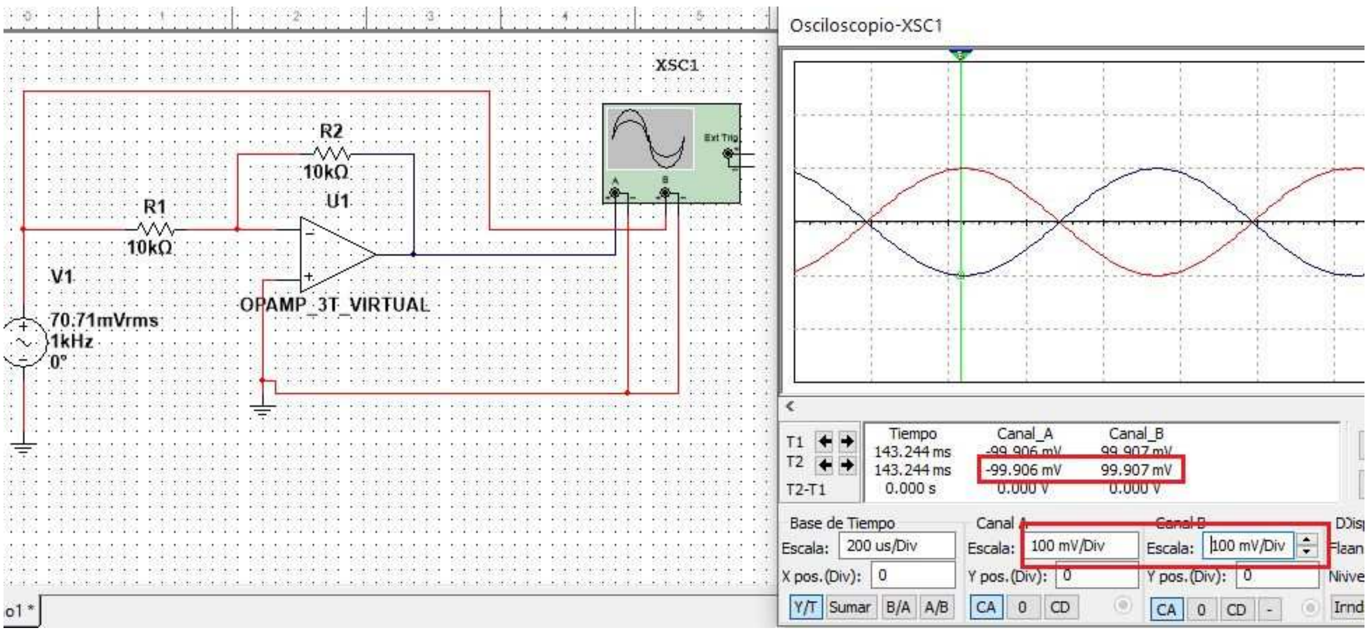

Figure 2. Simulation of the inverter amplifier with $R_1 = R_2$. Input and output voltages are shown.

$$\frac{-v_{in}}{R_1} = \frac{v_{in} - v_{out}}{R_2} \tag{17}$$

$$-v_{in}\frac{R_2}{R_1} = v_{in} - v_{out} \tag{18}$$

$$v_{out} = v_{in} + v_{in}\frac{R_2}{R_1} \tag{19}$$

$$v_{out} = v_{in}\frac{R_1 + R_2}{R_1} \tag{20}$$

In this new circuit again a relationship is established between the output voltage and input voltage, and again this relationship depends on the values of the two resistors. The resistors define the gain value of the circuit, which affects the magnitude at each instant of time, but since the relationship is constant, does not affect the output waveform. Unlike the inverter amplifier, the ratio or gain given by the resistors is positive (the resistors always have a positive value, we are not going to complicate the problem by talking about negative resistors), and again they can produce three behaviors depending on the selected values, these three cases are detailed in table 2.

First case: Voltage doubler ($R_1 = R_2$)

If the two resistors are taken from the same value, the output voltage will correspond to twice the input voltage. This relationship is constant, so as in the previous cases there is no distortion in the output, the waveform and frequency of the input are maintained. To evaluate this circuit we will use the following parameters:

- v_{in}: 200 mV peak at a frequency of 1 kHz.
- The operational amplifier is supplied with a dual voltage of ±15 V.
- $R_1 = R_2 = 10$ kΩ.
- The ideal model of operational amplifier is used.

According to equation 20, the output voltage of the circuit is:

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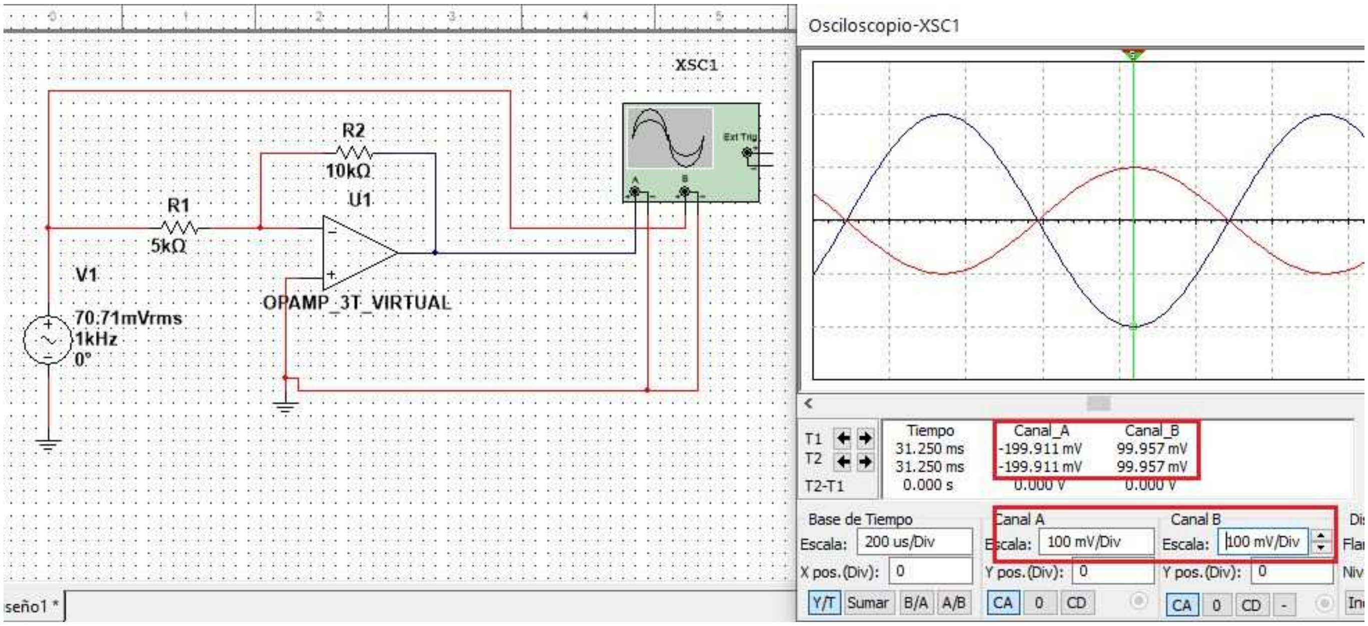

Figure 3. Simulation of the inverter amplifier with $R_1 < R_2$. Input and output voltages are shown.

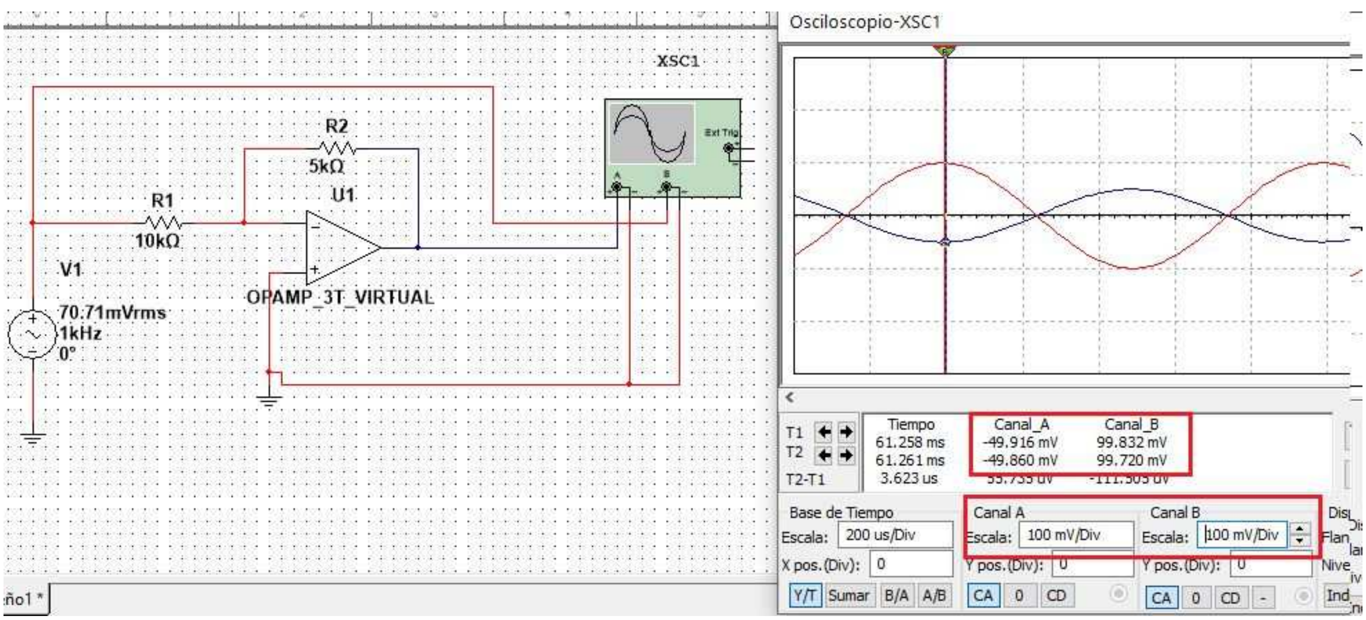

Figure 4. Simulation of the inverter amplifier with $R_1 > R_2$. Input and output voltages are shown.

$$v_{out}(t) = 0.2\, sin\,(2\pi f t)\, \frac{10000 + 10000}{10000}\, V \tag{21}$$

$$v_{out}(t) = 0.4\, sin\,(2000\pi t)\ V \tag{22}$$

Therefore, the output voltage has the same sinusoidal waveform as the input, with the same frequency, but its amplitude changes to twice the input value. The output voltage at each instant of time has twice the value of the input voltage and is in phase with it. This behavior can be seen in Fig. 6.

Second case: Voltage follower ($R_1 > R_2$)

To configure the voltage follower we use the following resistance values:

- R_1 = 10 kΩ.
- R_1 = 2 kΩ.

All other parameters remain the same, including the input signal. According to the resistance ratio, the output voltage is given by:

Table 2

Possible behavior of the non-inverter amplifier according to the relationship between the circuit resistors.

$R_1 = R_2$	$R_1 > R_2$	$R_1 < R_2$
$v_{out} = -2\,v_{in}$ The output voltage is equal to twice the input voltage.	$\frac{R_1+R_2}{R_1} \simeq 1$ The output voltage is very close to the input voltage. Since R_2 is negligible compared to R_1, the relationship between the resistors tends to one.	$\frac{R_1+R_2}{R_1} \simeq \frac{R_2}{R_1}$ $1 < \frac{R_2}{R_1}$ The output voltage is equal to a proportion of the input voltage given by R_2/R_1.

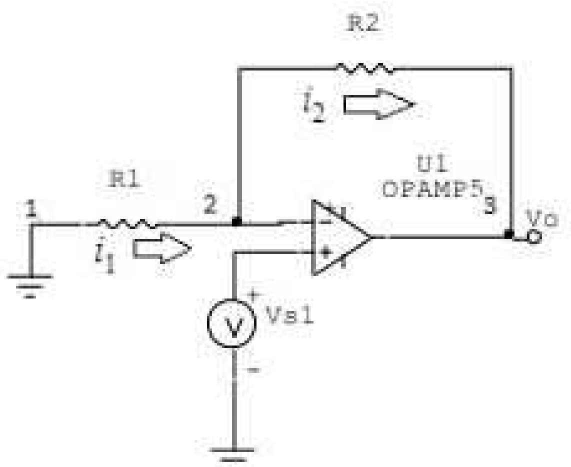

Figure 5. Non-inverting amplifier with 200 mV peak input at 1 kHz.

$$v_{out}(t) = 0.2\, sin\,(2\pi f t)\,\frac{10000 + 2000}{10000}\; V \tag{23}$$

$$v_{out}(t) = 0.24\, sin\,(2000\pi t)\;\; V \tag{24}$$

In this case, the gain given by the resistors is $\frac{R_1+R_2}{R_1} = 1.2$, which means that the magnitude of the output signal will have a 20% increase concerning the input signal. Although the circuit is ideally a voltage follower, this behavior will be valid as long as the size of R_1 is much larger than R_2, at least 10 times larger. Thus the value R_2 would have a negligible value against R_1, and the ratio of resistances would approach with negligible error to 1. Fig. 7 shows the ideal behavior of this circuit.

Third case: Voltage amplifier ($R_1 < R_2$)

The last case of this circuit occurs when the resistance R_1 is much lower than R_2, which makes the gain of the circuit tends to R_2/R_1. Again this depends on how big is R_2 concerning R_1, for this relationship to be met the difference must be at least 10 times. If this is not true, the ratio $\frac{R_1+R_2}{R_1}$ must be used to determine the circuit gain. To configure this voltage amplifier we use the following elements:

- R_1 = 3 kΩ.
- R_1 = 20 kΩ.

All other parameters remain the same, including the input signal. According to the resistance ratio, the output voltage is given by:

$$v_{out}(t) = 0.2\, sin\,(2\pi f t)\,\frac{3000 + 20000}{3000}\; V \tag{25}$$

$$v_{out}(t) = 1.53\, sin\,(2000\pi t)\;\; V \tag{26}$$

The gain defined by the two resistors is $\frac{R_1+R_2}{R_1} = 7.67$, which means amplification of almost eight times the input signal. Since the resistance R_2 is 6.67 times larger than R_1 ($R_2/R_1 = 6.67$), it is preferable to use the ratio $\frac{R_1+R_2}{R_1}$ to calculate the gain. If the approximate ratio of R_2/R_1 were used, the gain would be 1.33, which produces a considerable difference concerning the real value. Fig. 8 shows the behavior of this circuit.

Review of the voltage follower amplifier

The voltage follower circuit seeks to have an output signal that follows the input signal, isolating this input from the circuit that uses the output signal, mainly to avoid that due to current consumption the processed signal will be different from the one provided, for example, by some sensor. This circuit is implemented by directly feeding the output, without resistance, to the negative input of the OpAmp. The input voltage is fed directly to the positive input of the OpAmp, so this circuit does not use resistance for its configuration (Fig. 9).

According to the circuit, the following nodal relationships can be established:

$$v_1 = v_{s1} = v_2 = v_0 \tag{27}$$

To analyze this circuit we will use the following design parameters:

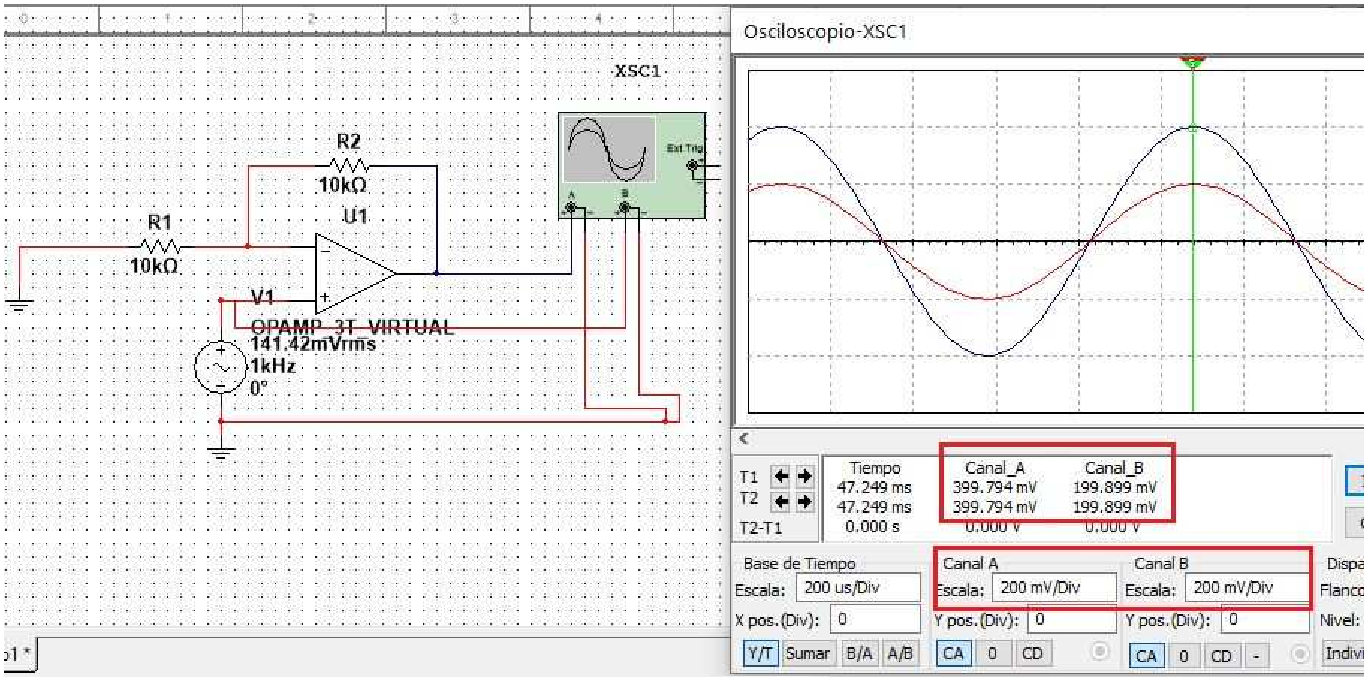

Figure 6. Simulation of the non-inverting amplifier with $R_1 = R_2$. Input and output voltages are shown.

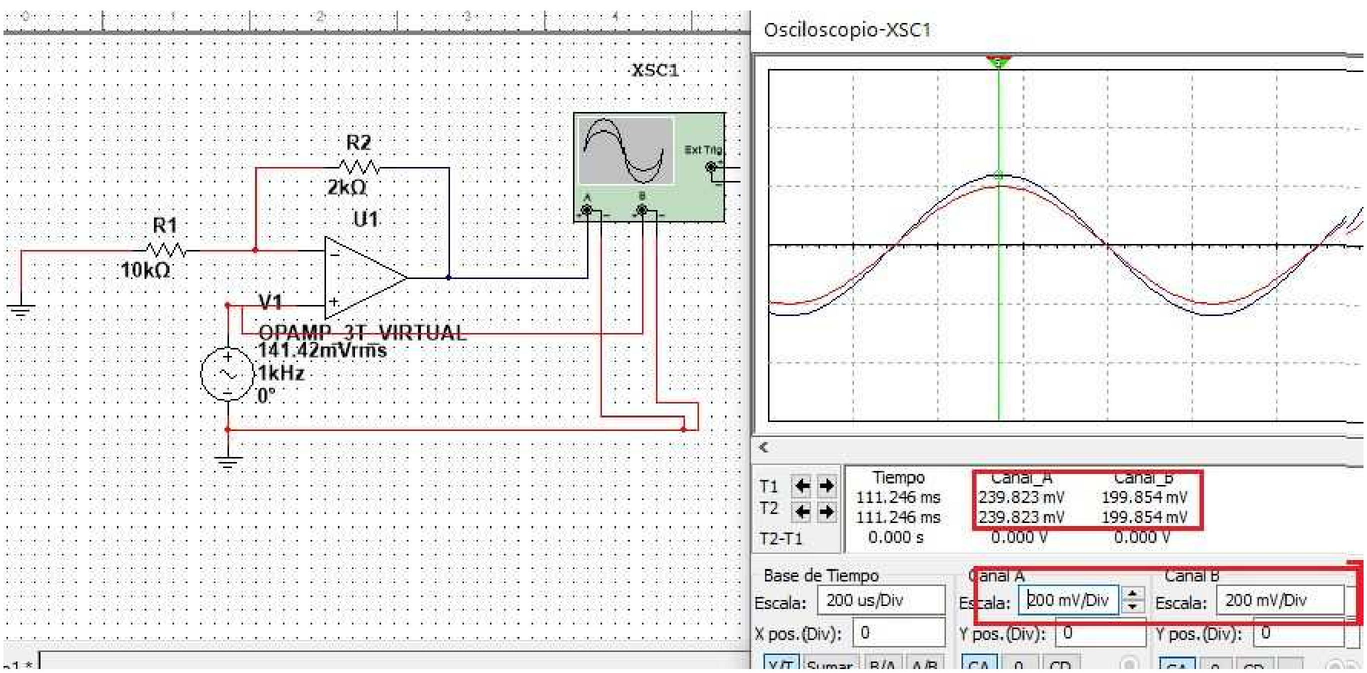

Figure 7. Simulation of the non-inverting amplifier with $R_1 > R_2$. Input and output voltages are shown.

- v_{in}: 1 V peak-to-peak at a frequency of 1 kHz.
- The operational amplifier is supplied with a dual voltage of ±10 V.
- The ideal model of operational amplifier is used.

Therefore, the output voltage of the circuit is given by:

$$v_{out}(t) = v_0(t) = 0.5\,sin(2\pi f t)\ V \tag{28}$$

Fig. 10 shows the behavior of this voltage follower circuit.

Let's now consider the circuit in Fig. 11. In this case, we have the same voltage follower, but we have added resistance in the negative feedback loop (R_1).

From this new configuration we conclude two facts:

1. Due to the high input impedance of the OpAmp, the current through the OpAmp is minimal. Therefore,

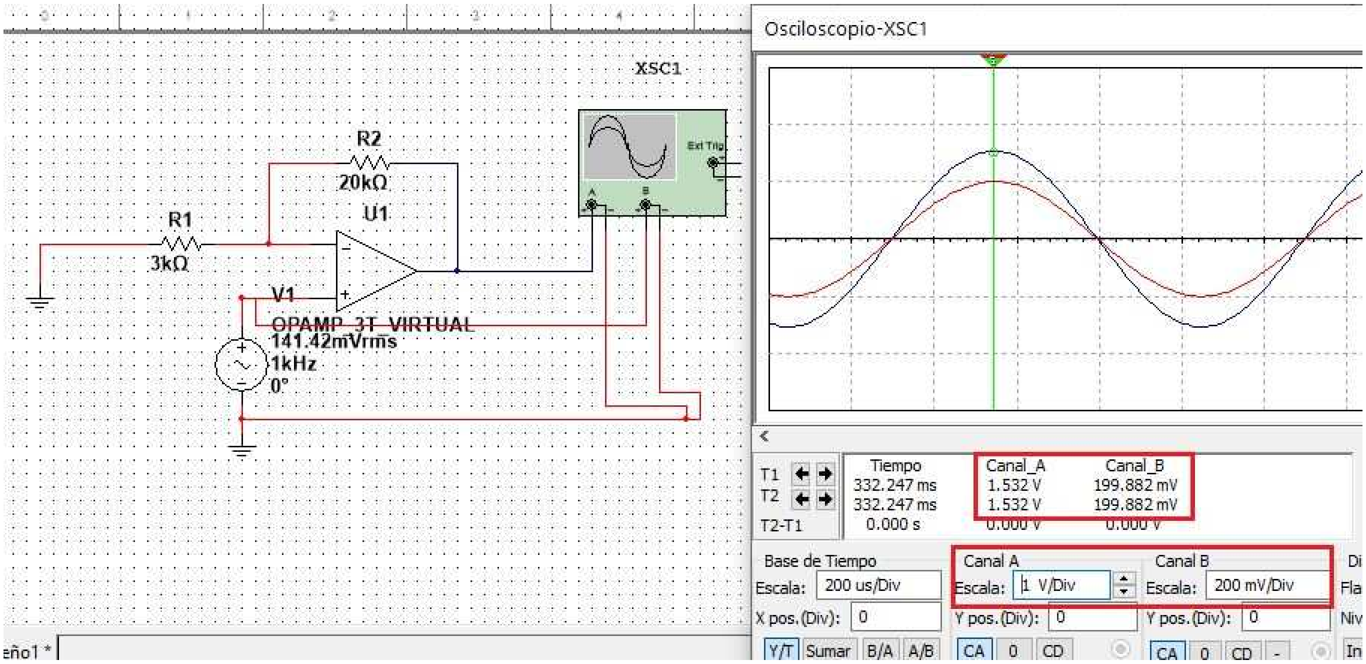

Figure 8. Simulation of the non-inverting amplifier with $R_1 < R_2$. Input and output voltages are shown.

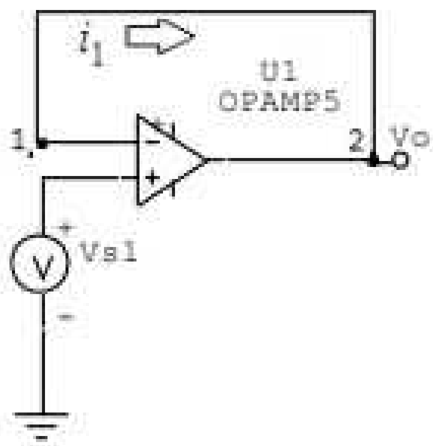

Figure 9. Voltage follower amplifier with 1 V peak-to-peak input.

the voltage drop in the input impedance is almost zero. Consequently, it is valid to assume that $v_{in} \simeq v_1$.

2. Because the current passing through the input impedance is very small, the voltage drop at resistor R1 is minimal and can be assumed that $v_1 \simeq v_{out}$.

Therefore, we can say that:

$$v_{in}(t) = v_{out}(t) \tag{29}$$

$$v_{in}(t) = v_{out}(t) = 0.5\, sin(2\pi f t)\ V \tag{30}$$

Inverter amplifier design

It is common to implement an amplifier circuit with an OpAmp under some design restrictions, such as a certain voltage gain value. As an example we design a voltage inverting amplifier with a voltage gain of $A_V = -250$. We will assume that the output voltage of the circuit will be applied over a load resistance of $R_L = 2\,k\Omega$, over which a current amplitude of 2 mA is expected.

The design of such a circuit can be as follows. If a constant and negative voltage gain is requested, the simplest option is to use a reversing amplifier circuit. Also, since the gain is greater than one, then this circuit must have two resistors so that $R_1 > R_2$. Consequently, according to Table 1 and Equation 6, we can set a restriction on the values of the resistors like this:

$$\frac{R_2}{R_1} = -250 \tag{31}$$

Since this is the only functional constraint, to select the resistance values we can pose another current constraint. For example, we can restrict the currents to the order of mA, that is, the resistances should be in the order of $k\Omega$. If for example, we choose:

$$R_1 = 0.5\,k\Omega \tag{32}$$

$$\Rightarrow\ R_2 = 250 \times 0.5\,k\Omega = 125\,k\Omega \tag{33}$$

If a resistor $R_L = 2k\Omega$ is used as the output load, with a current of:

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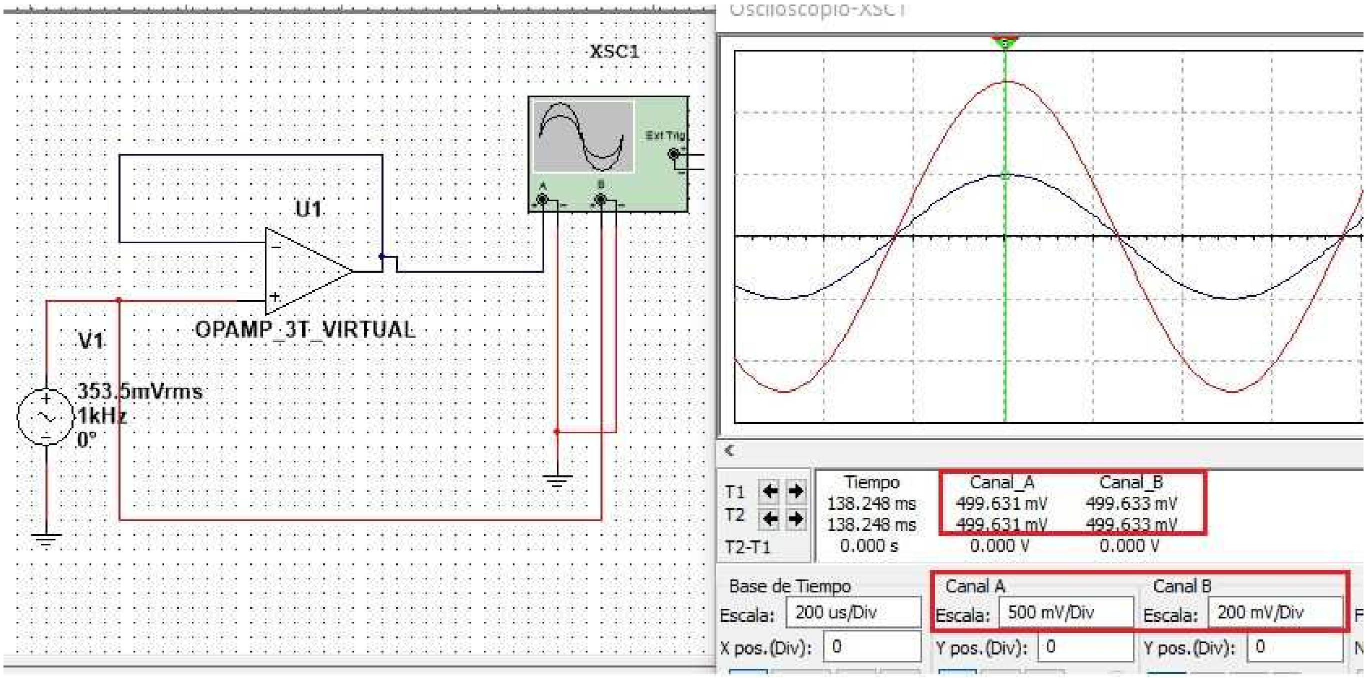

Figure 10. Simulation of the voltage follower amplifier. Input and output voltages are shown.

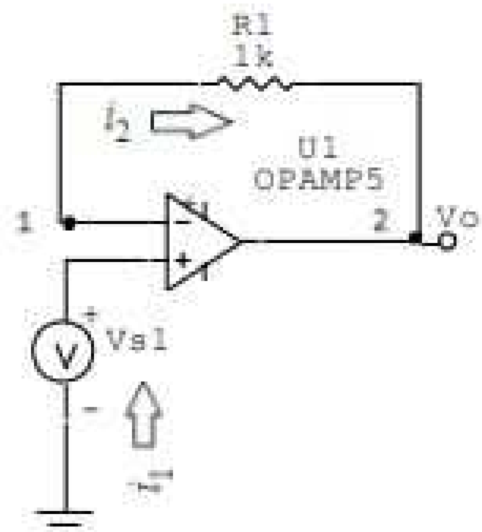

Figure 11. Voltage follower amplifier with feedback resistance.

$$i_L(t) = 2 \times 10^{-3} sin(2\pi ft)\ A \tag{34}$$

$$\Rightarrow\ v_{out}(t) = R_L \times i_L(t) \tag{35}$$

$$v_{out}(t) = (2000) \times \left(2 \times 10^{-3} sin(2\pi ft)\right) \tag{36}$$

$$v_{out}(t) = 4\, sin(2\pi ft)\ V \tag{37}$$

To guarantee this current at the load, with the voltage gain value given by the design, it is necessary to feed the next input voltage:

$$v_{in}(t) = \frac{v_{out}(t)}{250} \tag{38}$$

$$v_{in}(t) = \frac{4}{250} sin(2\pi ft)\ V \tag{39}$$

$$v_{in}(t) = 0.016\, sin(2\pi ft)\ V \tag{40}$$

To finish the design, the resistances must be completely defined. To determine their size (nominal power) we must calculate the currents that circulate through them. In this circuit, the same current circulates through both and is given by:

$$i_{R1,R2} = \frac{v_1 - v_2}{R_1} = \frac{v_{in}}{R_1} \tag{41}$$

Instead of the instantaneous value, we will use the RMS value:

$$I_{R1.R2} = \frac{\frac{0.016}{\sqrt{2}}}{500} = 22.6 \times 10^{-6}\, Arms \tag{42}$$

Therefore, the power that these resistors will dissipate is:

$$P_{R1} = \left(22.6 \times 10^{-6}\right)^2 500 = 255.4 \times 10^{-9}\ W \tag{43}$$

$$P_{R2} = \left(22.6 \times 10^{-6}\right)^2 125000 = 63.8 \times 10^{-6}\, W \tag{44}$$

To configure this circuit the two resistors can be 1/4 watt. As OpAmp it is possible to use, for example, the LM741, which has a maximum output current of 25 mA (it is not necessary to implement a power stage at the output). Fig. 12 shows the behavior of this circuit.

Circuit coupling

In this last section, we will observe the behavior of a circuit formed by the coupling of the three circuits analyzed: an inverting amplifier, a non-inverting amplifier, and a voltage follower. This type of coupling is very common in electronic instrumentation, and it is essential to ensure that the output voltages at each stage are not distorted in the final coupling.

To evaluate the performance of this coupling we will use the following parameters:

- v_{in}: Fed from a DC resistive divider with current values in the order of milliamps. It will simulate a signal from a sensor.
- The operational amplifiers will be supplied with a dual voltage of ±15 V.
- The voltage divider must deliver a voltage of 385 mV from a 10 Vdc source.
- The output of the voltage divider must feed the voltage follower.
- The output of the voltage follower must simultaneously feed the inputs of the inverting amplifier and the non-inverting amplifier.
- The voltage gain of the inverter amplifier should be $A_V = 24$.
- The output voltage of the non-inverting amplifier must be 6 Vdc.
- The ideal model of operational amplifier is used.

According to the restrictions of the voltage divider, two resistors can be selected with the following values.

$$v_{in} = 385\, mV = (10\, V) \times \frac{R_{lower}}{R_{upper} + R_{lower}} \tag{45}$$

A possible combination could be:

$$R_{lower} = 4\, k\Omega \text{ and } R_{upper} = 100\, k\Omega \tag{46}$$

In the case of the inverter amplifier, the requested gain value can be met with the following combination of resistors:

$$A_V = 24 = \frac{120\, k\Omega}{5\, k\Omega} \tag{47}$$

Therefore, the circuit that meets the specifications is the one shown in Fig. 13.

To obtain the 6 Vdc at the output of the non-inverting amplifier, we assume as input the output of the voltage follower amplifier, which follows the 385 mV of the voltage divider. According to the gain of this circuit, the following equation can be written.

$$v_0 = 6\, V = v_{in} \frac{R_5 + R_6}{R_6} \tag{48}$$

$$6\, V = 385\, mV \frac{R_5 + R_6}{R_6} \tag{49}$$

$$\frac{R_5 + R_6}{R_6} = 15.58 \tag{50}$$

A possible combination of resistors that meets these requirements may be:

$$R_5 = 1560\, \Omega \text{ and } R_6 = 100\, \Omega \tag{51}$$

The voltage gain of this non-inverting amplifier is:

$$A_{V2} = \frac{R_5 + R_6}{R_6} \tag{52}$$

$$A_{V2} = \frac{1560 + 100}{100} \tag{53}$$

$$A_{V2} = 16.6 \tag{54}$$

In the case of the inverter amplifier, the output voltage would be:

$$A_{V1} = -24 = \frac{v_0}{v_{in}} = \frac{v_0}{385 \times 10^{-3}} \tag{55}$$

$$\Rightarrow \quad v_0 = -24\left(385 \times 10^{-3}\right) \tag{56}$$

$$v_0 = -9.24\, V \tag{57}$$

Fig. 14 shows the behavior of this circuit.

Conclusions

This paper reviews the design and performance of the OpAmp in three basic linear configurations: inverting amplifier, non-inverting amplifier, and voltage follower. Each of these circuits is analyzed according to the elements used for their configuration. Based on this analysis, their possible behaviors are characterized and supported by simulation. The final part shows an example of design from functional requirements and evaluates a typical scheme of coupling these circuits in a basic signal conditioning system.

ISSN 1692-8407

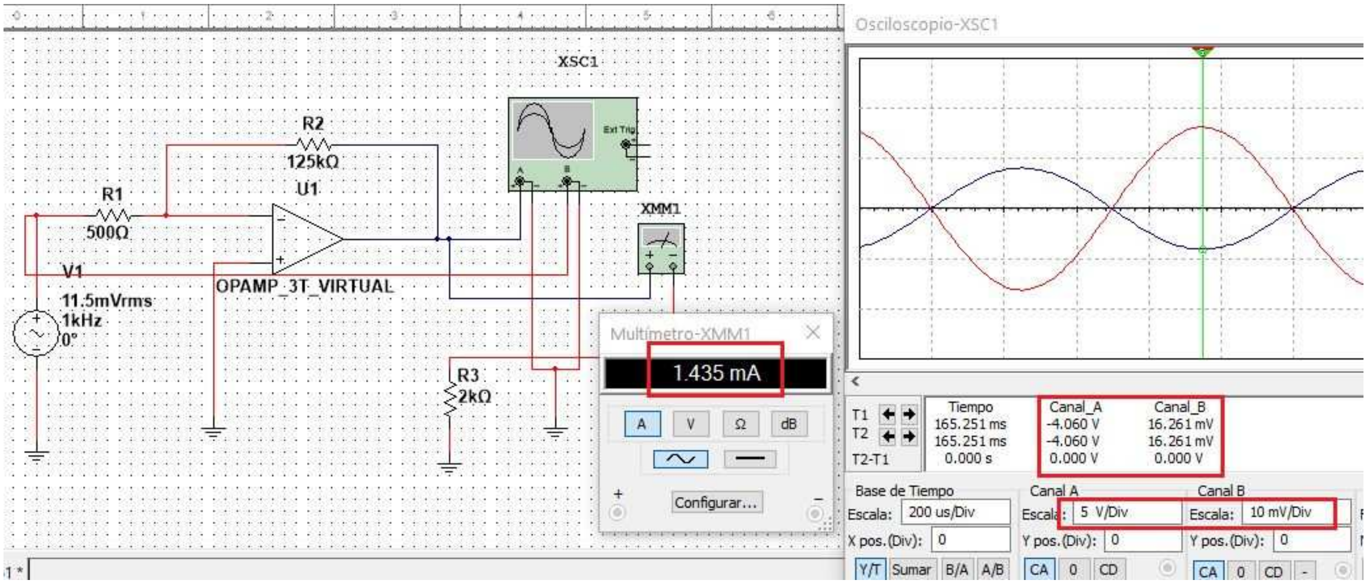

Figure 12. Inverter amplifier simulation with voltage gain of $A_V = -250$.

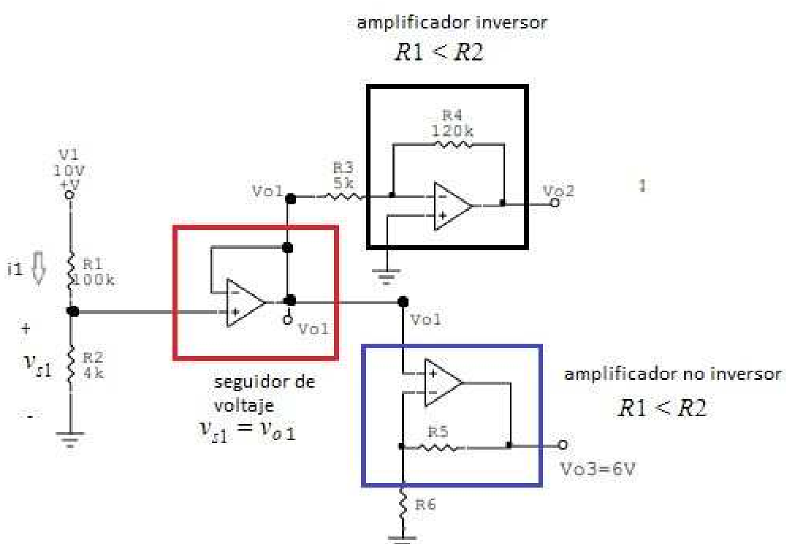

Figure 13. Circuit coupling with operational amplifier: voltage follower amplifier, inverter amplifier, and non-inverter amplifier.

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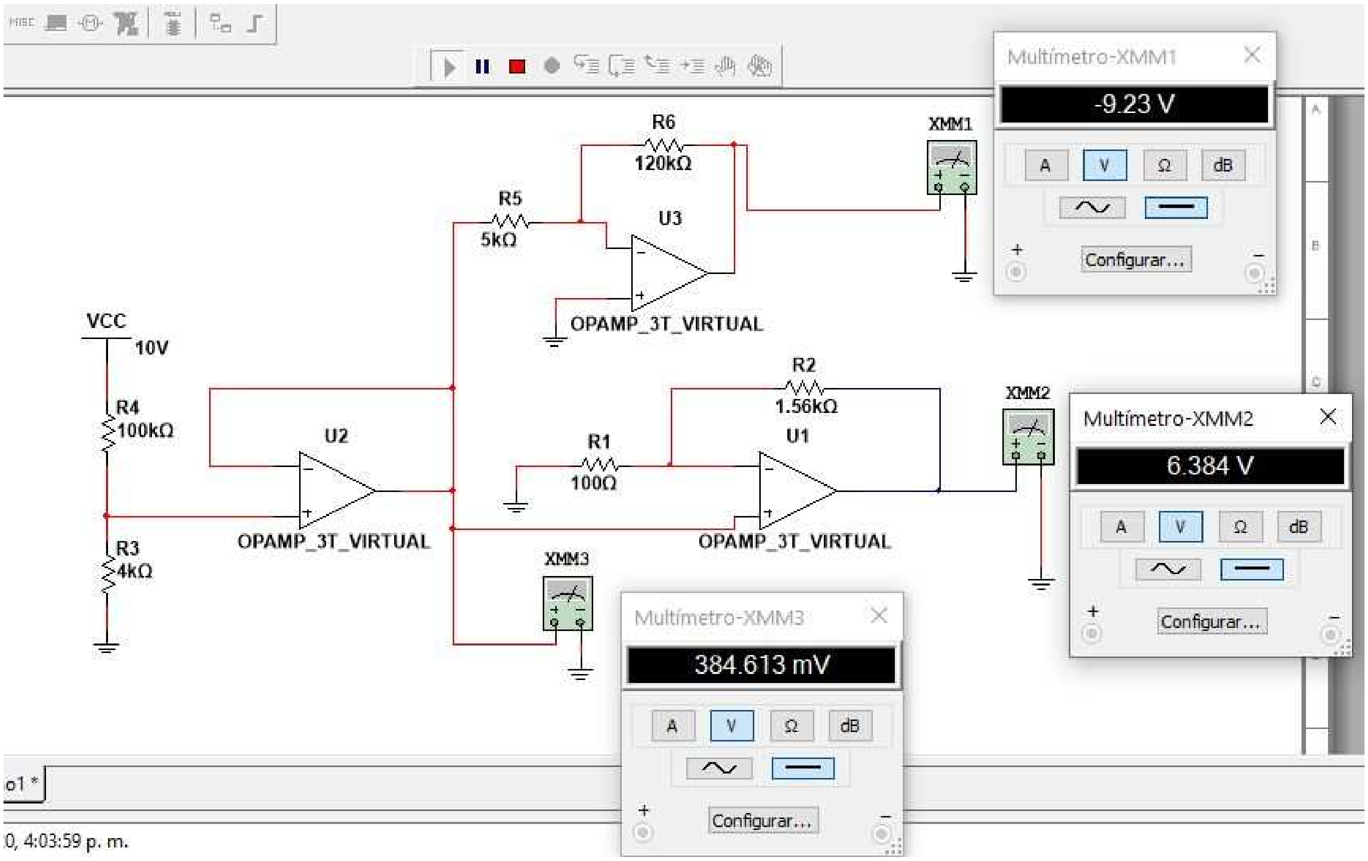

Figure 14. Simulation of circuit coupling with operational amplifier Stationary voltage values are shown for each circuit clamp.

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