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Design and evaluation of Volume Unit (VU) meter from operational amplifiers

Diseño y evaluación de vúmetro a partir de amplificadores operacionales

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A VU meter is a volume level indicator device used in audio equipment. Its function is to show the user the signal level in volume units. By construction, this device displays a rectified sample of the audio signal voltage. However, the VU-meter does not measure the input voltage, but rather a reference of the average volume in decibels. This visual indicator was introduced in the 1940s as a way of normalizing levels on telephone lines, but it became a visual indicator of the amplitude of the input signal that was pleasing to the eye because of its synchrony with the music. Consequently, digital versions have been introduced as a replacement for analog schemes with LED (Light Emitting Diode) displays that provide more information and greater visual effect. In this paper, a simple operational amplifier (Op-Amp) based VU-meter design is proposed.

Keywords: Design, electronic instrumentation, operational amplifier, VU meter

Un vúmetro es un dispositivo indicador de nivel de volumen utilizado en equipos de audio. Su función es mostrar al usuario el nivel de señal en unidades de volumen. Por construcción, este dispositivo visualiza una muestra rectificada del voltaje de la señal de audio. Aun así, el vúmetro no mide realmente el voltaje de entrada, sino una referencia del volumen medio en decibelios. Este indicador visual fue introducido en los años 40 como forma de normalizar los niveles en las líneas telefónicas, pero se convirtió en un indicador visual de la amplitud de la señal de entrada agradable al ojo por su sincronía con la música. En consecuencia, se han introducido versiones digitales como reemplazo de los esquemas análogos con visualización LED (Diodo Emisor de Luz) que brindan mayor información y mayor efecto visual. En este artículo se propone un simple diseño de vúmetro basado en amplificador operacional (Op-Amp).

Palabras clave: Amplificador operacional, diseño, instrumentación electrónica, vúmetro

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Introduction

A Volume Unit (VU) meter is a device that was used in speech research before current digitization strategies and digital instrumentation (Lobdell & Allen, 2007). Its importance was such that standards were developed for its design and use (ASA 1954, ANSI 1969) (Blaeser & Struck, 2019; Edgerton, Beattle, & Helmerich, 1982). The function of these devices is to visually represent an acoustic power level in the average and peak value ranges reflecting the amplitude and frequency behavior of the acoustic signal (mainly human voice and music). These analog needle instruments, however, had many shortcomings in terms of reliability, and it is well known that the readings of one user for a given audio sample are not repeatable by another user, causing different individuals to have different readings for the same sample (Killion, 2009).

The adjustment of a VU meter is performed by mapping the RMS (effective sound pressure) sound pressure of a 1 kHz signal to a deflection in the VU meter corresponding to the speech signal (Schmid, 1977). Therefore, there is no real 1 vu calibration in the instrument. The instrument unit, called vu, is a unit defined to characterize the volume, which is an average electrical power level. From this point of view, the VU meter is a kind of voltmeter calibrated in such a way that the user can observe and measure a certain power level.

The initial use of this instrument was to verify the power level in the twisted wire telephone lines, which after long distances lost power in transmission. The test and measurement were performed by transmitting voice over the telephone line according to a pre-established program, and the VU was used to check the transmission peaks at the other end of the line. In the sound players, this device provided a visual representation of the music that has been maintained to date with much more striking visual systems, which has led to its current design with new technologies and adding the visual element (McGowan, Leplatre, & McGregor, 2017). This type of visual indication is also used in other types of measurements (Feier, Enatescu, Ilie, & Silea, 2014; Muliawan, Nahar, Sebastian, Yuliza, & Khairurrijal, 2015; Nair, 1965).

Due to their functional nature, operational amplifiers (Op-Amp or OpAmp) become the ideal device for the design of VU meters (Jacinto, Montiel, & Martínez, 2017; Rendón, 2019). These circuit devices are ideal for electrical signal conditioning and instrumentation due to their high input impedance, low cost, and simple configuration for handling continuous signals, such as small voltage levels (Garcia, Osuna, & Martinez, 2018; Gordillo & Martínez, 2018; Martínez, Rendón, & Arbulú, 2018). They are typically used as an intermediate stage between a sensing system and a digitizing system and can even be used for digital implementations (Martinez, Montiel, & Martínez, 2018).

Problem statement

It is desired to develop a five-stage VU meter whose structure is based on OpAmp. Each stage functions as a voltage comparator, taking as input reference a portion of the supply voltage through a resistive divider. This reference voltage is compared with the audio signal to scale its average RMS value and turn on some LEDs (Light-Emitting Diode) proportional to the estimated input value. The circuit will be powered from a dual constant source of ±10 Vdc, the design value for the electronic components of the circuit.

Fig. 1 shows one stage of this design. At the output of the OpAmp, a 220 Ω resistor is connected in series with a rectifier diode, which in turn is in series with an LED. This has the function of further limiting the range of the output signal from ±10 Vdc to a range of 0 - 10 Vdc. This occurs as a function of the rectifier diode, which essentially acts as a one-way switch for the current.

When a positive saturation voltage (V_{sat}) is present, it is satisfied that:

$$V_{sat} = V_{in} - V_{ref} \tag{1}$$

$$V_{in} > V_{ref} \longrightarrow +V_{sat} \tag{2}$$

Under this condition, the rectifier diode is conducting, therefore the LED is turned on (LED = ON).

Fig. 1 shows the diode of the circuit in conduction since it fulfills equation 2. Applying equation 1, and assuming that the input audio signal has a value of 12 Vdc (input to the positive terminal of the OpAmp), we have that:

$$V_{sat} = 12 - 10 = 2\,\text{Vdc} \tag{3}$$

Therefore:

$$12\,\text{V} > 10\,\text{V} \longrightarrow +V_{sat} \tag{4}$$

If, on the other hand, the V_{sat} is negative, then:

$$V_{in} < V_{ref} \longrightarrow -V_{sat} \tag{5}$$

Fig. 2 shows the diode of the circuit in interruption, since it fulfills equation 5. Applying equation 1 we have that:

$$V_{sat} = 5 - 10 = -5\,\text{V} \tag{6}$$

Therefore:

$$12\,\text{V} > 10\,\text{V} \longrightarrow -V_{sat} \tag{7}$$

This means that the rectifier diode is unable to conduct, and therefore the LED is turned off (LED = OFF).

This block constitutes the basic structure of the circuit. To complete the design, similar structures are added in parallel but fed at the negative terminal of the OpAmp with a different value of reference voltage. These reference voltages are

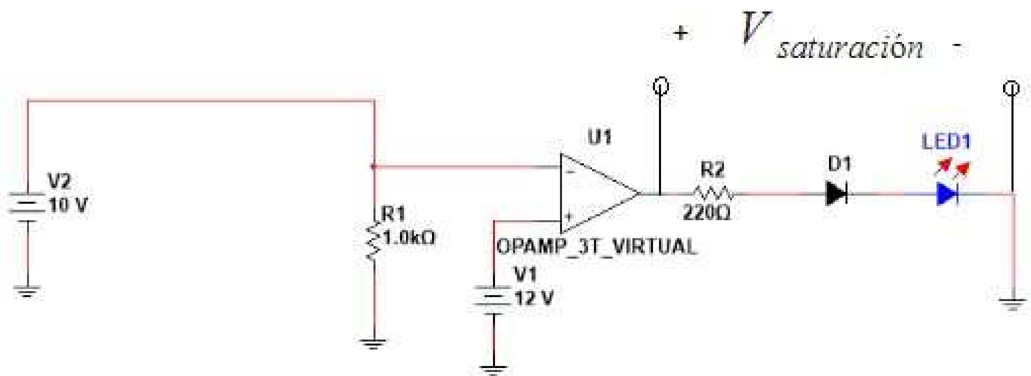

Figure 1. Saturation voltage positive, diode in conduction, LED=ON.

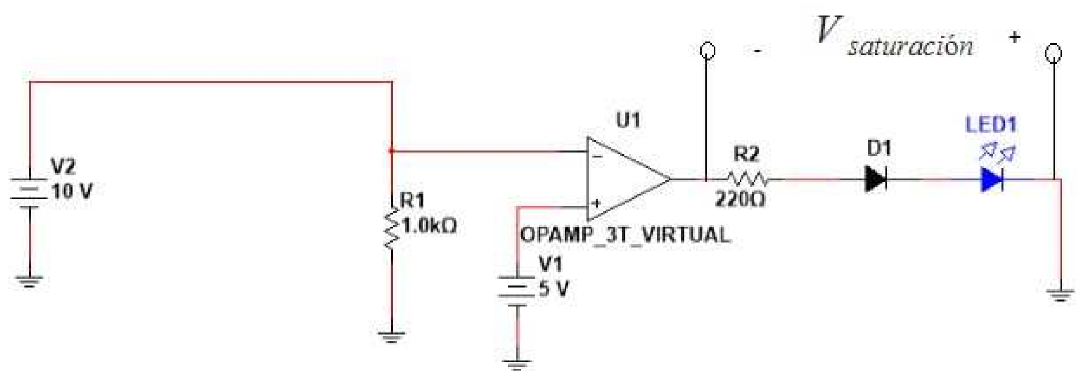

Figure 2. Negative saturation voltage, diode in interruption, LED=OFF.

proportions of the voltage used in the first block, which can be achieved using resistive dividers. For example, to add a second stage, the second block can be fed with a resistive divider that feeds half the voltage used in the first block (Fig. 3).

In this new circuit, we can observe several changes. The reference voltage V_{ref} of the circuit for OpAmp 1 has changed and was reduced to half the supply voltage $\left(V_{ref} = \frac{10}{2} = 5\,\text{V}\right)$, and OpAmp 2 has an initial reference voltage $V_{ref} = 10\,\text{V}$. The reference voltage of the circuit behaves like a resistive divider, so the reference voltage for each amplifier is a proportion of the total voltage.

$$V_{ref} = 10 \times \frac{R_1}{R_1 + R_2} \tag{8}$$

In Fig. 3 we can see that the two LEDs of the circuit are turned on, this is because the input voltage that simulates the audio input is higher than the total reference voltage.

The circuit in Fig. 4 shows a completely different picture. In this case, the input voltage simulating the audio input is lower than the total reference voltage, which becomes a negative saturation on OpAmp 2, and therefore the rectifier diode is interrupted (LED = OFF). However, for OpAmp 1 this reference voltage is lower than the input voltage, and therefore in this case the rectifier diode is activated and presents conduction (LED = ON).

These behaviors provide the basis for the design of our VU meter.

Volume Unit (VU) meter design

The proposed design for the OpAmp-based VU meter circuit is shown in Fig. 5. Two key elements were considered for this design:

1. The input voltage (audio signal as voltage from the acoustic source) must be higher than the reference voltage for the rectifier diode to conduct and the LED = ON.

2. The reference voltage fed to each OpAmp block is different according to the position of the element within the circuit in coherence with the desired display of the input signal. For example, for the lowest block, it must be fulfilled that:

$$V_{ref(\text{level 1})} = \frac{V_{total}}{5} \tag{9}$$

This proportion is fulfilled because it is desired that the five resistors are equal. If this is not the case, we must

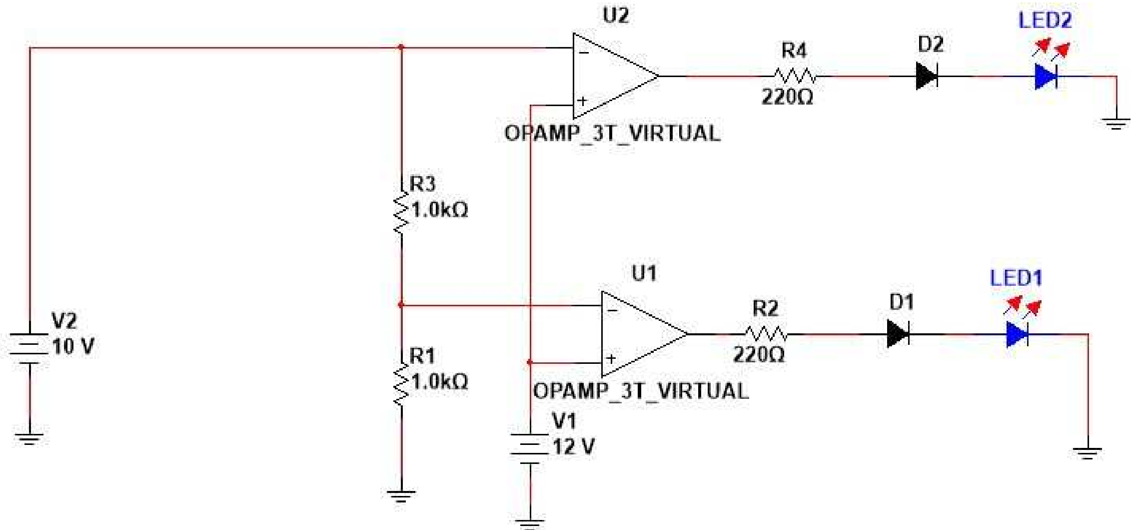

Figure 3. Simulation, coupling of a second amplifier, LED1=ON and LED2=ON.

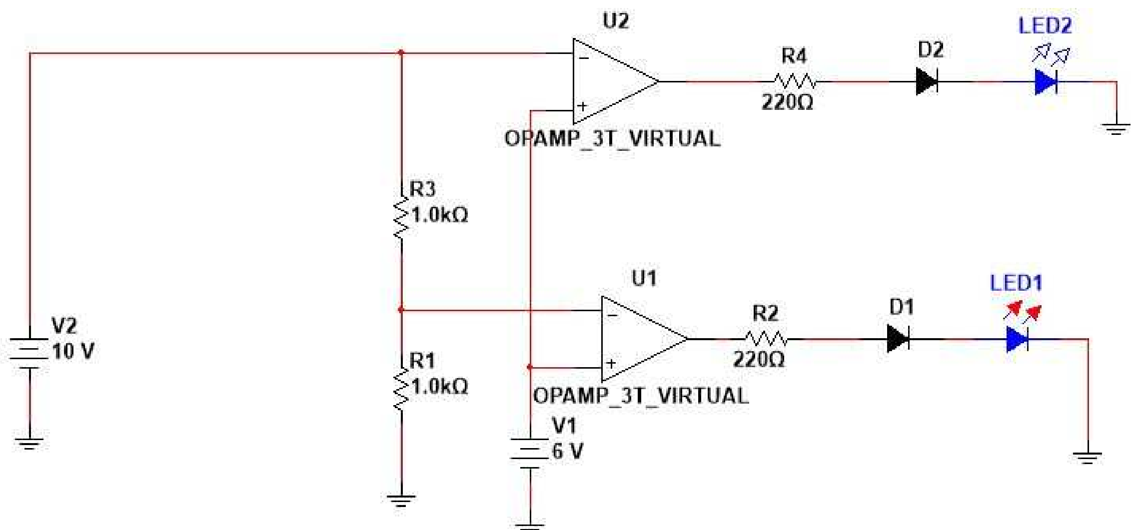

Figure 4. Simulation, coupling of a second amplifier, LED1=ON and LED2=OFF.

calculate the respective voltage values. In Fig. 6, we can confirm that this ratio is indeed fulfilled.

The circuit corresponds to an indicator device, therefore the LEDs indicate when the reference voltage (in this case 10 Vdc) and its proportions have been exceeded by the input voltage (the audio signal). This indicator consists of intermediate levels, so it not only shows when the level is higher than the maximum (all LEDs = ON) or minimum (all LEDs = OFF), but it is also able to measure, for example, when the input voltage is equal to $\frac{3}{5}$ of the reference voltage (LEDs 1 and 2 = ON), and so on, until it reaches the top which is when the input voltage is greater than $\frac{5}{5}$ of the reference voltage (all LEDs = ON).

Currents on resistors

As is well known, the input impedance in OpAmp is very high, therefore the current they draw is minimal and can be neglected. Thus, the current passing through the 1 kΩ resistors is equal to:

$$I = \frac{V_{ref}}{\sum_{i=1}^{5} R_i} \tag{10}$$

Applying equation 10 we have:

$$I = \frac{10}{5000} = 2\,\text{mA} \tag{11}$$

These values can be verified by simulation regardless of the value of the input audio signal (Fig. 7).

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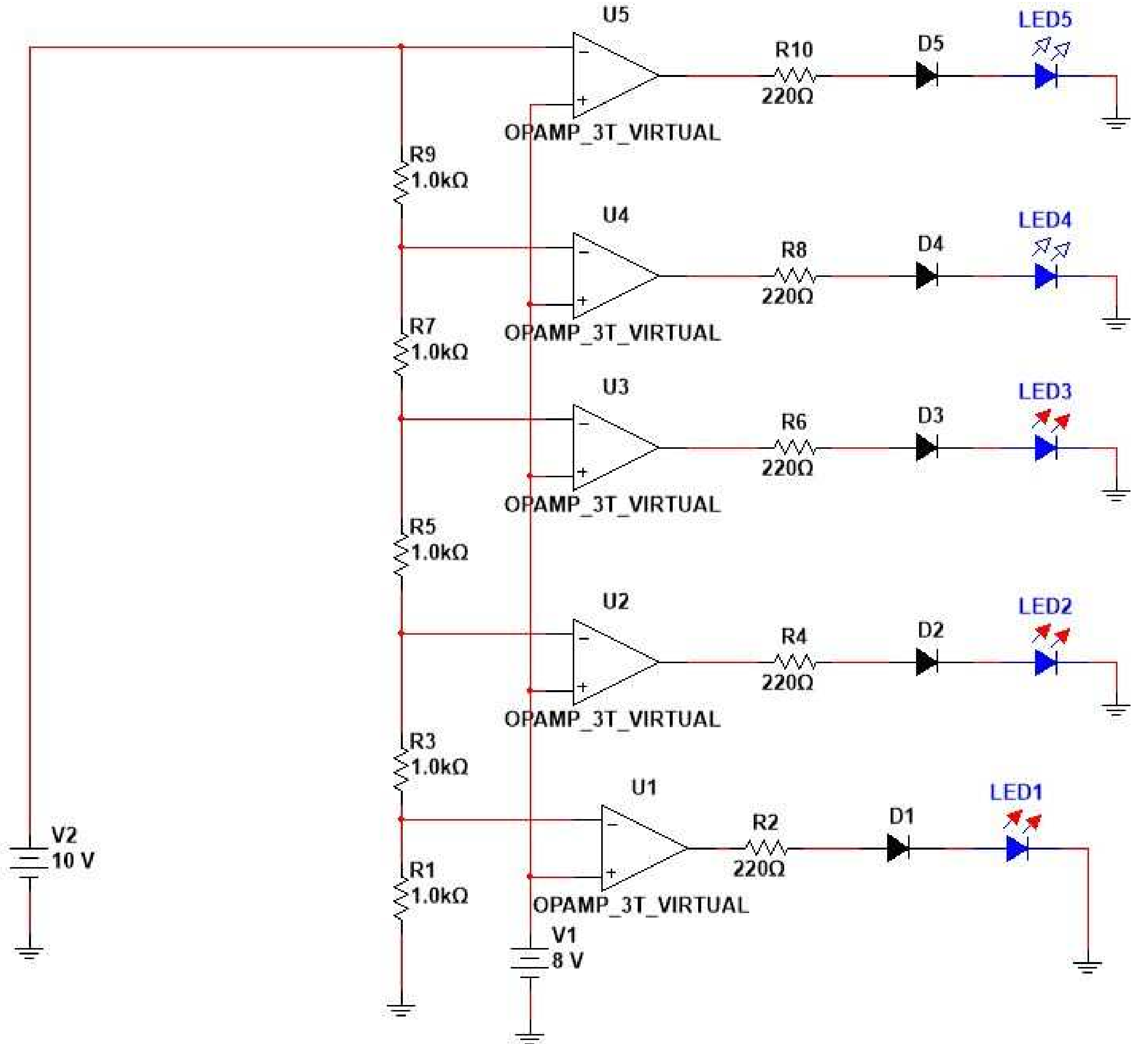

Figure 5. Full circuit simulation, input voltage $V_{in} = \frac{4V_{ref}}{5}$.

This is a standard symmetrical design, where all resistors have the same value, and therefore there is a constant $\triangle V$ between each reference of each OpAmp. However, according to user needs, it is possible to change the value of the resistors. If, for example, the value of the resistors changes, and they all remain equal to each other, but different at 1 kΩ, then two cases can occur, where the current decreases:

$$I \downarrow = \frac{10}{R_{total} \uparrow} \tag{12}$$

Or increase the current:

$$I \uparrow = \frac{10}{R_{total} \downarrow} \tag{13}$$

Because the source voltage is constant, the reference voltage at each level tends to remain constant as well. The decrease in current is compensated by the increase in resistance.

If the value of the resistors changes and they are different from each other, the reference voltage at each OpAmp will depend on the resistance values of the resistors. The ratio of the reference voltage used for comparison at each stage would no longer be constant.

Rectifier diodes

When the input voltage is higher than the reference voltage, the following occurs:

$$V_{in} < V_{ref} \longrightarrow -V_{sat} \tag{14}$$

The differential voltage is negative, and we will have a negative saturation voltage. In this case, the rectifier diode does not allow the LED to turn on, since by nature a diode

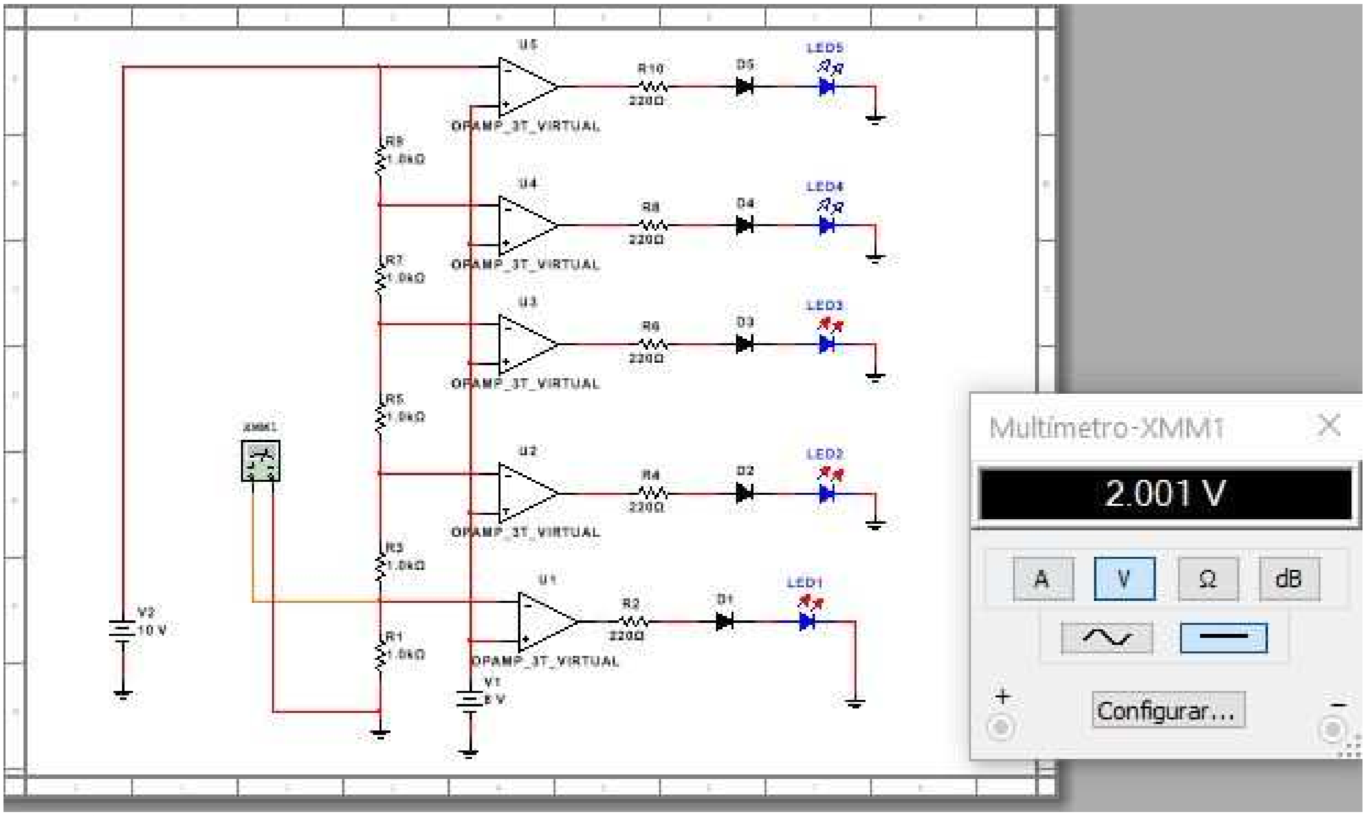

Figure 6. Simulation, reference voltage measurement on OpAmp 1.

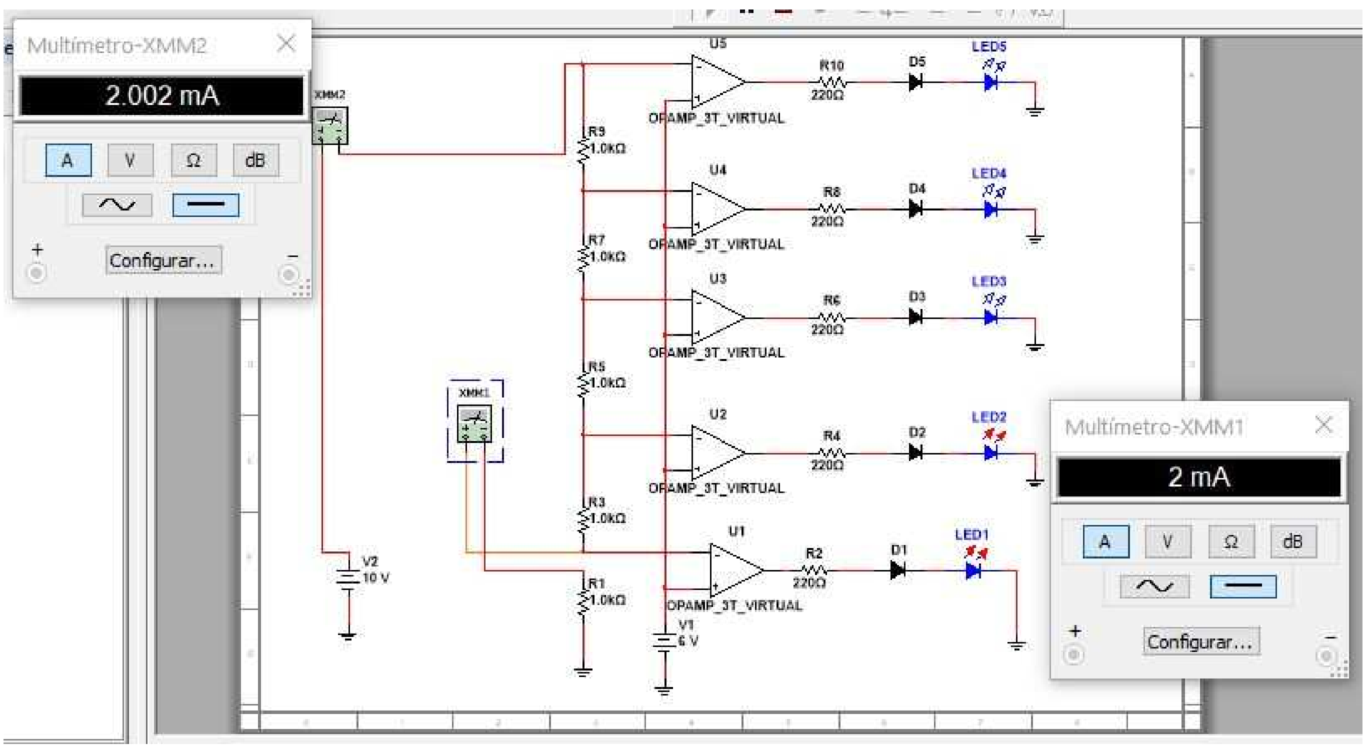

Figure 7. Simulation, current measurement through 1 kΩ resistors.

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is a semiconductor device that acts essentially as a one-way switch for current, and with voltage polarity for activation.

OpAmp supply voltage

In case of the OpAmp supply voltage changes, we would have an increase in the saturation voltage, and therefore an increase in current through the 220 Ω resistor that is in series with the rectifier diode, and turn in series with the LED. If the 220 Ω resistor is maintained, the output voltage increases, and thus the current, depending on how much current the LED can withstand, could burn out. If this power supply is separated from the reference voltage, there are no functional changes in the circuit, the comparison voltages at each stage remain the same, despite changing the output voltage (saturation voltage) of each OpAmp.

For the actual circuit assembly, it is possible to use an OpAmp such as the LF353. This is a low-cost device with JFET type input (high input impedance, in the order of $10^{12}\,\Omega$), short-circuit protected output, and with wide availability in the market. The power supply range of the device is ±18 V, which implies that it can well be used in our design.

If the circuit is implemented with this OpAmp, what would happen if the LF353 operational amplifier is biased with a simple 10 V source, that is if the -10 V source is replaced by a connection directly to the ground? If this were to happen, the saturation voltage would always be positive, it would oscillate between 0 and 10 V, which is the same as it currently does because of the rectifier diode.

VU meter design under functional requirements

In this section, as an example, we seek to design the VU meter circuit so that a maximum voltage of up to 5 Vdc can be displayed on the LEDs, in steps of 0.5 Vdc per LED. The current through the resistive divider should be 2 mA. The LM324 is to be used for the implementation.

In this case, it is intended to work with the LM324. This OpAmp is characterized by working with a single power supply with a range from 3 V to 32 V. Operating in the linear zone, the common-mode input voltage range includes ground. The output voltage can also approach the ground, even when working with a single supply. The unity frequency gain is temperature compensated. The input bias current is also temperature compensated.

Among the features of this OpAmp we can detail the following ones:

- Internally frequency compensated for unity gain.
- High DC gain (100 dB).
- High bandwidth (unity gain) 1MHz (temperature compensated).
- High power supply range.
- Single supply between 3V and 32V.
- Very low current consumption (700 μA) independent of power supply.
- Very low input bias current (45 nA) (temperature compensated).
- Low input voltage offset (2 mV) and current offset (5 nA).
- Common mode input voltage range includes ground.
- Input differential voltage range is equal to supply voltage.
- Maximum output voltage excursion: from 0 V to V+ - 1.5 V.

Based on the above characteristics of the LM324 amplifier, the general characteristics of operational amplifiers can be modified in circuit simulation software to evaluate the performance of the element. The tests in our case were performed in NI Multisim, an electrical circuit simulator based on Berkeley's SPICE simulator. The test setup considered the following parameters.

High DC gain (100 dB)

The gain is calculated as follows:

$$100\,\text{dB} = 20\,log_{10}\,(A_V) \tag{15}$$

$$A_V = 10^5 \tag{16}$$

Bandwidth (unity gain)

According to the manufacturers, the value is set at 1MHz.

NI Multisim configuration

The final configuration used to replicate the behavior of the LM324 in NI Multisim is shown in Fig. 8.

Design criteria

The following are the criteria used for the design sought.

$$I_R = 2 \times 10^{-3}\ \text{A} \tag{17}$$

$$V_{source} = 4\ \text{V} \tag{18}$$

$$R = \frac{0.5}{2 \times 10^{-3}} = 250\,\Omega \tag{19}$$

$$\text{Number of resistors} = \frac{4}{0.5} = 8 \tag{20}$$

With these parameters, it is possible to implement the entire VU meter circuit. To verify the performance, eight blocks of the circuit were implemented with eight LM324 OpAmp, as well as a resistive divider consisting of eight resistors of 250 U each. The operating point of the circuit can be seen in Fig. 9.

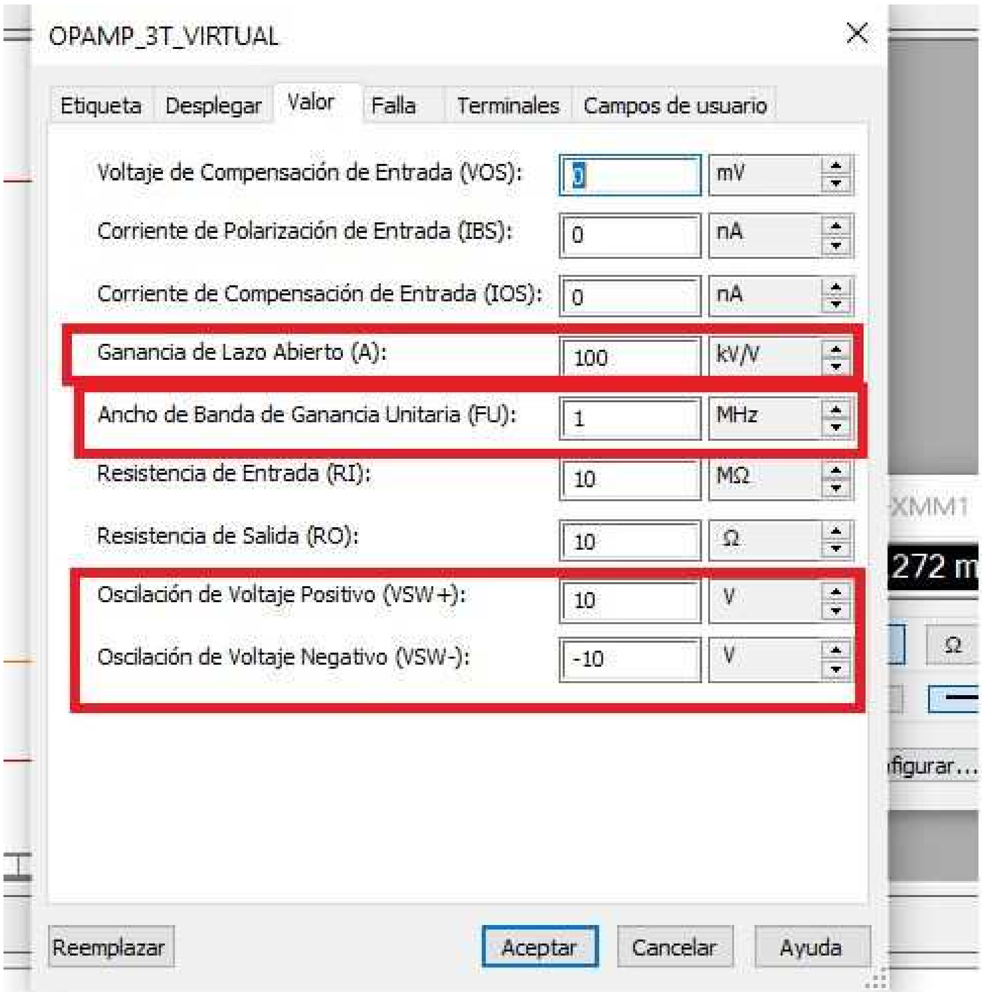

Figure 8. Configuration of OpAmp to behave similar to LM324.

The values displayed by the simulator confirm the design parameters. A voltage of about 500 mV is applied to each resistor, and the current drawn by the voltage divider circuit is 2 mA. Under these conditions, each of the eight LEDs is expected to light according to 5 V voltage increments.

Consequently, according to the voltage levels expected as the maximum in the audio input signal, it is possible to define the required comparison voltages according to the resolution sought in the VU meter design. A large number of small LEDs arranged in line can provide a lot of information in real-time about the behavior of the audio signal, and provide parameters for the volume control of the equipment.

Conclusions

This paper presents the design details of a VU meter for application in sound reproduction systems using several stages of voltage comparators. These voltage comparators are implemented using operational amplifiers without feedback loops and configured with reference voltages derived from the maximum voltage expected in the input audio signal. The maximum value is used as a design parameter to define the input voltage divider circuit configuration (reference for the OpAmps) and output resolution configuration (visualization) of each OpAmp. The visualization is done by a typical LED connected to the output of each OpAmp. These LEDs are protected with a resistor according to the saturation voltage of each OpAmp (based on their supply voltages) and guarantee their correct operation with a series rectifier diode, which also eliminates the need for a dual source for the power supply of the op-amps. Performance tests were performed on an example design, showing the necessary parameters to be defined in the circuit, and verifying its operating point by simulation.

References

Blaeser, S., & Struck, C. (2019). A history of asa standards. *The Journal of the Acoustical Society of America*, *145*(77).

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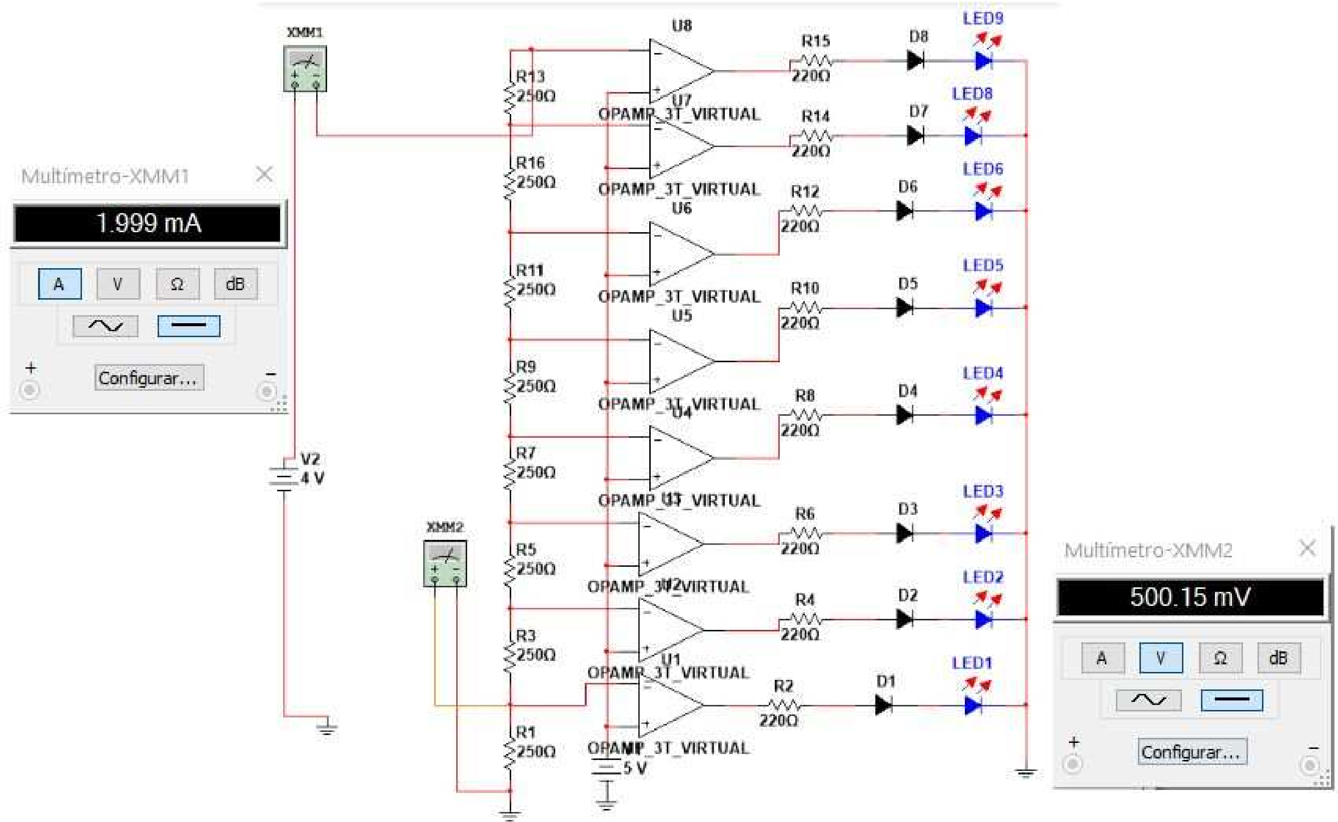

Figure 9. Simulation, voltage meter indicator up to 5 Vdc, in steps of 0.5 Vdc per LED. Current through divider 2 mA.

Edgerton, B., Beattle, R., & Helmerich, L. (1982). Relationship between the calibration tone and speech volume unit (vu) levels for some commercially available test tapes. *Ear and Hearing*, *3*(5), 280-283.

Feier, F., Enatescu, I., Ilie, C., & Silea, I. (2014). Newborns' cry analysis classification using signal processing and data mining. In *International conference on optimization of electrical and electronic equipment (optim 2014).*

Garcia, C., Osuna, B., & Martinez, F. (2018). Safe grasping system for robotic hand with fingers. *Contemporary Engineering Sciences*, *11*(40), 1991-1998.

Gordillo, J., & Martínez, F. (2018). Fuzzy control for bipedal robot considering energy balance. *Contemporary Engineering Sciences,*, *11*(39), 1945-1952.

Jacinto, E., Montiel, H., & Martínez, F. (2017). Circle hough transform implementation for dots recognition in braille cells. In *Eighth international conference on graphic and image processing (icgip 2016)* (Vol. 10225, p. 102250N).

Killion, M. (2009). Comparison of vu-meter-based and rms-based calibration of speech levels. *The Journal of the Acoustical Society of America*, *126*(EL97).

Lobdell, B., & Allen, J. (2007). A model of the vu (volume-unit) meter, with speech applications. *The Journal of the Acoustical Society of America*, *121*(279).

Martinez, F., Montiel, H., & Martínez, F. (2018). Blueprints obtention by means of using digital image processing algorithms. *International Journal of Engineering and Technology*, *10*(4), 1129-1135.

Martínez, F., Rendón, A., & Arbulú, M. (2018). A data-driven path planner for small autonomous robots using deep regression models. In *Data mining and big data (dmbd 2018)* (p. 596-603).

McGowan, J., Leplatre, G., & McGregor, I. (2017). Cymasense: A real-time 3d cymatics-based sound visualisation tool. In *Acm conference companion publication on designing interactive systems* (p. 270-274).

Muliawan, W., Nahar, W., Sebastian, C., Yuliza, E., & Khairurrijal, K. (2015). Implementing project-based learning in making a weight meter. *Journal of Physics: Conference Series*, *739*(1), 1-7.

Nair, N. (1965). Vu meter as a monitoring device for indian programmes. *IETE Journal of Research*, *11*(1), 35-48. Retrieved from `https://doi.org/10.1080/`

03772063.1965.11485122
Rendón, A. (2019). Operational amplifier performance practices in linear applications. *Tekhnê*, *16*(1), 57-68.
Schmid, H. (1977). Audio program level, the vu meter, and the peak-program meter. *IEEE Transactions on Broadcasting*, *BC-23*(1), 22-26.