Bilkent University

Electrical and Electronics Department

EE202-03 Lab 3 Report:

“The Design of a Linear Circuit to Generate Trapezoid Waveforms from Square Wave Signals”

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1- Software Implementation

1.1- Introduction:

We were assigned to design a circuit that generates the output in the figure below **(Figure 1.1.1)** from a square pulse input by using resistors, capacitors and operational amplifiers. We were obligated to choose an input frequency less than 50Hz.

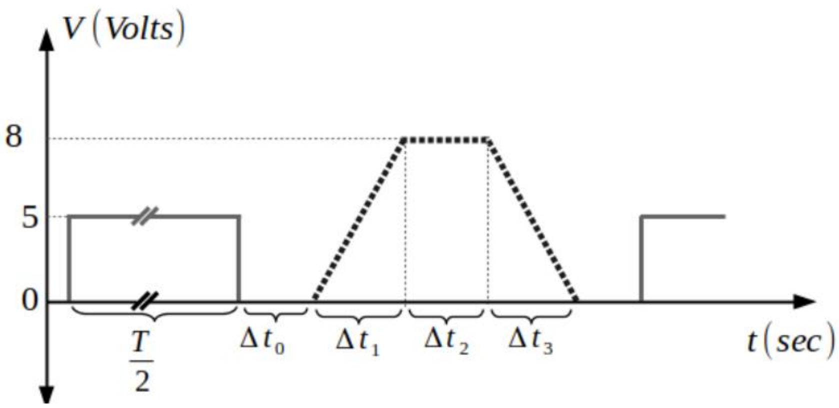

Figure 1.1.1: The desired circuit behaviour; Input: solid gray lines, Output: dashed lines

Here you can see the numeric values of the variables in Figure 1 **(Figure 1.1.2)**:

$$\Delta t_0 = 2ms, \quad \Delta t_1 = 2ms, \quad \Delta t_2 = 3ms, \quad \Delta t_3 = 2ms$$
$$\text{Input peak voltage: } 5V$$
$$\text{Output peak voltage: } 8V$$
$$\text{Input frequency: } f < 50Hz, \quad T = \frac{1}{f}$$

Figure 1.1.2: The numeric values of the variables in Figure 1

My initial thoughts about the problem definitely had nothing to do with the actual solution I came up with in the end. I was stuck in a dead-end. Then after carefully reading the lab manual, I started to try out different mechanisms using only RC circuits and OpAmps.

I found out that in order to get the trapezoid shape; I should be using a subtractor OpAmp in the very end of the circuit. Then, I started working out on how to get the desired input signals of the subtractor OpAmp using other types of OpAmps.

In the very end, I've used two separate RC circuits and 5 different OpAmps in order to get the desired output. I've used a single subtractor OpAmp, 2 comparator OpAmps and 2 integrator OpAmps.

Comparator OpAmps are used with RC circuits attached to them and they create the delay necessary for the trapezoid shape. Integrator OpAmps are used to obtain the incline and decline signals in the trapezoid shape. Subtractor OpAmps is used to achieve the final desired output shape.

1.2- Analysis:

In this part, I will explain individually what each circuit element does, and how they work.

<u>1.2.1- Comparator OpAmps:</u>

In the circuit, there are two comparator OpAmps. These comparators aim to create two different time delays for the trapezoid shape. The delays must be at Δt0 and Δt0+ Δt1+ Δt2 respectively. So, one comparator will create a delay of Δt0=2ms, whereas the other comparator will create a delay of Δt0+ Δt1+ Δt2=7ms. The saturation property of the LM324 OpAmps will be used. Here you can see the form of a sample comparator OpAmp **(Figure 1.2.1)** and the relevant equation **(Equation 1)** regarding the output of the OpAmp:

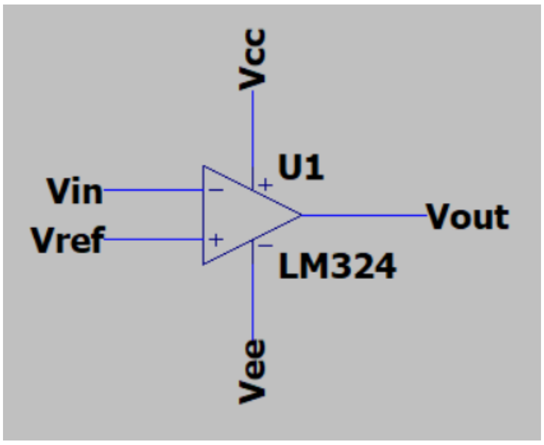

Figure 1.2.1: A sample Comparator OpAmp

$$V_{out} = \begin{Bmatrix} V_{cc}, & V_{in} < V_{ref} \\ V_{ee}, & V_{ref} < V_{in} \end{Bmatrix} \qquad \textbf{(Equation 1)}$$

A time delay can be created if a comparator OpAmp is used alongside an RC circuit. The OpAmp will enter the + saturation mode when the signal coming from the RC circuit exceeds the reference input node of the OpAmp in terms of voltage. For this specific lab, I've chosen V_{ref} to be 2 volts. Here are the set of equations that helps us determine 2 distinct RC values for two distinct time delays: 2ms **(Equations 2.1 to 2.6)** and 7ms **(Equations 2.7 to 2.12)**.

For 2ms delay:

$$V_c = V \quad \textbf{(Equation 2.1)}$$

$$V_c = 5 \cdot e^{\frac{t}{RC}} = V \qquad \textbf{(Equation 2.2)}$$

$$5 \cdot e^{\frac{t}{RC}} = 2V \quad \textbf{(Equation 2.3)}$$

$$\ln\left(\frac{5}{2}\right) = \frac{t}{RC} = \frac{0.002}{RC} \quad \textbf{(Equation 2.4)}$$

$$RC = \frac{2 \cdot 10^{-3}}{\ln\left(\frac{5}{2}\right)} = 0.00218\,\Omega \cdot F \quad \textbf{(Equation 2.5)}$$

$$R \cdot C = 6.8 \cdot 10^{3}\,\Omega \cdot 320 \cdot 10^{-9}\,F = 0.002176\,\Omega \cdot F \cong 0.00218\,\Omega \cdot F \qquad \textbf{(Equation 2.6)}$$

So, for the 2ms delay, the desired RC value is 0.00218. The chosen R value is 6.8kΩ, and the chosen C value is 320nF. Here you can see the schematic of the comparator OpAmp circuit with 2ms delay **(Figure 1.2.2)**:

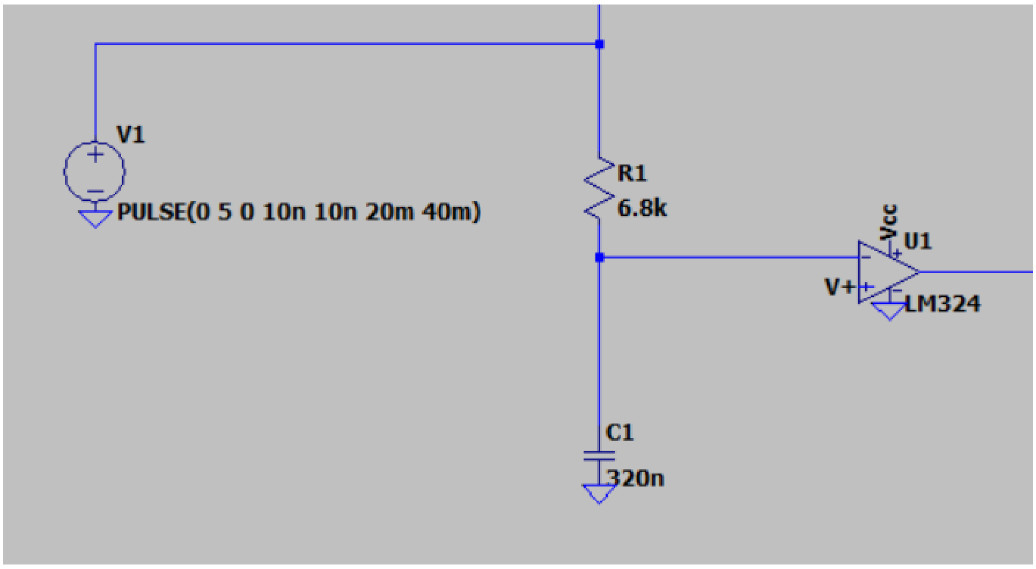

Figure 1.2.2: The Schematic of the Comparator OpAmp Circuit with 2ms Delay

For 7ms delay:

$$V_c = V \quad \textbf{(Equation 2.7)}$$

$$V_c = 5 \cdot e^{\frac{t}{RC}} = V \qquad \textbf{(Equation 2.8)}$$

$$5 \cdot e^{\frac{t}{RC}} = 2V \quad \textbf{(Equation 2.9)}$$

$$\ln\left(\frac{5}{2}\right) = \frac{t}{RC} = \frac{0.007}{RC} \quad \textbf{(Equation 2.10)}$$

$$RC = \frac{7 \cdot 10^{-3}}{\ln\left(\frac{5}{2}\right)} = 0.00764\,\Omega \cdot F \quad \textbf{(Equation 2.11)}$$

$$R \cdot C = 17 \cdot 10^{3}\,\Omega \cdot 450 \cdot 10^{-9}\,F = 0.00765\,\Omega \cdot F \cong 0.00764\,\Omega \cdot F \qquad \textbf{(Equation 2.12)}$$

So, for the 7ms delay, the desired RC value is 0.00764. The chosen R value is 17kΩ, and the chosen C value is 450nF. Here you can see the schematic of the comparator OpAmp circuit with 7ms delay **(Figure 1.2.3)**:

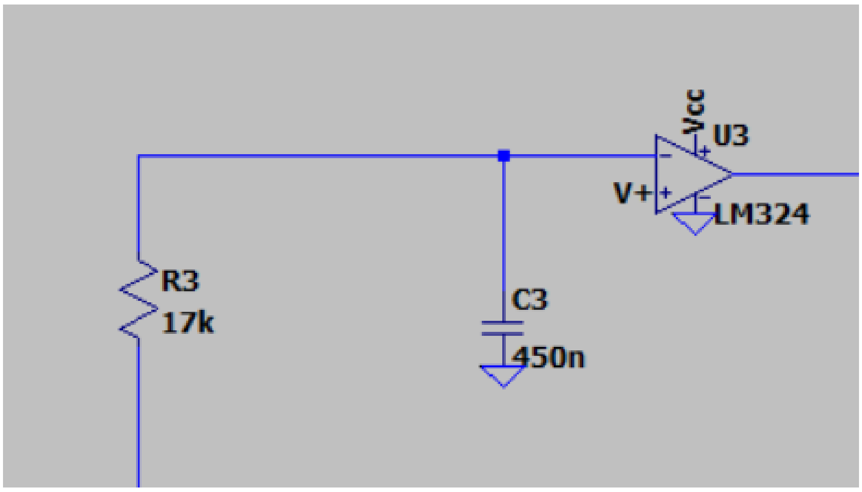

Figure 1.2.3: The Schematic of the Comparator OpAmp Circuit with 7ms Delay

<u>1.2.2- Integrator OpAmps:</u>

In the circuit, there are 2 integrator OpAmps. The purpose of these integrators is to create the inclined and declined shape in the desired trapezoid output. If we used no integrators, the output signal would basically be a rectangle and not a trapezoid. Here you can see a sample integrator OpAmp **(Figure 1.2.4)**:

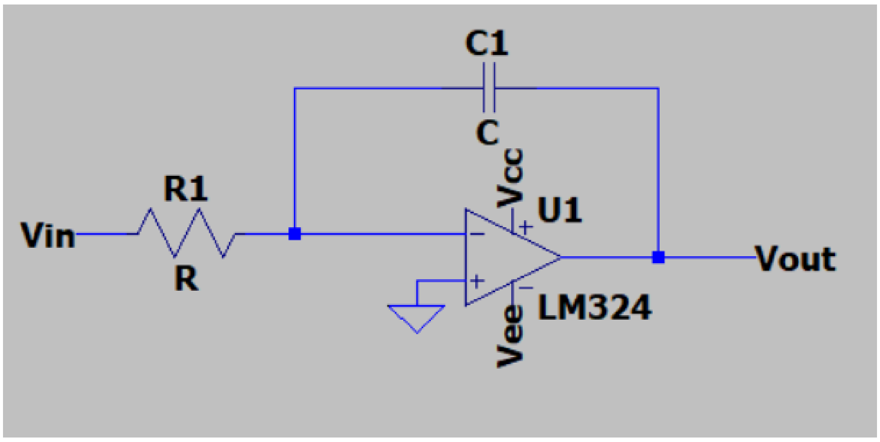

Figure 1.2.4: A sample Integrator OpAmp

We will connect the outputs of the comparator OpAmps ,i.e. the 2ms and 7ms delayed square wave input signals, to the input of the integrator OpAmps. The following set of equations **(Equations 3.1 to 3.7)** help us determine the R and C values we will use:

KCL at node V- :

$$I_C = I_R \qquad \textbf{(Equation 3.1)}$$

$$C \cdot \frac{d(V_+ - V_{out})}{dt} + \frac{V_+ - V_{in}}{R} = 0 \, \textbf{(Equation 3.2)}$$

$$\frac{d(V_{out})}{dt} = \frac{2 - V_{in}}{RC} \qquad \textbf{(Equation 3.3)}$$

$$V_{out} = \frac{1}{RC} \cdot \int_0^t (2 - V_{in}) dt \qquad \textbf{(Equation 3.4)}$$

$$V_{out} = \frac{1}{RC} \cdot \int_0^{0.002} (2 - 8) dt \qquad \textbf{(Equation 3.5)}$$

$$RC = \frac{6 \cdot 0.002}{8} = 0.0015\, \Omega \cdot F \, \textbf{(Equation 3.6)}$$

$$RC = 15 \cdot 10^3\, \Omega \cdot 100 \cdot 10^{-9}\, F = 0.0015\, \Omega \cdot F \qquad \textbf{(Equation 3.7)}$$

So, for the incline and decline of the trapezoid output, i.e. Δt1 and Δt3, to be 2ms each; the chosen R value is 15kΩ and the chosen C value is 100nF. Since both Δt1 and Δt3 are 2ms; two integrators will be identical in the design in terms of R and C values. Here are the two integrator OpAmp circuits we used in our design **(Figure 1.2.5)**:

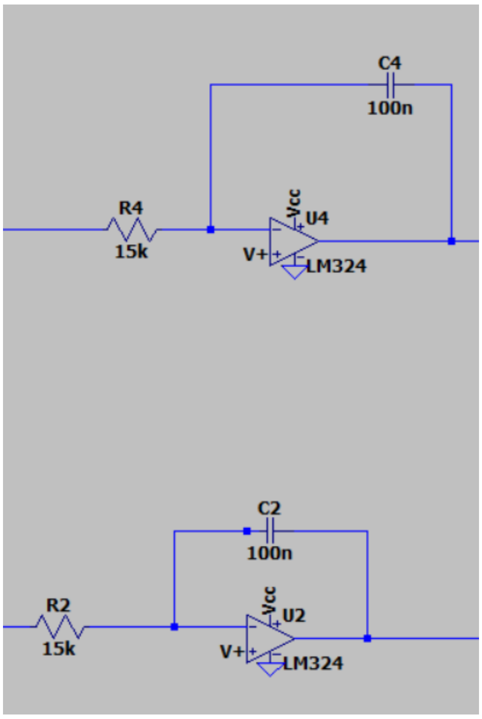

Figure 1.2.5: The Two Identical Integrator OpAmps we used in our design

1.2.3- Subtractor OpAmp:

In the circuit, there is only a single subtractor OpAmp used in the very end of the circuit. The output of the subtractor OpAmp is the output of the entire circuit. Here you can see a sample subtractor OpAmp **(Figure 1.2.6)** and the relevant equations **(Equations 4.1 to 4.6)**:

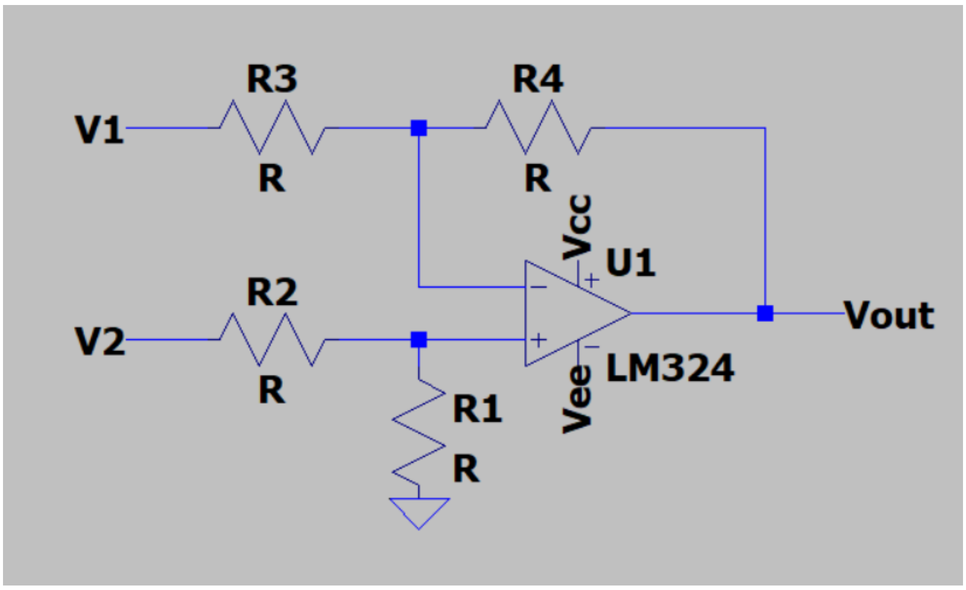

Figure 1.2.6: A sample Subtractor OpAmp

KCL at nodes V+ and V- :

$$V_{-} = \frac{R_1}{R_1 + R_2} \cdot V_2 \qquad \textbf{(Equation 4.1)}$$

$$\frac{V_{+} - V_1}{R_3} + \frac{V_{+} - V_{out}}{R_4} = 0 \qquad \textbf{(Equation 4.2)}$$

$$V_{+} \cdot \left(\frac{R_4 + R_3}{R_3}\right) - V_1 \cdot \left(\frac{R_4}{R_3}\right) = V_{out} \qquad \textbf{(Equation 4.3)}$$

$$V_{+} = V_{-} \qquad \textbf{(Equation 4.4)}$$

$$V_{out} = V_2 \cdot \left(\frac{R_1}{R_1 + R_2}\right) \cdot \left(\frac{R_4 + R_3}{R_3}\right) - V_1 \cdot \left(\frac{R_4}{R_3}\right) \qquad \textbf{(Equation 4.5)}$$

$$V_{out} = V_2 - V_1 \qquad \textbf{(Equation 4.6)}$$

Since R_1, R_2, R_3 and R_4 will be picked as the same value, 1kΩ in our case, equation 4.6 holds true for our specific case. Equation 4.5 is the general equation for subtractor OpAmps.

A large resistance is added at the end of the circuit in order to observe the final signal. Here you can see the entire circuit diagram **(Figure 1.2.7)**:

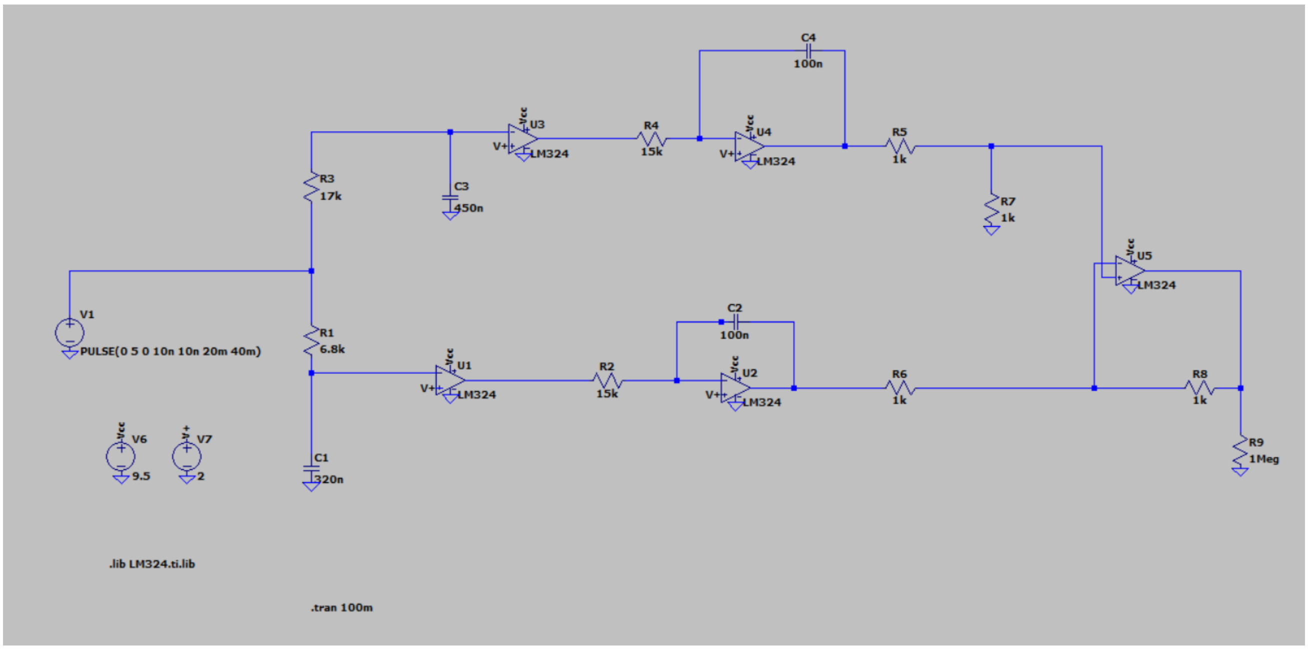

Figure 1.2.7: The Complete Circuit Diagram

1.3- Simulation:

Here is the final signal we obtain from the circuit and the numeric values of $\Delta t0$, $\Delta t1$, $\Delta t2$ and $\Delta t3$ **(Figures 1.3.1 to 1.3.5)**:

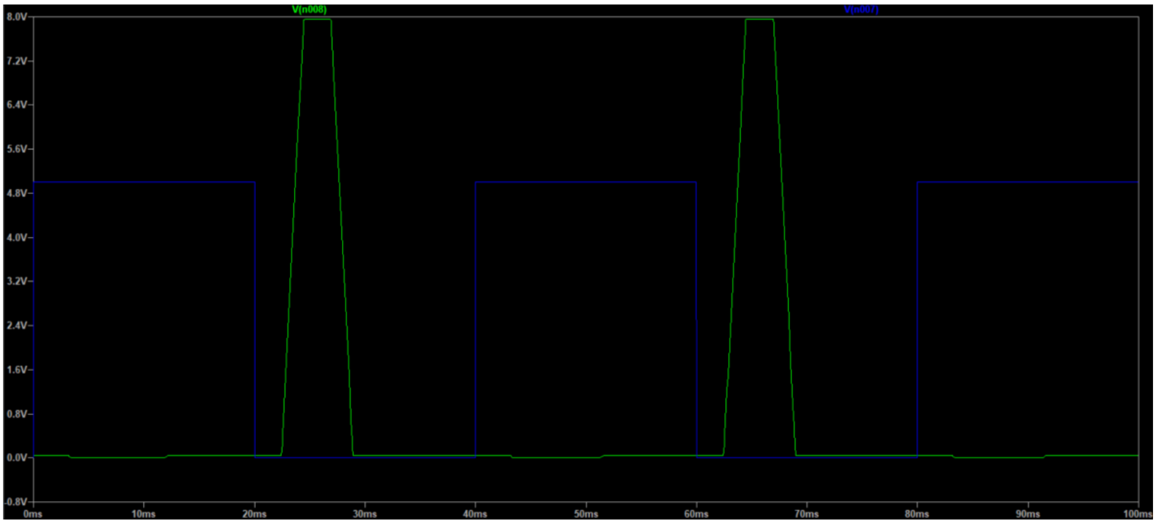

Figure 1.3.1: The Final Output of the Circuit

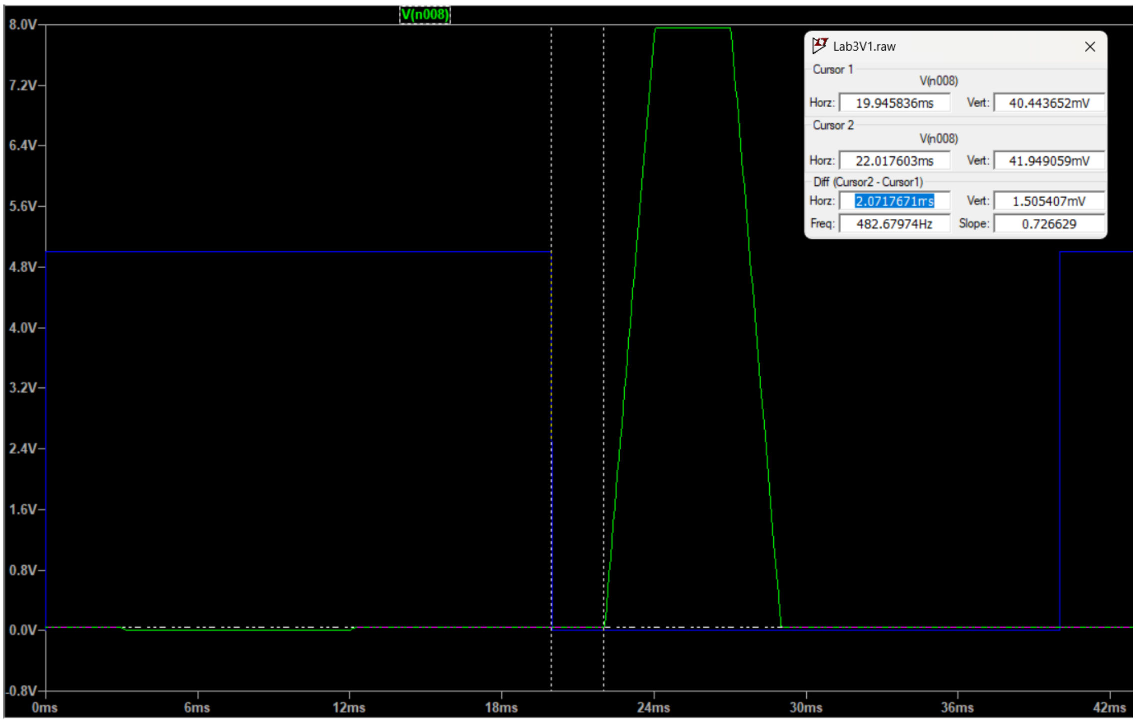

Figure 1.3.2: $\Delta t0$ measured as 2.07ms with an error of 3.5%

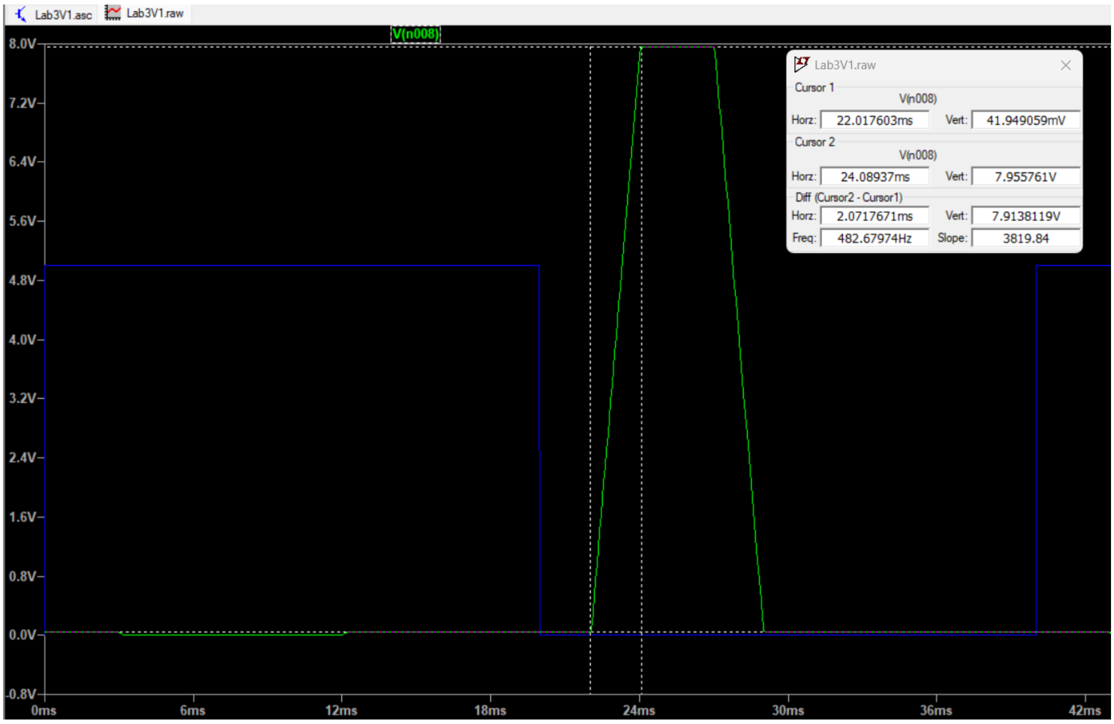

Figure 1.3.3: Δt1 measured as 2.07ms with an error of 3.5%

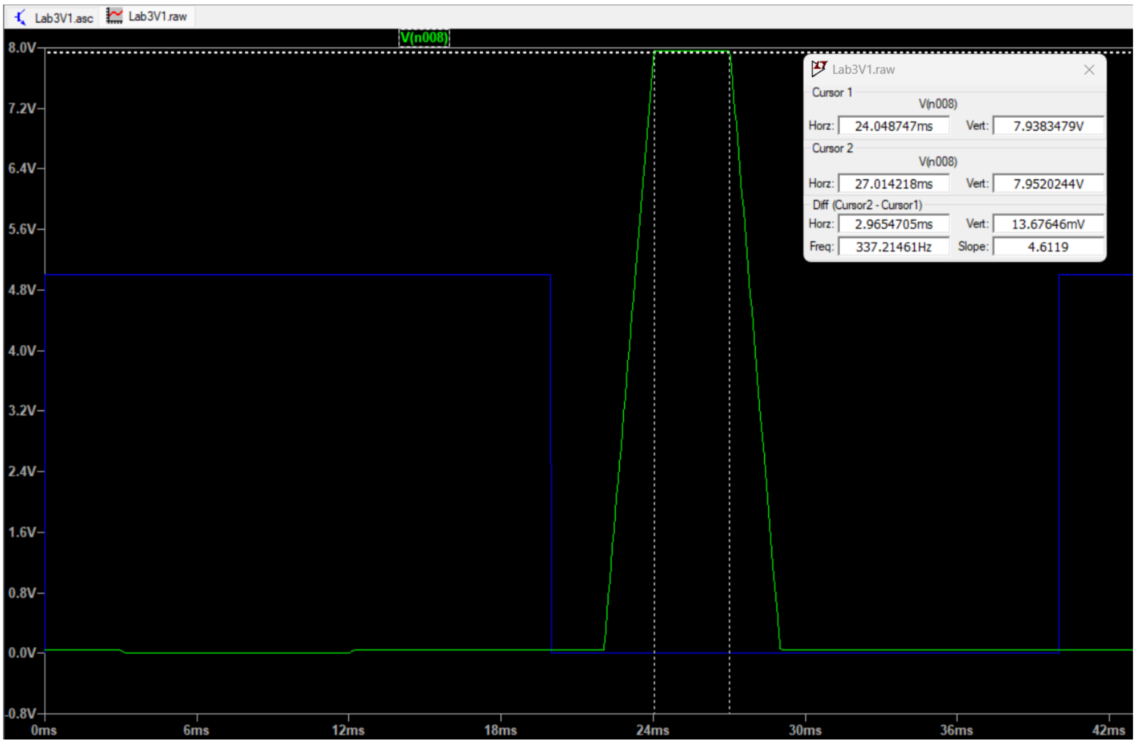

Figure 1.3.4: Δt2 measured as 2.96ms with an error of 1.33%

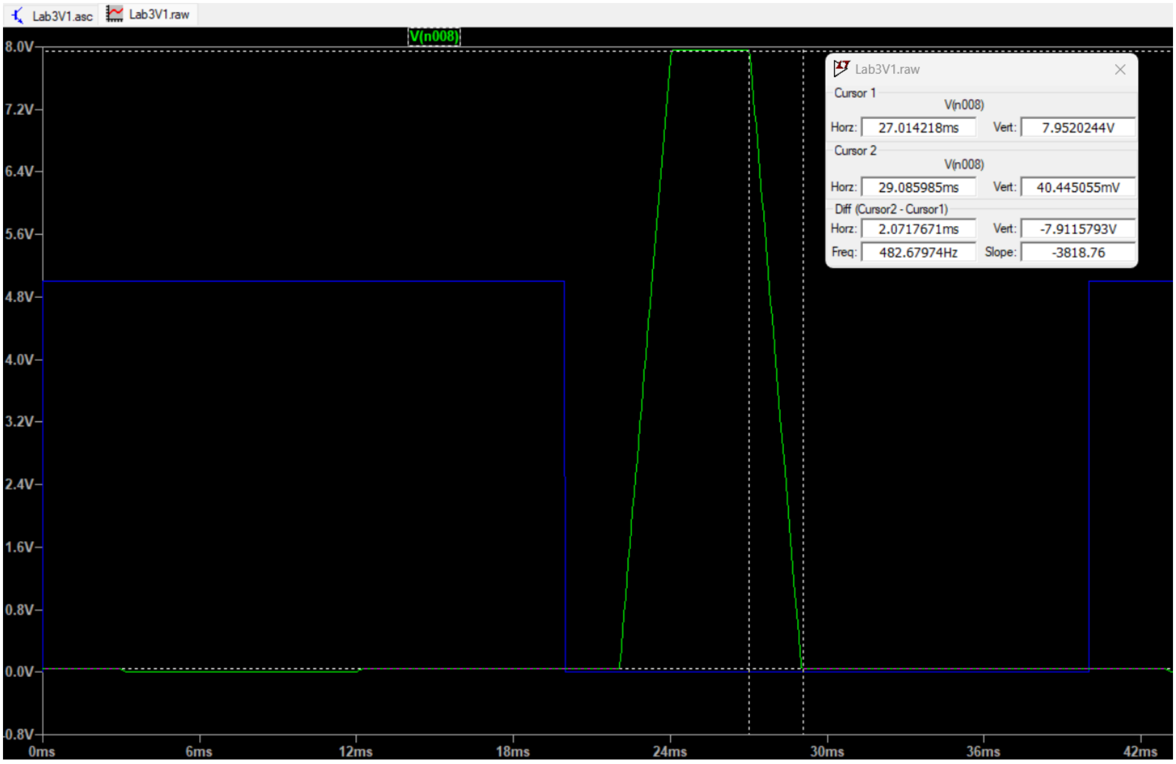

Figure 1.3.5: Δt3 measured as 2.07ms with an error of 3.5%

	Δt0 (ms)	Δt1 (ms)	Δt2 (ms)	Δt3 (ms)
Expected Value	2	2	3	2
Obtained Value (Simulation)	2.07	2.07	2.96	2.07
Error (%)	3.5%	3.5%	1.3%	3.5%

Table 1: Results of the Simulation

Here are the outputs of several important nodes within the circuit **(Figures 1.3.6 to 1.3.9)**:

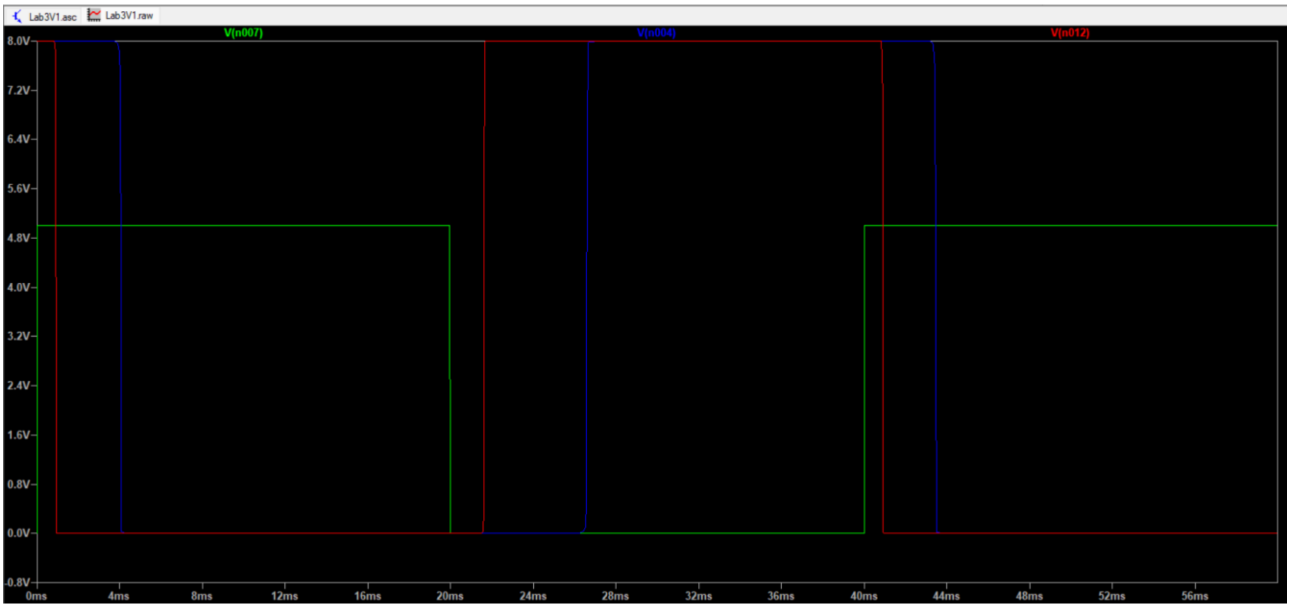

Figure 1.3.6: The Outputs of the Comparator OpAmps; **Green:** Input; **Red:** 2ms delay; **Blue:** 7ms delay

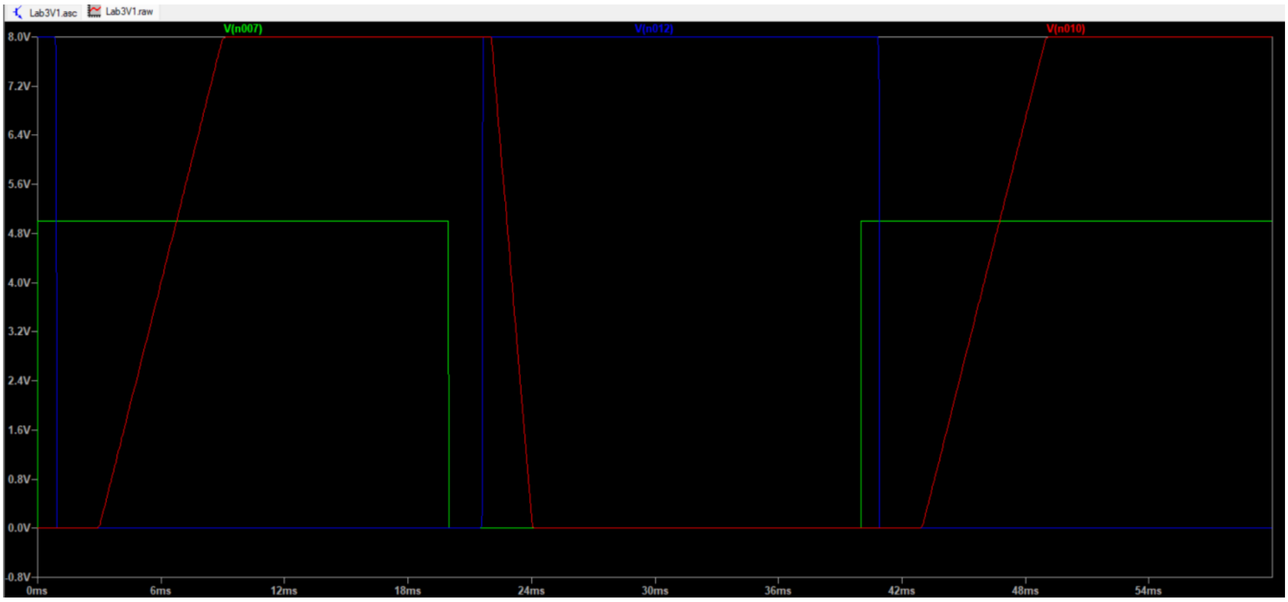

Figure 1.3.7: The Input&Outputs of the Integrator with 2 ms delay; **Green:** Input; **Red:** Integrator Output;

Blue: Integrator Input & 2ms Comparator Output

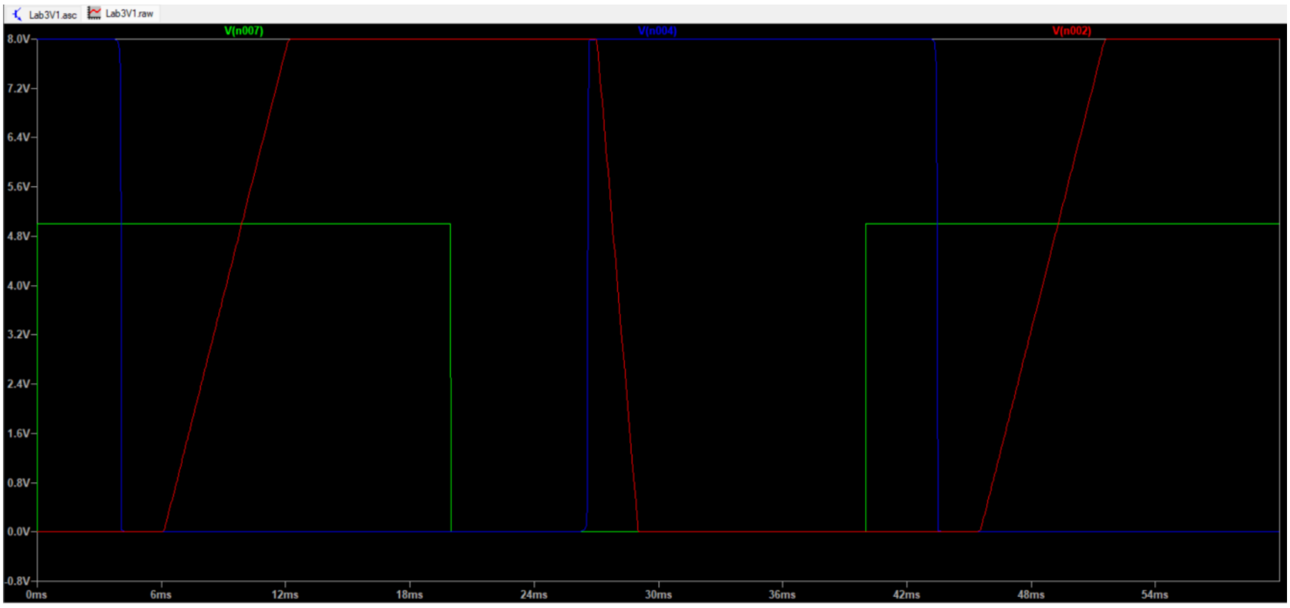

Figure 1.3.8: The Input&Outputs of the Integrator with 7 ms delay; **Green:** Input; **Red:** Integrator Output; **Blue:** Integrator Input & 7ms Comparator Output

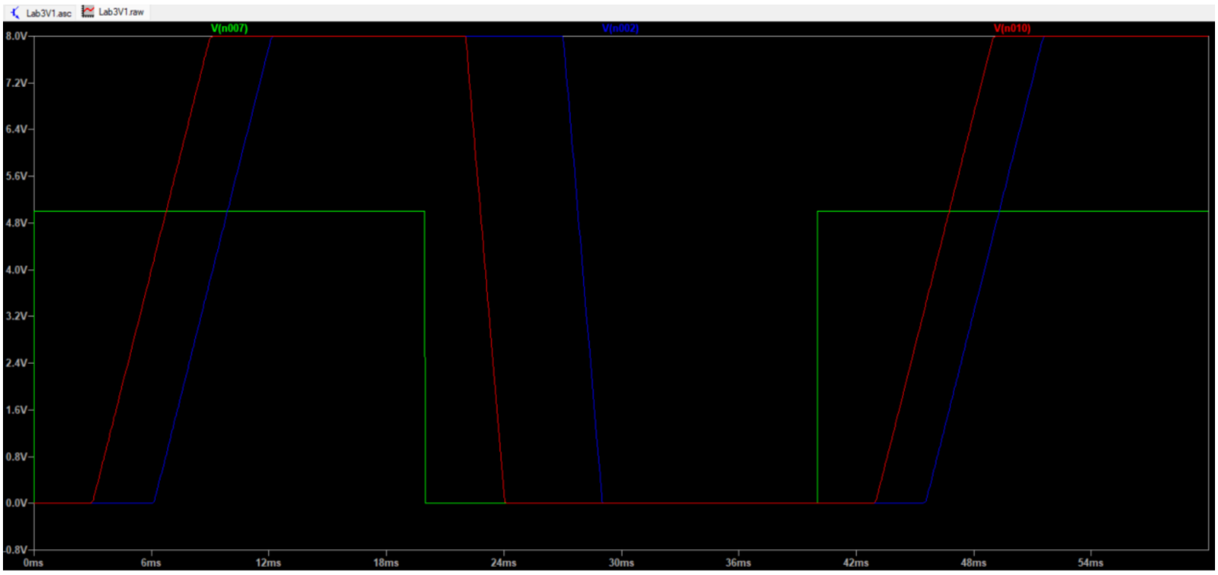

Figure 1.3.9: The Outputs of the 2 Integrators with respect to the input signal; **Green:** Input Signal; **Red:** 2ms delayed Integrator Output; **Blue:** 7ms delayed Integrator Output

2- Hardware Implementation

2.1- Introduction:

In the laboratory, we were provided with 2 OpAmp IC's which have a total of 8 OpAmps within themselves. After completing the simulation part of the lab, I implemented the design on a breadboard. The input signal was a 5V Pk-Pk 25Hz square wave signal with an offset of 2.5 volts. This offset was due to us wanting the signal to be oscillating between 0 and 5 Volts; not –2.5 and +2.5 Volts. Also, I used a DC power source and provided 2 and 9.5 Volts potential differences from two distinct channels.

Here is the circuit I've implemented on the breadboard **(Figure 2.1.1)**:

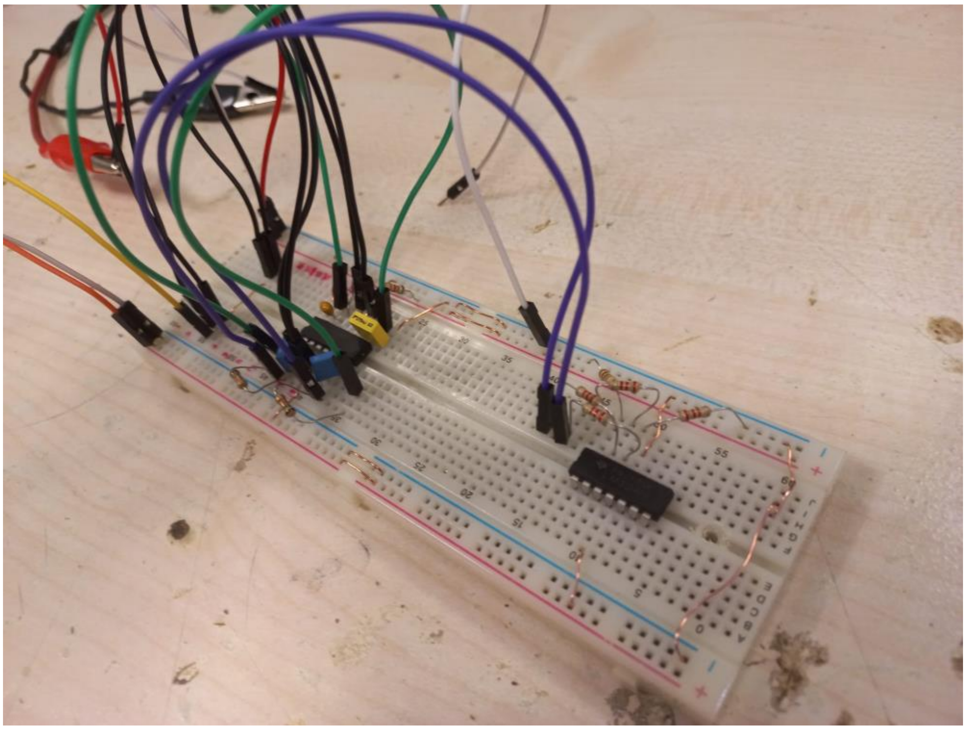

Figure 2.1.1: The implemented circuit on the breadboard

2.2- Results

Here are the results of the experiment **(Figures 2.2.1 to 2.2.11)**:

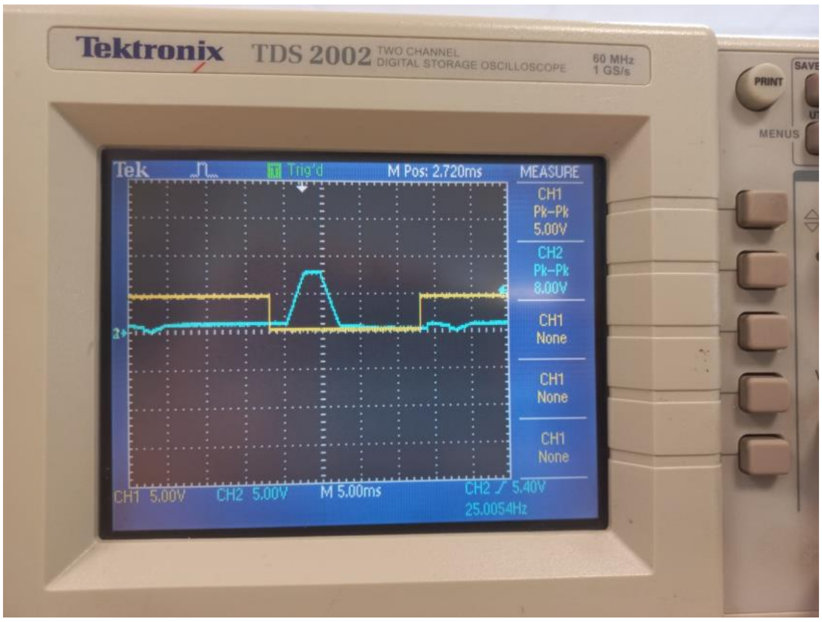

Figure 2.2.1: The Final Output of the Circuit with Respect to the Input Signal; Vpp = 8.00 Volts

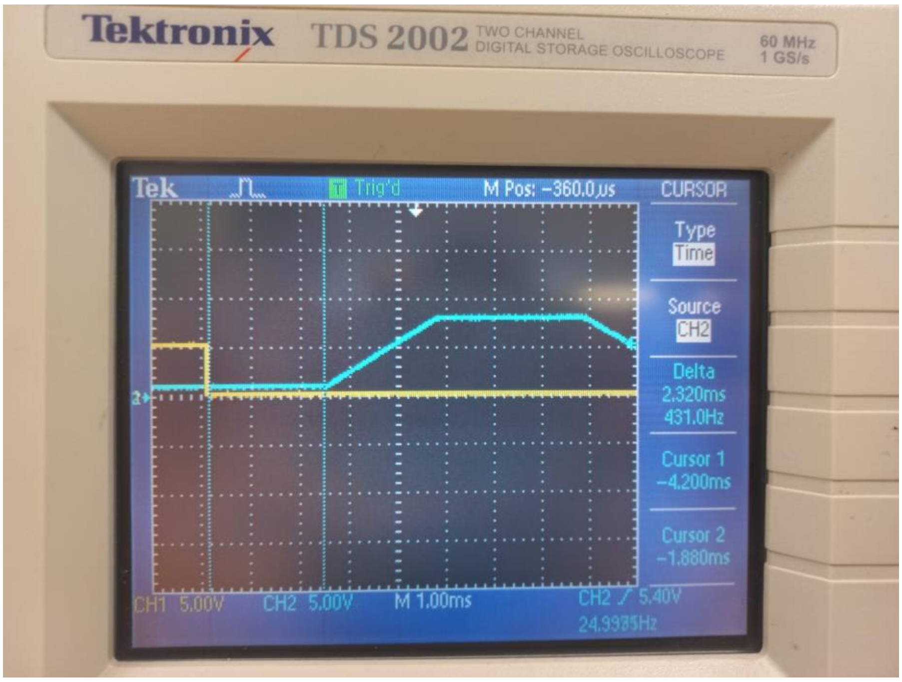

Figure 2.2.2: The measured $\Delta t0 = 2.32$ms

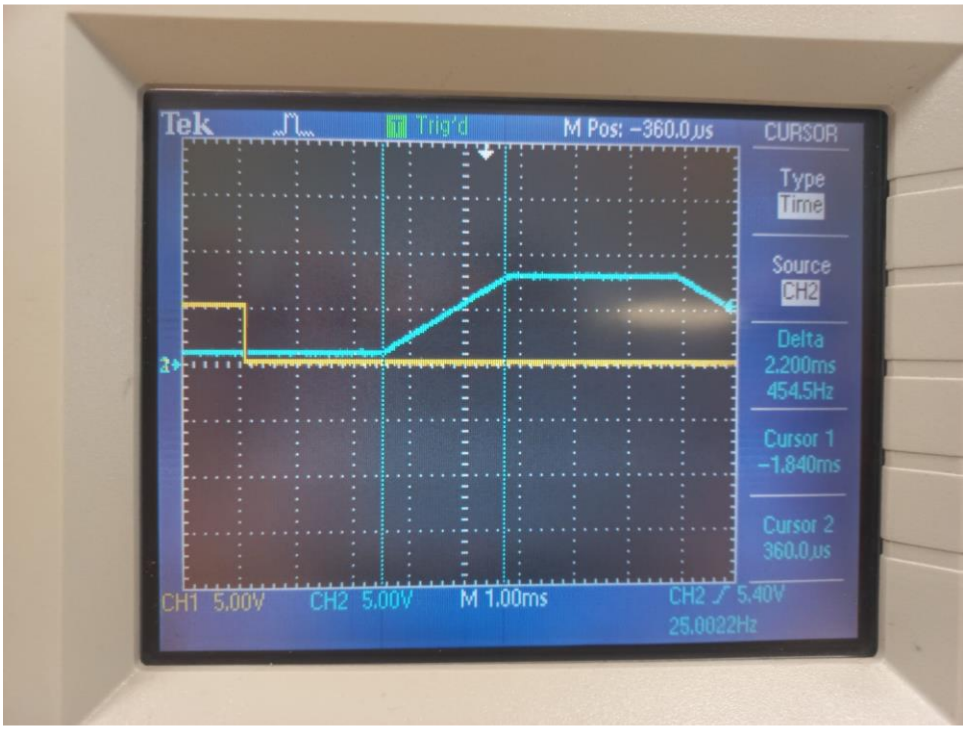

Figure 2.2.3: The measured Δt1 = 2.20ms

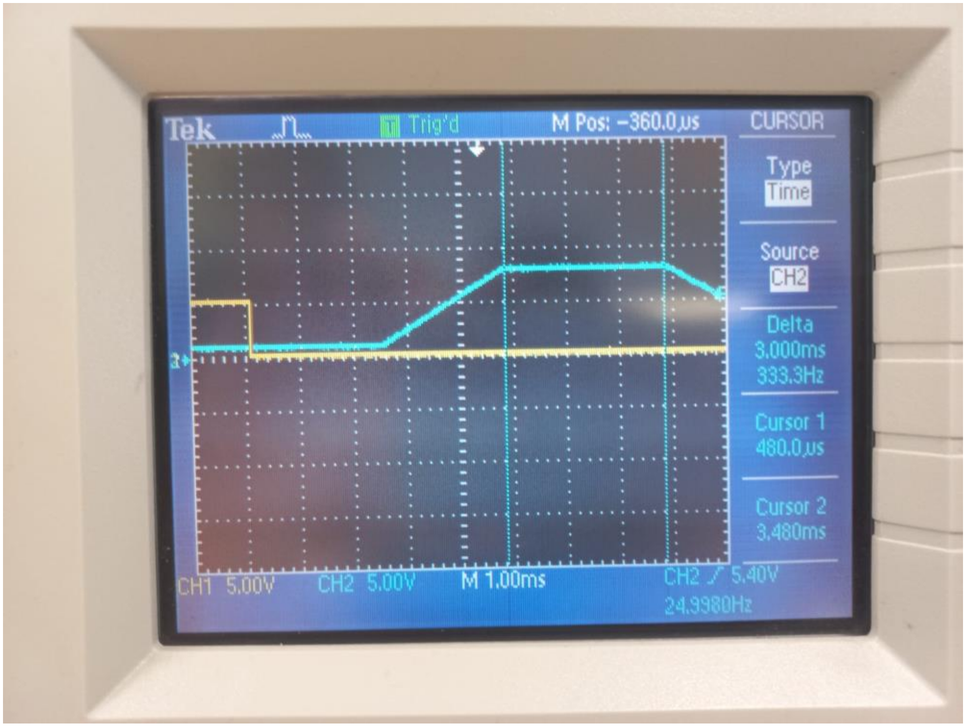

Figure 2.2.4: The measured Δt2 = 3.00ms

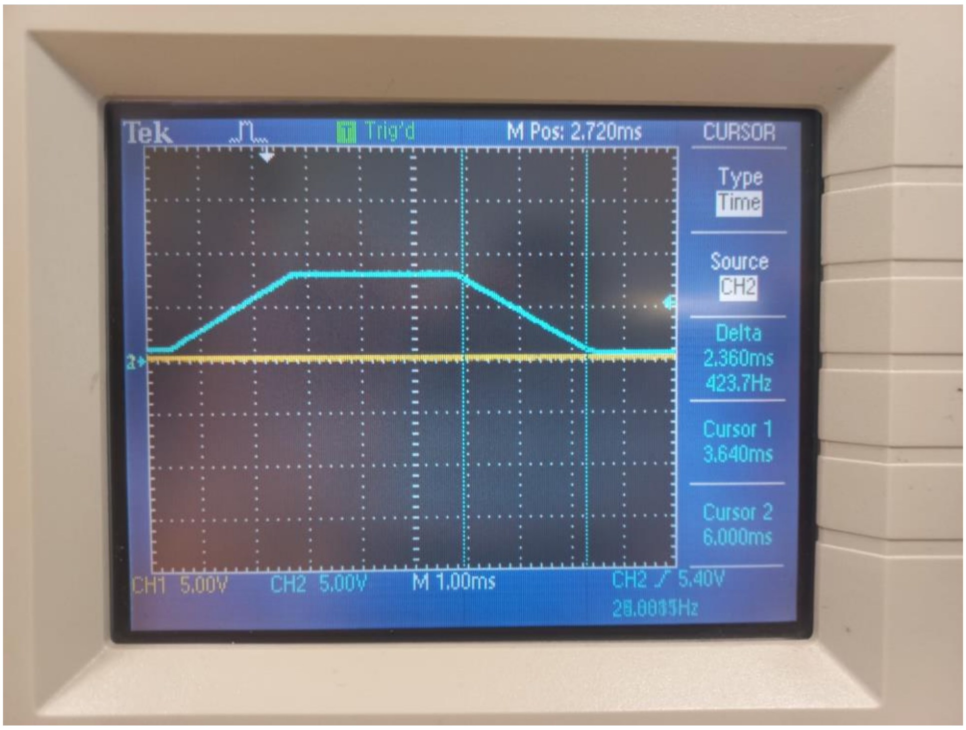

Figure 2.2.5: The measured $\Delta t3 = 2.36ms$

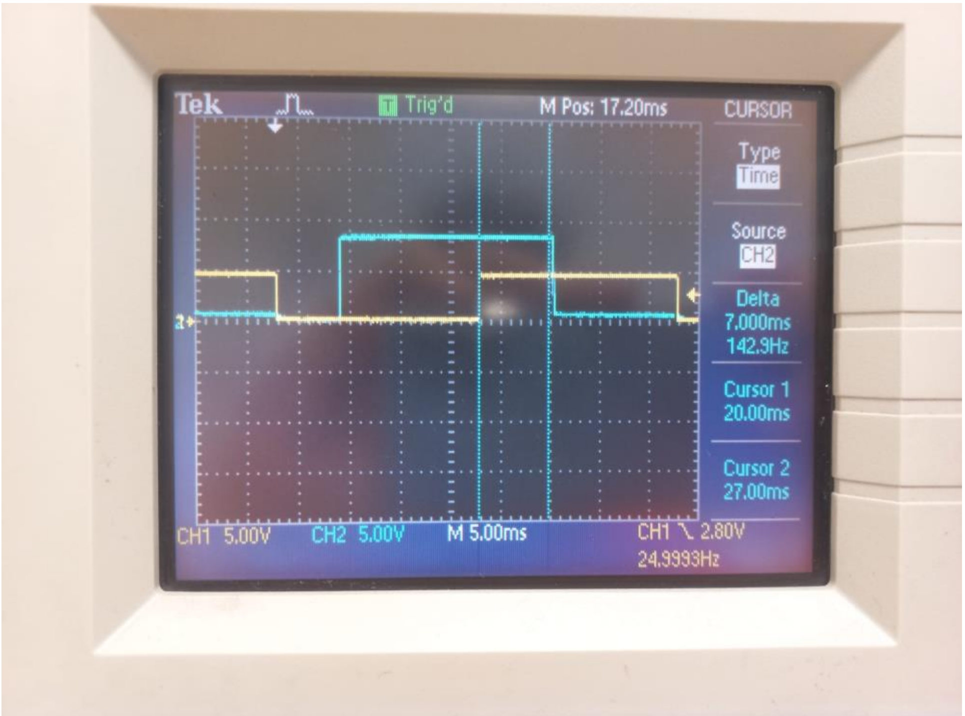

Figure 2.2.6: The Output of the Comparator OpAmp with 7ms delay

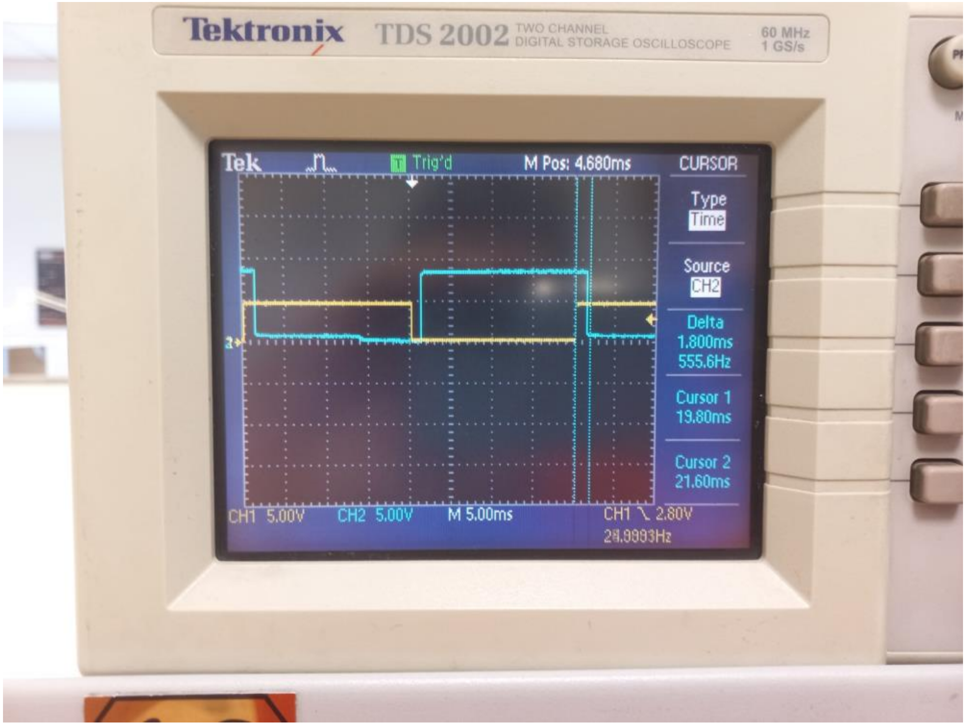

Figure 2.2.7: The Output of the Comparator OpAmp with 2ms delay

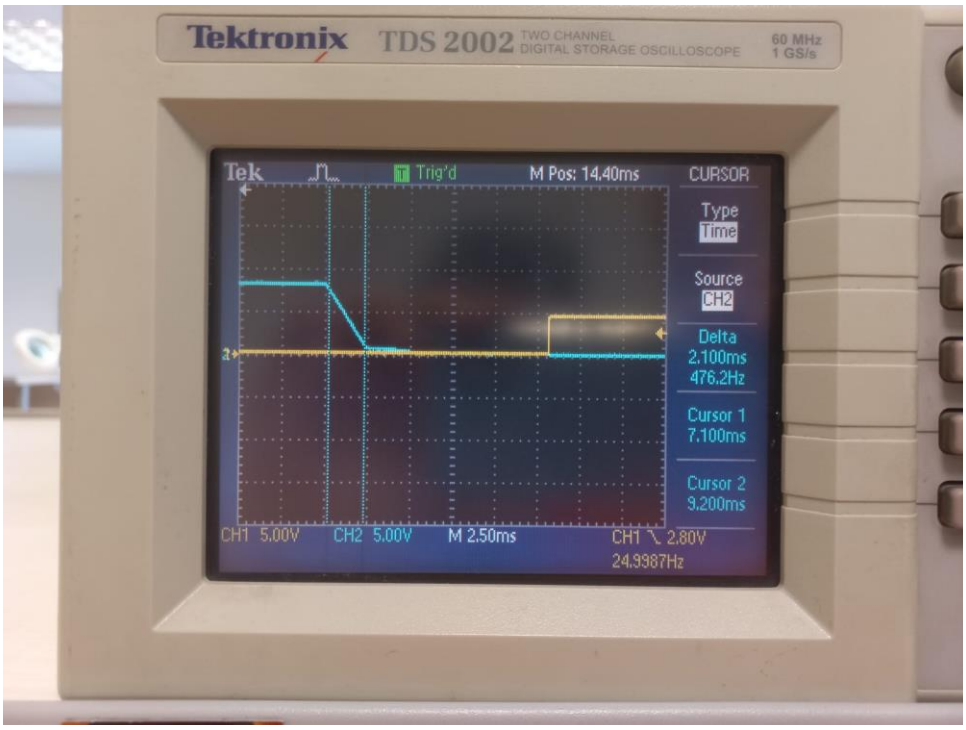

Figure 2.2.8: The Output of the Integrator OpAmp with 7ms delay (1)

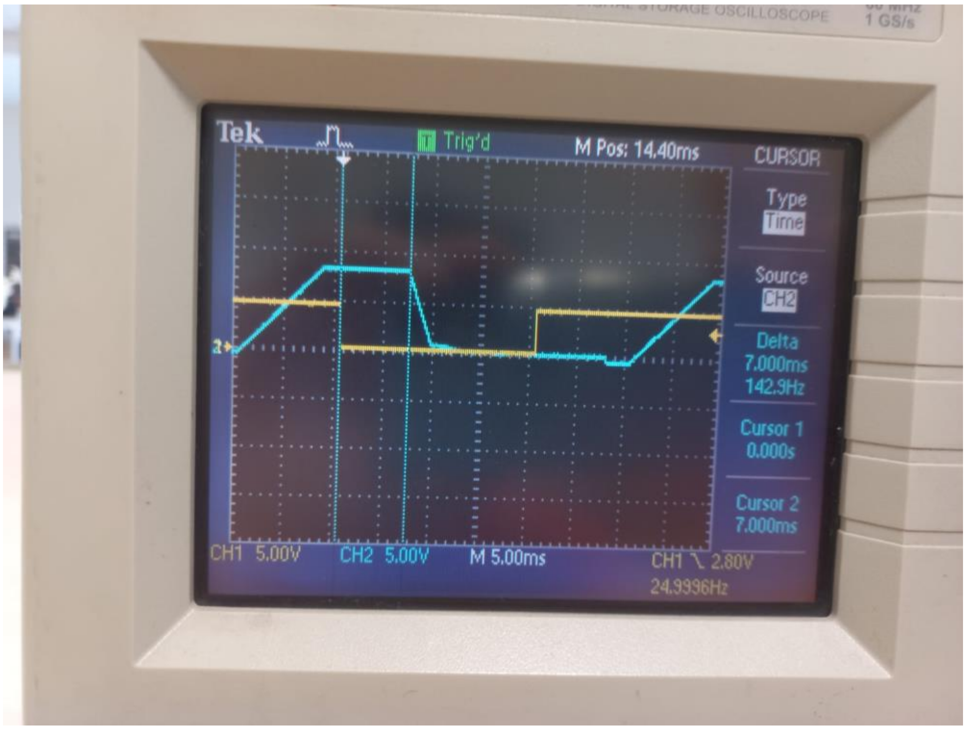

Figure 2.2.9: The Output of the Integrator OpAmp with 7ms delay (2)

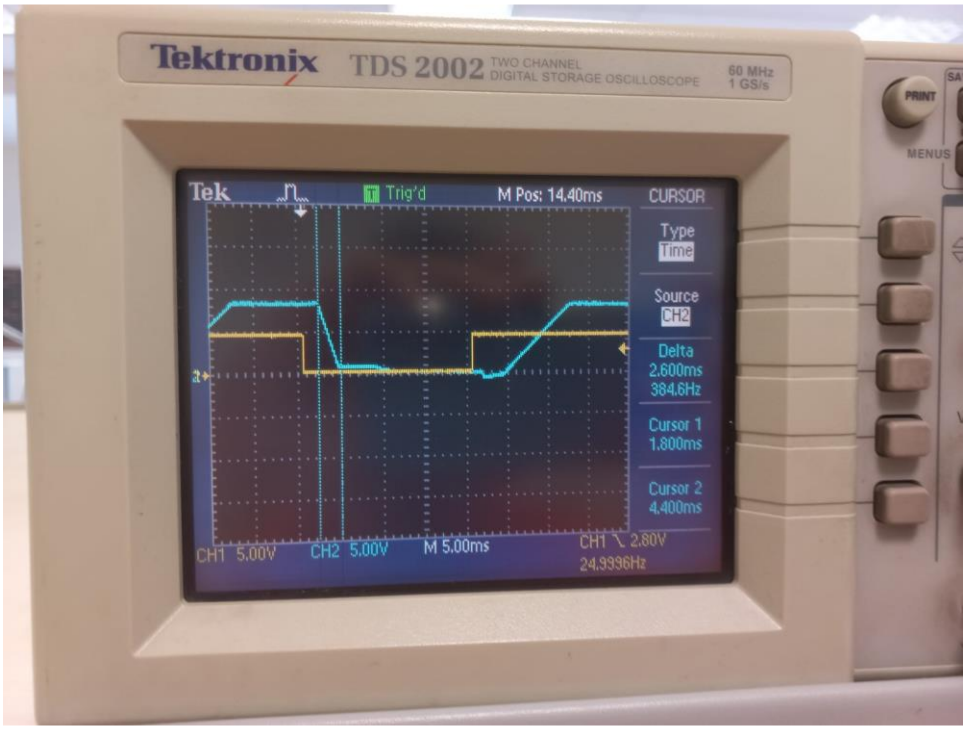

Figure 2.2.10: The Output of the Integrator OpAmp with 2ms delay (1)

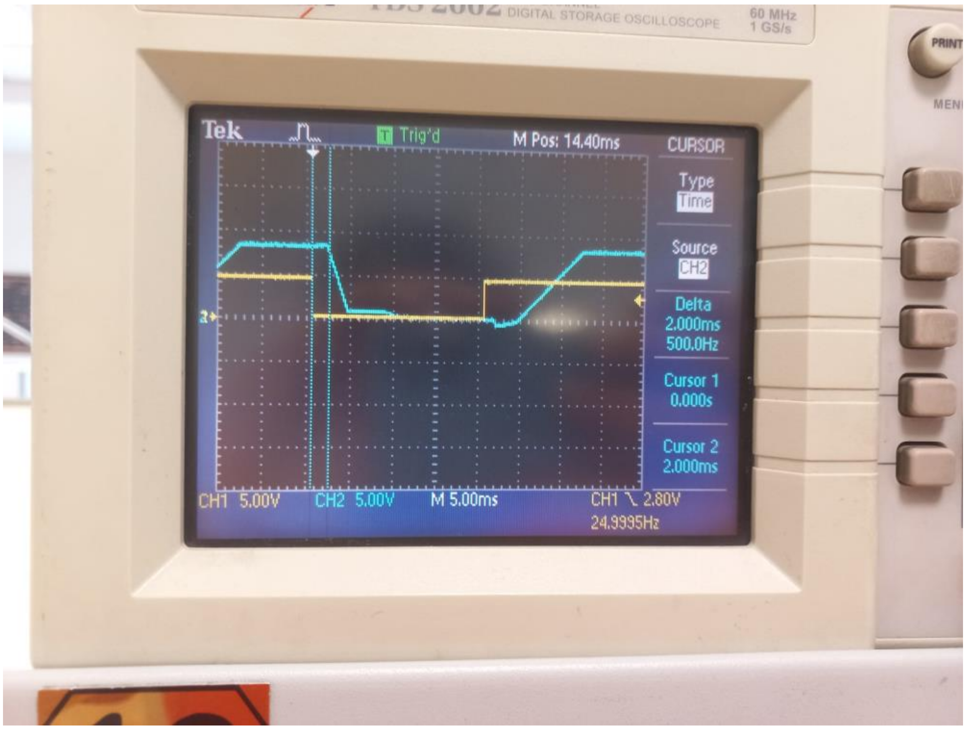

Figure 2.2.11: The Output of the Integrator OpAmp with 2ms delay (2)

	Δt0 (ms)	Δt1 (ms)	Δt2 (ms)	Δt3 (ms)	Vpp(V)
Expected Value	2	2	3	2	8
Obtained Value (Hardware Implementation)	2.32	2.20	3.00	2.36	8
Error (%)	16%	10%	0%	18%	0%

Table 2: Results of Hardware Part

3- Conclusion

The main purpose of this experiment was to create a trapezoid waveform from a square wave input using OpAmps and RC circuits. I have successfully managed to do that with small errors. The errors I obtained in the hardware part was higher than the ones on the software part. This was probably due to the physical material and the environment we do the hardware experiment in. Also, the errors which might be caused from the DC power source or the oscilloscopes might play a role in this.

In the lab manual, the error limit for the software part was under 10%. The error limit for the hardware part was 20%. My design successfully managed to stay under the limits in both parts of the experiment.

I believe this experiment was very helpful for us in order to have better understanding of linear circuit elements such as capacitors and OpAmps.