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Faculty of Engineering, Architecture and Science

Department of Electrical and Computer Engineering

Program: Electrical Engineering

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| Course Title | **Electronic Circuits II** |
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| **Formal Technical Report** | **8** |

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| Report Title | Linear voltage-controlled frequency, square and triangle wave function generator with gain control |

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(Note: remove the first 4 digits from your student ID)

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**Abstract:**
This project focuses on making a linear voltage-controlled function generator to produce symmetrical triangular and square waves. The circuit would be able to work with two frequency ranges, 100 - 4200 Hz and 20 - 840 Hz by varying the input DC voltage Vc. The main components used to make this function generators were based on Operation Amplifiers and included DC to +/-DC converter, Inverting Integrator, and Inverting Bistable Comparator.

**Objective:**
The purpose of this project is to implement our knowledge of Op-amp circuits acquired through the lectures and apply it into creating one functional device with several components. The main objective was to create, over the course of several weeks, a voltage controlled frequency square and triangle wave generator with incorporated gain control. The final product was to be adherent to the following specifications (The value of fx we used is 4200 Hz):

- **Waveform Functions**: User selectable symmetrical **TRIANGULAR** or **SQUARE** wave waveform output.

- **Frequency Range, Δ $f_O$**:- User selectable as:-
  - **Range #1** ≈100Hz to $f_x$ Hz.
  - **Range #2** ≈20Hz to $f_x$**/5** Hz

- **Input d.c. Voltage Control Range,** $V_C$ :- User controlled from ≈ **0.1V** to **5V**

- **Output Amplitude Control Range for each waveform** (triangular and square wave): Using a potentiometer for each output, a user should be able to control the output voltage levels of the signals in the range from **0** to **8**$V_{peak\text{-}to\text{-}peak}$ (i.e. **0** to **4**$V_{peak}$)

- **Power Supplies** available for use: **only +/-12V d.c.** allowed for the completed design.

**Experimental Procedure:**

The very first step to creating this voltage controlled frequency square and triangle wave generator with incorporated gain control was taken in the completion of the first milestone- a fixed frequency square and triangle wave generator. To begin the development of this backbone of the final product, we investigated the operation of an inverting integrator circuit and a non-inverting bistable comparator circuit. After conducting the analysis we selected the right resistor and capacitor values to allot us our required fx and selected threshold high and low voltage values.

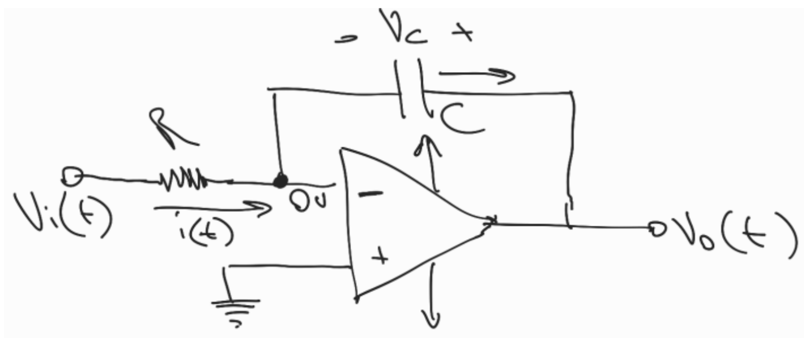
The next step, implemented in the second milestone, was to create a DC to +-DC converter which was to be used for frequency control of our function generator circuit in future milestones; as well as a voltage limiter circuit which would allow us to get a precise output of 6.3Vp from the bistable. The biggest challenge in this step was implementing a switch using a BJT transistor for the convertor.

The third milestone of this project was simply combining the DC to +-DC converter with the fixed frequency function generator (with voltage limiter circuit), so that the output of the bistable now fed into the switch of the converter driving it between cutoff and saturation. The input to the convertor was a variable DC voltage source, thus, the combined circuit now functioned as a voltage controlled frequency function generator. To make sure that the overall feedback of the circuit remained negative, the non-inverting bistable needed to be changed to inverting.

The final step of this project was to add gain control to the existing circuit through the use of potentiometers at the output of both the integrator and bistable. The R value of the integrator was recalculated to allow for the application of the second voltage controlled frequency range of fx/5.

**Inverting Integrator:**

First looking at the inverting integrator in which the Op-amp is assumed to be ideal and negative feedback exists so the negative terminal tracks the positive terminal:




After conducting simple mesh analysis using KVL around the negative feedback loop, we arrive at the equation:

$$(1)\quad V_o(t) = 0v - V_c(t) + V_c$$

Where 0 is the voltage at the negative terminal since it tracks the positive terminal, Vc(t) is the voltage drop across the capacitor and Vc represents the voltage due to any initial charge on the capacitor (given the able polarity it is positive). Next, for Vc(t) we know that the voltage across a capacitor is equal to charge over capacitance; knowing that the charge across a capacitor does not change instantaneously, we get the following equation:

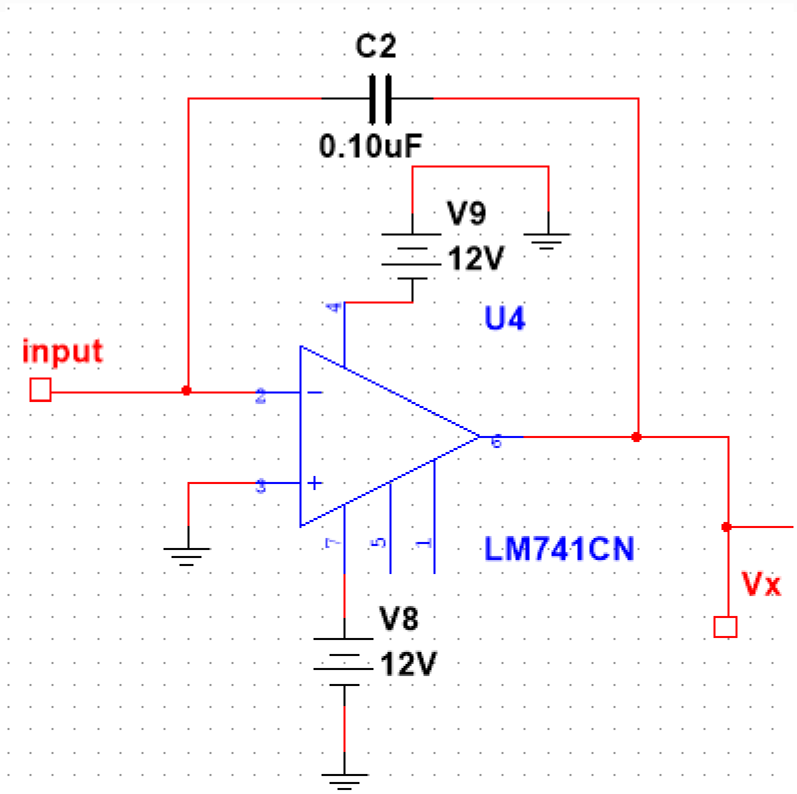
$$(2)\quad V_c(t) = \frac{1}{C}\int i(t)\,dt$$

From Ohm's law we know that current at any given instant in time is equal to the voltage at that instant over the resistance, we can use this to find the current I(t) through resistor R:

$$(3)\quad i(t) = \frac{V_i(t)}{R}$$

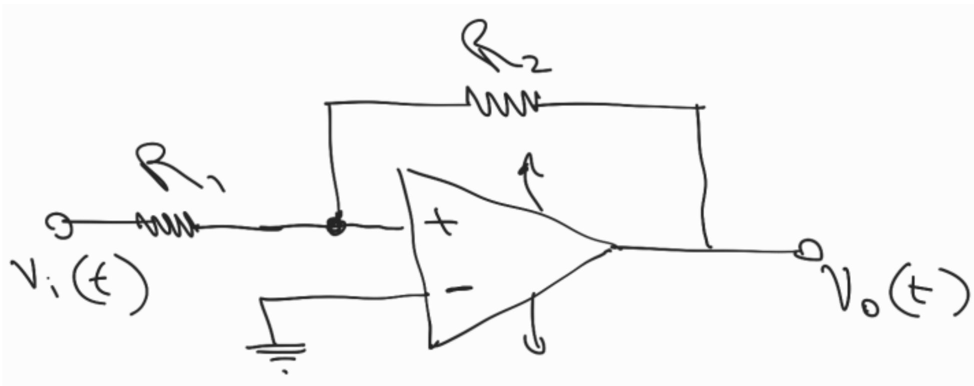
Now, substituting equation 3 into 2 and then substituting 2 into 1, we arrive at the following equation which allows us to form a relationship between the input voltage signal and the output of the integrator:

$$V_o(t) = -\frac{1}{RC}\int V_i(t)\,dt + V_c$$

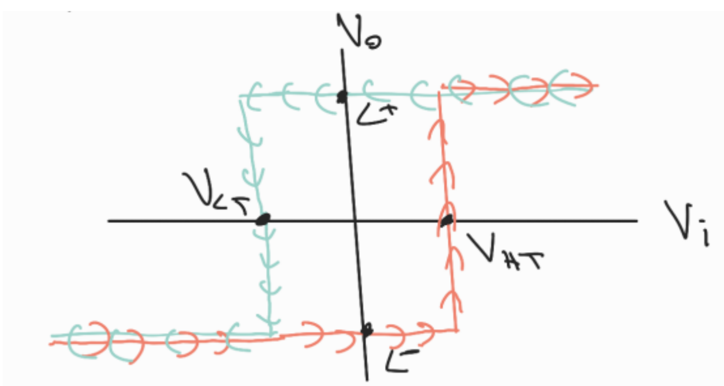


**Bistable Comparator:**

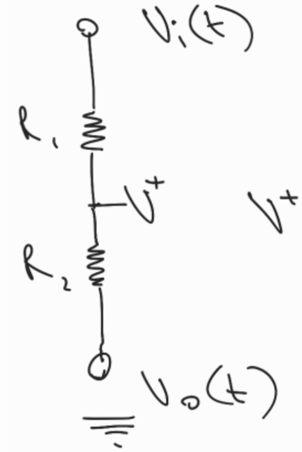
Now looking at the circuit of the bistable comparator, again assuming the op-amp is ideal, we can see that positive feedback exists; so right away we know that the output will be positive saturation (L+) when the voltage at the positive terminal is greater than at the negative terminal, and negative saturation (L-) when the voltage at the negative terminal is greater than at the positive terminal:




What interests us is when the switch from L+ to L- is made. This phenomenon can be explained through the hysteresis operation model of the comparator which relates Vi to Vo:




This basically states the following: starting with Vi at negative infinity, thus ensuring that the voltage at the positive terminal is less than the negative, we know Vo will be at negative saturation. However, when Vi reaches a certain low threshold value (Vlt) at which the positive terminal is equal to the negative terminal (at 0V in our case), Vo switches to L+. Similarly this model can be explained for when Vi approaches a high threshold value (Vht) approaching from positive infinity, at which point Vo switches from positive saturation to negative. To analyze the above comparator circuit, we can use a simple voltage divider principle, which allows us to set up an equation for the voltage at the positive terminal:




$$\frac{V_i(t) - V^+}{R_1} = \frac{V^+ - V_o(t)}{R_2}$$

$$V^+ = \left(\frac{R_2}{R_2+R_1}\right)V_i + \left(\frac{R_1}{R_1+R_2}\right)V_o$$

When V+ reaches 0 while Vi comes up from negative infinity and Vo switches to positive saturation, we can calculate the low threshold value. Similarly we can calculate the high threshold voltage value when V+ reaches 0 while Vi comes down from positive infinity and Vo switches to negative saturation:

$$\text{1) @ } V^+ = 0 = \left(\frac{R_2}{R_2+R_1}\right)V_i + \left(\frac{R_1}{R_1+R_2}\right)V_o$$

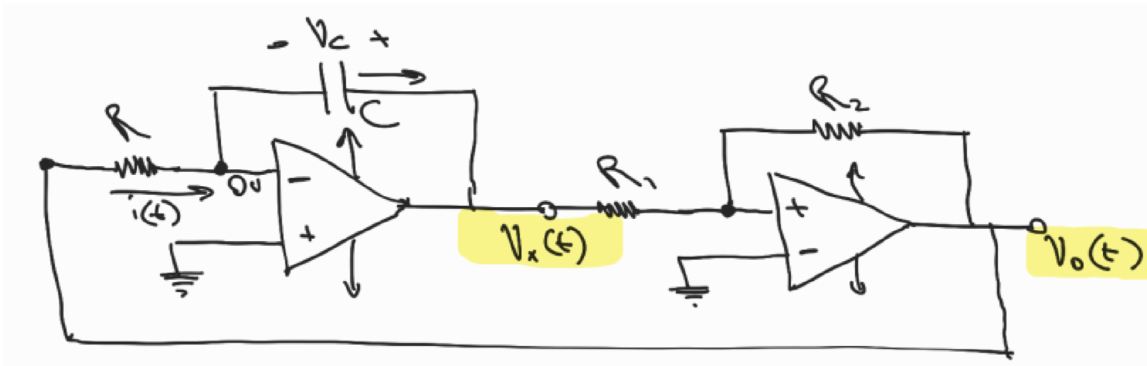
$$\hookrightarrow V_i = V_{LT} = -\frac{R_1}{R_2}L^+$$

$$\text{2) @ } V^+ = 0 = \left(\frac{R_2}{R_2+R_1}\right)V_i + \left(\frac{R_1}{R_1+R_2}\right)V_o$$

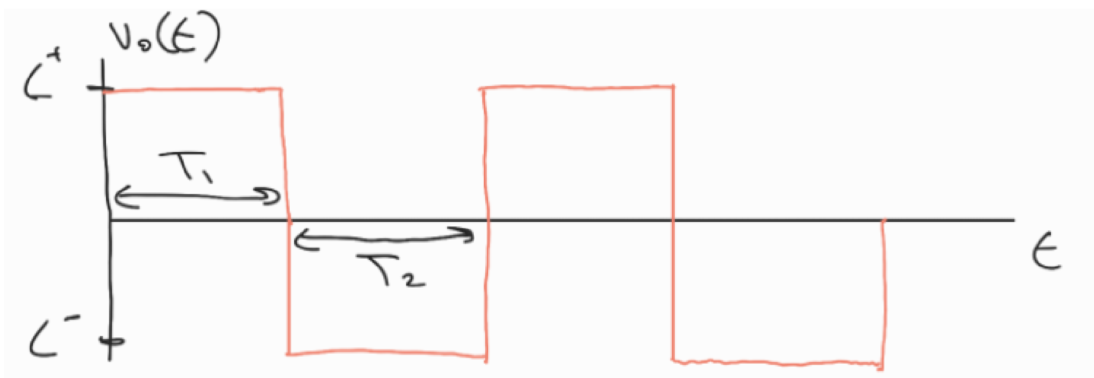
$$\hookrightarrow V_i = V_{HT} = -\frac{R_1}{R_2}L^-$$

**Fixed Frequency Function Generator (Combination of Bistable and Integrator):**

When we combine the integrator and bistable circuits:




We have a square wave being fed into the integrator. The integrator periodically integrates 2 constant values (L+ and L-) from the bistable- the integral of which is a linear equation with plus and minus slope respectively. This generates a triangle wave output from the integrator which oscillates between the threshold high and low of the bistable:




$V_o(t)$ is feeding into integrator:

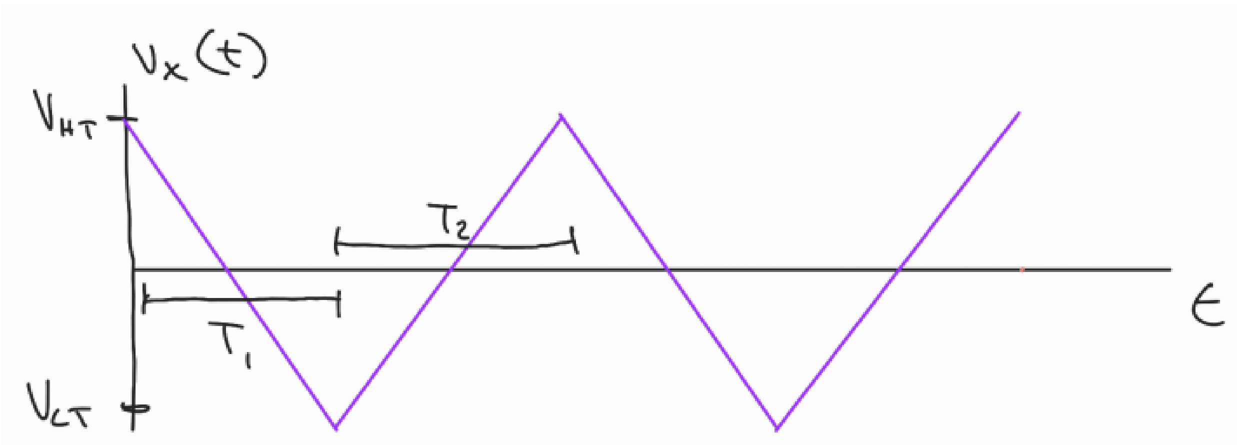
$$V_o(t) = -\frac{1}{RC}\int V_i(t)\,dt + V_C$$

when $V_i(t) = L^+$ (constant)

$$V_o(t) = -\frac{L^+}{RC}t + V_{HT}$$ → straight line, negative slope

When $V_i(t) = L^-$

$$V_o(t) = -\frac{L^-}{RC}t + V_{LT}$$ → straight line positive slope.




Taking the slope from the above formulated equation and equating it with the slope from the graph, we can derive an equation for the period and frequency of this fixed frequency square and triangle wave function generator:

Slope from equation: $\frac{-C^+}{RC}$

slope from graph: $\frac{V_{CT} - V_{HT}}{T_1 - 0}$

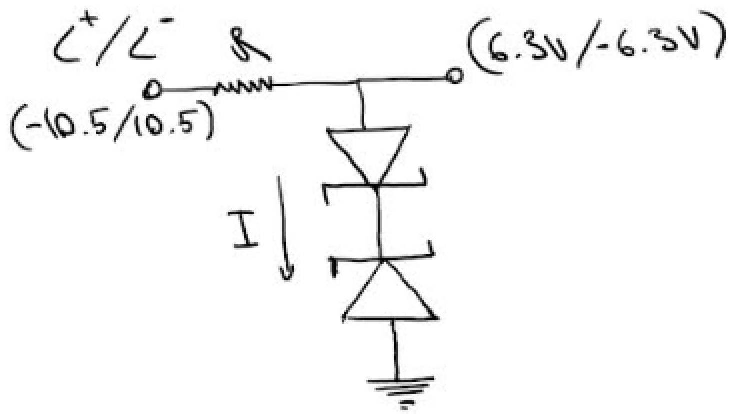
$$\therefore \frac{-C^+}{RC} = \frac{V_{CT} - V_{HT}}{T_1} \rightarrow T_1 = \frac{RC(V_{CT} - V_{HT})}{-C^+}$$

↳ since $T_1 = T_2$

Net period $T = T_1 + T_2$

$$T = \frac{2RC(V_{CT} - V_{HT})}{|C|} = \frac{1}{f_x}$$

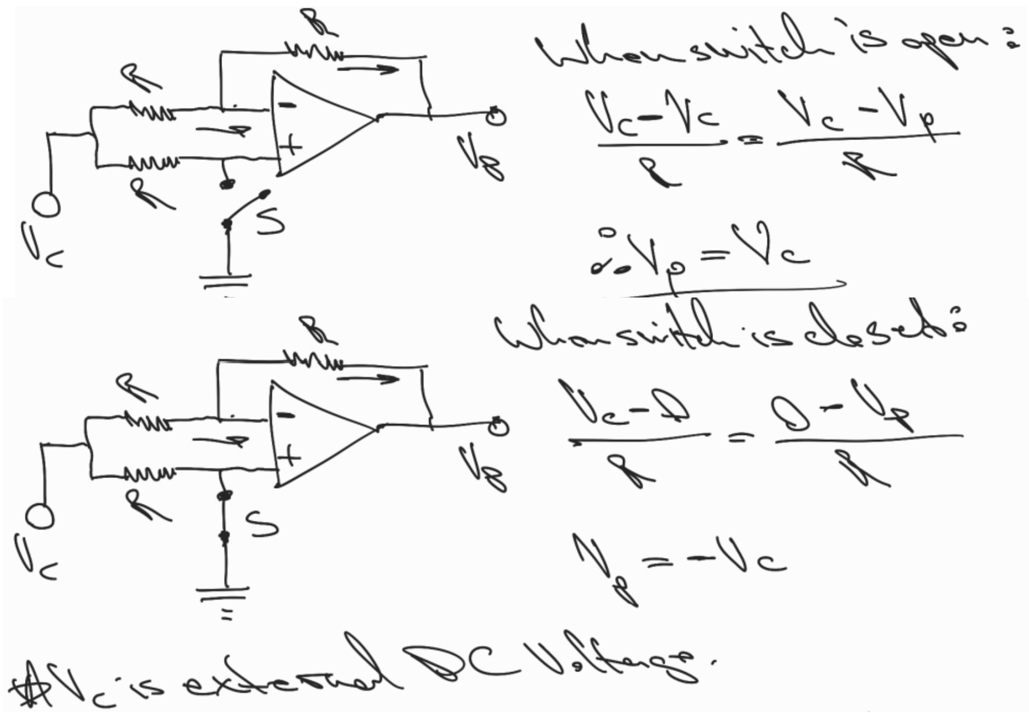
Up until now the output of the saturation values of bistable are unfixed; we are assuming them to be 10.5V given that the voltage of the power supply is 12V, however, this is not reliable. In order to have a reliable, fixed voltage at the output of the bistable, we add a voltage limiter circuit which brings it down to a fixed 6.3V. This can be done in a variety of ways, of which the most efficient in terms of components used is using two zener diodes facing each other. The voltage across a forward biased zener diode is 0.7 (same as normal diode); when reverse biased, the voltage drop is 5.6V. The following circuit is the equivalent of this:

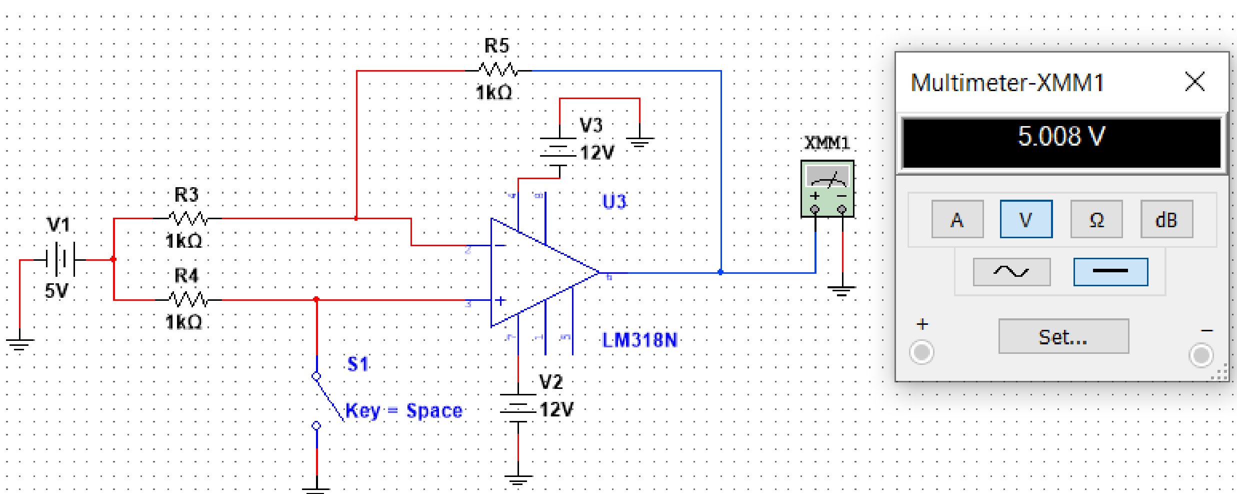


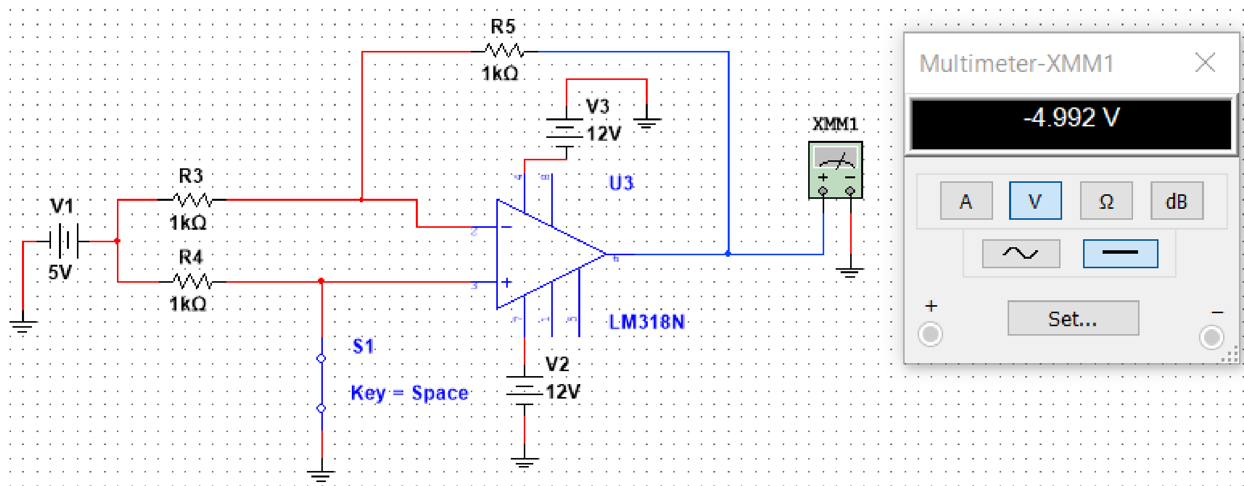

Here the R value limits the current flowing through the zener diode to keep it under the maximum- according to the datasheet.

**DC to +/- DC Converter & Digital Switch:1**

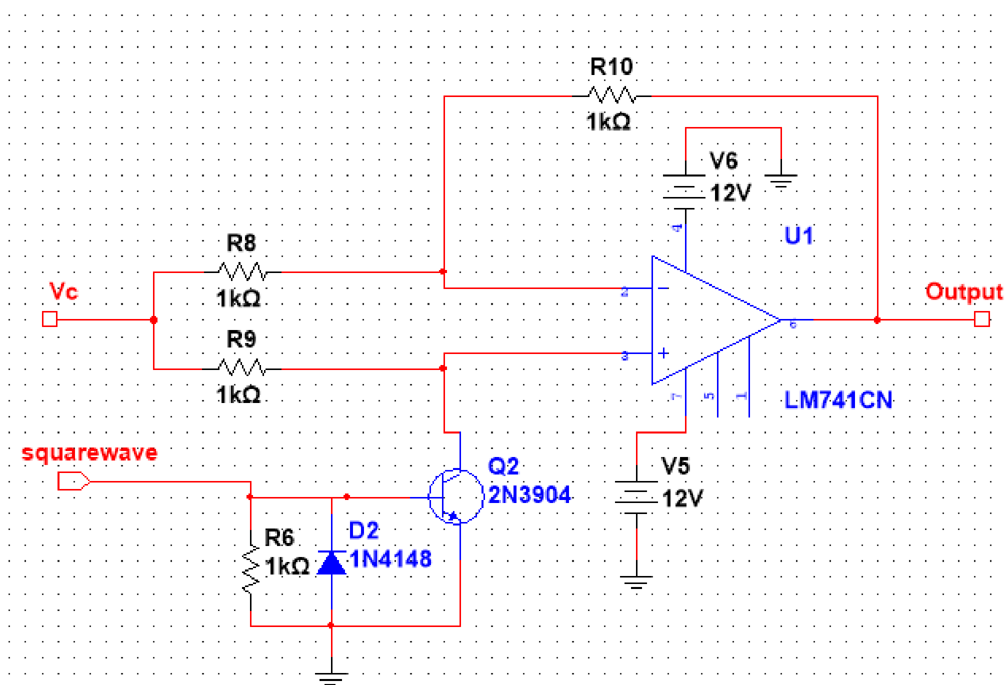
Another component in the making of the Linear Voltage-Controlled Function Generator was a DC to +/- DC Converter. The functionality of this circuit is to convert a DC input voltage Vc (ranges from 0.1V to 5V) into positive or negative depending on the state of the switch connected to the positive terminal of the OP Amp. The circuit would produce the same voltage as the input when the switch is open and would produce a negative output when the switch is closed. The figures below shows the schematic and analysis of the circuit.






The Digital switch was implemented so it could open or close the switch used in the DC to +/- DC circuit. Since the output of Inverting Bistable produces a square wave, we can use the signal produced to make our digital switch. The combination of these two circuit will act as an inverting circuit with a positive input voltage from the square waveform it would produce -Vc and viceversa .The figure below shows the Digital switch implemented into the DC to +/- DC converter.



## Design Analysis:

Fixed frequency function generator:

let triangular wave = 5.25 $V_p$

knowing $L^+/L^- = 10.5V/-10.5V$

and $f_x = 4700\,Hz$

$$V_{HT} = -\frac{R_1}{R_2} \cdot L^+ \rightarrow 5.25_v = -\frac{R_1}{R_2} \cdot 10.5_v$$

$$\frac{R_1}{R_2} = \frac{1}{2} \quad \therefore \text{ let } R_1 = 10K\Omega \;\; \& \;\; R_2 = 20K\Omega$$

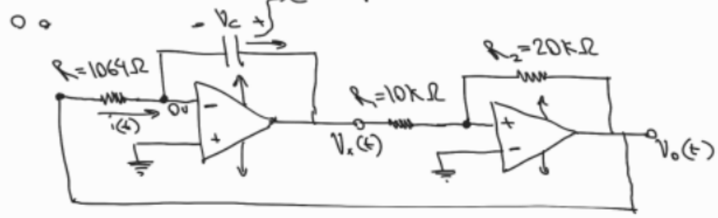
$$f_x = \frac{1}{T} = \frac{|L|}{2(V_{HT} - V_{LT}) \cdot R \cdot C}$$

*let C = 0.1µF

$$R = \frac{|L|}{f_x \cdot 2(V_{HT} - V_{LT}) \cdot C}$$

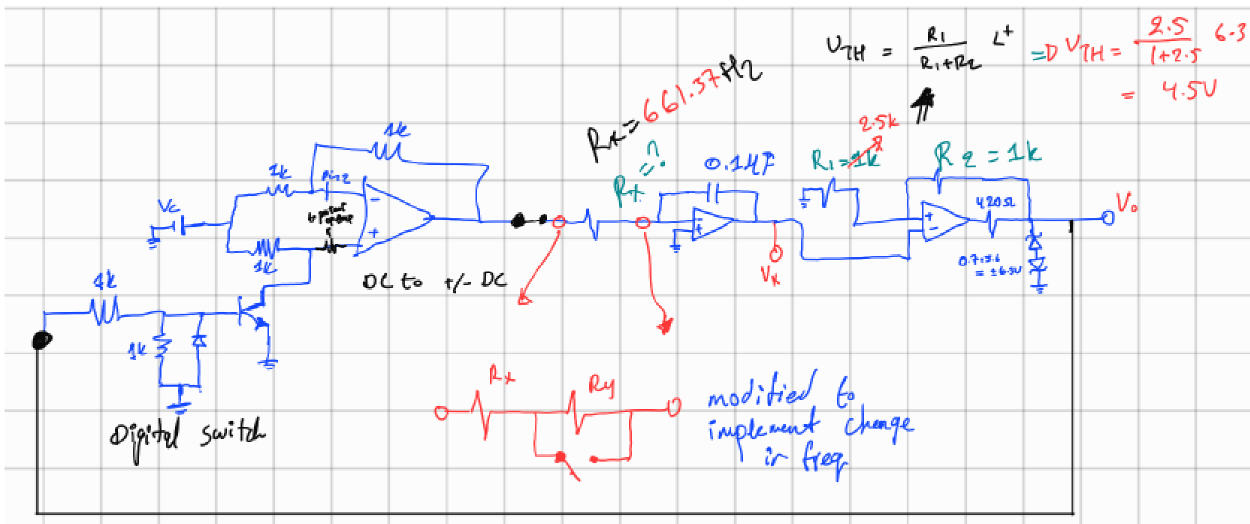
$$= \frac{10.5}{4700 \cdot 2(5.25 + 5.25) \cdot 0.1\mu} = \underline{1063.8\Omega}$$

$\therefore$



**Final Design:**

The final design for the Linear Voltage-Controlled function generator is formed using the components designed above. An additional resistor was placed in the output of each signal to correct the amplitude to 4Vp. Additionally, potentiometers were used so the user could change the amplitude of the signal from 0 - 4Vp. To arrange a secondary range for the frequency, a manual switch was place at the input terminal of the inverting integrator so that the user could change the frequency range. Below is the design for the final design including frequency range select, amplitude correction resistors, and added potentiometers.



To achieve Range 2 ($\frac{f_x}{5}$):

$$f_{o_1} = \frac{V_c}{2(V_{TH} - V_{TL})(0.1\,\mu F)(R_x)}$$

We need to change $R_x$ in a way which would result in

$$f_{o_2} = \frac{f_{o1}}{5}$$

$$f_{o_2} = \frac{V_c}{2(V_{TH} - V_{TL})(0.1\,\mu F)(R_x)} \cdot \frac{1}{5}$$

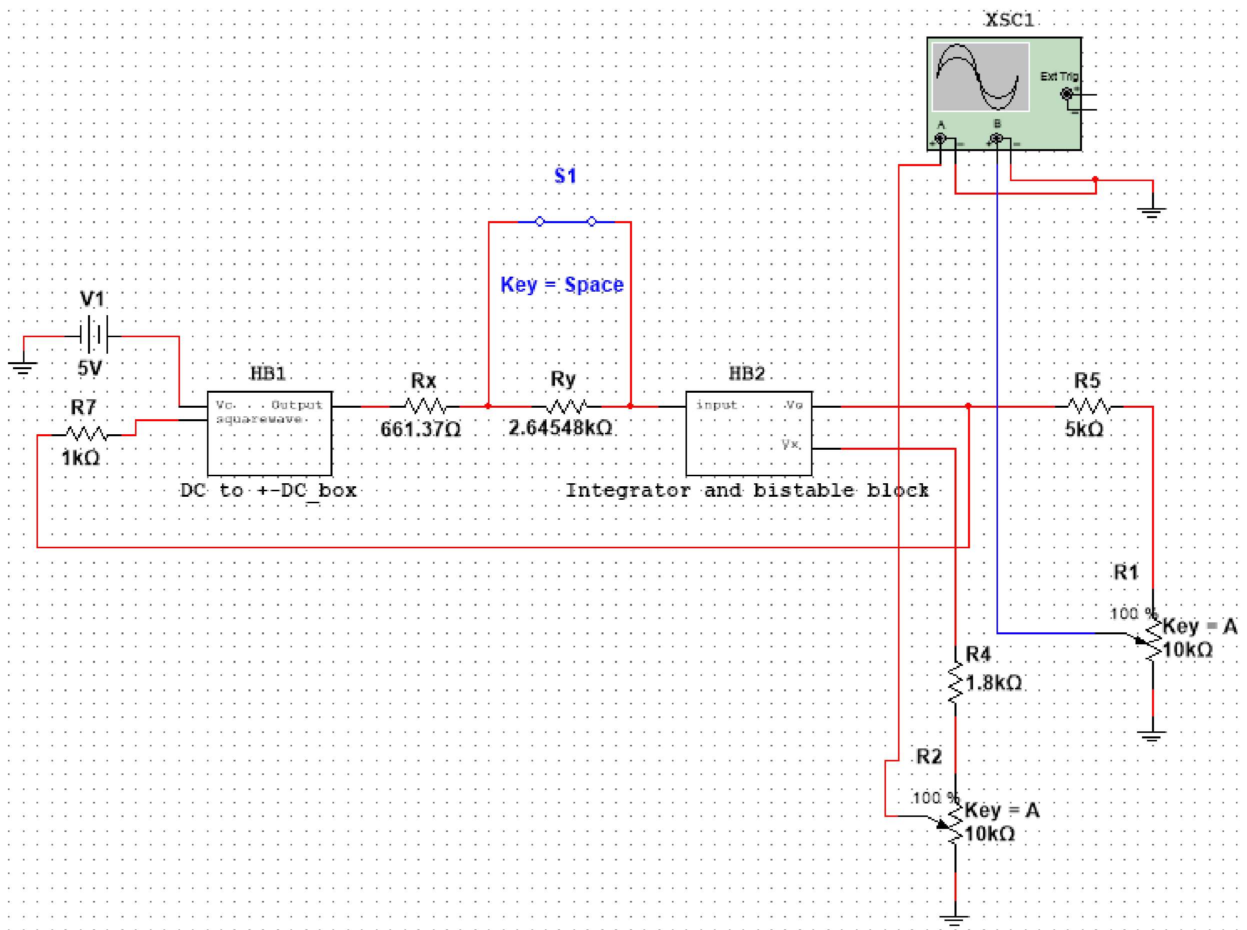
adding $R_y$ as shown above and using eqn

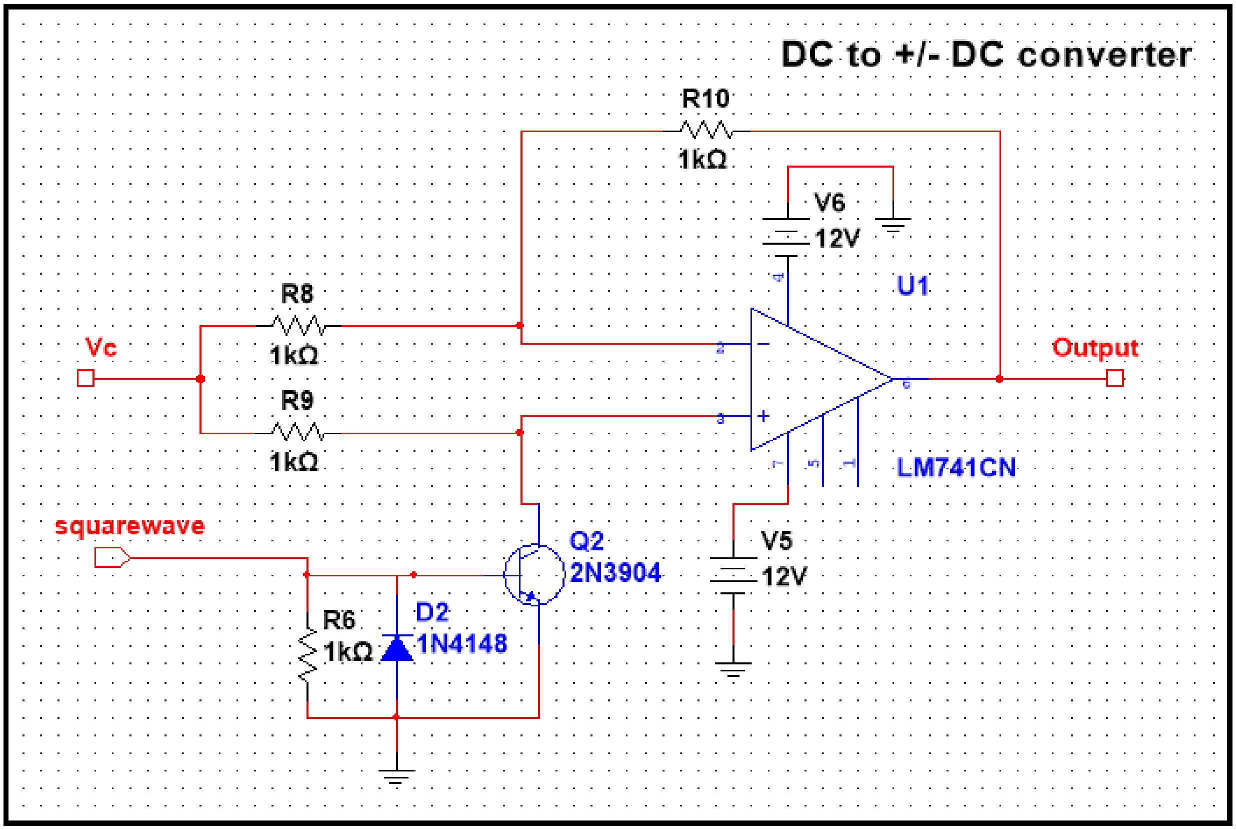
$$R_x + R_y = 5R_x$$

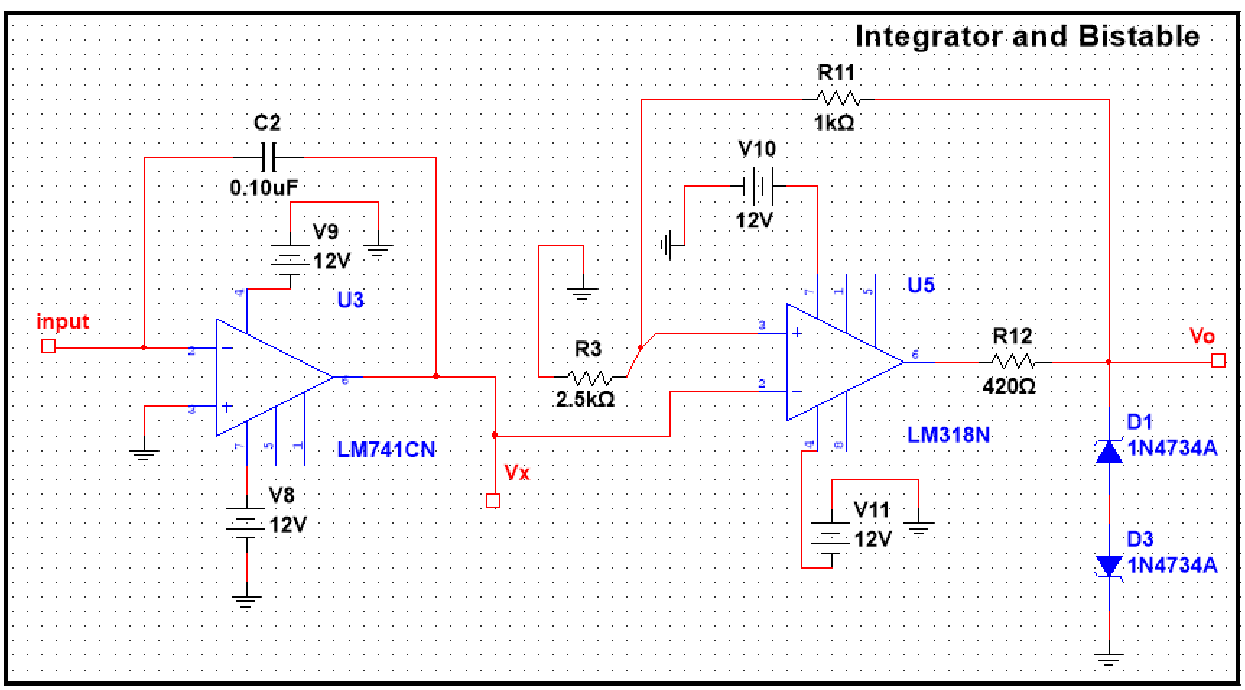
$$\underline{R_y = 4R_x} \qquad \therefore \; R_y = 4(661.37\,\Omega)$$

$$\underline{R_y = 2645.48\,\Omega}$$

The simulated design in multisim is shown as below:




DC to +/- DC converter
R10
1kΩ
V6
12V
U1
R8
1kΩ
Vc
R9
1kΩ
Output
LM741CN
squarewave
Q2
2N3904
V5
12V
R6
1kΩ
D2
1N4148


Integrator and Bistable
R11
1kΩ
C2
0.10uF
V10
12V
V9
12V
U3
U5
input
R3
2.5kΩ
R12
420Ω
Vo
LM741CN
LM318N
Vx
D1
1N4734A
V8
12V
V11
12V
D3
1N4734A

**Measurements and Observations:**
(In lab data from of final circuit, verifying its compliance with all the specifications)

| Frequency Range 1 (Switch Closed - fx) | | |
|---|---|---|
| Vc (V) | Vp-p | Frequency (Hz) |
| 0.5 | 8 | 294 |
| 1 | 8 | 640 |
| 2 | 8 | 1.35k |
| 3 | 8 | 1.97k |
| 4 | 8 | 2.57k |
| 5 | 8 | 3.1k |

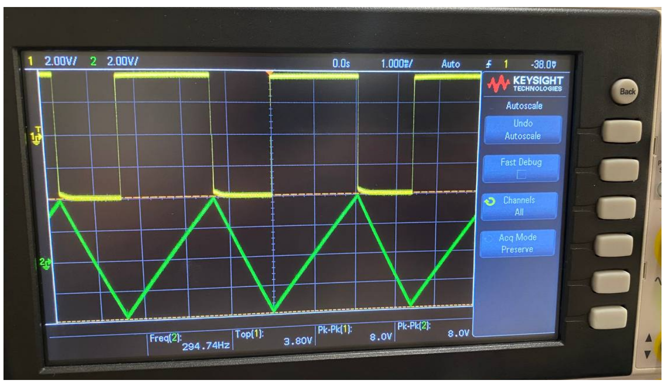
| Frequency Range 1 (Switch Closed - fx) | | |
|---|---|---|
| Vc (V) | Vp-p | Frequency (Hz) |
| 0.5 | 4 | 234 |
| 1 | 4 | 585 |
| 2 | 4 | 1.25k |
| 3 | 4 | 1.87k |
| 4 | 4 | 1.87k |
| 5 | 4 | - |

| Frequency Range 2 (Switch open - fx/5) | | |
|---|---|---|
| Vc (V) | Vp-p | Frequency (Hz) |

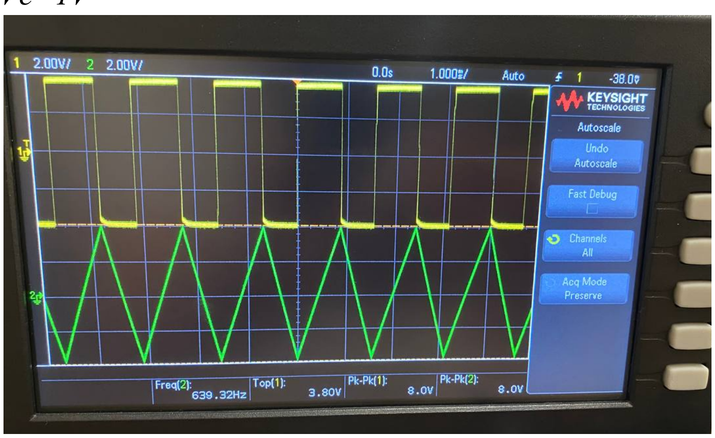
| | | |
|---|---|---|
| 0.5 | 8 | 60 |
| 1 | 8 | 129.5 |
| 2 | 8 | 273 |
| 3 | 8 | 417 |
| 4 | 8 | 555 |
| 5 | 8 | 687 |

<u>Pictures of Waveforms:</u>

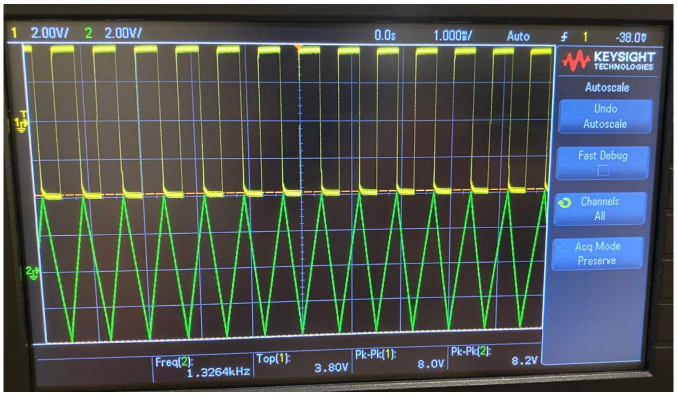
*Frequency Range 1 (Switch Closed- fx), 8Vp-p:*
*Vc =0.5V*



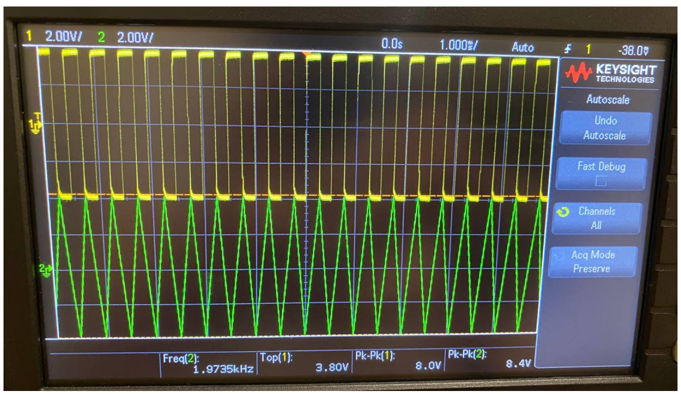

*Vc=1V*



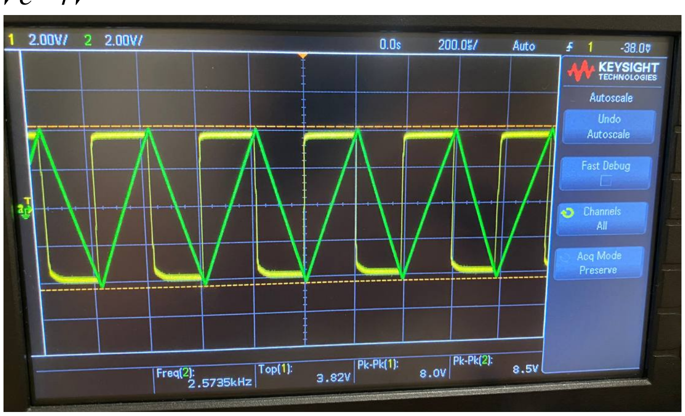
*Vc=2V*



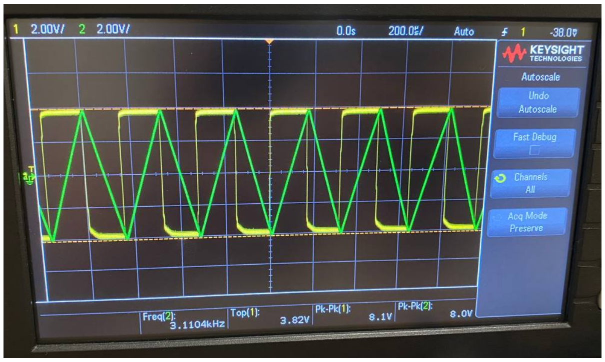

*Vc=3V*



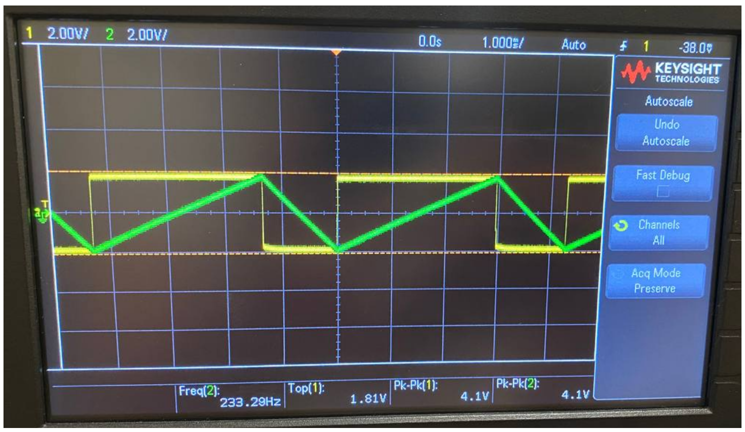

*Vc=4V*



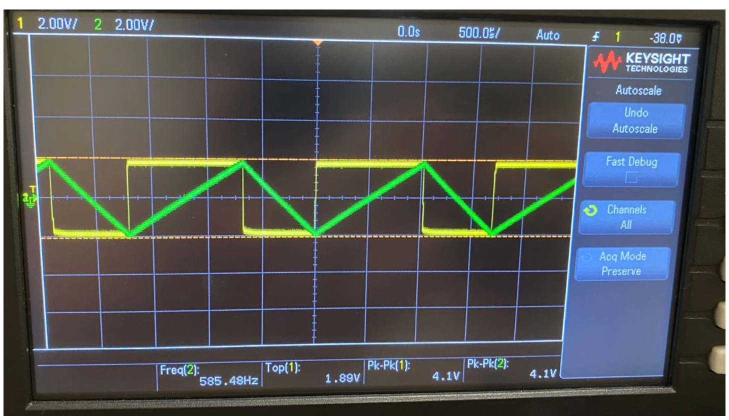
*Vc=5V*



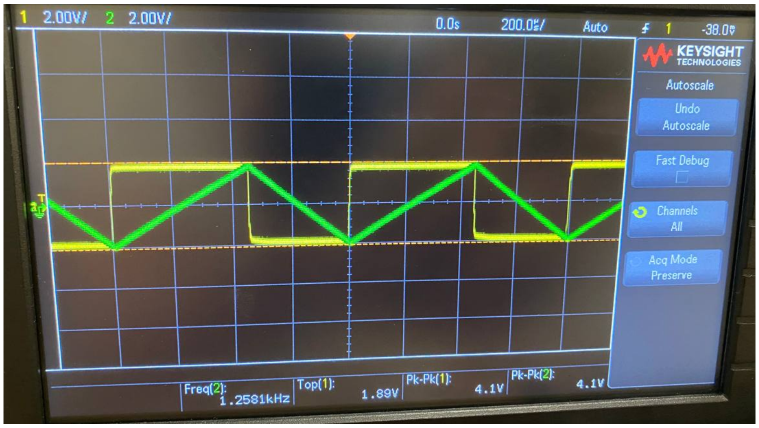

*Frequency Range 1 (Switch Closed- fx), 4Vp-p:*
*Vc =0.5V*



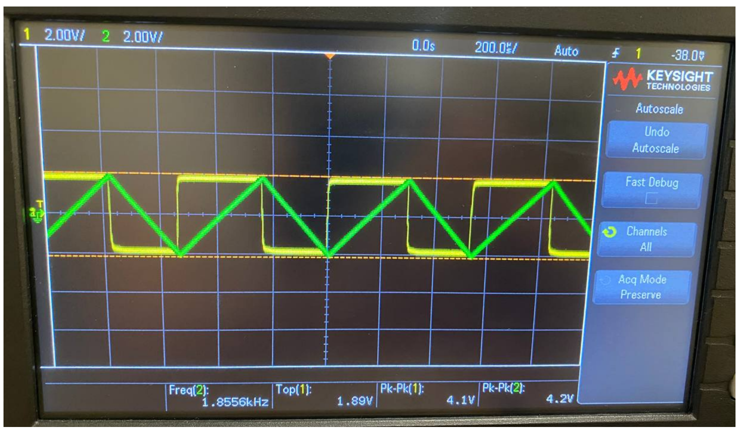

*Vc=1V*



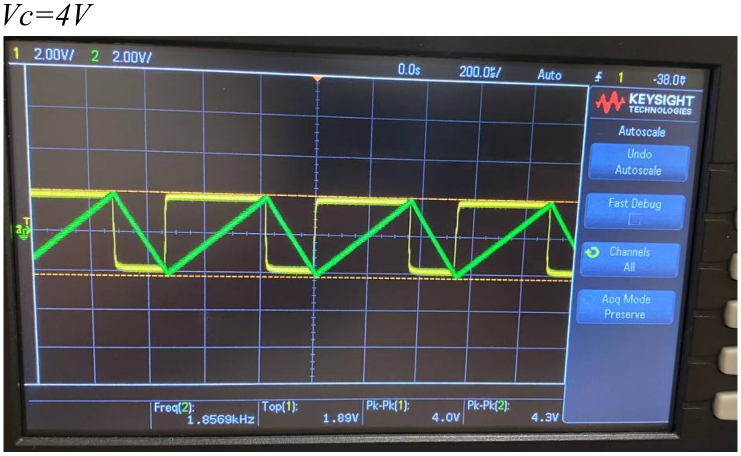
*Vc=2V*



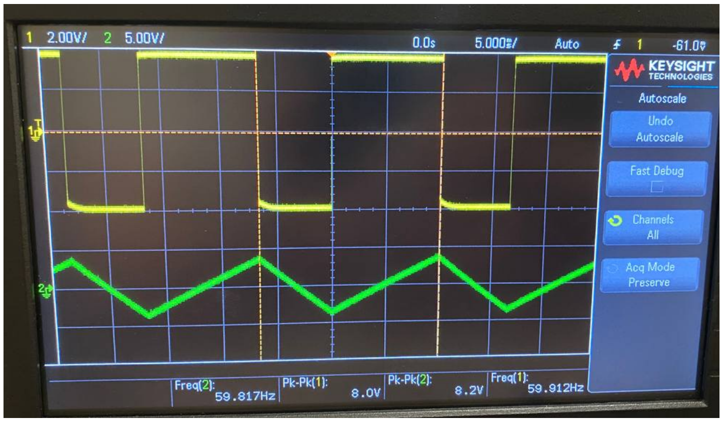

*Vc=3V*



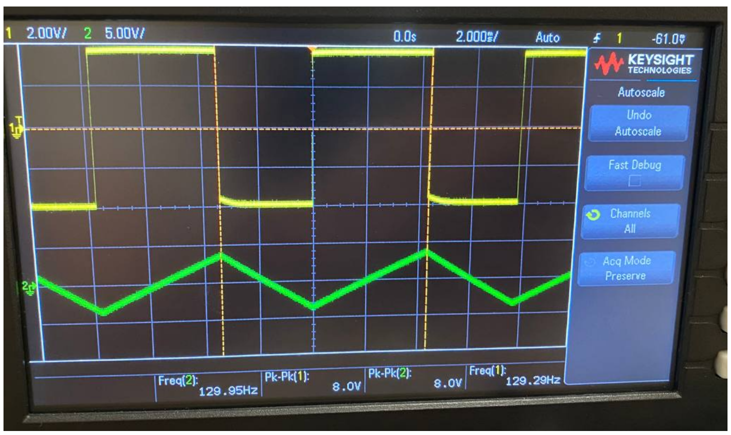

*Vc=4V*



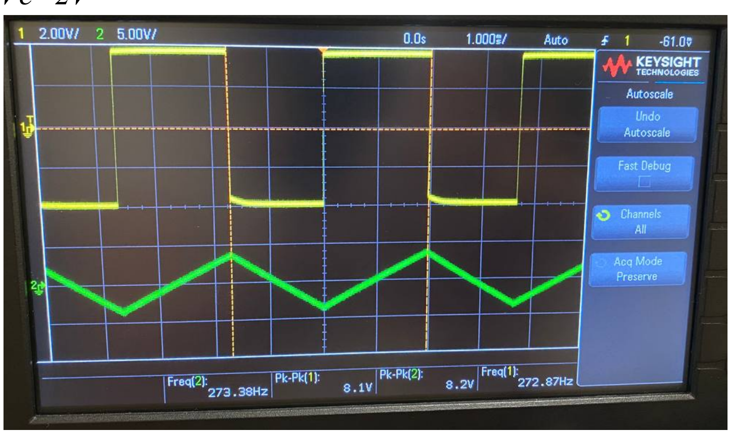
*Frequency Range 2 (Switch Open- fx/5):*
*Vc =0.5V*



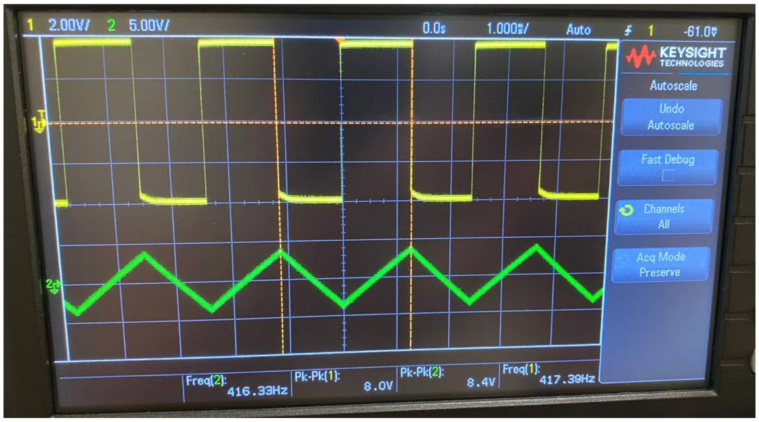

*Vc=1V*



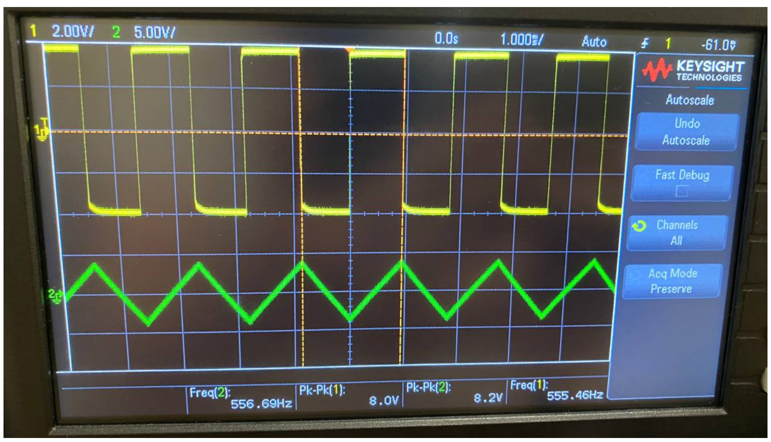

*Vc=2V*



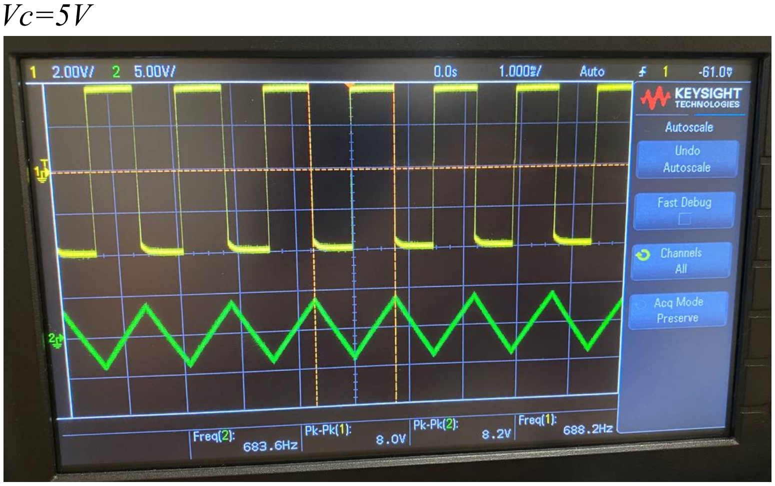
*Vc=3V*




*Vc=4V*




*Vc=5V*



**<u>Conclusion and Recommendations:</u>**

In conclusion through this project, we were able to design, simulate and practically implement a voltage-controlled frequency square and triangle wave function generator with gain control for two different linear frequency ranges (fx and fx/5). We were able to intuitively understand the operation of the several circuit components that made up the final product, including the integrator, bistable comparator, voltage limiter, and DC to +- DC convertor with a digital switch. Through our in-lab implementation of our final design model, we were able to generate perfectly good waveforms adherent to the specifications listed earlier in the report, and abiding by our calculations, with next to no distortion. We ended up using a combination of LM741CN and LM318CN Op-amps. The biggest challenge we faced in this lab was selecting the right Op-amps- which was through trial and error irrespective of the model- as the circuit simply didn't function with certain Op-amps (some of which happened to be dead while others had unexpected behavior). Comparing our calculations and handwritten analysis, Multisim simulations and in-lab design implementation results, although during the process (over the course of the milestones) we at times struggled to achieve results matching our calculations, our final design was entirely adherent to our calculations. The only discrepancy between the requirements and our final waveform is the mismatch in the linear frequency control; we had calculated the R value of the integrator so that our frequency fx (4200Hz) occurred when VC of the +-DC convertor was 5V and linearly decreased as Vc went down. However, in our practical model, although the relationship was still linear the frequency was lower than fx (the ideal linear frequency range). The cause of this issue must have been due to the insufficient slew rate of the Op-amp model we were using which was unable to keep up with our required frequency specification. To improve this design we could have used a better, more expensive LM318CN Op-amp model with its high slew rate throughout the design; this would make sure that the output of all the individual component circuits were synchronized. However, as stated earlier with such an Op-amp configuration the behavior and functionality of our circuit was un-predictable for reasons unknown. In an attempt to prove that the gain control of our final circuit was linear, we tried adjusting the potentiometers to 50% of what we used to get 8Vp-p, however when the potentiometer was increased above 50% of its 10k ohms max range, it adversely affected our frequency and distorted our waveforms. Thus we were unable to prove the linearity of our gain control.

**REFERENCES**

## Works Cited

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