

Linear Voltage-Controlled Frequency, Square and Triangle Wave Function generator with Added Gain Control Design

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Abstract:

This project focuses on making a linear voltage-controlled frequency function generator to produce symmetrical triangular and square waves. The circuit was able to work with two frequency ranges, 100 - 4200 Hz and 20 - 840 Hz by varying the input DC voltage V_c . The main circuit components used to make this function generator consisted of a DC to +/-DC converter, Inverting Integrator, and Inverting Bistable Comparator.

Objective:

The purpose of this project is to implement knowledge of Op-amp circuits, while selecting the optimal design based on intrinsic properties of Op-amps (slew rate, gain) as well as configurations (negative feedback, positive feedback).

The design specifications, the final product was to be made adherent to, were the following:

1. User selectable symmetrical triangular or square wave output
2. Operation in 2 user selectable frequency ranges:
 - Range 1: 100 Hz - 4200 Hz
 - Range 2: 20 Hz - 840 Hz
3. User controlled DC input voltage control range of 0.1V to 5V
4. User controlled gain at output of each waveform ranging from 0 - 4V_p
5. Exclusive use of +/-12V DC power supplies

Experimental Procedure:

The first step to creating this function generator was the development of the inverting integrator and non-inverting bistable comparator design. After conducting the analysis, the right resistor and capacitor values were selected that would allot the required starting frequency of 4200Hz and selected threshold high and low voltage values.

The next step was to create a DC to +/-DC converter consisting of a BJT switch, to be used for frequency control of the function generator, as well as a voltage limiter circuit which would allow a precise output of 6.3V_p from the bistable.

The following phase of the project entailed integrating the DC to +/-DC converter with the fixed-frequency function generator, including the voltage limiter circuit. By connecting the output of the bistable to the converter's switch, the circuit was able to drive the switch between cutoff and saturation. A variable DC voltage source was used as the input to the converter, effectively transforming the combined circuit into a voltage-controlled frequency function generator. To maintain negative feedback in the circuit, the non-inverting bistable configuration was modified to an inverting one.

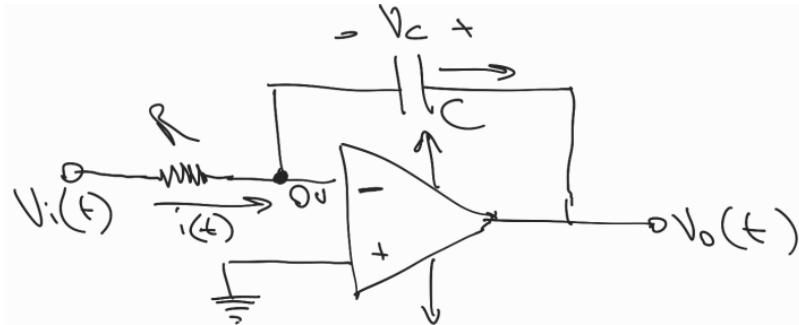
The final aspect of the project involved incorporating gain control into the existing circuit. This was achieved by introducing potentiometers at the output of both the integrator and bistable. Furthermore, the recalibration of the integrator's R value allowed for the application of the second voltage-controlled frequency range of 20 Hz - 840 Hz.

Design of Components

We start by looking at the design configuration and variable analysis of the circuit components.

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:

$$\textcircled{1} \quad V_o(t) = 0_v - V_c(t) + V_c$$

Where 0_v is the voltage at the negative terminal since it tracks the positive terminal, $V_c(t)$ is the voltage drop across the capacitor and V_c represents the voltage due to any initial charge on the capacitor (given the able polarity it is positive). Next, for $V_c(t)$ 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:

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

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 :

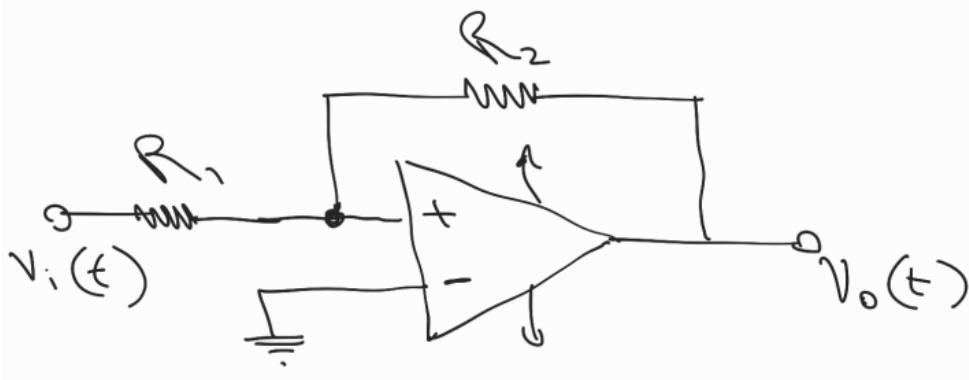
$$\textcircled{3} \quad i(t) = \frac{V_i(t)}{R}$$

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:

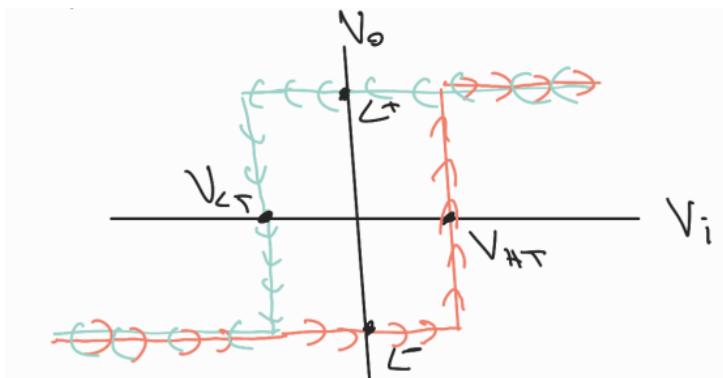
$$V_o(t) = -\frac{1}{RC} \int V_i(t) dt + V_c$$

Bistable Comparator:

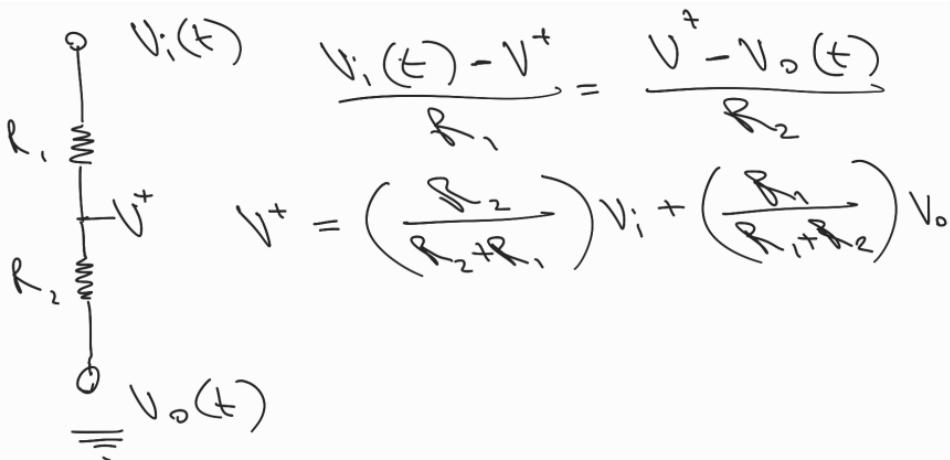
Now looking at the circuit of the bistable comparator, again assuming the op-amp is ideal, we can see that positive feedback exists; so right away we know that the output will be positive saturation ($L+$) when the voltage at the positive terminal is greater than at the negative terminal, and negative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



This basically states the following: starting with V_i at negative infinity, thus ensuring that the voltage at the positive terminal is less than the negative, we know V_o will be at negative saturation. However, when V_i reaches a certain low threshold value (V_{LT}) at which the positive terminal is equal to the negative terminal (at 0V in our case), V_o switches to $L+$. Similarly this model can be explained for when V_i approaches a high threshold value (V_{HT}) approaching from positive infinity, at which point V_o 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:



When V^+ reaches 0 while V_i comes up from negative infinity and V_o 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 V_i comes down from positive infinity and V_o switches to negative saturation:

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

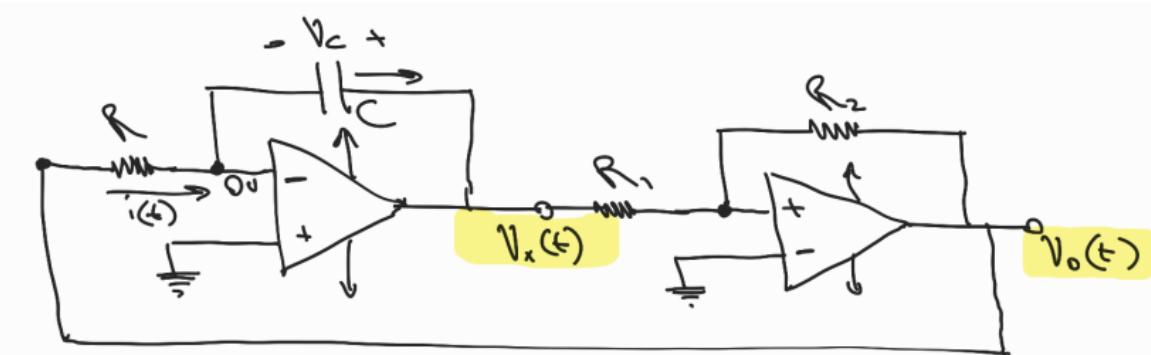
$$\hookrightarrow V_i = V_{LT} = - \frac{R_1}{R_2} L^+$$

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

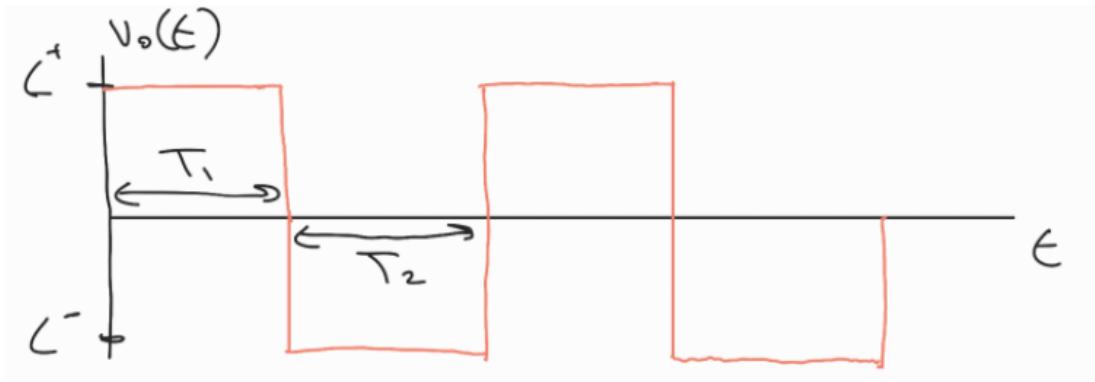
$$\hookrightarrow V_i = V_{HT} = - \frac{R_1}{R_2} L^-$$

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:

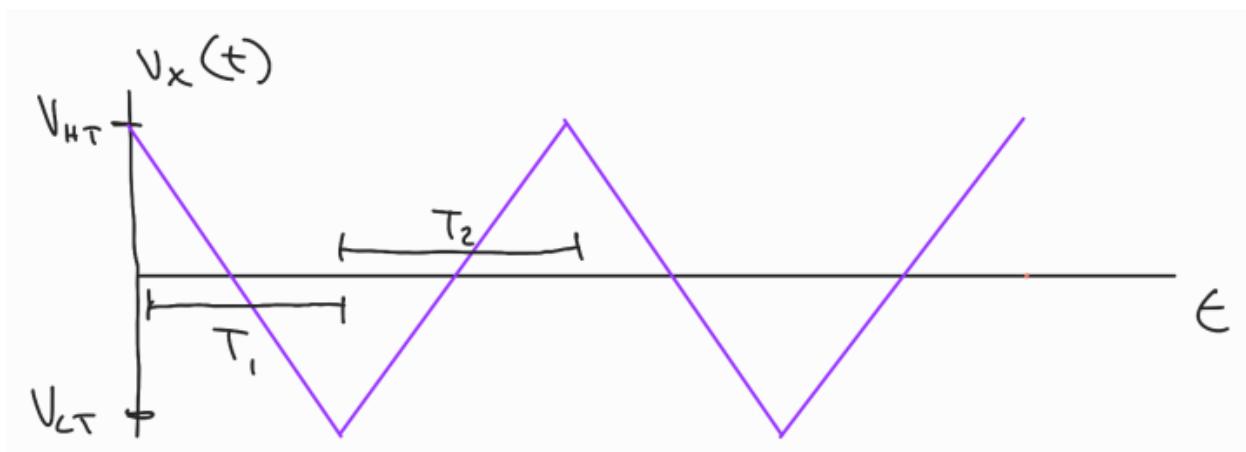
$$V_o(t) = -\frac{1}{RC} \int V_i(t) dt + V_c$$

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

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

when $V_i(t) = L^-$

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



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:

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

$$\text{Slope from graph: } \frac{V_{CT} - V_{HT}}{\tau_1 - 0}$$

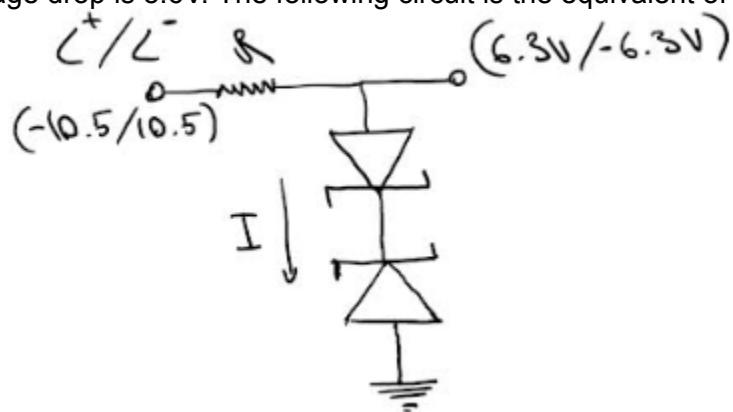
$$\therefore -\frac{C^+}{RC} = \frac{V_{CT} - V_{HT}}{\tau_1} \rightarrow \tau_1 = \frac{RC(V_{CT} - V_{HT})}{-C^+}$$

\hookrightarrow since $\tau_1 = \tau_2$

Net period $T = \tau_1 + \tau_2$

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

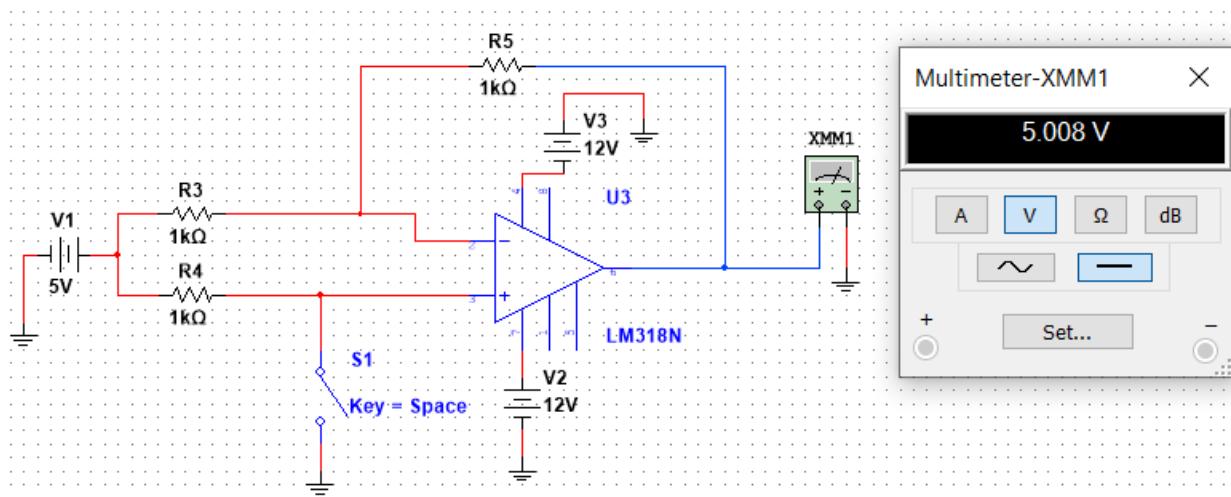
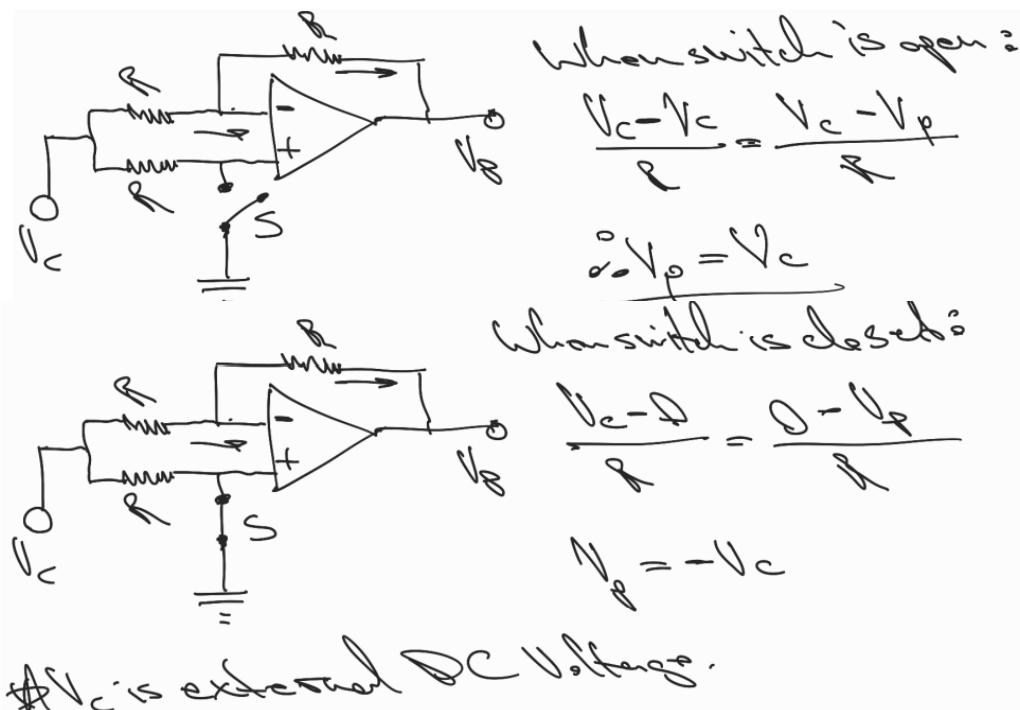
Up until now the output of the saturation values of bistable are not fixed; we are assuming them to be 10.5V given that the voltage of the power supply is 12V (taking into account less than ideal conditions), however, this is not reliable. In order to have a reliable, fixed voltage at the output of the 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 towards each other. The voltage across a forward biased zener diode is 0.7V (same as normal diode); when reverse biased, the voltage drop is 5.6V. The following circuit is the equivalent of this:

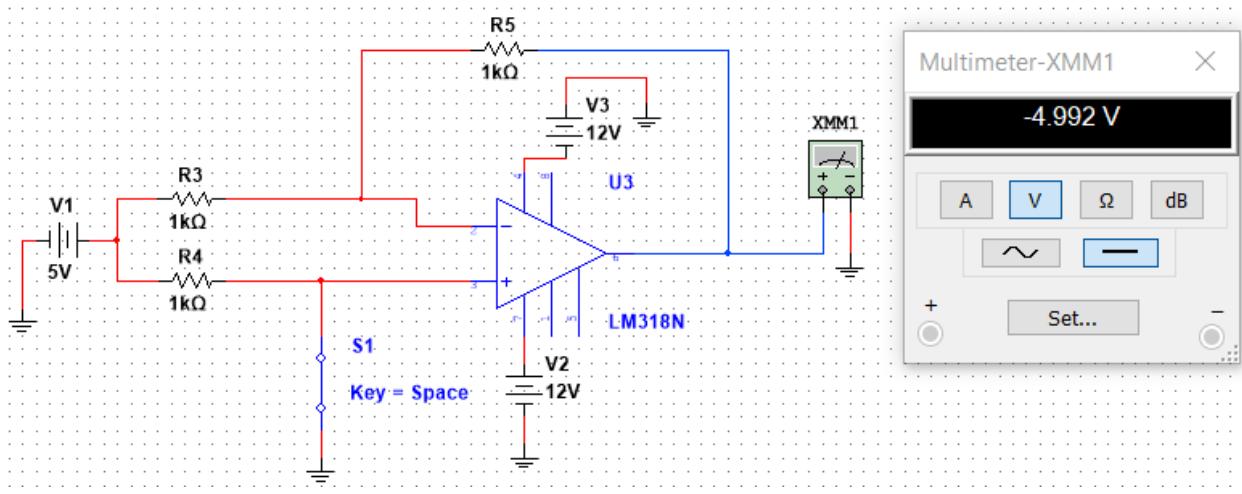


Here the R value limits the current flowing through the zener diode to keep it under the maximum current of 10mA - according to the datasheet.

DC to +/- DC Converter:

The functionality of this circuit is to convert a DC input voltage V_c (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 show the schematic and analysis of the circuit.

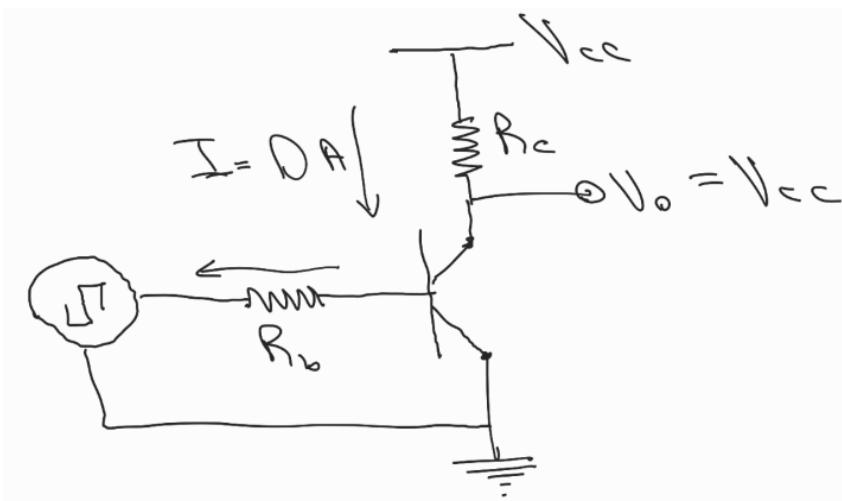




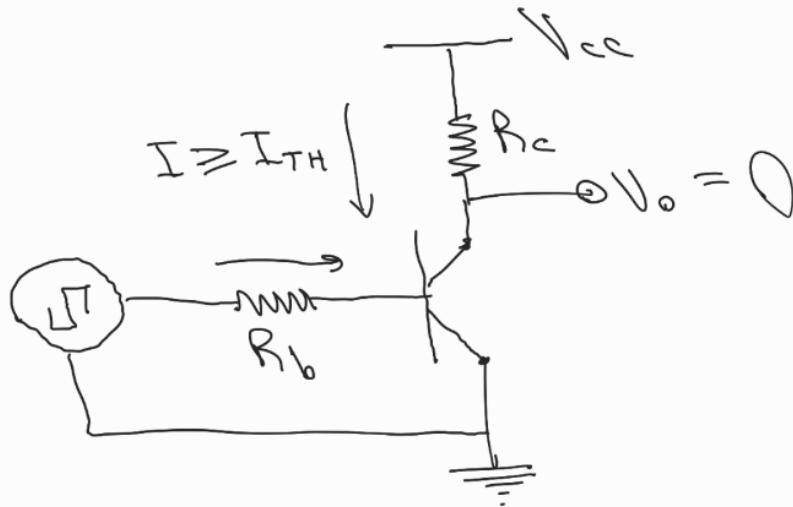
Digital Switch:

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.

To enable the switch to function as an open circuit and closed circuit, we utilize the saturation and cutoff modes of the transistor. In cutoff mode, the base-emitter junction is reverse biased, causing no current to flow from the collector to the emitter. Consequently, the voltage drop across the collector resistor (R_c) is zero, resulting in the output voltage (V_o) being equal to the supply voltage (V_{cc}):

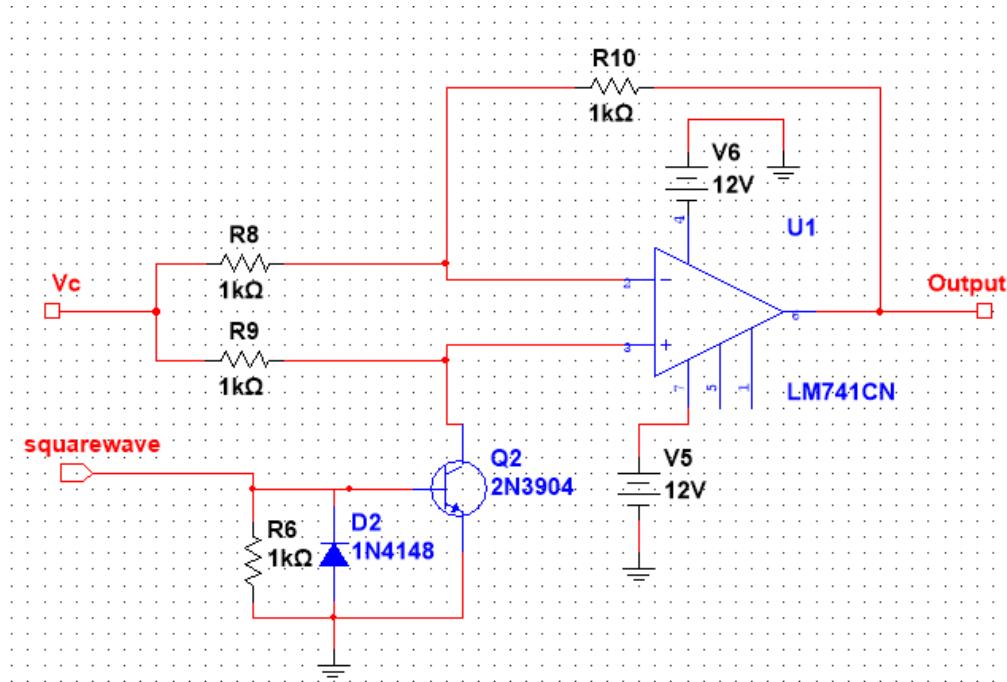


Conversely, in saturation mode, the collector current exceeds a certain threshold, causing a complete voltage drop across the collector resistor (R_c), thereby making the output voltage (V_o) equal to zero:



The combination of these two circuits will act as an inverting circuit with a positive input voltage from the square waveform it would produce $-V_c$ and vice versa .

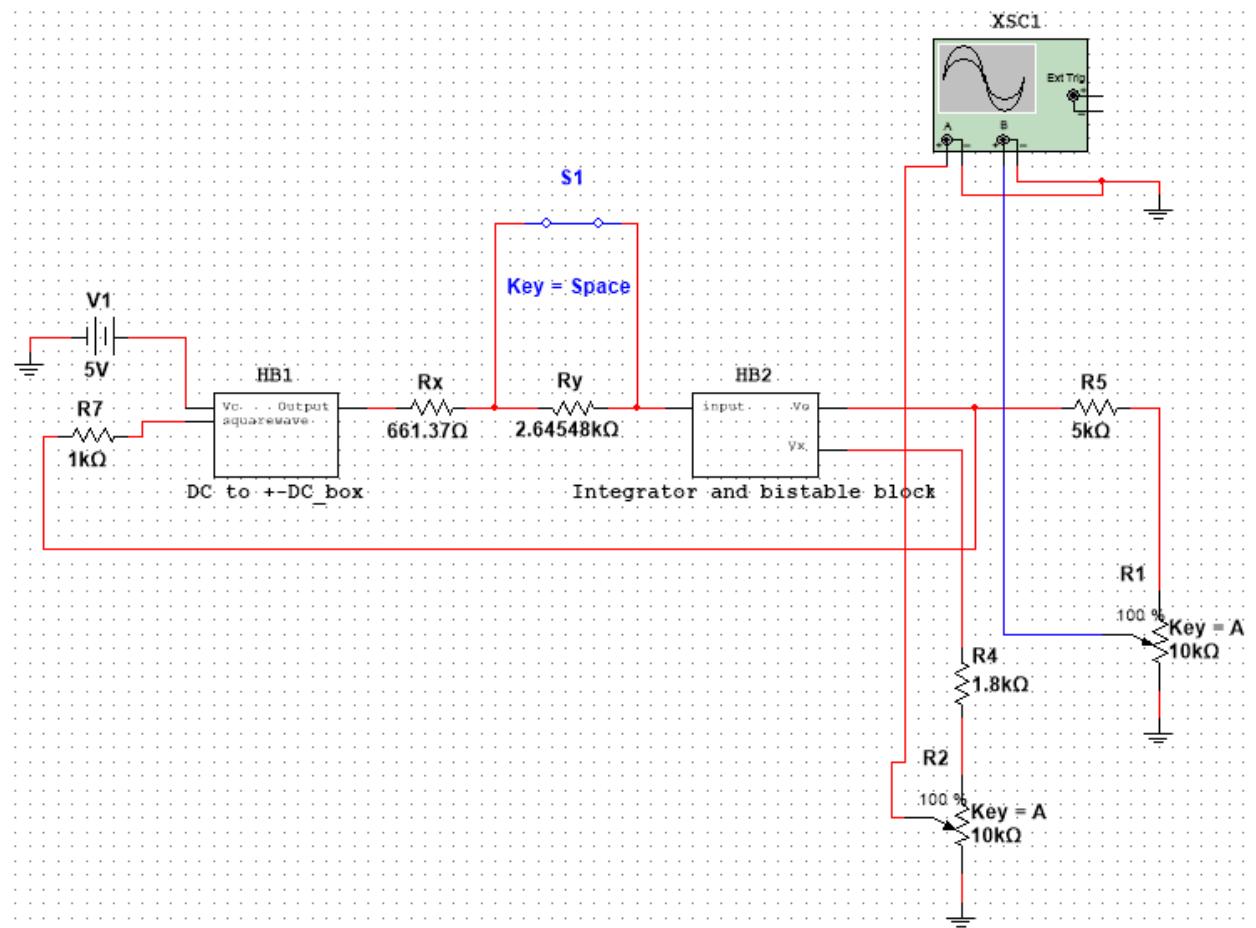
The figure below shows the Digital switch implemented into the DC to +/- DC converter.

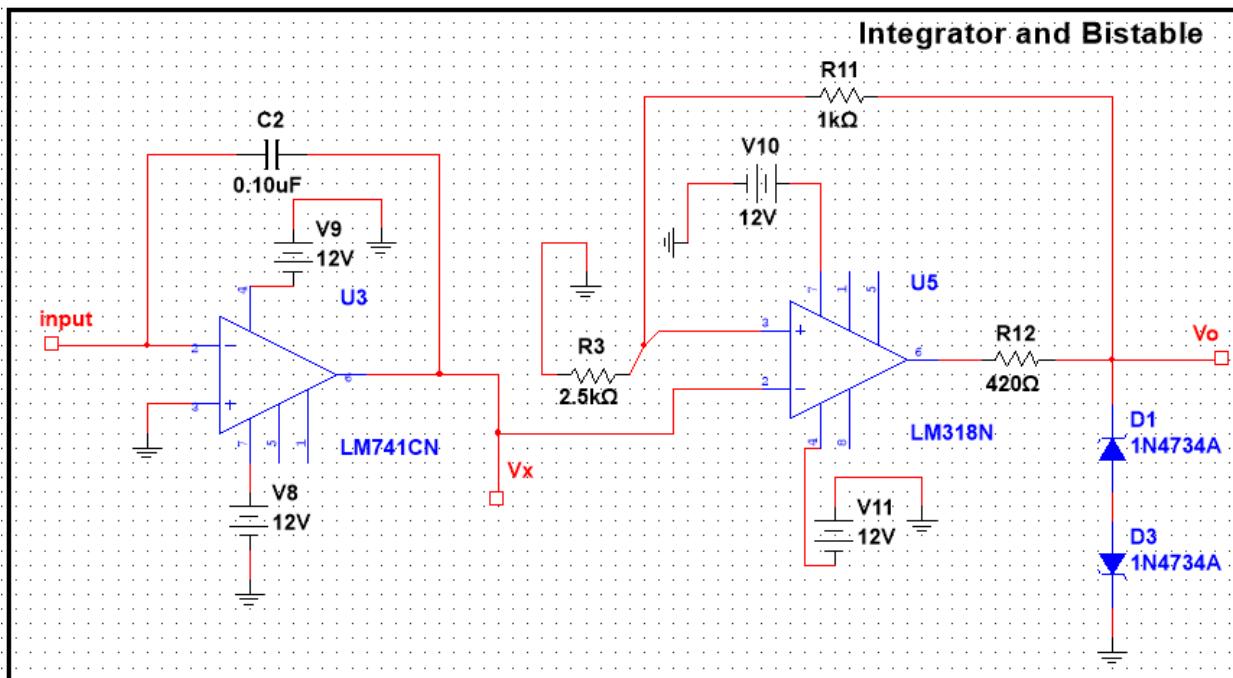
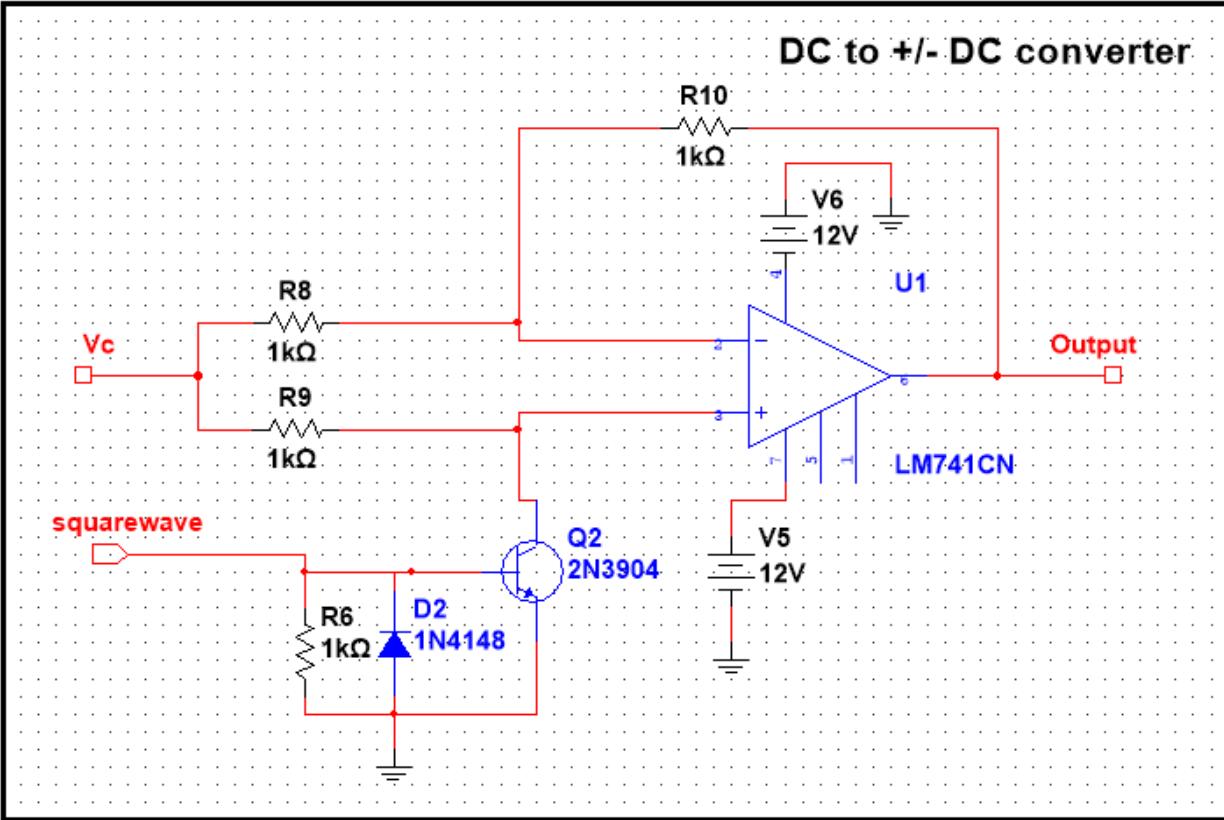


Final Design:

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 placed 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.

The simulated design in multisim is shown as below:





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	-

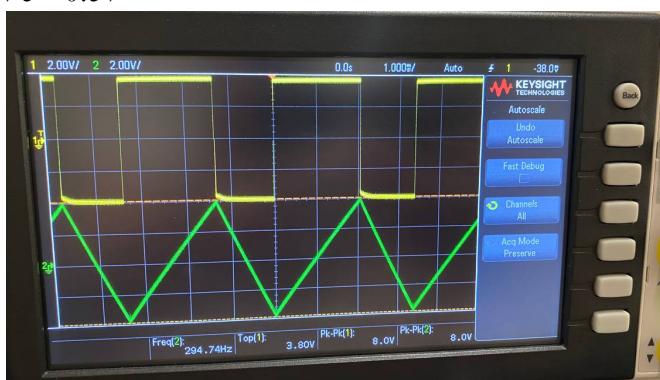
Frequency Range 2 (Switch open - fx/5)		
Vc (V)	Vp-p	Frequency (Hz)
0.5	8	60
1	8	129.5

2	8	273
3	8	417
4	8	555
5	8	687

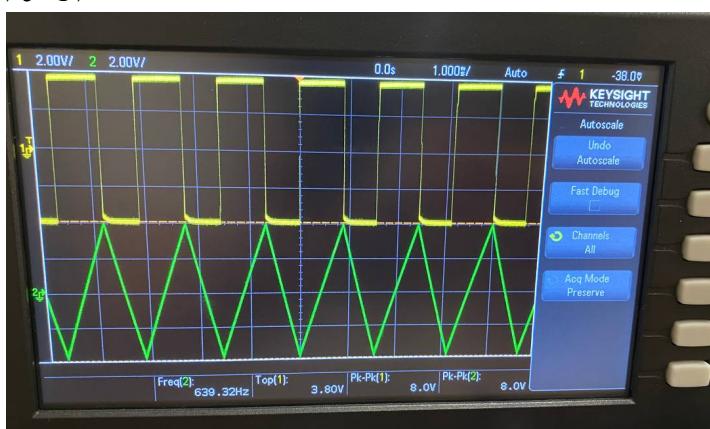
Pictures of Waveforms:

Frequency Range 1 (Switch Closed- fx), 8Vp-p:

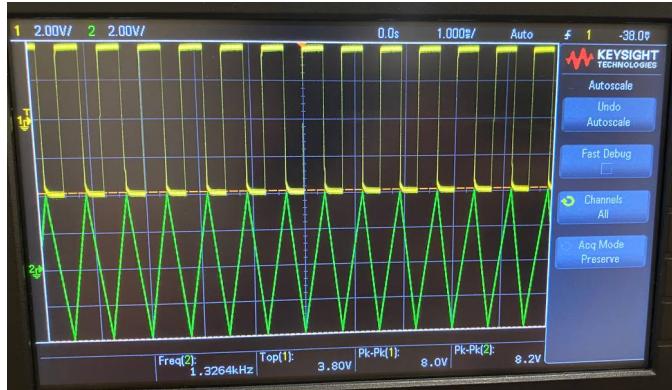
$V_c = 0.5V$



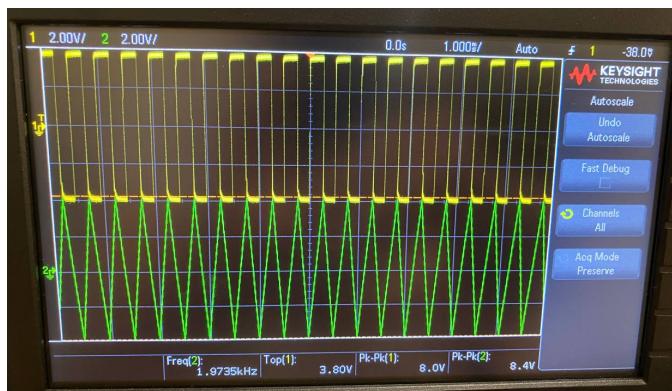
$V_c = 1V$



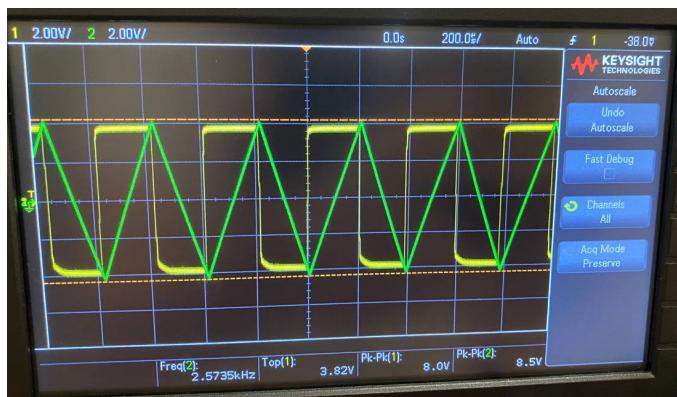
$V_C=2V$



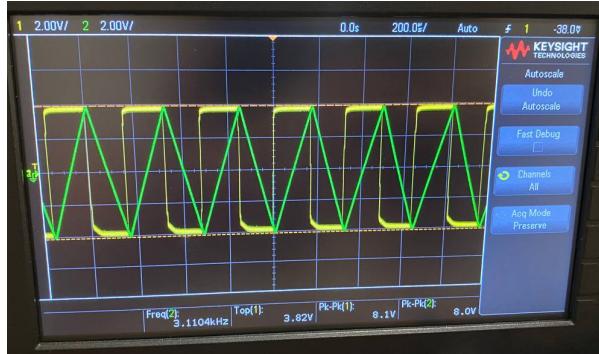
$V_C=3V$



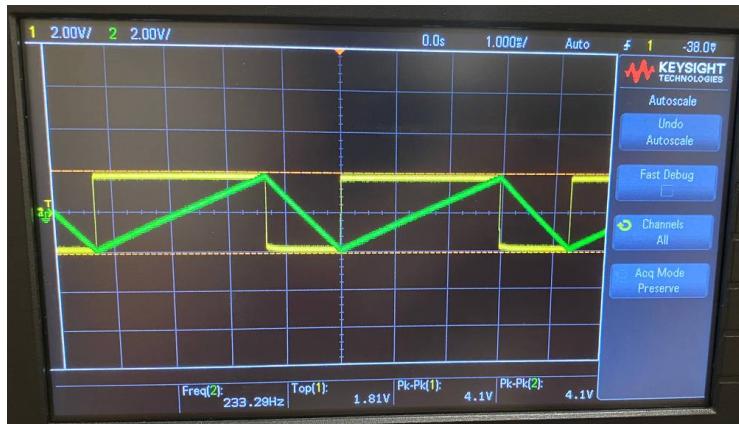
$V_C=4V$



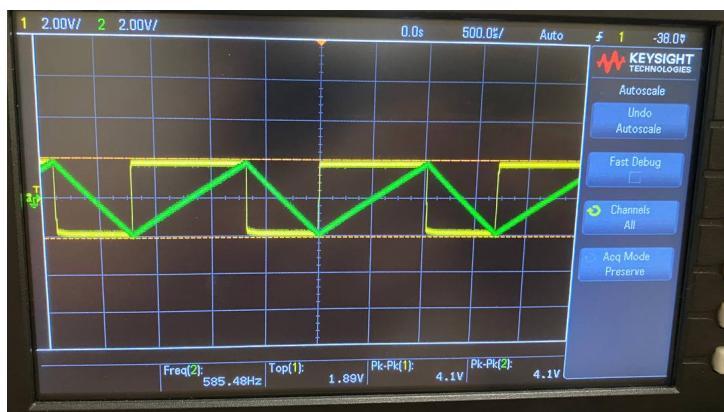
$V_C = 5V$



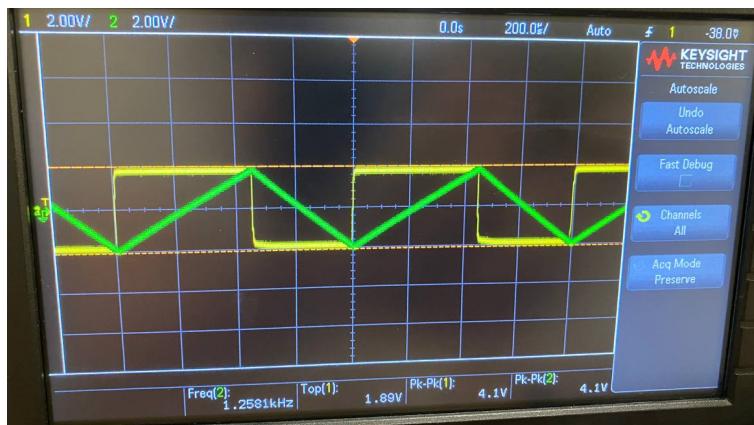
Frequency Range 1 (Switch Closed- f_x), 4Vp-p:
 $V_C = 0.5V$



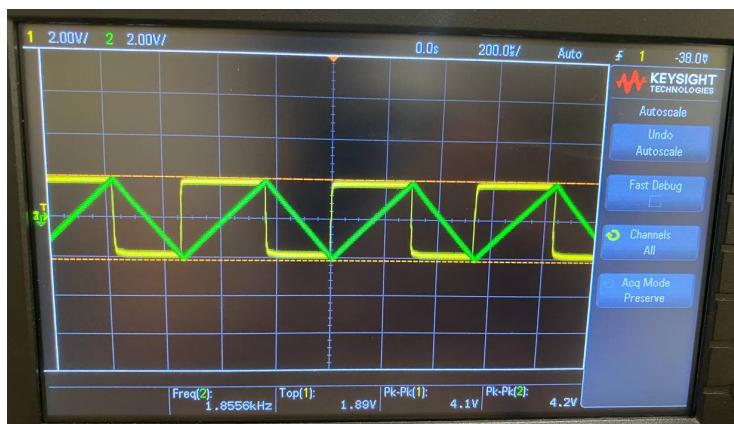
$V_C = 1V$



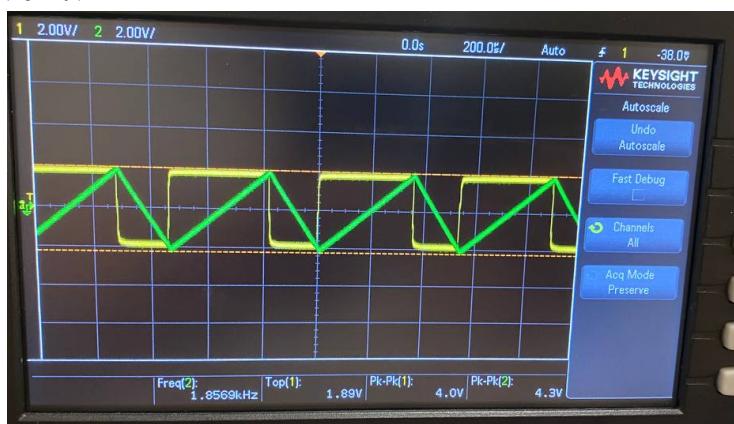
$V_C=2V$



$V_C=3V$

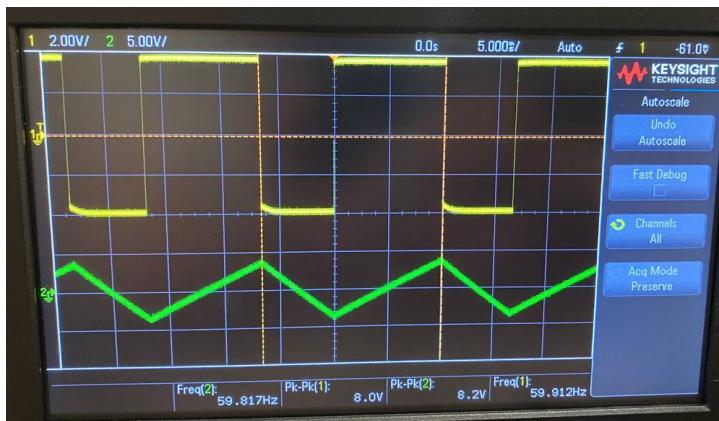


$V_C=4V$

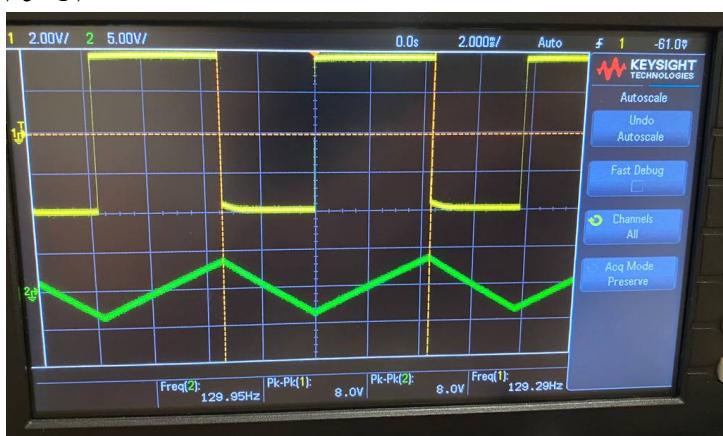


Frequency Range 2 (Switch Open- fx/5):

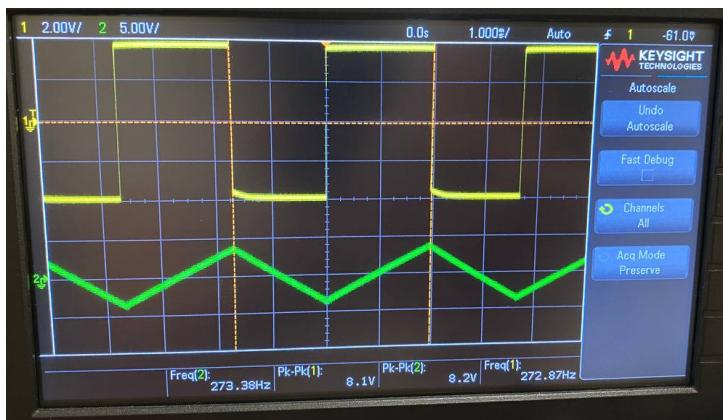
$$Vc = 0.5V$$



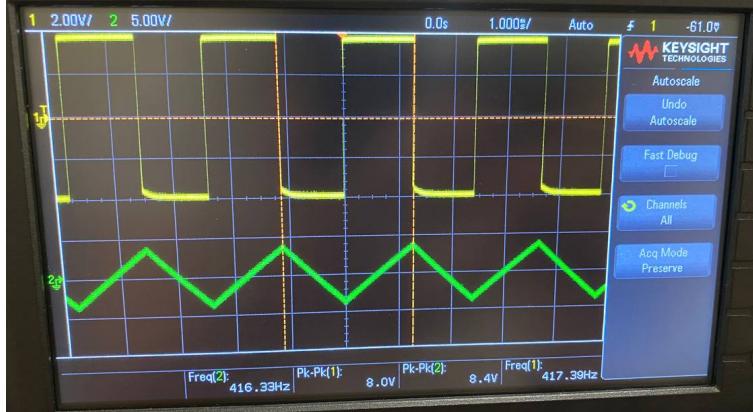
$$Vc = 1V$$



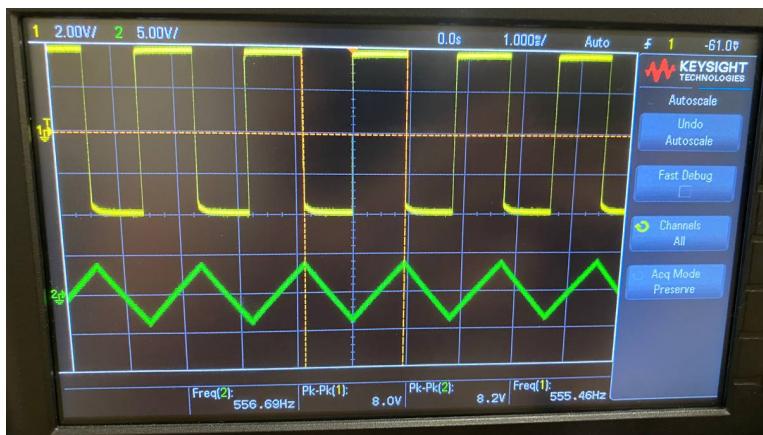
$$Vc = 2V$$



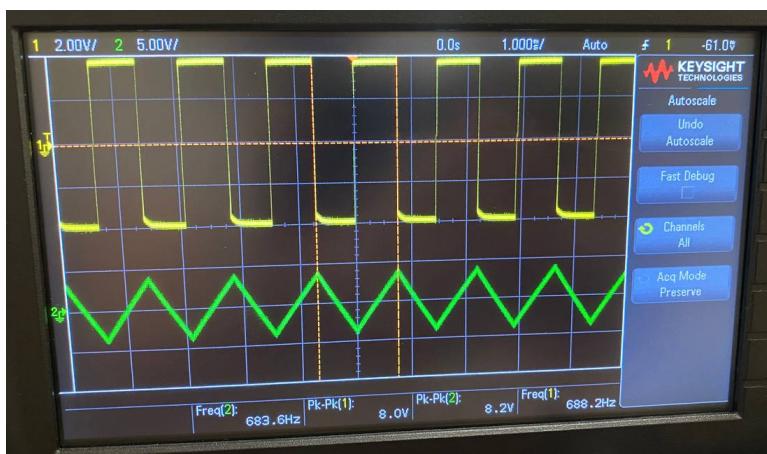
$V_C=3V$



$V_C=4V$



$V_C=5V$



Conclusion and Recommendations:

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 (f_x and $f_x/5$). 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 relatively low frequency and gain involved in our project allowed us to disregard the consideration of op-amp slew rate and gain when selecting the appropriate op-amp. 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/ handwritten analysis, Multisim simulations and in-lab design implementation results, our final design was entirely adherent to our calculations. The only discrepancy between the requirements and our final waveform was the mismatch in the linear frequency control; we had calculated the R value of the integrator so that our frequency f_x (4200Hz) occurred when V_C of the +-DC convertor was 5V and linearly decreased as V_C went down. However, in our practical model, although the relationship was still linear the frequency was lower than f_x (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

- [1] Sedra, A. S., & Smith, K. C. (2004). Microelectronic circuits. Oxford University Press.
- [2] Kassam, M. S. (2022). ELE504 - Major Design Project. Toronto Metropolitan University.