Linear Voltage Controlled Function Generator (VCFG)

Joshua Jayakumar

Objective

The objective of this project is to design and implement a linear voltage controlled triangular and square wave generator consisting of a user-selectable frequency range, with a maximum frequency of 5600 Hz.

- Waveform Functions:
  - User selectable symmetrical triangular and square wave waveform
- Frequency Range - User selectable:
  - Range #1 = 100 Hz to 5600 Hz
  - Range #2 = 20Hz to 5600/5 Hz
- Input DC Voltage Control Range -User Selectable:
  - From 0.1V to 5V
- Power Supplies:
  - +/-12V D
- Square Waveform voltage must be:
  - 12.6 volts peak to peak (6.3 V and -6.3 V)

Theory

Integrator:

In order to create a square waveform and a triangular waveform an integrator must be made using op-amps.

We know the time domain response of an integrator is given by the following equation.

$$V_o = -\frac{1}{R_1 C_1}\int V_i(t)\,dt \qquad (1)$$

Therefore, when a square signal is fed in as Vi(t), the output is the negation of the area under the function, as shown below in figure 3.

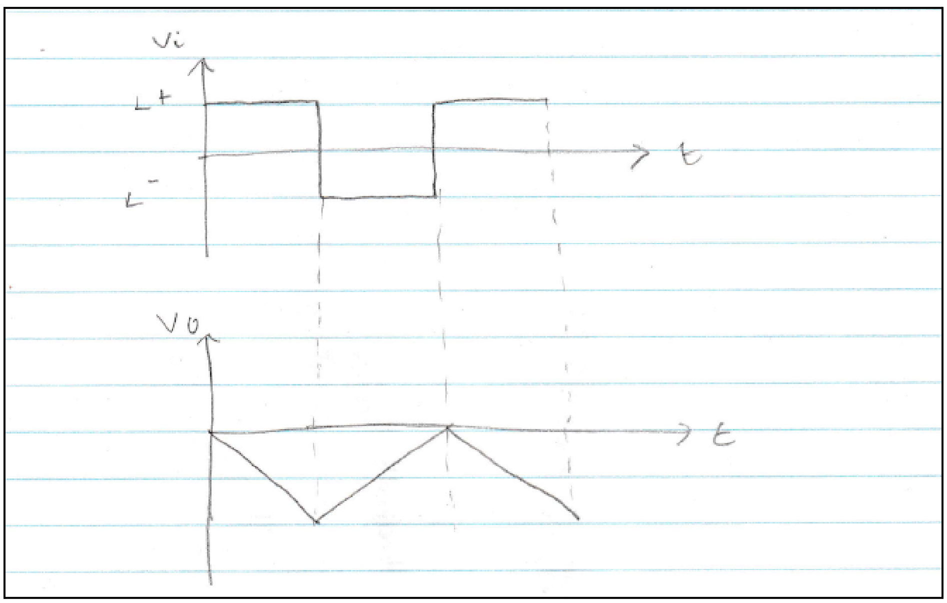

Figure 3. Input and output graphs of equation 1.

As we can see already, integrating a square wave produces a triangular wave.

Now triangular waves are above and below the x-axis, therefore, we can push the triangular signal up by an arbitrary voltage of Vth, which should be incorporated into the equation for Vo.

$$\therefore V_o = -\frac{1}{R_1C_1}\int V_i(t)\,dt + V_{th} \qquad (2)$$

Now when the same input signal is applied, the following waveform should be seen for Vo.

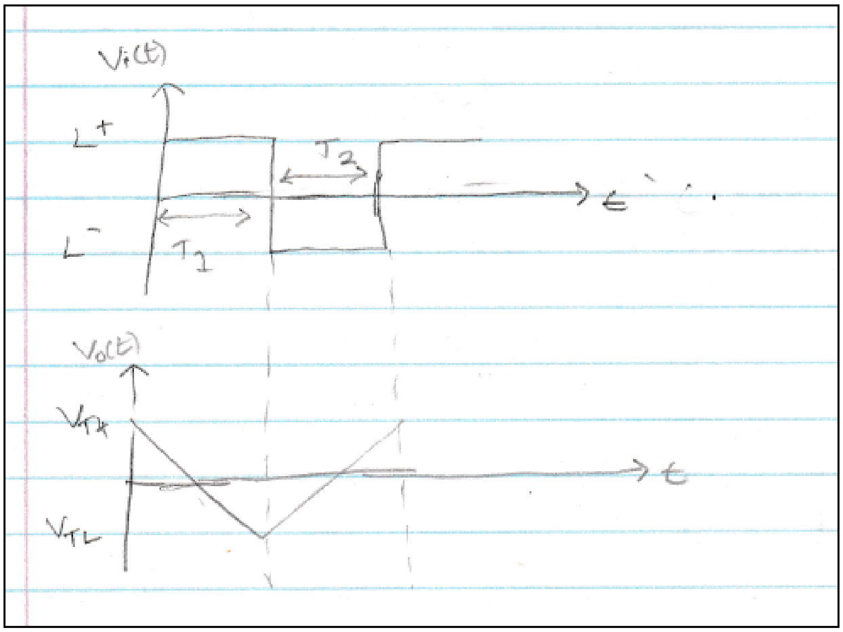

Figure 4. Input and output graphs of equation 1, where L+ and L- represent the saturation voltages of the square wave, and Vth and Vtl represent the peaks and valleys of the triangular waveform, respectively.

Vo in equation 1 can be written in terms of L^+, which is the positive saturation voltage seen in the square wave.

$$\therefore V_o = -\frac{1}{R_1C_1}\int L^+\,dt + V_{th} \qquad (3)$$

The most important part of the project is to be able to control the frequency of the waveforms. Hence a formula for frequency is needed. A formula for frequency of the waveforms can be derived from figure 4.

From figure 3, we can see that an equation for slope can be written for the triangular waveform, for the time period T1.

$$slope = \frac{V_{TL} - V_{Th}}{T_1} \qquad (4)$$

Now the slope can be equated to the derivative of the equation for Vo in equation 3 shown above.

$$\frac{d}{dt}\left(V_o\right) = \; -\frac{L^+}{RC} = \frac{V_{TL} - V_{Th}}{T_1} \qquad (5)$$

Now the equation above can be solved for the period (T1) from figure 4.

$$T_1 = \frac{(V_{TH} - V_{TL})\, RC}{L^+} \qquad (6)$$

Now an equation for T2 from figure 4 can be written.

$$T_2 = \frac{(V_{TH} - V_{TL})\, RC}{-L^-} \qquad (7)$$

Now if L^+ is equal to the magnitude of $-L^-$, then T1 will equal T2.

$$\therefore Total\ period \; = \; T_1 + T_2 = 2T_1 = \frac{2(V_{TH} - V_{TL})RC}{L^+} \qquad (8)$$

Now if the period is known, then the frequency can be found for the triangular wave, where the variables R and C represent the resistor and capacitor values of the integrator, respectively.

$$f = \frac{1}{T} = \frac{L^+}{2\left(V_{TH} - V_{TL}\right) RC} \qquad (9)$$

Bistable Multivibrator:

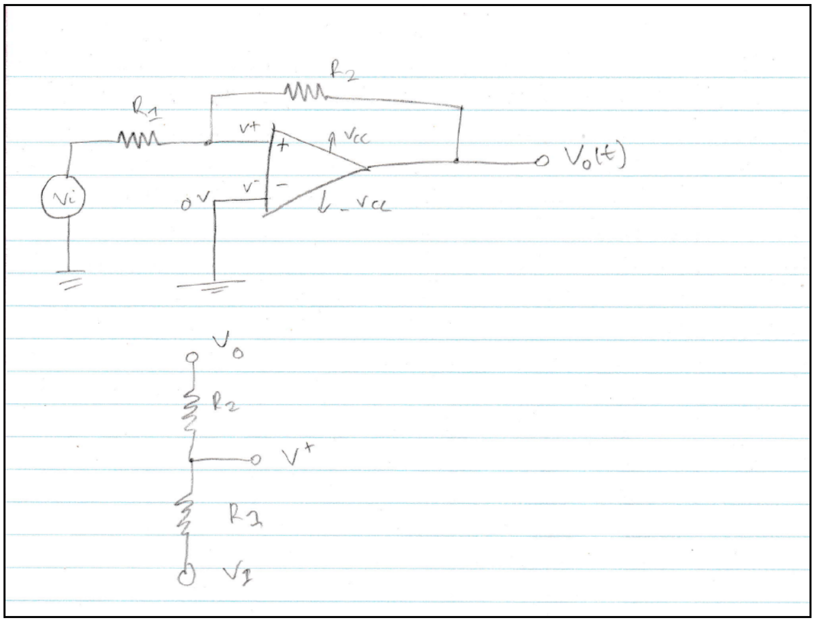

Figure 5. Non Inverting bistable multivibrator

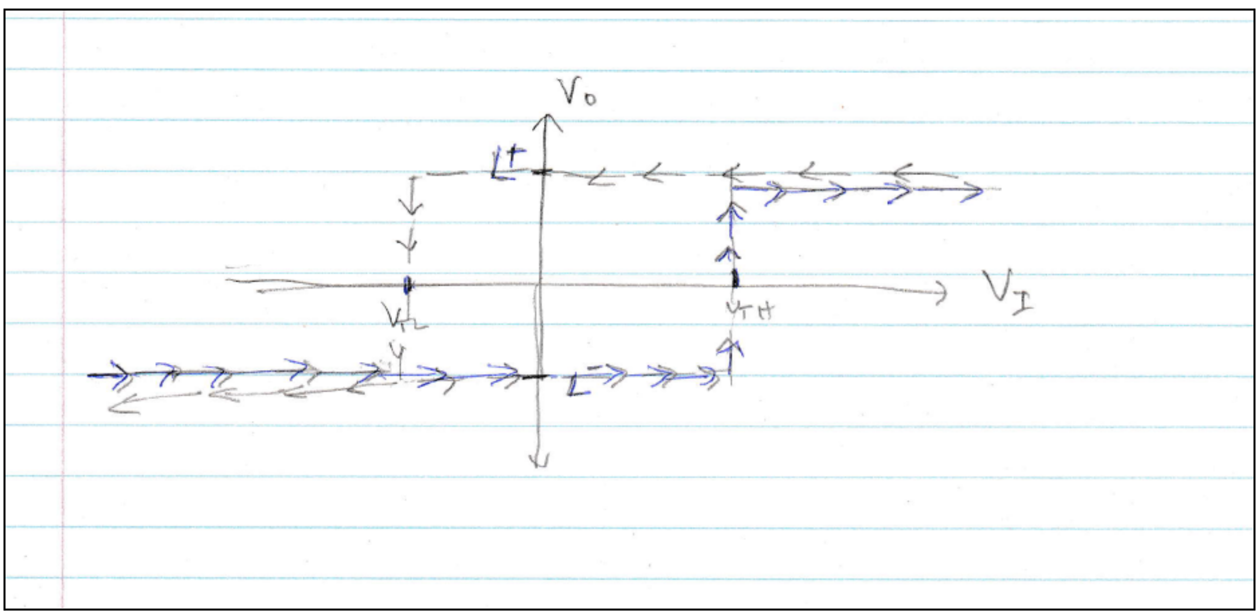

Figure 6. Hysteresis graph for bistable multivibrator.

Now we know that a simple open-loop comparator made using an op-amp outputs the positive saturation voltage when the input voltage is greater than the reference voltage, and a negative saturation voltage when the input voltage is less than the reference voltage.

The problem with using a simple open-loop comparator to generate a square wave is that it is very sensitive to noise around the reference voltage area of the input signal.

Hence a bistable multivibrator or a comparator with hysteresis is used.

We can find the resistance values for the bistable multivibrator, by using the voltage divider equation from the output terminal to the input terminal of the non-inverting bistable multivibrator in figure 5.

$$V+ \;= \left(\frac{R_1}{R_1+R_2}\right)V_o + \left(\frac{R_2}{R_1+R_2}\right)V_i \qquad (10)$$

Now in the hysteresis graph in figure 6, we can set V+ in equation 10 to 0, and Vi to Vtl, Vo to the maximum saturation voltage L^+, to find the value of Vtl.

$$0 = \left(\frac{R_1}{R_1+R_2}\right)L^+ + \left(\frac{R_2}{R_1+R_2}\right)V_{TL} \qquad (11)$$

$$V_{TL} =- \left(\frac{R_1}{R_2}\right)L^+ \qquad (12)$$

The same approach as mentioned above can be used to find the value of Vth.

$$V_{TH} =- \left(\frac{R_1}{R_2}\right)L^- \qquad (13)$$

Now if the values of Vth or Vtl and $L^{+/-}$ is known, then the resistor values of R1 and R2 of the bistable multivibrator can be found using either equation 12 or 13.

DC - ±DC Converter:

Assume Ideal op-amp for calculation purposes

To create a DC - ±DC Converter, the following circuit topology, with a switch is required, where the switch opens and closes, when a square wave of positive and negative voltage are fed into it respectively.

Switch Open:

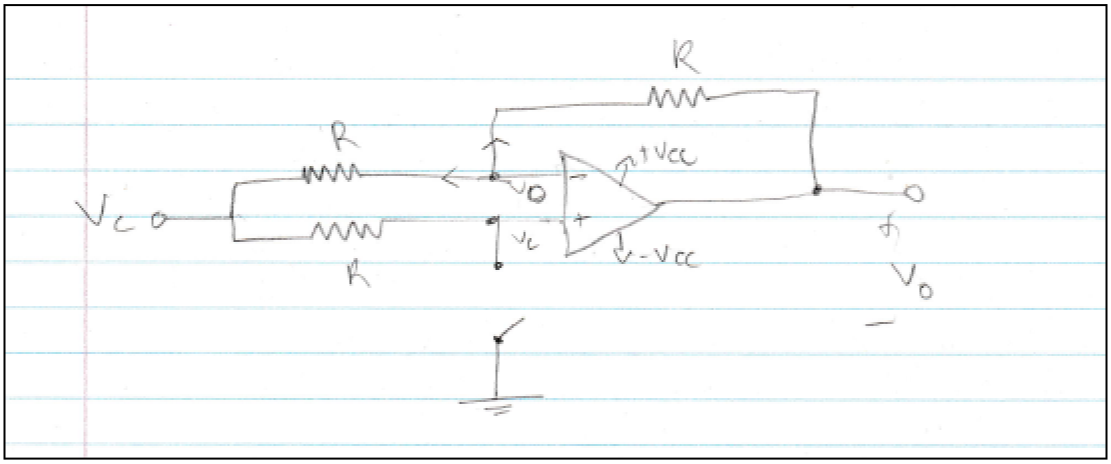

Figure 8. DC-DC converter with switch open

As we can see, when the switch is open the output voltage (Vo) is also seen at the negative terminal, and can be seen as equivalent to the input voltage Vc.

$$\therefore When\ the\ switch\ is\ open,\ \ V_o = V_c$$

Switch Closed:

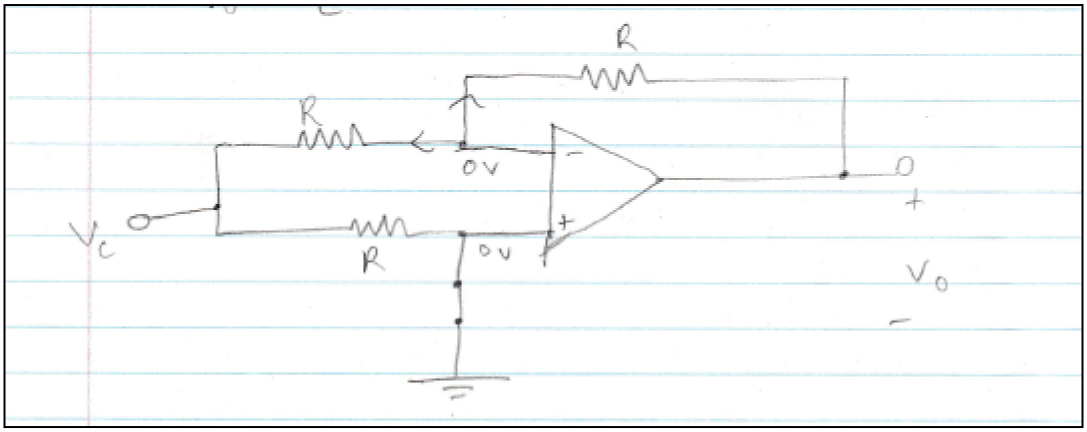

Figure 9. DC-DC converter with switch off.

KCL @ Negative terminal

$$\frac{0-V_c}{R} + \frac{0-V_o}{R} = 0 \quad (14)$$

$$V_o = -V_c$$

$$\therefore When\ the\ switch\ is\ closed,\ V_o = -V_c$$

Now if we insert the DC to DC converter in front of the integrator, we can see the input of the integrator depends on an external voltage source connected to the DC to DC converter, and not on the voltages from the bistable multivibrator

Designing the Switch of the DC to DC converter:

The switch needs to be an electronic switch which can take a square wave input, therefore a BJT is chosen as the device to be modeled as a switch.

The 2N3904 transistor is chosen from the lab kit, which from previous labs was given a beta value of 150.

Switch Off:

- ❖ The BJT is off (open switch) when it is in the cut-off region.
- ❖ Ib = Ic =0 in the cut-off region.

Switch On:

- The BJT is on (closed switch) when it is in the saturation region.
- Vce is approximately zero, and Ic is equivalent to the saturation current.

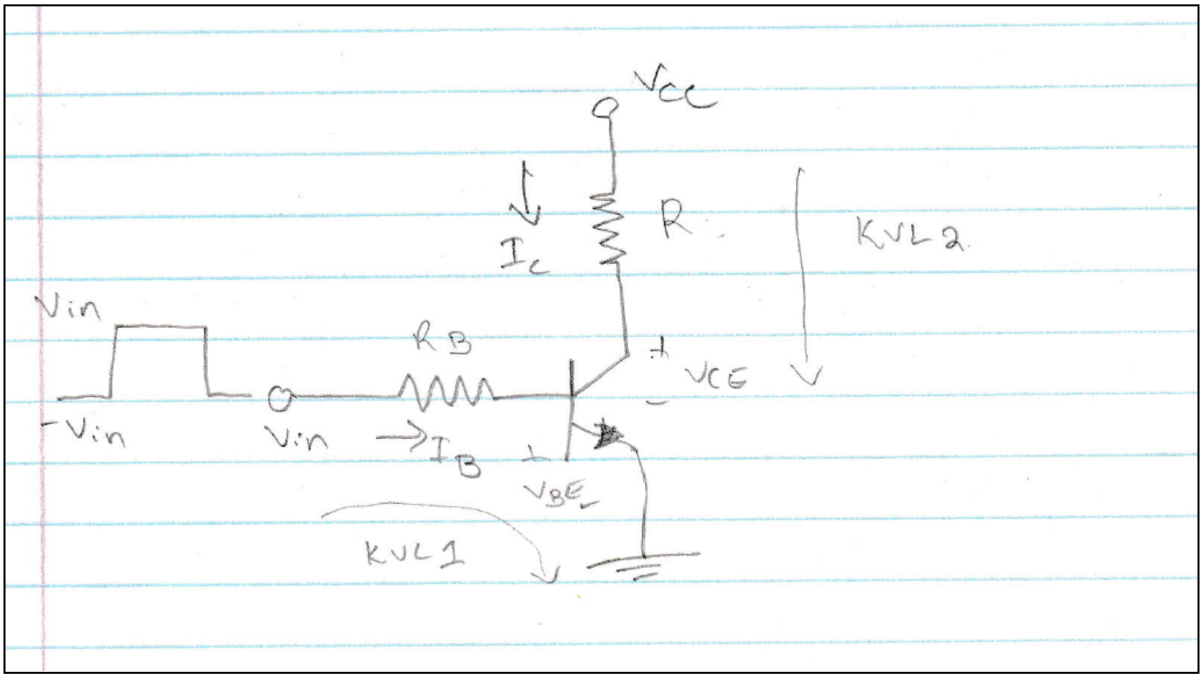

Figure 10. BJT switch design

Calculation for the cut-off region:

KVL 1:

$$V_{in} - I_B R_B - V_{BE} = 0 \quad (15)$$

$$V_{BE} = - V_{in} \quad (16)$$

Calculation for the saturation region operation:

$$V_{cc} - I_{c,sat} R - V_{CE} = 0 \quad (17)$$

$$I_{c,sat} = \frac{Vcc}{R} \quad (18)$$

Now let Vcc be 10 v, R be 1 kiloohm as four resistors are required and there are 5 of these resistors available in the lab kit.

$$I_{c,sat} = \frac{Vcc}{R} = \frac{10V}{1\ kilo\ ohm} = 10\ mA \quad (19)$$

$$I_{c,sat} = \frac{Vcc}{R} = \frac{10V}{1\ kilo\ ohm} = 10\ mA \quad (20)$$

$$I_B = \frac{I_{c,sat}}{\beta} = \frac{10mA}{150} = 0.066\ mA \quad (21)$$

$$V_{in} - I_B R_B - V_{BE} = 0 \quad (22)$$

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{6.3\ V - (-6.3\ V)}{0.066\ mA} = 189,000\ ohms \quad (23)$$

Now to make sure the BJT stays in saturation, Ib must be greater than Ic,sat/β.

Clipper Circuit:

We need to use a diode to create a clipper circuit.

When a single Zener diode is used in the following configuration, we can see when the input exceeds 0.6 V the diode clips, but when input exceeds -5.0 volts, it clips it.

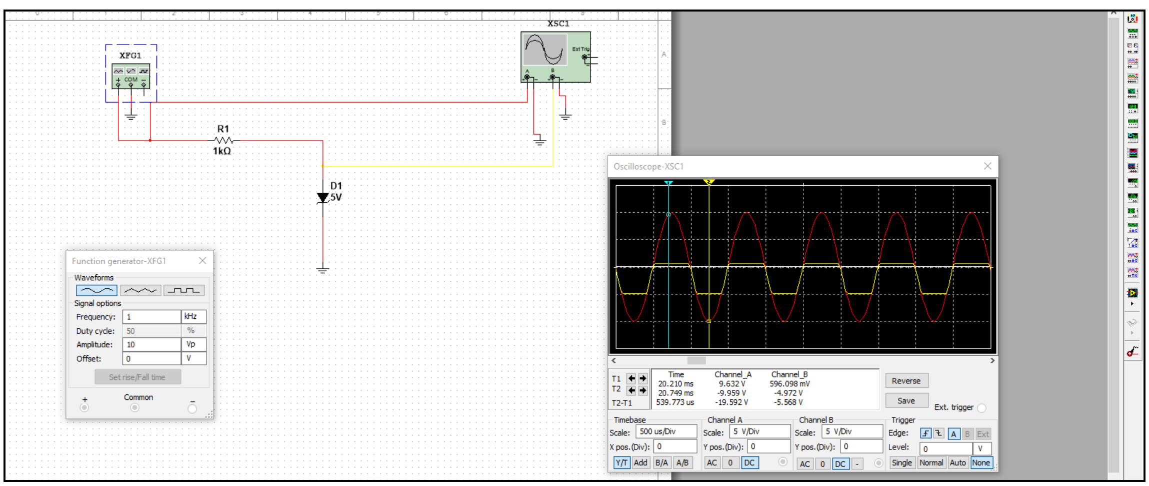

Figure 11. 5 Volt Zener diode circuit, showing the output voltage in yellow, an input sinusoid in red.

The opposite is true, when a 5-volt Zener diode is placed in the opposite direction.

However, when 2 Zener diodes, placed in a configuration like this, the circuits clip at 0.6 and -0.6 volts, as shown in figure 12.

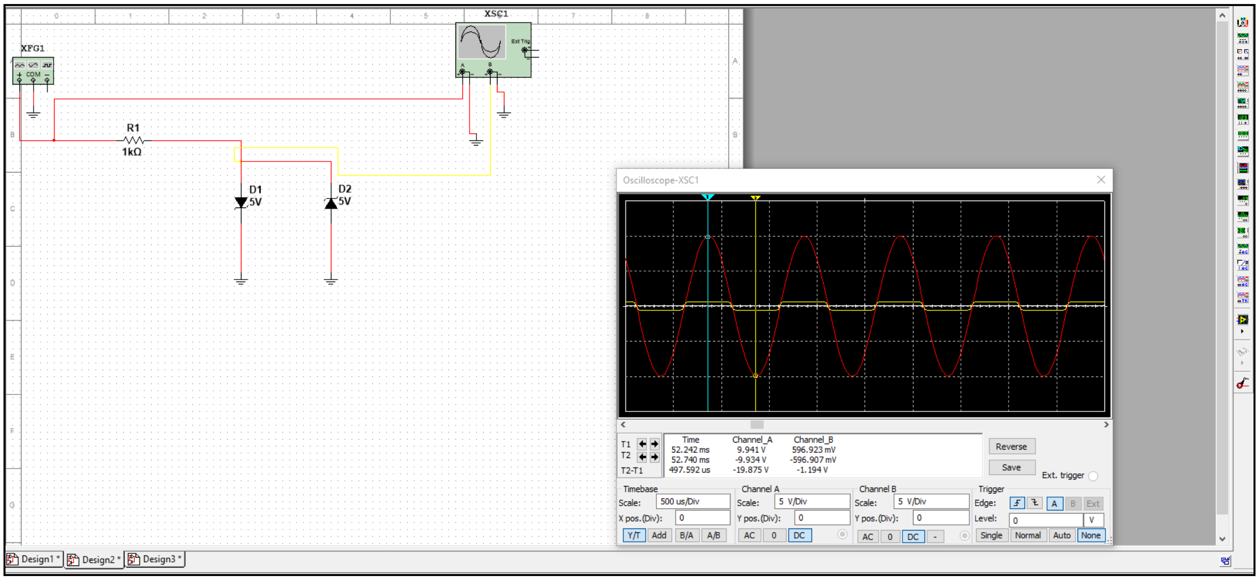

Figure 12. Two Zener diodes in opposite directions, where the waveform in yellow is the output clipped at positive and negative 0.6 volts

Therefore, we must use regular diodes in series with the Zener diodes to create a square waveform with our desired results.

<u>Frequency range selection</u>:

The first frequency that users can select is 100Hz to 5600 (fx)Hz. The second frequency users can select is between 20 Hz and to 1120 (fx /5) Hz.

Range 1 100 Hz – 5600(Hz):

$$f_o = m\, V_C ;$$

Vc is the user-controlled DC external voltage.

$$f_o = \frac{1}{2\left(V_{th} - V_{tl}\right)RC} V_C$$

$$\frac{f_o}{V_c} = \frac{1}{2\left(V_{th} - V_{tl}\right)RC}$$

Now the frequency must be equal to 5600 Hz, when Vc is at 5 V.

$$\frac{1}{2\left(V_{th} - V_{tl}\right)RC} = \frac{(5600\ Hz)}{5V} = 1120\ Hz/V$$

Vth and Vtl are chosen to be half of L+, where L+ is set to 6.3 V in milestone 2, and the capacitance is chosen to be 0.01 μF.

$$\frac{1}{2\left(\frac{6.3}{2}--\frac{6.3}{2}\right)R\left(0.01\times10^{-6F}\right)} = 1120\ Hz/V$$

$$R = 7086.2\ \Omega$$

Range 2 20 Hz – 1120(Hz):

$$\frac{f_o}{V_c} = \frac{1}{2\left(V_{th}-V_{tl}\right)RC}$$

Now the frequency must be equal to 5600 Hz, when Vc is at 5 V.

$$\frac{1}{2\left(V_{th}-V_{tl}\right)RC} = \frac{(5600/5\ Hz)}{5V} = 224\ Hz/V$$

$$\frac{1}{2\left(\frac{6.3}{2}--\frac{6.3}{2}\right)R\left(0.01\times10^{-6F}\right)} = 224\ Hz/V$$

$$R = 35430.8\ \Omega$$

Design Analysis

Fixed frequency Waveform Generator:

The first part of the project requires the design of a waveform generator that produces a triangle and square wave.

The waveform generator is built using an integrator and a bistable multivibrator circuit. The integrator produces a triangular waveform and the bistable multivibrator produces a square waveform.

As mentioned in the theory section, to create the integrator circuit, we only need to find the resistance if the other values in equation 9 are known.

The frequency of the waveform generator is given to be 5600 Hz, the output saturation voltage is chosen to be 10.5 and -10.5 volts, when a power supply voltage is 12 V. Therefore, the peak and valley voltage values of the triangular waveform (Vth and Vtl) are arbitrarily chosen to be half of the output saturation voltages. The capacitor value is chosen to be 0.1 microfarad, as it is part of the lab kit.

- Frequency = 5600 Hz
- L^+/L^- = 10.5/-10.5 V
- Vth/VtL = $(L^+/2)$ / $(L^-/2)$ = 5.25 / - 5.25 V
- C = 0.1 microfarad

Integrator:

$$f = \frac{L^+}{2(V_{TH} - V_{TL})RC}$$

$$R = \frac{L^+}{2(V_{TH} - V_{TL})fC} = \frac{10.5\,V}{2(5.25\,V - (-5.25\,V))(5600\,Hz)(0.1\,\mu F)} = 892.85\,\Omega$$

Since there is no 890-ohm resistor in the lab kit, the closest resistance value of 910 ohms will be used as the resistance of the integrator.

Bistable Multivibrator:

As mentioned above in the theory section, equation 12 or 13 can be used to find the resistance values of the non-inverting bistable multivibrator.

$$V_{TH} =- \left(\frac{R_1}{R_2}\right)L^-$$

$$5.25\,V =- \left(\frac{R_1}{R_2}\right)(-\ 10.5\,V)$$

$$\left(\frac{R_1}{R_2}\right) = \frac{1}{2}$$

$$R_1 = R_2\frac{1}{2}$$

Let R2 be equal to 4.7 kiloohms, therefore R1 is equal to 2.35 kiloohms. Since 2.35 is not part of the lab kit, the closest value of 2.2 kilo ohms will be used.

$$R_2 = 4.7\ kiloohms,\ \ R_1 = 2.2\ kiloohms$$

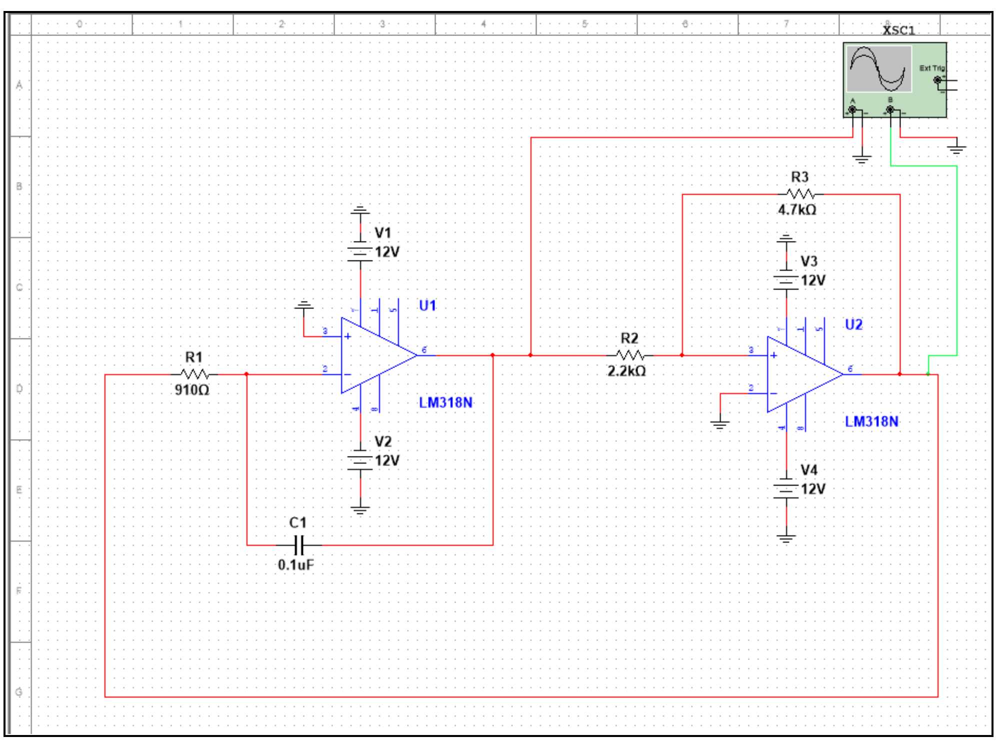

Figure 13 . Multisim schematic of waveform generator using 2 LM318N amplifiers.

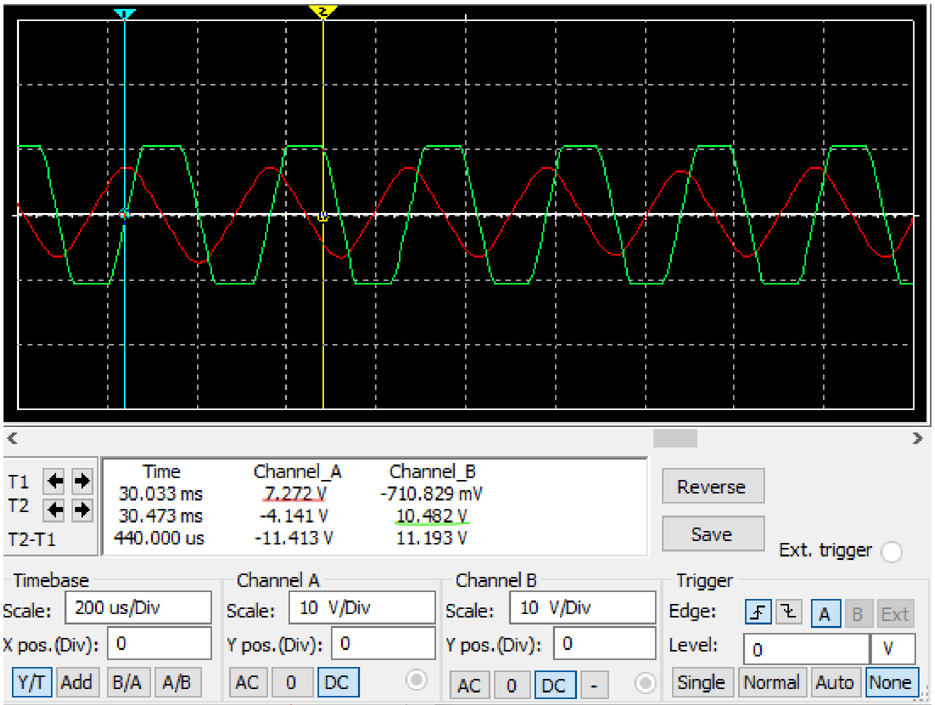

Figure 14. Output of the integrator and bistable multivibrator in multisim, shown in red and green respectively.

Fixed Frequency @5600Hz - Waveform Generator with a limiter circuit, and a DC to +/-DC Convertor:

Next we are required to clip the square waveform of the bistable multivibrator at 6.3 and -6.3 V. This was made using a limiter circuit that used 5.6 V zener diodes and 0.7 V regular diodes.

A DC-to-DC converter circuit with a digital switch was implemented and tested using a function generator.

DC to DC converter:

As mentioned above in the theory section, to make sure the BJT stays in saturation, Ib must be greater than Ic,sat (saturation current) divided by the beta (β) value of the transistor.

Therefore, the value of Rb is taken to be half of 189 kiloohms derived above.

Therefore, the value of Rb is 100 kiloohms as that is the closest to the half of 189,000 ohms, which is 94.5 kiloohms.

We know from the lectures that the resistors part of the op-amp of a DC to DC converter are the same, hence 1 kilo ohm resistors are used, in the DC -DC converter design below.

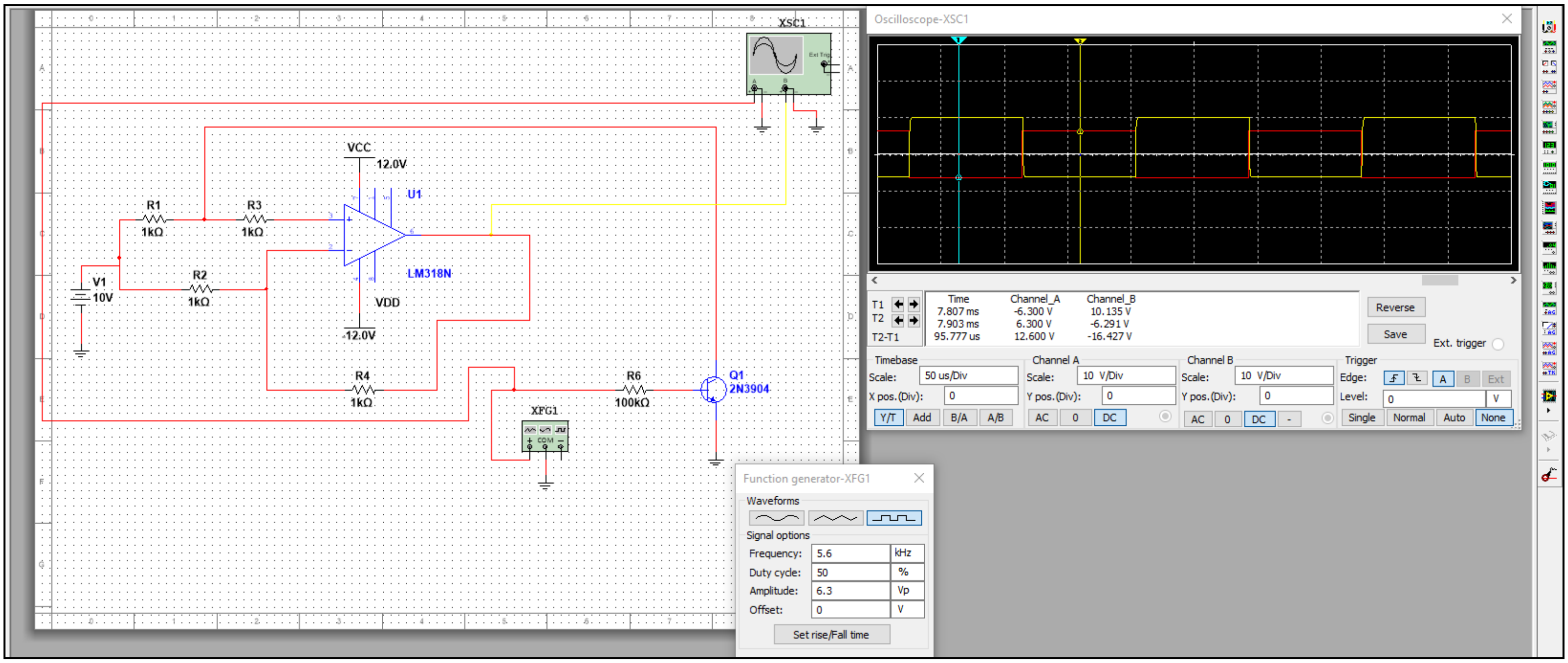

Figure 15. Multisim simulation of the DC – DC converter with a function generator feeding a 5.6 kHz wave at 6.3 Volts peak, with the yellow oscilloscope graph showing the output waveform, and the red showing the input waveform.

<u>Waveform generator with limiter circuit:</u>

As mentioned above, the limiter circuit was constructed using 2 5.6 volt zener diodes in series with 0.7 volt diodes to limit the square wave at 6.3 V.

When a 1 kilo ohm resistor was used with the clipper circuit, the output did not reach the desired positive and negative 6.3 volts. Therefore, the 1 kilo ohm resistor was switched to a 220-ohm resistor, and as we can see from the graph below, that the output in yellow reaches close to 6.3 volts, and the peak of the triangular wave is approximately half of 6.3 at 2.833 V.

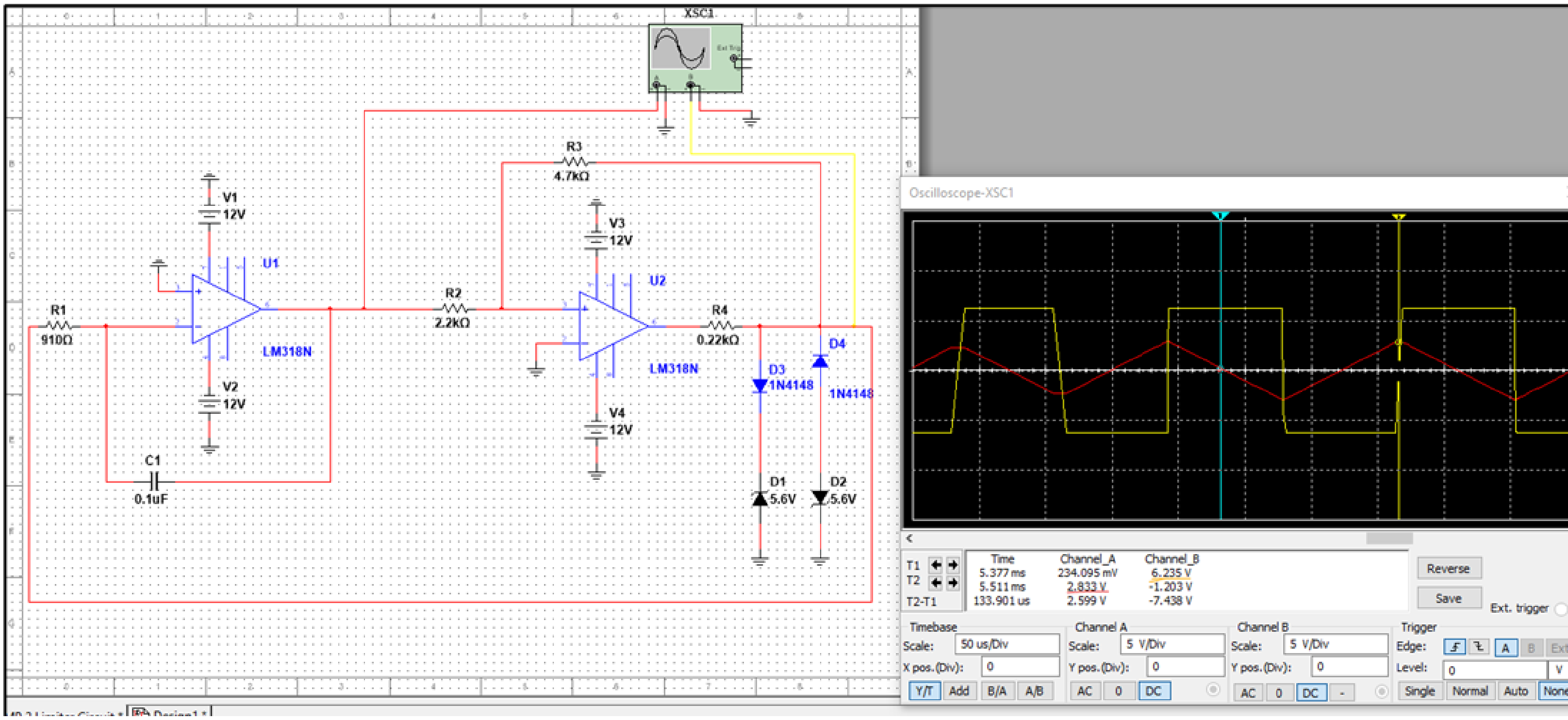

Figure 16. Waveform generator circuit from MP1 with limiter circuit clipping the square wave at the desired 6.3 volts, and a triangular wave at 2.833 volts peak.

Linear Voltage Controlled Frequency Waveform Generator:

The next step is to design a linear voltage controlled frequency waveform generator.

To accomplish this, the DC to DC converter is connected to the integrator and bistable multivibrator circuit. When this is done as the way it is, the overall gain of the circuit is positive, hence the bistable multivibrator is turned into an inverting configuration.

Furthermore, the resistor going into the non-inverting terminal of the op-amp is changed to 100 kiloohms, as it serves as a resistor to limit the current from flowing into the op-amp.

Now the resistor of the integrator is switched to 7 kiloohms, as the resistance required for the frequency selection using the DC to DC converter, as shown in the theory section.

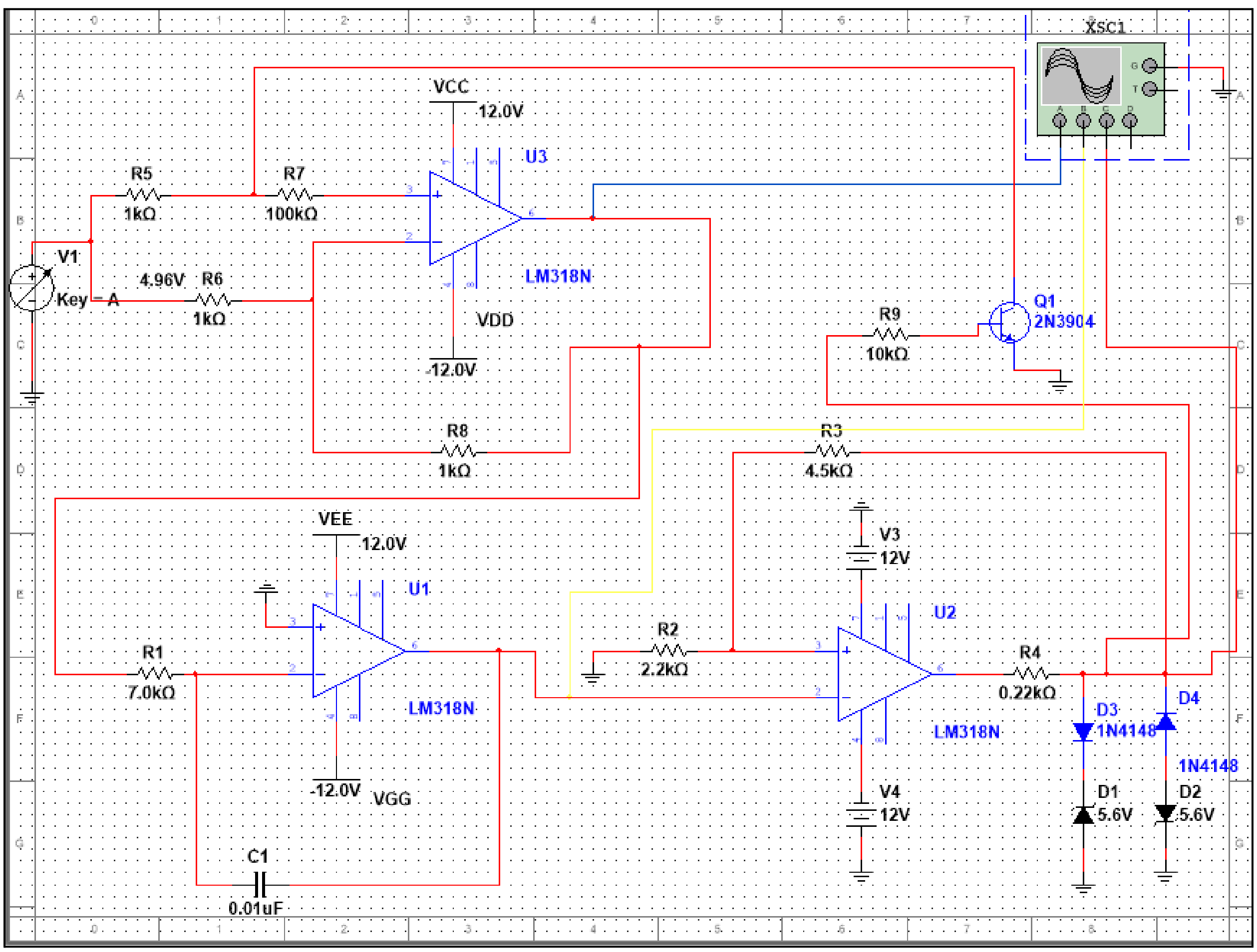

Figure 17. Multisim schematic of the DC-DC converter with the waveform generator with the limiter circuit.

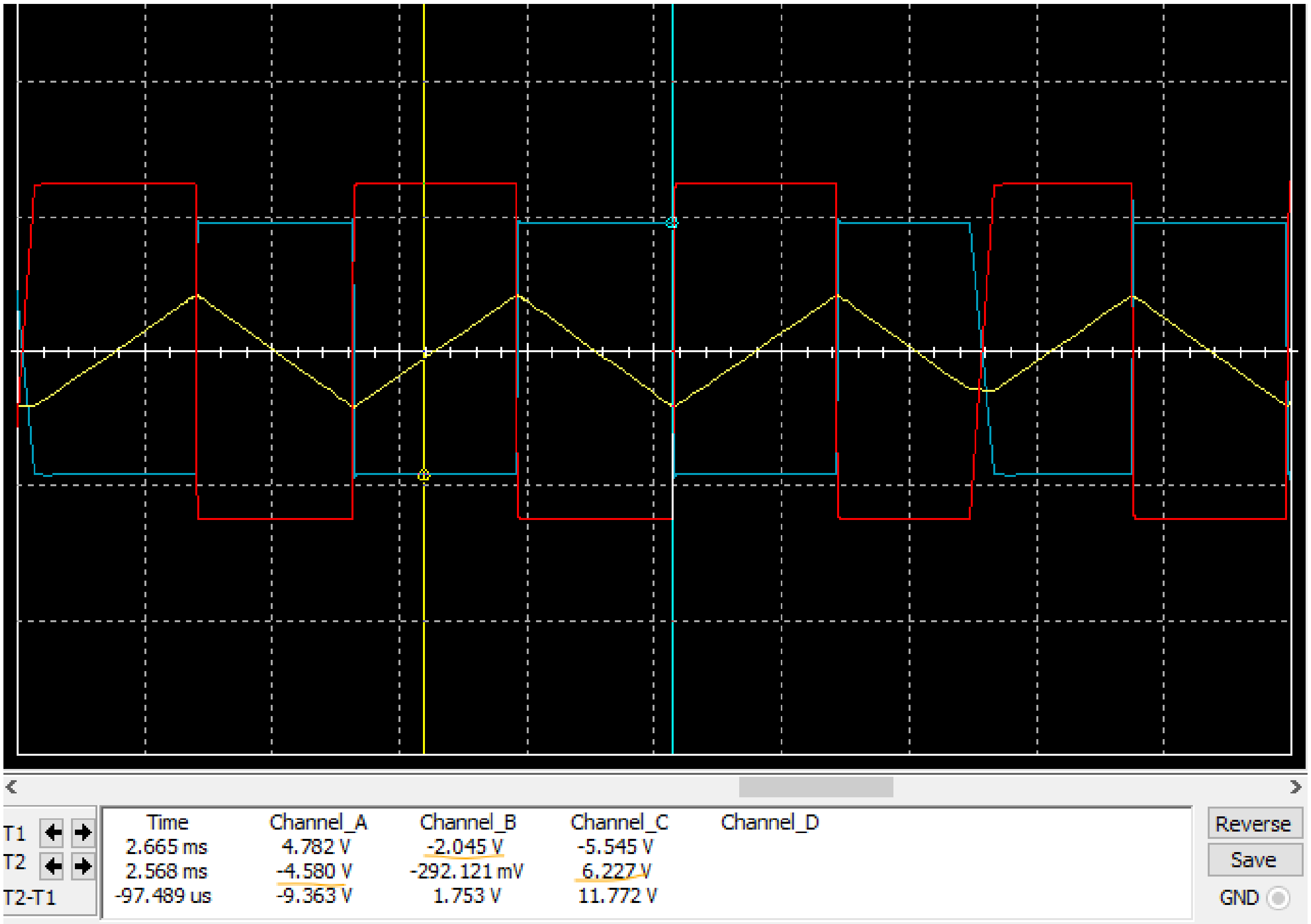

Figure 18. Output waveform of the circuit in figure 17, where the bistable multivibrator output of 6.27 volts is in red, the output of the triangular waveform of 2.0 volts is in yellow, and the output of the DC-DC converter is shown as 4.78 V in blue, when Vc is set to 4.96 volts.

The frequency of this output is found to be 7.9 Khz, which is close to the 5.6 kHz it should be when Vc is 5 volts.

Linear Voltage Controlled Frequency Waveform Generator with user-selectable frequency range

Frequency Range control

As mentioned above in the theory section to create a user defined frequency range control two different resistors are needed, with values of 7 kilo ohms for a frequency range of 100 Hz to 5.6 Khz and a resistance value of 35 kilo ohms for a frequency range of 20 Hz to 1120 Hz.

In multisim a switch was used to connect these two resistors to the DC-DC converter, hence a user can use a switch to change the frequency range.

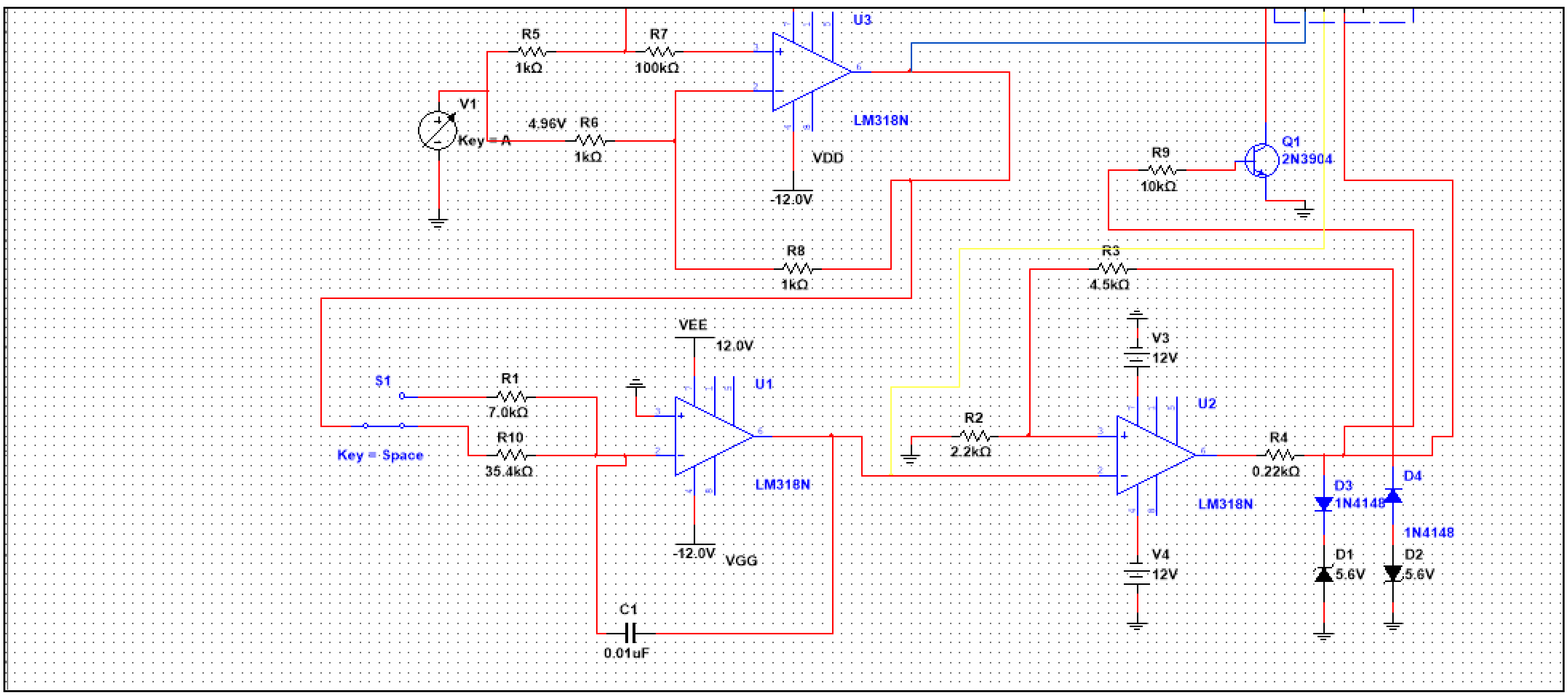

Figure 19. Multisim schematic of a waveform generator circuit with a switch to control frequency range.

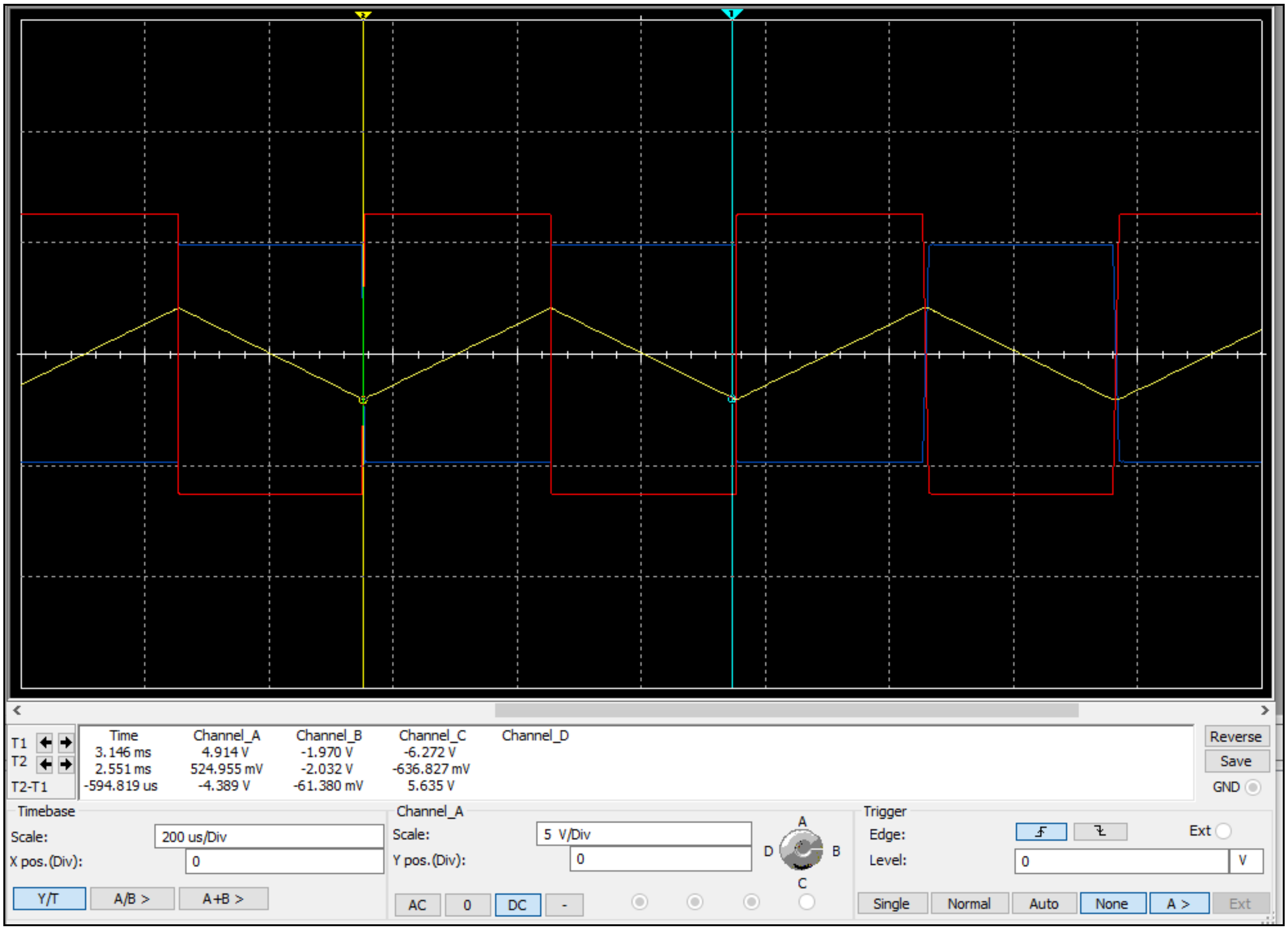

Figure 20. Output waveform of the circuit in figure 19, where the bistable multivibrator output of 6.27 volts peak is in red, the output of the triangular waveform of - 2.0 volts peak is in yellow.

As we can see from figure 20, when the integrator is connected to a 3.54 kilo ohm resistor, the frequency is 1681 Hz, which is close to the 1120 Hz it should be when Vc is 5 volts. Therefore satisfying the requirements above.

Conclusion

In conclusion, as we can see the requirements of the project are pretty well satisfied, where a voltage controlled waveform generator is designed and implemented with a maximum frequency of 5.6 kHz.