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Triangular and Rectangular Signal Generator

Computer Aided Design

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Requirements

The task is to design a non-sinusoidal oscillator with the following specifications:

$f_{min}[Hz]$	$f_{max}[Hz]$	$A_{\blacksquare}[V]$	$A_{\Delta min}[V]$	$A_{\Delta max}[V]$	Vps[V]	$R_{load}[\Omega]$
1600	2400	4	3	9	12	20

Such a circuit requires the following steps:

First we need to obtain a rectangular signal, which we then process into a triangular shape. During this step we can size our components to achieve the desired frequency, but in order to adjust the amplitudes of the outputs we need to feed each of the signals to an amplifier. Before doing so, we will use a voltage follower to make sure we don't influence the previous circuit's output impedance.

1. Generating the rectangular signal

For this purpose we will use a non-inverting hysteresis comparator. The amplitude of the signal is given by the voltage of the power sources. The circuit is shown in Figure I.1

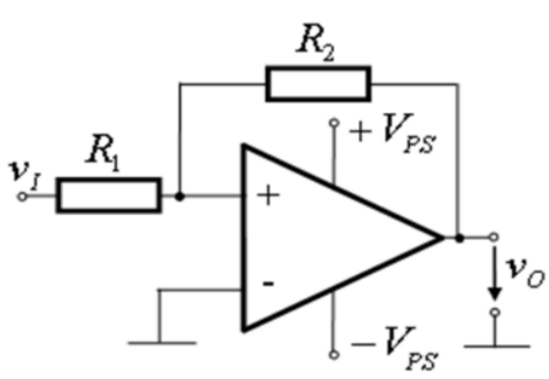


Figure I.1

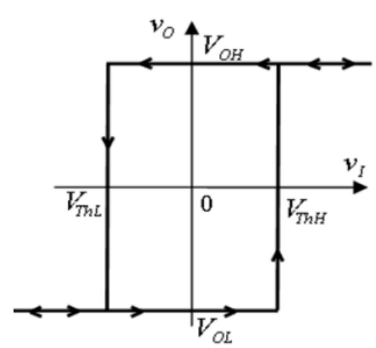


Figure I.2

In Figure I.2 is displayed the VTC. $V_{OH} = +V_{PS}$, $V_{OL} = -V_{PS}$

2. <u>Generating the triangular signal</u>

In order to obtain this signal we will feed the output of the comparator to the input of an integrator circuit. The shape of the output signal is given by the charging and discharging of the capacitor. The circuit is shown in Figure II.

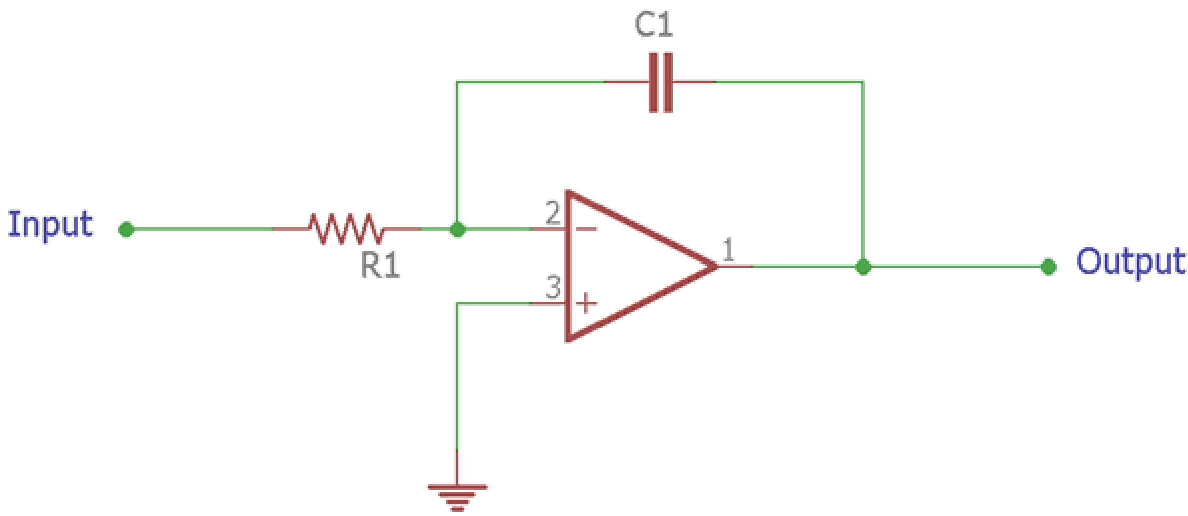


Figure II

3. <u>Non-sinusoidal oscillator</u>

This is the layout of the 2 circuits above after connecting them together:

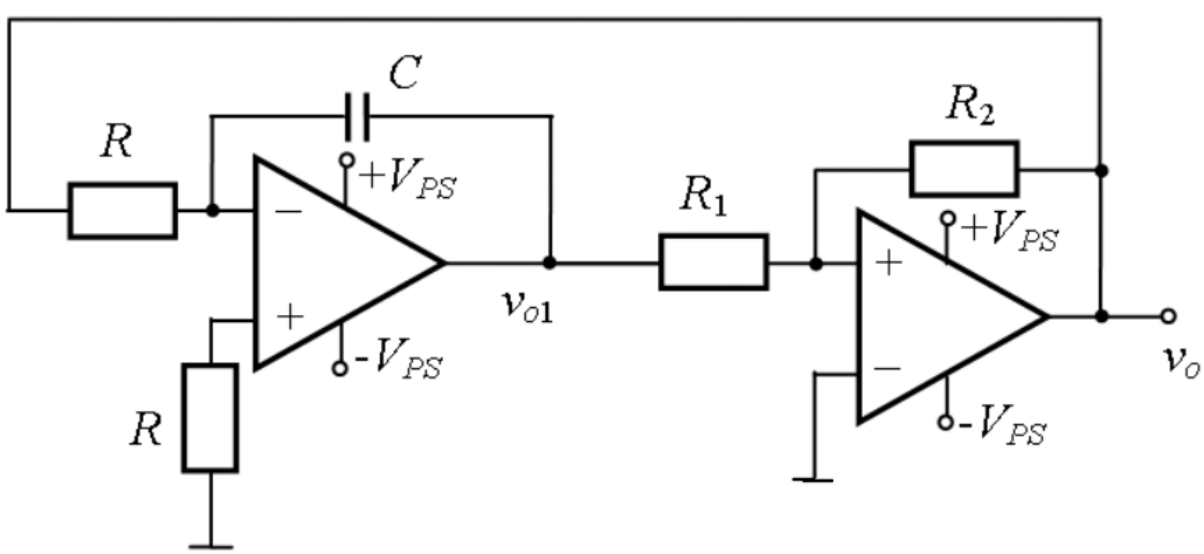


Figure III

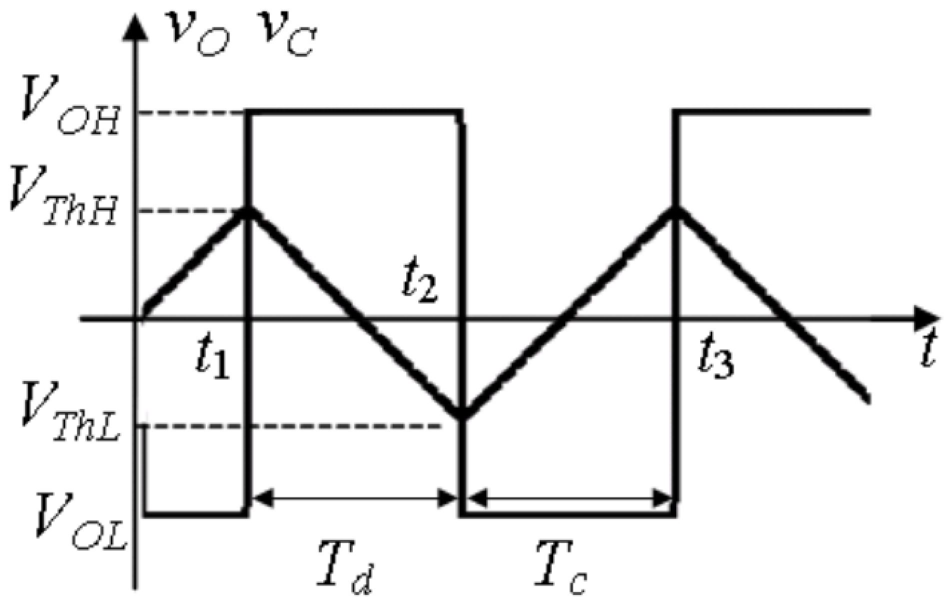


Figure IV presents the 2 outputs qualitatively.

Figure IV

4. Voltage follower

This is nothing more than an amplifier with unitary gain. Its purpose is to separate the output impedance of one circuit from the input impedance of the next and to eliminate any noise that may appear.

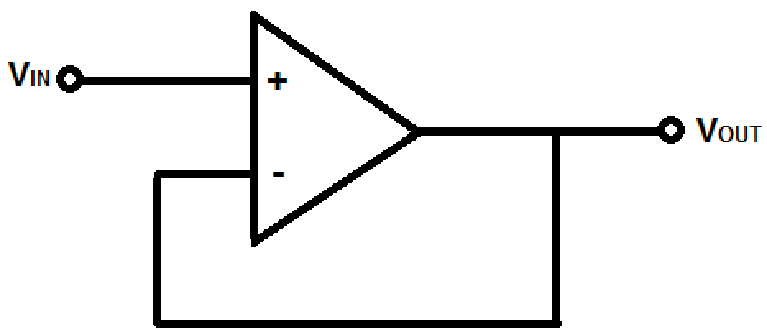


Figure V

$$\left.\begin{array}{l} V_{+}=V_{-}\ ; \\ V_{+}=V_{IN}; \\ V_{-}=V_{OUT} \end{array}\right\} \Rightarrow V_{OUT}=V_{IN}$$

5. Adjusting the amplitude

For this we need an OpAmp with negative feedback. The circuit is shown in Figure VI. Figure VII represents the VTC.

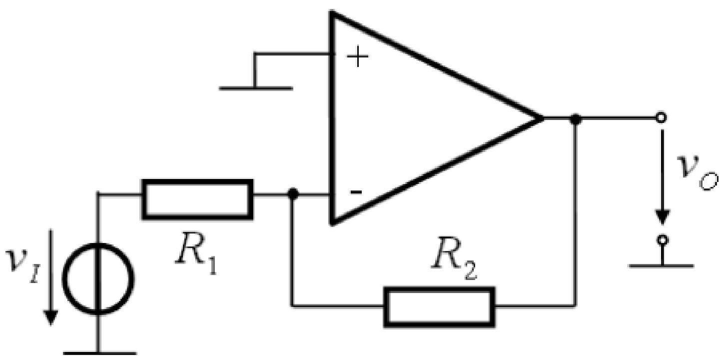


Figure VI

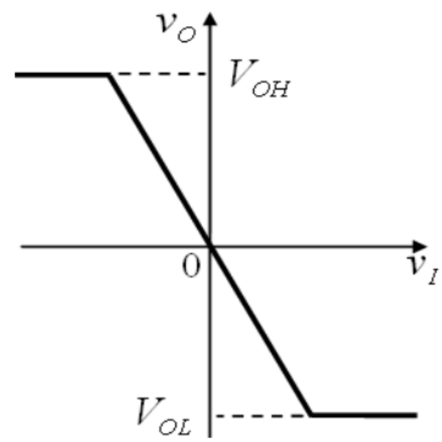


Figure VII

$$\left.\begin{aligned} &V_{+}=V_{-}\ ; \\ &V_{+}=0; \\ &V_{-}=\frac{R2*Vin+R1*Vo\iota}{R1+R2} \end{aligned}\right\} \Rightarrow V_{OUT} = -\frac{R2}{R1}*V_{IN}$$

To have an adjustable amplitude, we will add a potentiometer in series with R2.

6. Amplifying the power

Because of the relatively small load resistance (20 Ω), we need to boost the current without modifying the voltage, which can be achieved by using a power amplifier. For this purpose I have chosen a class AB power amplifier as to evoid any crossover distortions, circuit shown in Figure VIII.

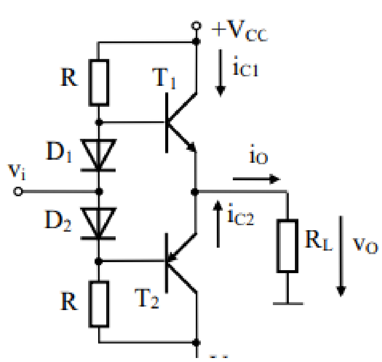


Figure VIII

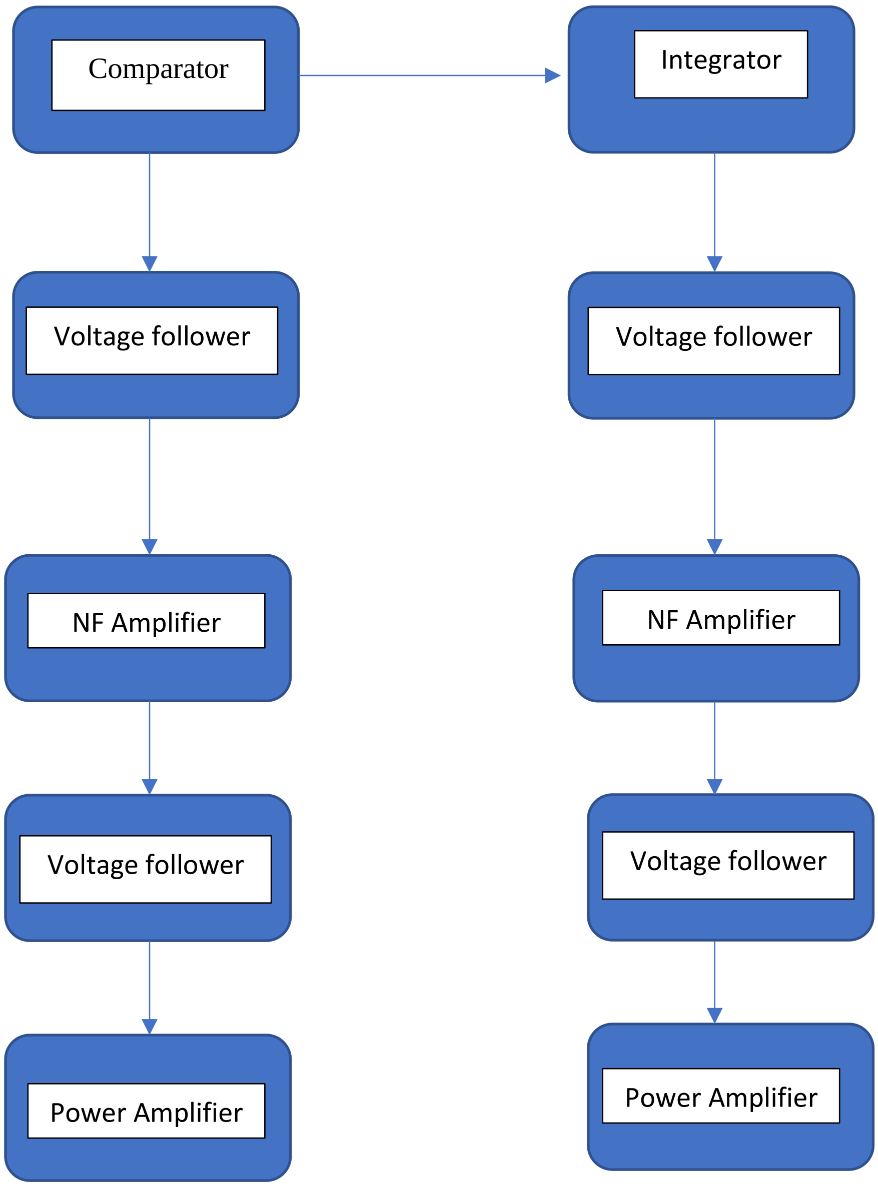
$$\begin{cases} V_{OUT} = V_{IN}+V_{D1}-V_{BE\_T1} \approx V_{IN}\text{ , for } V_{IN}>0 \\ V_{OUT} = V_{IN}-V_{D2}-V_{BE\_T2} \approx V_{IN}\text{ , for } V_{IN}<0 \end{cases}$$

$$\Rightarrow V_{OUT} = V_{IN}$$

So the voltage remains unchanged while the current is amplified by the transistors.

Block Diagram

In order to obtain signals with the given specifications we designed the following circuit:



Comparator – generates rectangular signal

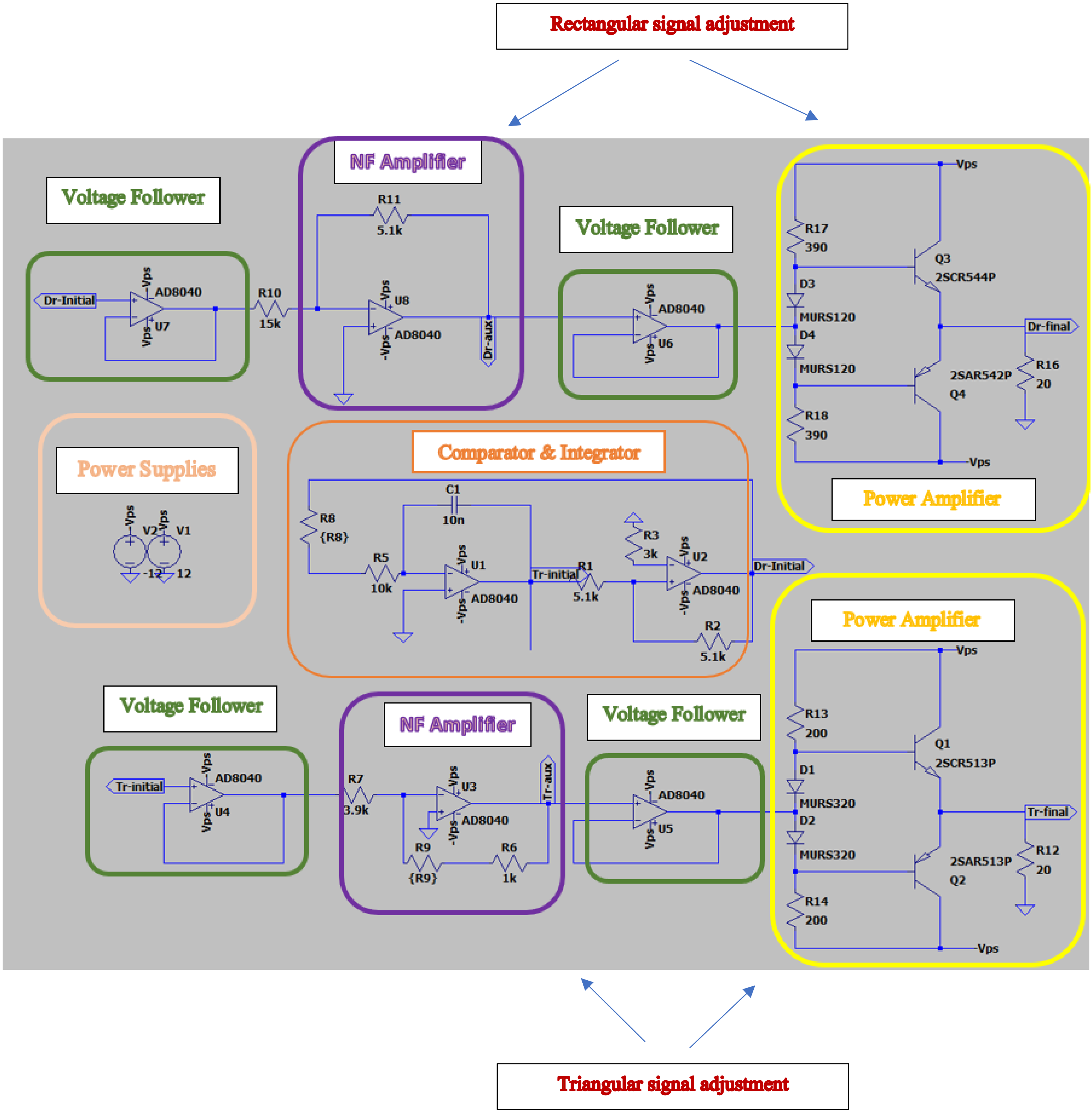
Integrator – transforms the output of the comparator into a triangular signal

Voltage follower – separates the impedances between 2 circuits and stabilizes the signal

NF Amplifier – regulates the output voltage in the desired range

Power Amplifier – increases the output current so that the signal is not cut off when placed on a small load resistance

Electrical Scheme



Calculus

When sizing the passive components I will be choosing the resistor values out of the the E24 Standard Resistor Series, which contains the following values per decade with ±5% tolerance.

E24 STANDARD RESISTOR SERIES		
1.0	1.1	1.2
1.3	1.5	1.6
1.8	2.0	2.2
2.4	2.7	3.0
3.3	3.6	3.9
4.3	4.7	5.1
5.6	6.2	6.8
7.5	8.2	9.1

In order to find values for my components I will follow the next steps:

1) Computing the frequency
2) Setting the amplitude of the voltage

1) Frequency setting

The frequency of the signal is set in the very first part of the circuit, namely by the resistors and capacitor attached to the comparator and integrator.

$$f = \frac{1}{4*(R5+k*R8)*C1*\frac{R1}{R2}}$$

R1 and R2 also have an impact on the amplitude of the triangular signal and because we do not want to change it yet we will set their ratio equal to 1, choosing standard values.

R1 = 5.1 kΩ , R2 = 5.1 kΩ

For the capacitor we will also choose a standard value that suits our needs.

These are the most commonly available capacitor values. Tolerances are highly dependent on dielectric and package type.										
pF	pF	pF	pF	µF	µF	µF	µF	µF	µF	µF
1.0	10	100	1000	0.01	0.1	1.0	10	100	1000	10,000

C1 = 10 nF → 0.01 µF

Now the only variables left in the equation are R5 and R8, which we can calculate. We know that the frequency must be between [1600Hz, 2400 Hz]. After replacing the values that we previously determined in the equation above, we are left with:

$$\text{for } k = 0 \Rightarrow f_{max} = \frac{1}{4*R5*C1*\frac{R1}{R2}} \Rightarrow R5 = \frac{1}{4*f_{max}*C1*\frac{R1}{R2}} = \frac{10^6}{4*24}$$

R5 = 10,4 kΩ → 10 kΩ

$$\text{for } k = 1 \Rightarrow f_{min} = \frac{1}{4*(R5+k*R8)*C1*\frac{R1}{R2}} \Rightarrow R8 = \frac{1}{4*f_{min}*C1*\frac{R1}{R2}} - R5 = \frac{10^6}{4*16} - R5$$

R8 = 5.22 kΩ → 5.1 kΩ

Results:

Freq: 1.6223351KHz

Freq: 2.4399919KHz

2) Amplitude adjustment

a) Rectangular signal

The amplitude of the rectangular signal must equal 4V at the output of the circuit. Because we previously set R1=R2, the signal seen at the input of the OpAmp based amplifier will measure V_{PS} = 12V, which is the maximum output of the hysteresis comparator.

$$\boldsymbol{A_v} = \frac{\boldsymbol{V_{OUT}}}{\boldsymbol{V_{IN}}} = -\frac{R11}{R10}$$

V_{OUT} = 4V

V_{IN} = 12V

$$\Rightarrow \frac{R11}{R10} = \frac{1}{3} \Rightarrow R12 = 3*R11$$

We choose:

R11 = 5.1kΩ , R10 = 15.3 kΩ → 15 kΩ

Result: 

b) <u>Triangular signal</u>

Its amplitude has to be adjustable in the interval [3V, 9V]. This requires a potentiometer in series with the resistor on the negative feedback loop.

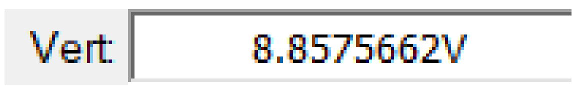
$$\left.\begin{array}{l} A_v = \frac{V_{OUT}}{V_{IN}} = -\frac{R6+k*R9}{R7} \\ V_{OUTmin} = 3V \\ V_{OUTmax} = 9V \end{array}\right\} \Rightarrow \frac{1}{4} \leq \frac{R6+k*R9}{R7} \leq \frac{3}{4} \Rightarrow \begin{array}{l} R7 = 4*R6 \\ R9 = 2*R6 \end{array}$$

V_{IN} = 12V

We choose:

R6 = 1kΩ , R9 = 2kΩ , R7 = 4 kΩ → 3.9 kΩ

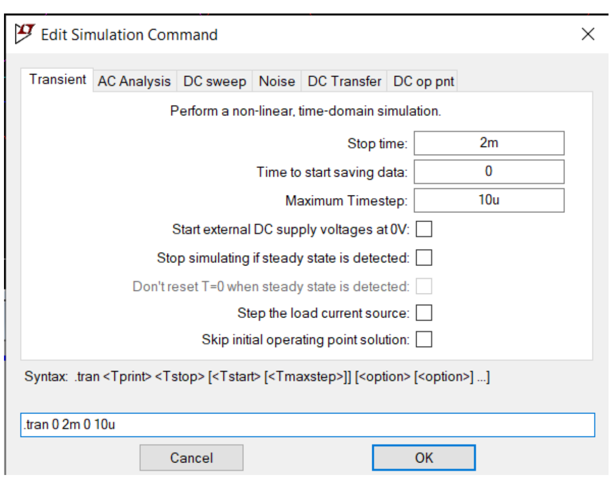
Results:



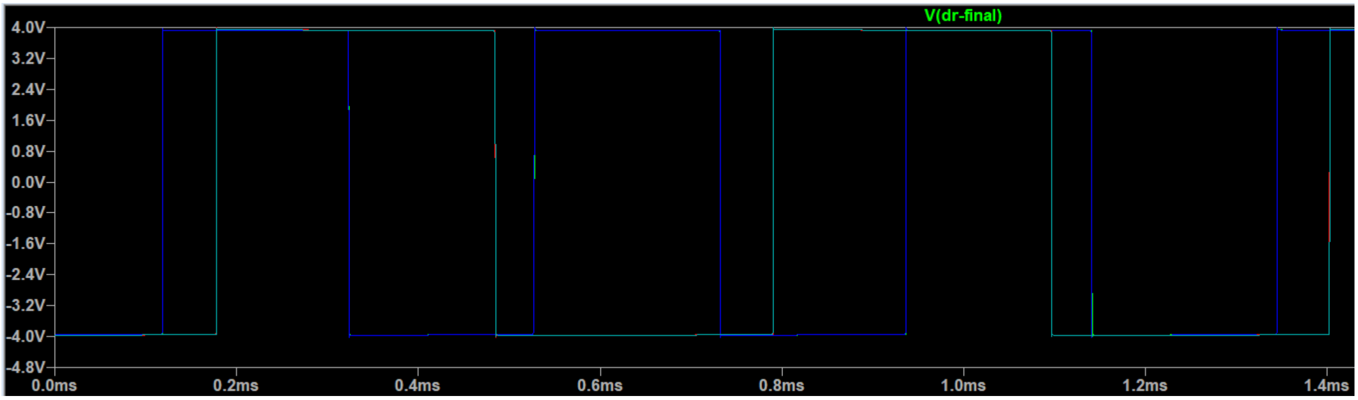
Simulation profile

1) Transient

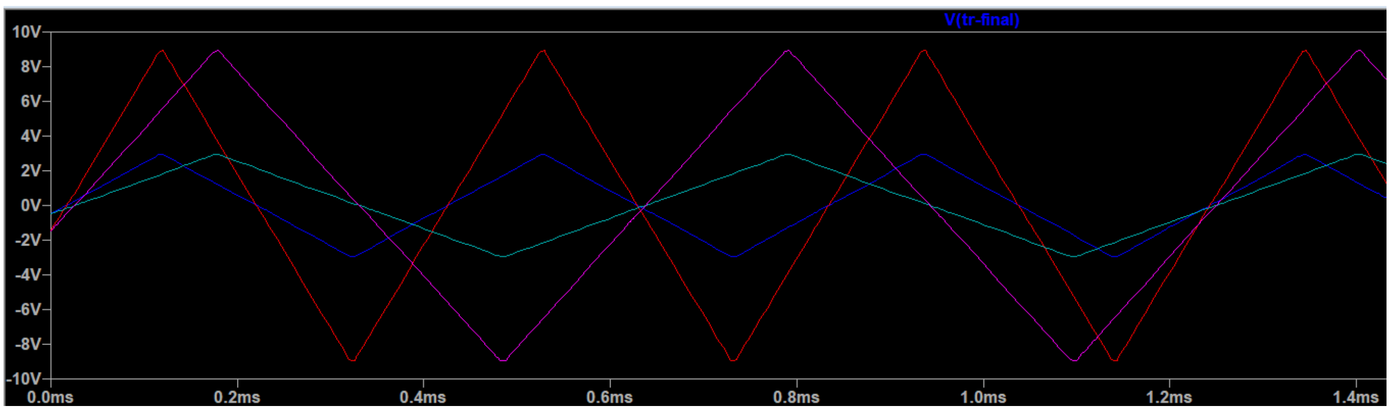
First we will check out the response of the circuit in the time domain.



a) Rectangular output



b) Triangular output



2) Parametric analysis

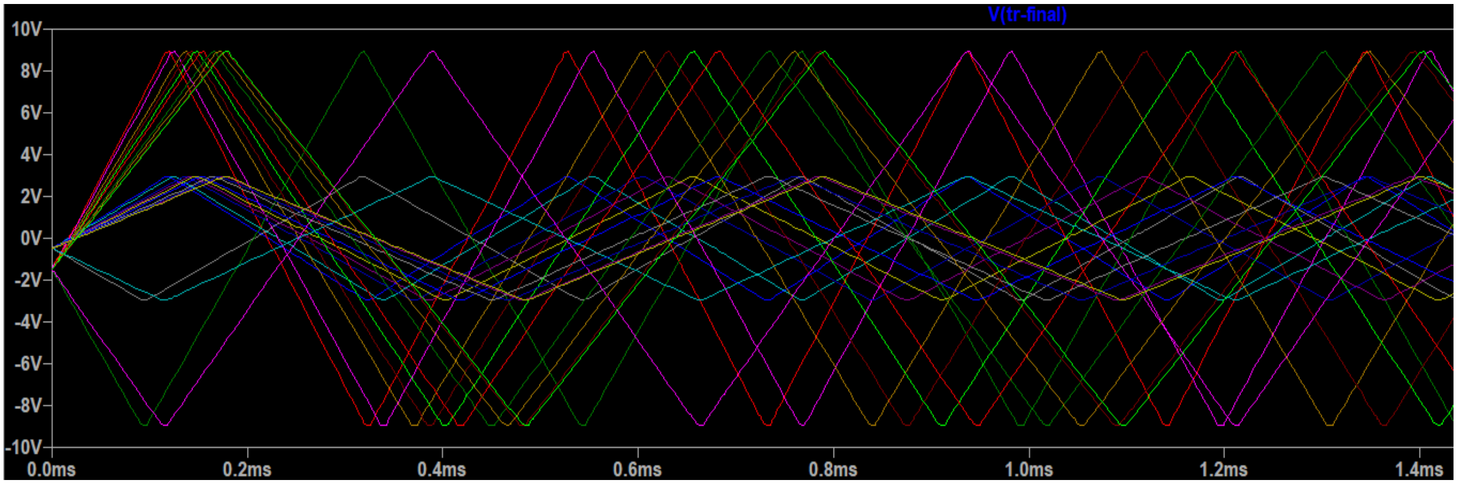
This analysis is performed in order to determine the behaviour of the circuit to all stimulus inside the given range. For this we will sweep 2 components, the potentiometer that controls the frequency and the potentiometer in charge of the amplitude of the triangular signal.

a) Frequency

I denoted this potentiometer with R8 in my circuit and the value that was previously computed for it is 5.22 kΩ. After standardization, we are left with 5.1 kΩ.

LTSpice command: **.step param R8 1 5100 500**

Start from 1Ω (can not start from 0 because of short circuit risks) and sweep up to 5100Ω, incrementing by 500Ω per step.



To interpret the results we will read the frequencies of the shortest and longest triangles from the simulation and check whether they fit between the given bounds of [1600Hz, 2400Hz].

In terms of time, the red triangle is the shortest one, which means that it has the greatest frequency, measured at:

Freq: 2.4490617KHz

Not quite 2400 Hz but it is not expected to be exact. This is due to the fact that no component is ideal, so there are losses that are unaccounted for.

As for the longest triangle in terms of time we will use the green one for measurements:

Freq: 1.63125KHz

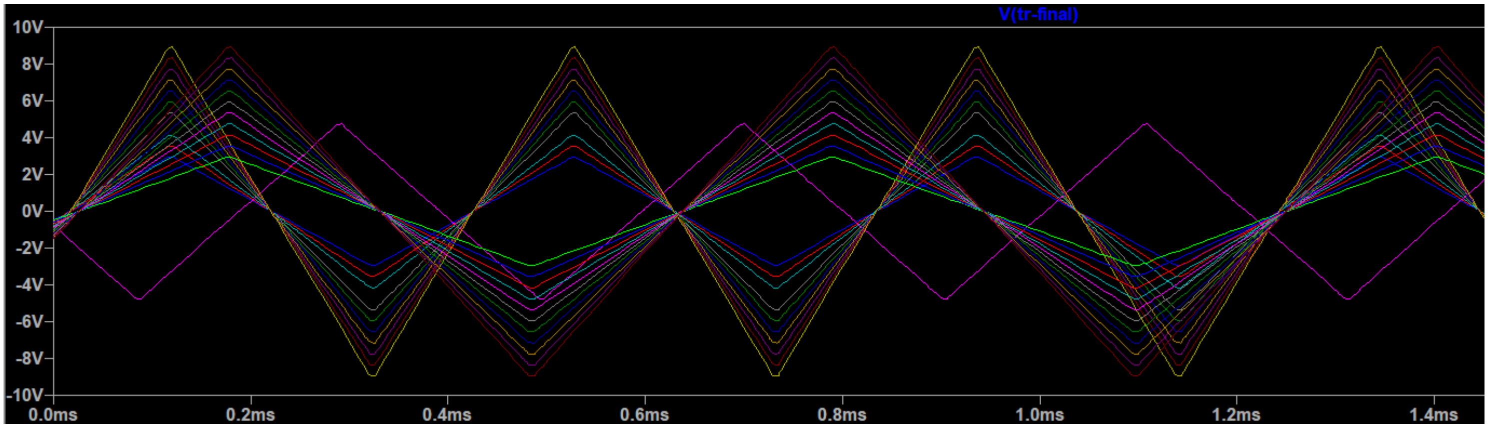
We can see that the circuit we designed gets sufficiently close to the values in the task.

b) Amplitude

Next up is the potentiometer on the negative feedback loop of the amplifier for the triangular wave, R9. Its computed value is 2kΩ.

LTSpice command: **.step param R9 1 2000 200**

Start from 1Ω and sweep up to 2000Ω, incrementing by 200Ω per step.



This time we will read the amplitudes of the outmost 2 triangles on display.

Vert: 2.9409061V   Vert: 8.8575662V

Again, this is pretty close but not exact. As for the rectangular signal, its amplitude must not be adjustable and its frequency is equal to the one of the triangular signal. To conclude the performance analysis, we can see that the designed circuit respects the requirements for both frequency and amplitude.

3) Monte Carlo

This analysis is useful to provide statistical data predicting the effect of randomly varying component values within specified tolerance limits. In the circuit I designed I chose all components to allow a ± 5% tolerance margin.

```
.param tol = 0.05
```

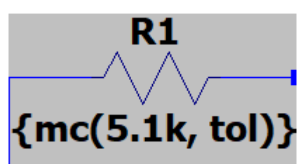
We will run the simulation 10 times, each time changing the values of the components at random, without exceeding the tolerance interval.

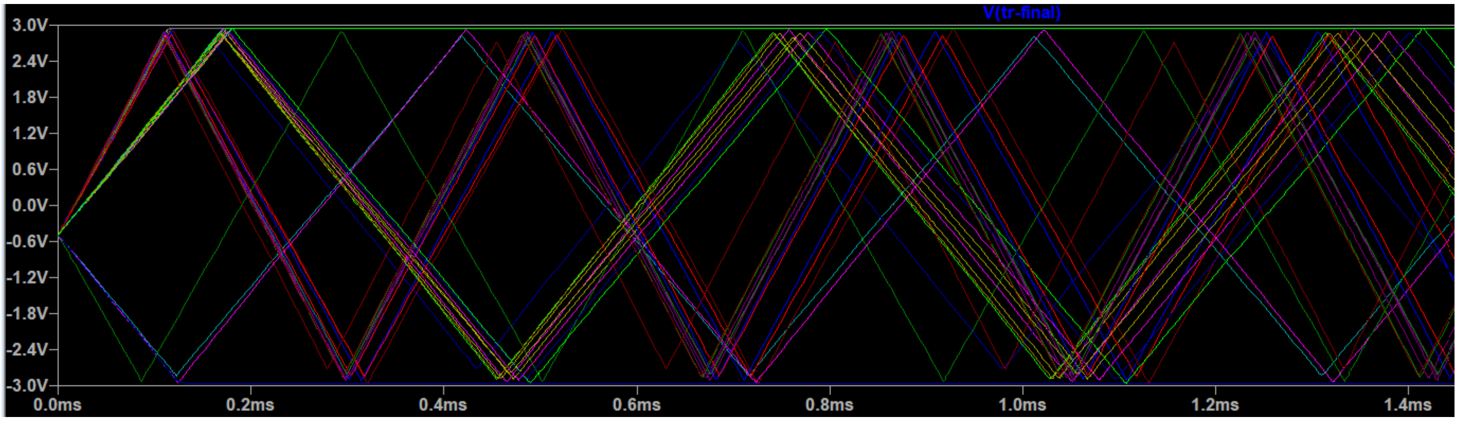
```
.step param run 0 10 1
```

a) <u>Frequency</u>

First we will look at the effect on frequency, so in order to eliminate some lines from the graphic for a better reading, I have set the value of the potentiometer in charge of the amplitude of the triangular wave to a fixed value, displaying only the waveforms with a 3V amplitude.

LTSpice syntax to account for tolerances using a Monte Carlo distribution:





Unfortunately, LTSpice does not have a built-in function to read the frequency, so I will do it manually, using 2 cursors, to see how much the frequency was affected when accounting for tolerance. The previous simulations and computations have shown that the initial frequency range was [1630 Hz, 2450Hz].

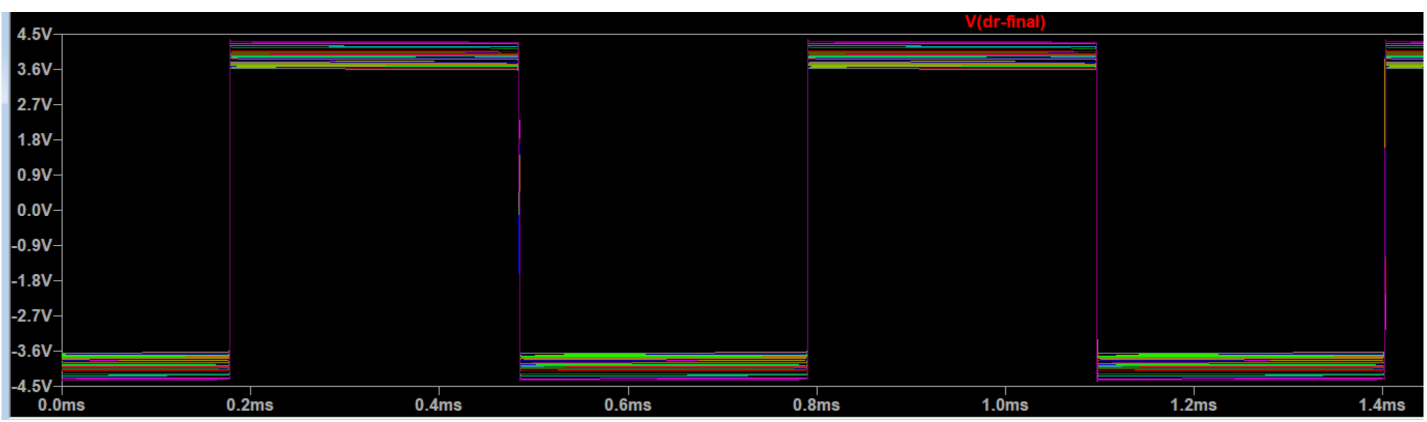
The lower limit of f_{max} is now 2420 Hz, while the upper limit is 2900 Hz.

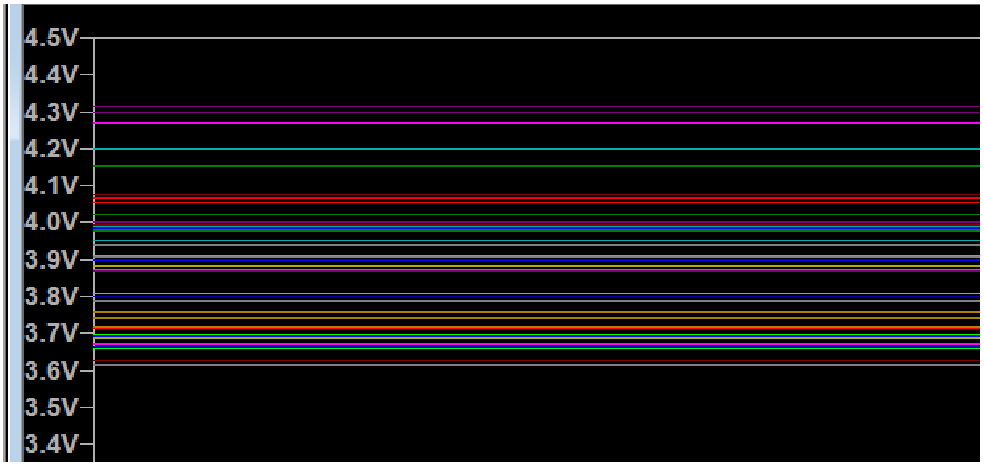
f_{min} is now bounded between 1590 Hz and 1745 Hz.

b) Amplitude

Next up, we will look at the rectangular signal, as it is easier to see the amplitude variation compared to the triangular signal. I will set the potentiometer in charge of the frequency to a fixed value to make the simulation more readable.

We expect to see values for the amplitude around 4V, or 3.86V as computed previously.





=> the amplitude varies between [3.6V, 4.3V] when accounting for tolerances

4) Worst Case

This analysis is similar to Monte Carlo, the difference being that for this one we will not use a distribution of values over a tolerance interval, but instead it computes only the values using the maximum tolerance, so either the nominal value – tolerance or the nominal value + tolerance. A third run with just the nominal value is also handy to have for reference.

However, LTSpice does not have this function built-in, so we will write it from scratch.

```
.func binary(run,index) floor(run/(2**index))-2*floor(run/(2**(index+1)))
```

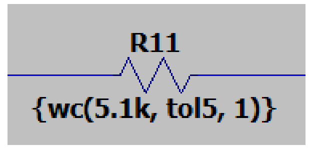
The *binary* function toggles each *index*'ed componment in the simulation so that all possible combination of *nom*(1+tol)* and *nom*(1-tol)* are simulated. Note that the index of components should start with *0.* The following table highlights the operation of the *binary()* function with results to each *index* and *run*, where 1 represents *nom*(1+tol)* and 0 represents *nom*(1-tol)*.

Run	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Index 0 (R4)	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Index 1 (R1)	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
Index 2 (R2)	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
Index 3 (R3)	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

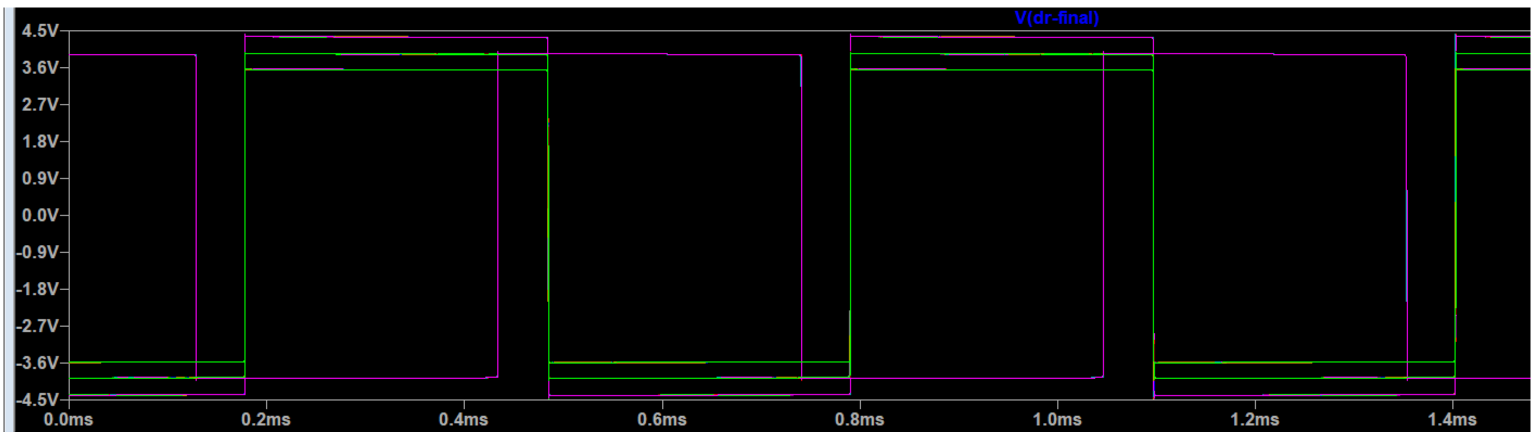
```
.func wc(nom,tol,index) if(run==numruns,nom,if(binary(run,index),nom*(1+tol),nom*(1-tol)))
```

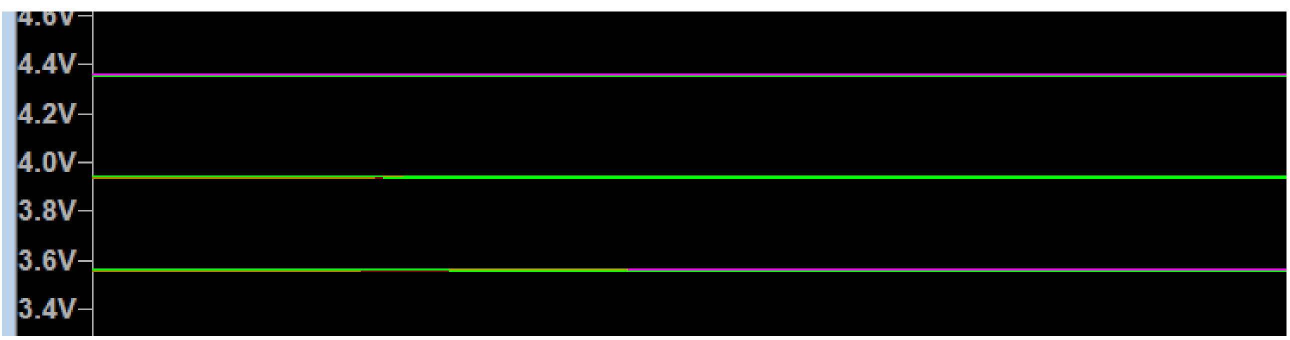
The number of runs is determined by 2^n +1, where n is the number of indexed components. This number allows us to run every possible combination of values.

LTSpice syntax:

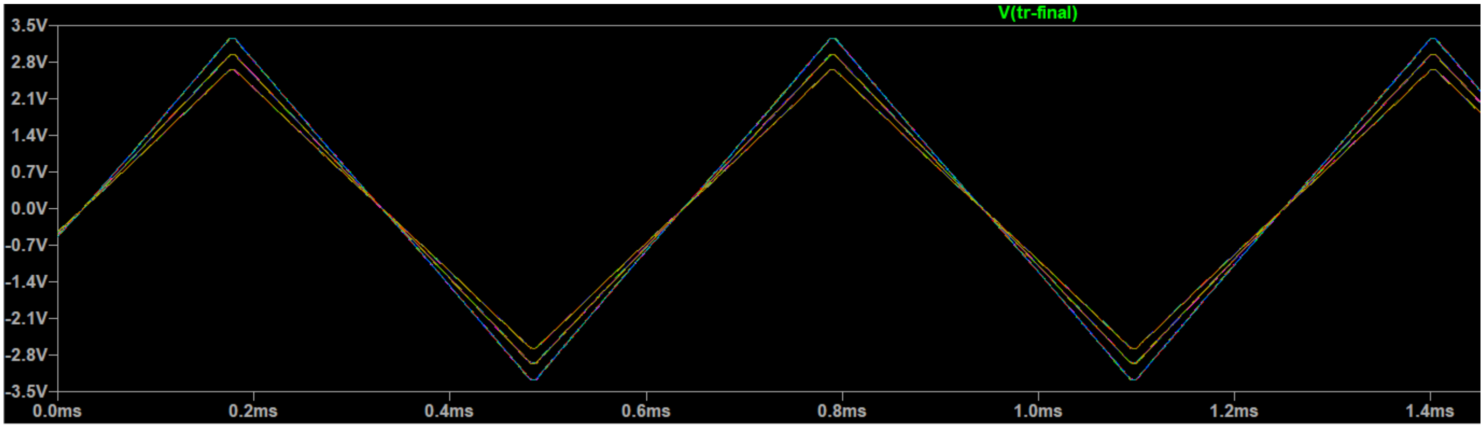


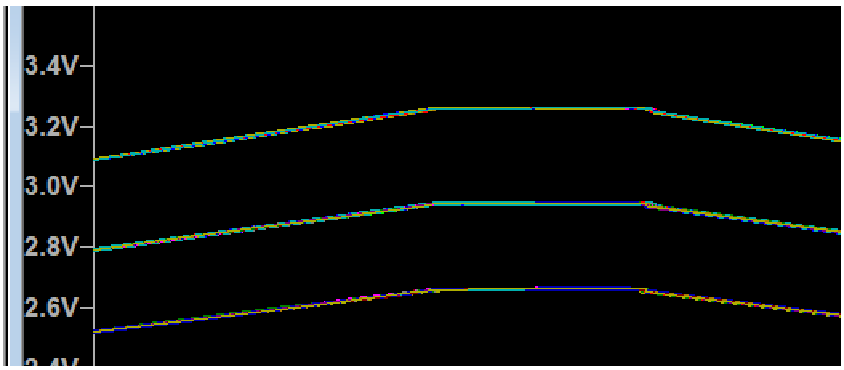
a) Amplitude



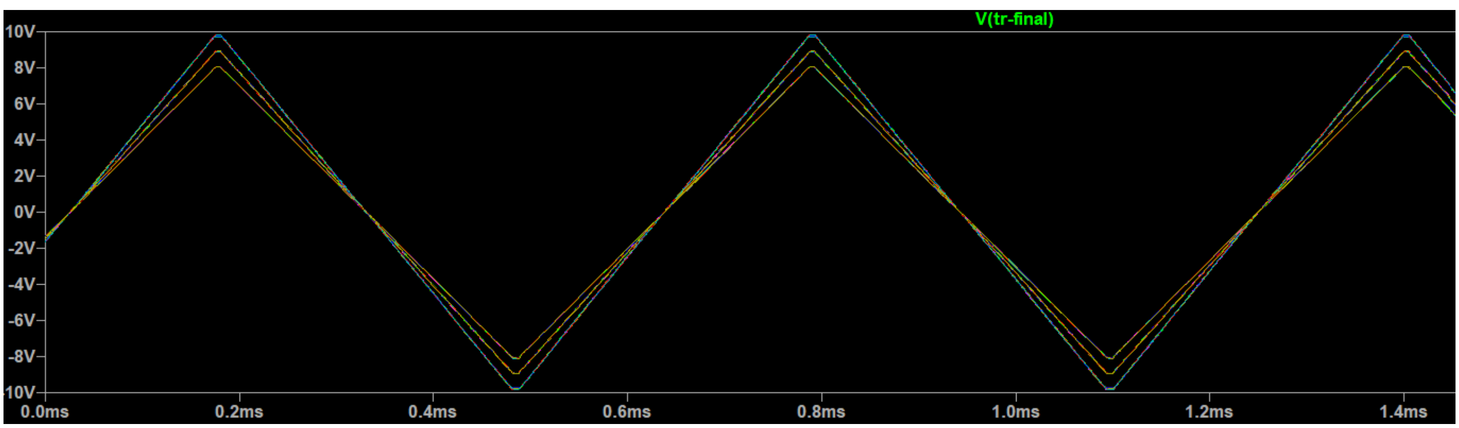


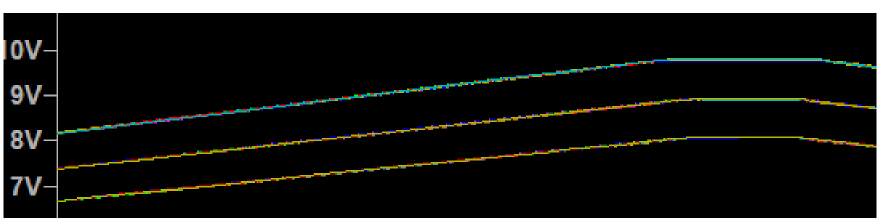
Worst case for the amplitude of the rectangular signal: [3.58V, 4.35V]





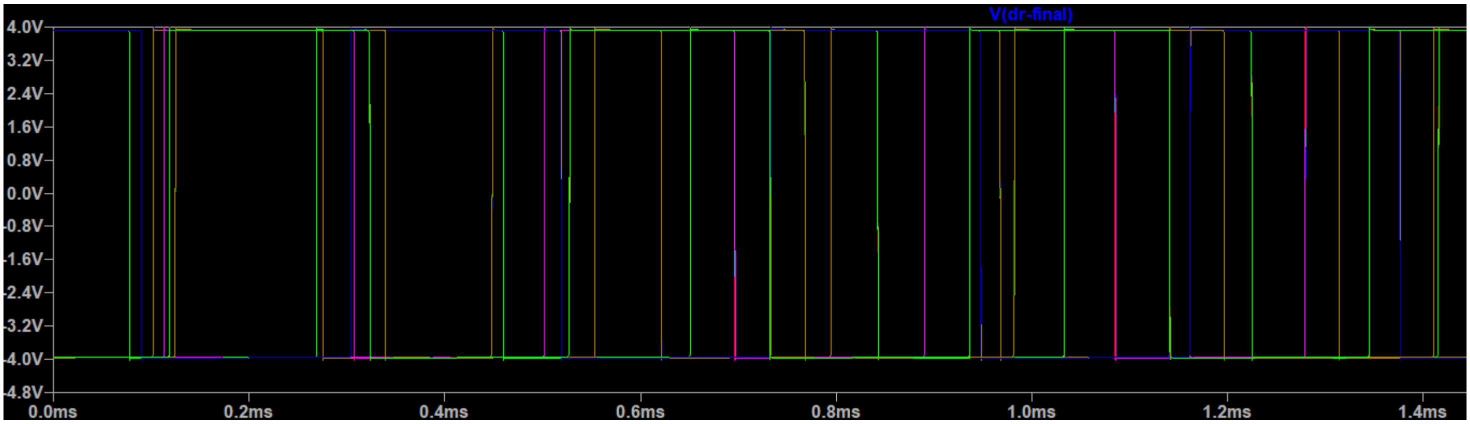
Worst case for the lower bound of the amplitude of the triangular signal: [2.62V, 3.25V]



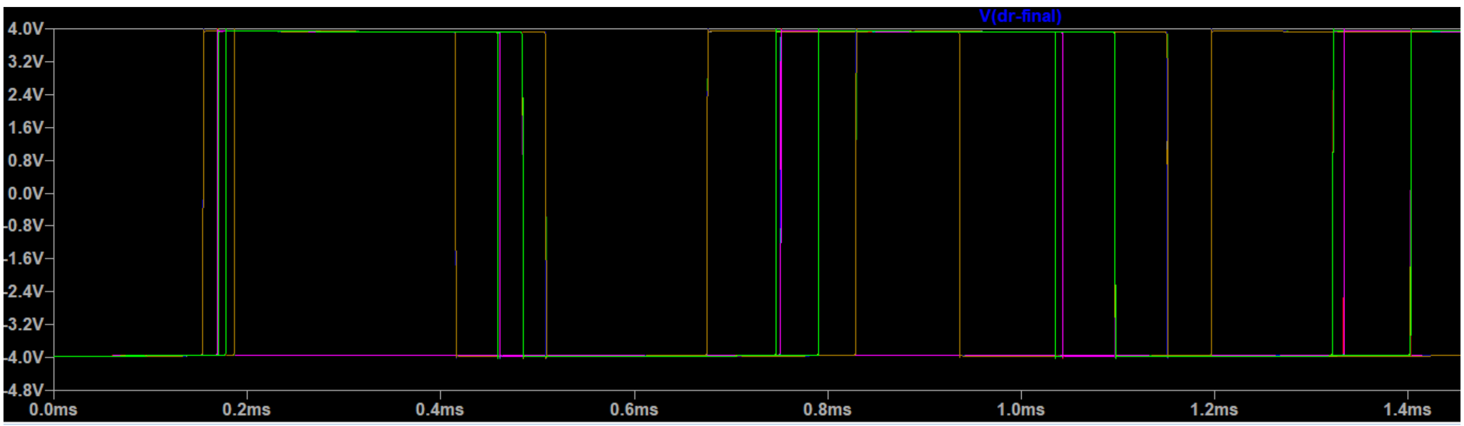


Worst case for the upper bound of the amplitude of the triangular signal: [8.05V, 9.8V]

b) <u>Frequency</u>



Worst case for the upper bound of the frequency: [2210 Hz, 2630 Hz]



Worst case for the lower bound of the frequency: [1333 Hz, 1920 Hz]

In conclusion, these are the most extreme values that the circuit we designed can reach. Although they do not respect the exact parameters that were given, we can not expect them to be perfect because no component is ideal, we didn't account for parasitic capacitances and inductances that may appear and we did not use the precise values computed through calculations. We used sets of standard values for resistors and capacitors that are actually available for purchase in the real world, so there will always exist a slight margin of error. Our job when designing circuits is merely to reduce this as much as possible without going overboard with the budget.

Bill of Materials

--- Bill of Materials ---

Ref.	Mfg.	Part No.	Description
C1	--	--	capacitor, 10nF
D1	OnSemi	MURS320	diode
D2	OnSemi	MURS320	diode
D3	OnSemi	MURS120	diode
D4	OnSemi	MURS120	diode
Q1	Rohm	2SCR513P	bipolar transistor
Q2	Rohm	2SAR513P	bipolar transistor
Q3	Rohm	2SCR544P	bipolar transistor
Q4	Rohm	2SAR542P	bipolar transistor
R1	--	--	resistor, 0
R2	--	--	resistor, 0
R3	--	--	resistor, 3K
R5	--	--	resistor, 0
R6	--	--	resistor, 1K
R7	--	--	resistor, 3.9K
R8	--	--	resistor, 1
R9	--	--	resistor, 0
R10	--	--	resistor, 15K
R11	--	--	resistor, 5.1K
R12	--	--	resistor, 20
R13	--	--	resistor, 200
R14	--	--	resistor, 200
R16	--	--	resistor, 20
R17	--	--	resistor, 390
R18	--	--	resistor, 390
U1	Analog Devices	AD8040	integrated circuit
U2	Analog Devices	AD8040	integrated circuit
U3	Analog Devices	AD8040	integrated circuit
U4	Analog Devices	AD8040	integrated circuit
U5	Analog Devices	AD8040	integrated circuit
U6	Analog Devices	AD8040	integrated circuit
U7	Analog Devices	AD8040	integrated circuit
U8	Analog Devices	AD8040	integrated circuit

References

http://www.bel.utcluj.ro/dce/didactic/fec/20_nonsinusoidal_oscillators.pdf

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http://www.bel.utcluj.ro/dce/didactic/fec/14_power_amplifier_class_B_AB.pdf

https://www.rfcafe.com/references/electrical/capacitor-values.htm

https://www.electronics-notes.com/articles/electronic_components/resistors/standard-resistor-values-e-series-e3-e6-e12-e24-e48-e96.php

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