Computer Aided Design
Rectangular and Triangular Signal Generator

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1. Introduction

1.1. About OrCAD Capture

OrCAD Capture is a schematic capture application, and part of the OrCAD circuit design suite. It includes a component information system (CIS), that links component package footprint data or simulation behavior data, with the circuit symbol in the schematic, [8].

SPICE ("Simulation Program with Integrated Circuit Emphasis") is a general-purpose, open-source analog electronic circuit simulator. It is a program used in integrated circuit and board-level design to check the integrity of circuit designs and to predict circuit behavior, [9].

1.2. Project requirements

Design a rectangular and triangular signal generator with the following specifications:

	Frequency	Rectangular Signal Amplitude	Triangular Signal Amplitude	Power Supply Voltage	Load Impedance
Description	adjustable	constant	adjustable	constant	constant
Value(s)	[1.8 kHz, 9.6 kHz]	8 V	[4 V, 6 V]	±15 V	25 Ω

2. Theoretical Approach

2.1. Circuit Description

The circuit is a function generator. It has to give at the first output (outs8) a **rectangular signal** with a **fix amplitude** of **8 V** and at the second output (out) a **triangular signal** with an **adjustable amplitude** between **4 V** and **6 V**. The frequency of the circuit must also be adjustable between **1.8 kHz** and **9.6 kHz**. The **supply voltage** must be **±15 V** and finally the **load resistance** must be **25 Ω.**

The working principle of the circuit is based on an astable multivibrator formed by a Trigger Schmitt whose output will generate a rectangular signal based on the comparison between the voltages from v+ and v-. When the voltage in the v+ is greater than the voltage in the v-, the comparator will give +VCC in the output; in the other case, when v- is greater than v+, the comparator will give -VCC in the output. After the rectangular wave is generated, it will be applied in the inverter pin of the integrator (2^{nd} OA) where it will be integrated, and therefore giving a descending linear growth when the rectangular signal is positive and an ascending linear growth on the negative half of the rectangular signal, [1][7].

After both the rectangular and the triangular signals are generated the signal will go in the Voltage Amplifier block, where we can adjust the amplitude of the triangular signal in the asked interval using the potentiometer P33, [4].

Finally, I have used a class AB power amplifier in order to increase the current in the output so the circuit could work with a small load resistance (25Ω). The class AB power amplifier works on two NPN and PNP transistors, the first one being ON for the positive half of the signal and the other one being ON for the negative half of it. The two diodes makes the difference between a class AB amplifier and a class B amplifier, they will bias the transistors so the base-emitter voltage will not make distortions in the output signal when the input signal is between $-V_{BE}$ and $+V_{BE}$. The two resistors should allow the currents in the diodes and in the bases of the transistors, even for the maximum output current, [1].

2.2. Electrical Scheme

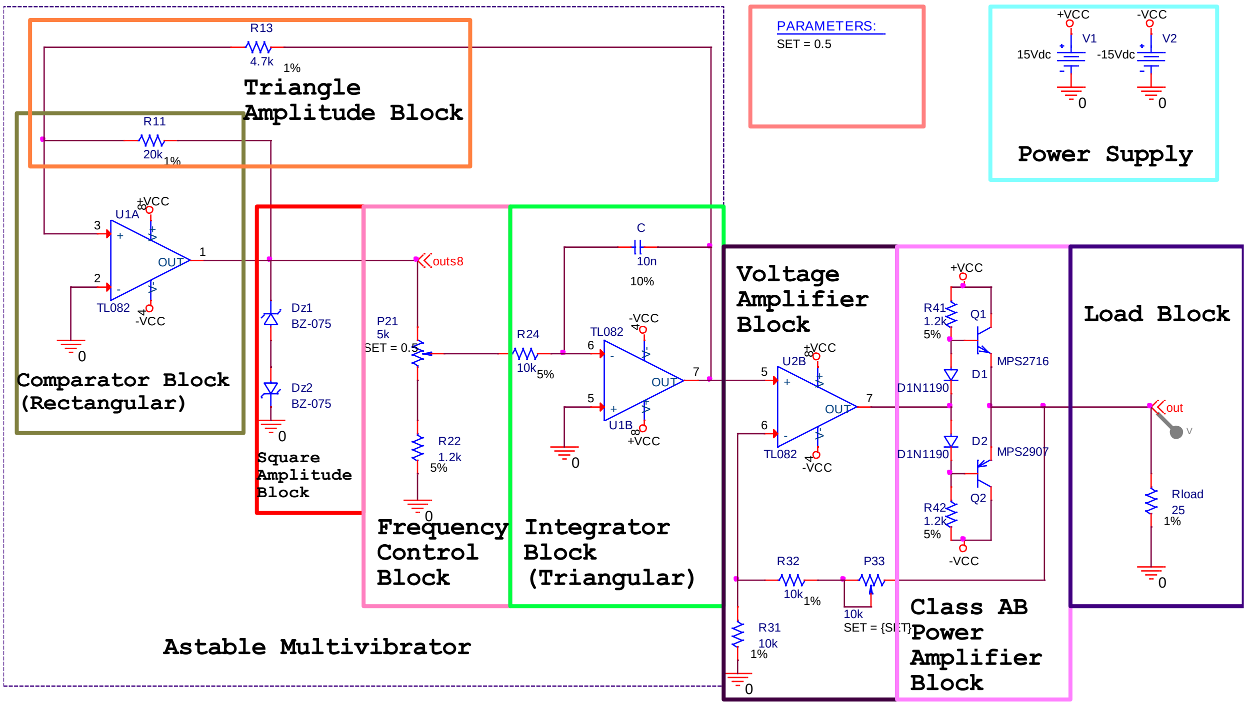


Figure 1 – Electrical Scheme

2.3. Circuit Block Diagram

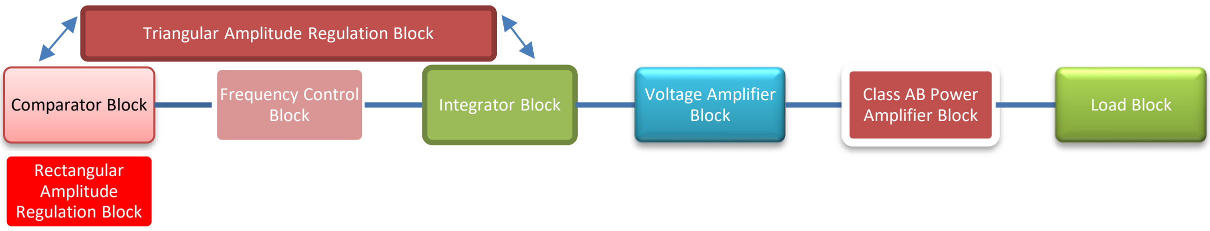


Figure 2 - Block Diagram

2.3.1. Comparator Block (Schmitt Trigger)

A Schmitt trigger is a comparator circuit implemented by applying a positive feedback to the noninverting input of an operational amplifier. This block converts an analog input signal to a digital output signal by comparing the non-inverting input and the inverting one, therefore generating a rectangular signal, as presented in [7].

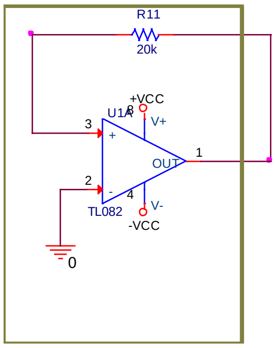


Figure 3 - Comparator Block

2.3.2. Rectangular Amplitude Regulation Block

This block is composed by two Zener diodes with Vz = 7.5 V placed in „anti” series (back to back) and it’s role is to set the output voltage from the Schmitt trigger (the rectangular signal) to approximately 8V. For the positive part of the rectangular signal Dz1 will be in reversed bias region and Dz2 will be in forward bias, therefore the voltage across Dz1 will be 7.5 V and the voltage across Dz2 will be 0.6 V, setting the positive half to about 8.1 V. For the negative part of the rectangular signal Dz1 will be in forward bias, while Dz2 will be in reversed bias, thus the voltage across Dz1 will be -0.6 V and the voltage across Dz2 will be -7.5 V, setting the negative half to about -8.1 V, [4].

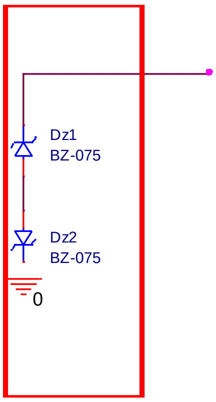


Figure 4 - Rectangular Amplitude Regulation Block

2.3.3. Frequency Control Block

The frequency for the circuit can be adjusted in this block by using the potentiometer P21. The frequency must be adjusted between 1.8 Khz and 9.6 Khz, the real frequencies will have some errors due to the losses in the circuit. The maximum and minimum ideal frequencies can be calculated, according to [1], by using the next formulas:

$$f_{max} = \frac{1}{4 \times R23 \times C} \times \frac{R11}{R13} \tag{1}$$

$$f_{min} = \frac{1}{4 \times R23 \times C} \times \frac{R11}{R13} \times \frac{R22}{R22 + P21} \tag{2}$$

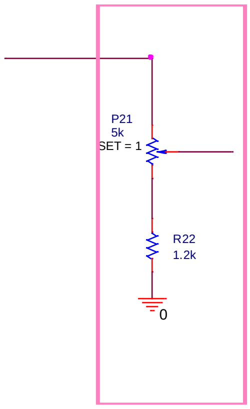


Figure 5 - Frequency Control Block

2.3.4. Triangular Amplitude Regulation Block

In this block I chose to set the amplitude of the triangular wave to one quarter of the rectangular signal's amplitude, so to about 2 V. The resistors R13 and R11 set the amplitude of the triangular signal as a fraction of the rectangular one after the next relation, according to [1]:

$$V_{Triangle} = -V_{Rectangle} \times \frac{R13}{R11} \tag{3}$$

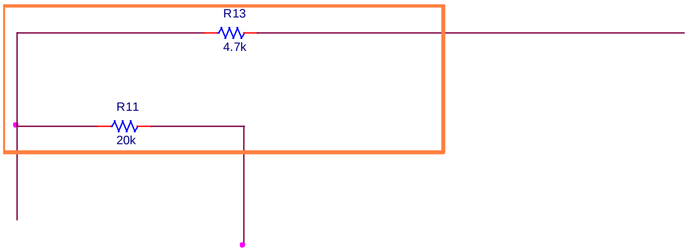


Figure 6 - Triangular Amplitude Regulation Block

2.3.5. Integrator Block

This block takes the rectangular signal after it is set to ±8 V through the inverting input of the operational amplifier and integrates it, thus generating an inverted triangular waveform. The rectangular signal integrated determines an ascending linear growth on the descending semiperiod and a descending linear growth on the ascending semiperiod. Therefore the triangular signal is generated.

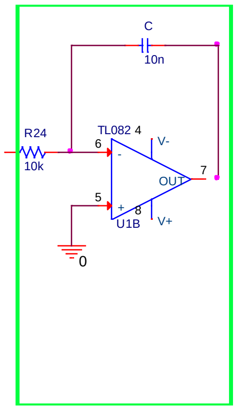


Figure 7 - Integrator Block

2.3.6. Voltage Amplifier Block

As I decided to let the amplitude of the triangular wave constant because the resistors which control the amplitude also influence the frequency in a small ratio, I need a voltage amplifier. This block takes the signal from the integrator block with an amplitude of 2 V through the non-inverting input and amplifies it with a factor of 2 up to 3, depending on the potentiometer. Therefore the triangular signal's amplitude can be adjusted between 4 V and 6 V. The formula that can be use to calculate the gain of the voltage amplifier is, according to [4] (in the circuit presented above):

$$V_{out} = V_{in} \times \left(1 + \frac{R32 + k \times P33}{R11}\right) \tag{4}$$

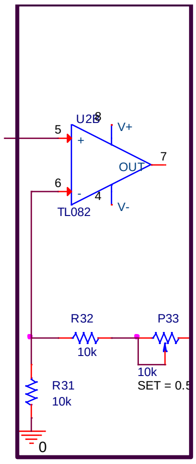


Figure 8 - Voltage Amplifier Block

2.3.7. Class AB Power Amplifier Block

A normal operational amplifier is able to give at its output a current between 20 mA to 30 mA. This current is far away from being enough to put at the output of the circuit a load resistance equal to 25 **Ω**. To fix this, I decided to place a class AB Power Amplifier to boost the current in the operational amplifier's output for it to maintain a voltage up to 6 V, if the resistor is 25 **Ω** and the voltage is 6 V, according to Ohm's Law we need a current of 240 mA. I used a class AB amplifier instead a class B one because of the fact that the last one produces some distortions when the input voltage is between -V_{BE} and +V_{BE}; therefore we need to bias the transistors so that we do not lose that base-emitter voltage across the transistors. For this, the class AB power amplifier uses 2 diodes that bias the transistors with the necessary voltage in order to compensate the base-emitter voltage of approximate 0.6 V. Therefore, according to [3], the output voltage will be:

$$v_{out}(t) = v_{in}(t) + V_{D1} - V_{BEn} \approx v_{in}(t), \qquad for\ v_{in}(t) > 0 \tag{5}$$

and,

$$v_{out}(t) = v_{in}(t) + V_{D2} - V_{BEp} \approx v_{in}(t), \qquad for\ v_{in}(t) < 0 \tag{6}$$

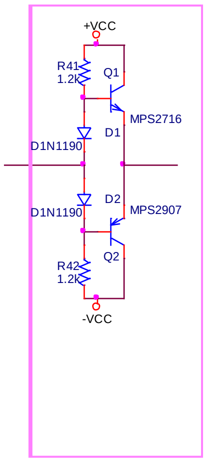


Figure 9 - Class AB Power Amplifier Block

2.3.8. Load Block

In this block we connect the load of the circuit. The project requirements were to place a load resistance of 25 **Ω**, which implies a higher current in order to maintain the desired amplitude of the triangular signal.

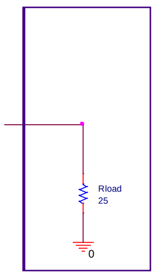


Figure 10 - Load Block

3. Circuit Design - Calculus

3.1. The amplitude of the rectangular signal

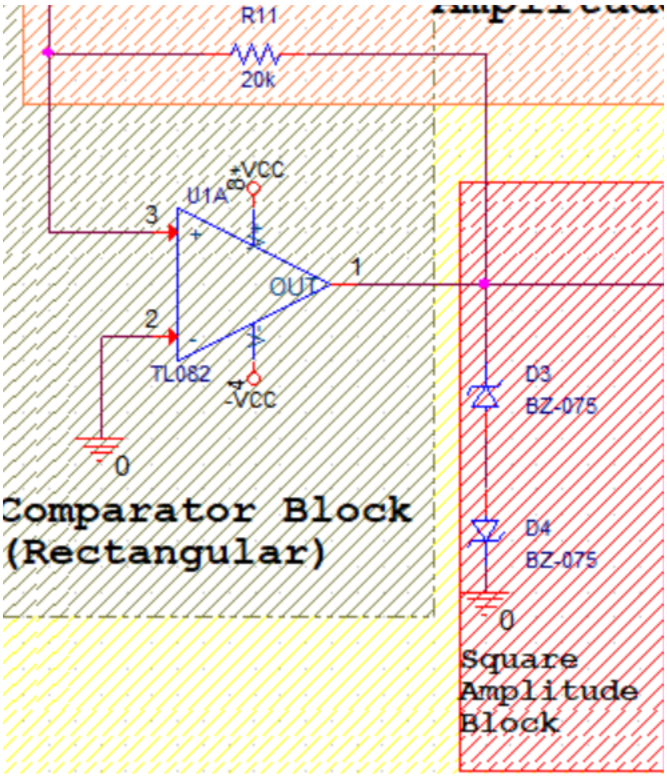


Figure 11 - How the rectangular signal's amplitude is set

In order to obtain a rectangular signal's amplitude of 8V I decided to use 2 Zener diodes with V_Z equal to 7.5 V, therefore for the positive part of the rectangular signal, Dz1 will be in reversed bias, acting like a voltage source with V_{Dz1} = 7.5 V and Dz2 will be in forward bias, acting like a normal diode with V_{Dz2} = 0.6V, see *Figure 12*; thus we have got 8.1 V. For the negative part of the rectangular signal, Dz1 will be in forward bias, acting like a normal diode with V_{Dz1} = -0.6 V, and Dz2 will be in reversed bias, acting like a voltage source with V_{Dz2} = -7.5 V, see *Figure 13*; thus we have got -8.1V for the negative part of the signal. Therefore the amplitude of the rectangular signal will be theoretically 8.1 V, but due to losses and imperfections of the diodes we have got approximately 8 V (7.9784 V), as we can see in *Figure 14*.

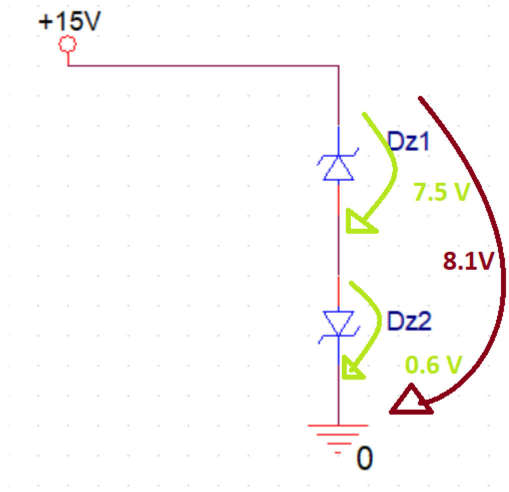


Figure 12 - The voltages on diodes when the rectangular signal is positive

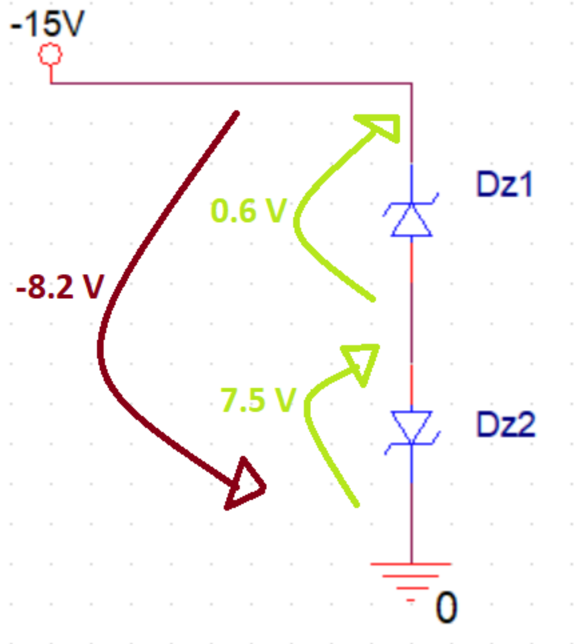


Figure 13 - The voltages on diodes when the rectangular signal is negative

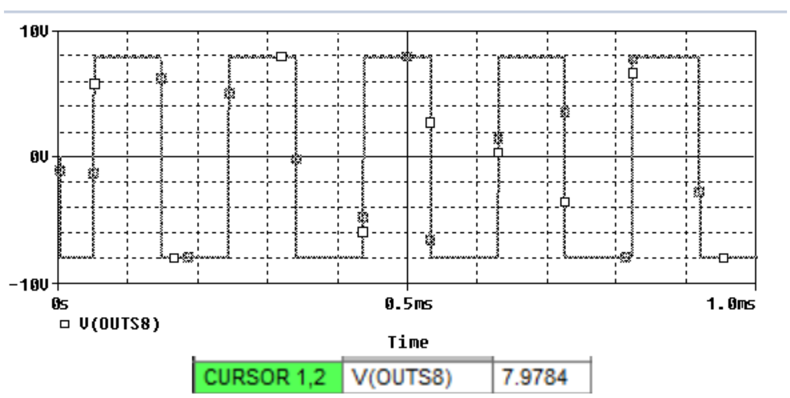


Figure 14 - The amplitude of the rectangular signal

3.2. The amplitude of the triangular signal

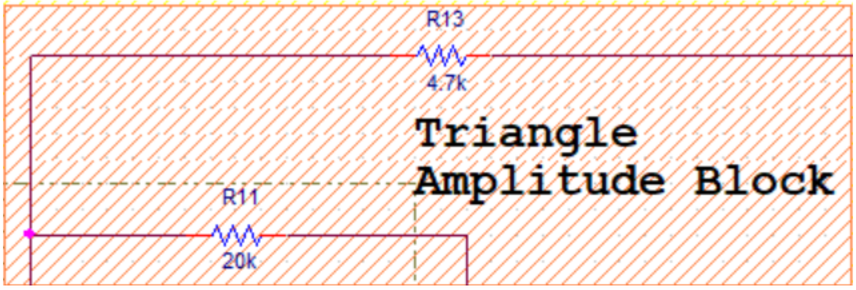


Figure 15 - How the triangular signal's amplitude is set

According to [1] you can adjust the triangular signal's amplitude by varying the resistors R13 and R11 in the circuit, as you can see in (7) and (8), but that will affect the frequency. In order to avoid that, I decided not to use a potentiometer, thus letting the resistors with fix values to determine an amplitude of 2 V and after that I used a voltage amplifier to adjust the amplitude of the signal between 4 V and 6 V as you can see in *Figure 18.*

$$V_{triangleLow} = -\frac{R13}{R11} \times V_{rectangularHigh} \tag{7}$$

$$V_{triangleHigh} = -\frac{R13}{R11} \times V_{rectangularLow} \tag{8}$$

As I want the amplitude of the triangular signal to be 2 V, so that I can adjust it later, I will choose R13 and R11 so that their ratio will be a quarter of the rectangular signal (of amplitude 8 V). Therefore R13 should be 5 kΩ and R11 should be 20 kΩ so that:

$$V_{triangleLow} = -\frac{5\ \text{k}\Omega}{20\ \text{k}\Omega} \times 8\ V = -\frac{1}{4} \times 8\ V = -2\ V \tag{9}$$

$$V_{triangleHigh} = -\frac{5\ \text{k}\Omega}{20\ \text{k}\Omega} \times (-8\ V) = -\frac{1}{4} \times (-8\ V) = 2\ V\ , \tag{10}$$

but due to some errors between the ideal and the real circuit, for R13 = 5 kΩ, the amplitude will not be 2 V, but about 2.1 V, which amplified 2 to 3 times will give a bigger error, so I needed to make R13 a little bit smaller. That is why I chose R13 = 4.7 kΩ, thus the amplitude will be 1.9902 V. We can observe in *Figure 16* and *Figure 17* the small difference in amplitudes.

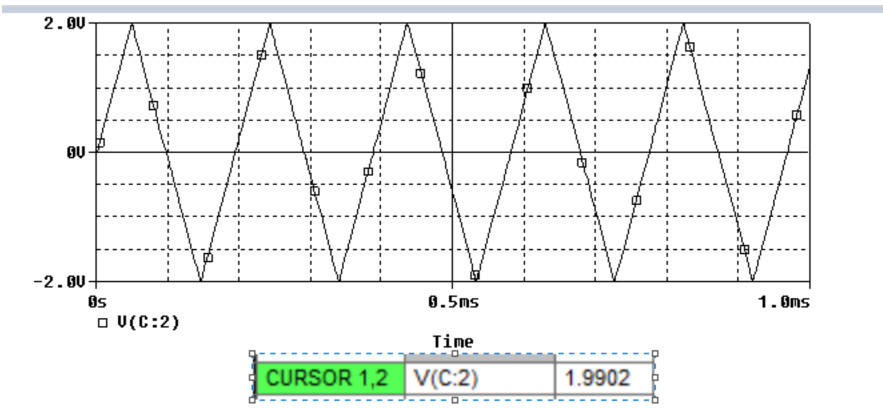


Figure 16 - The amplitude with 4.7 kΩ resistor

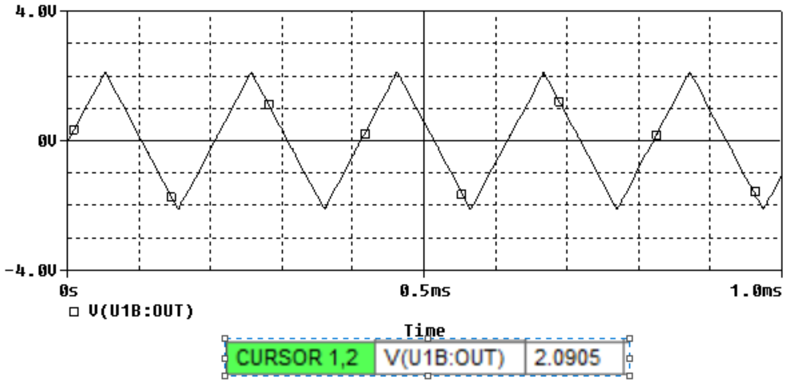


Figure 17 - The amplitude with 5 kΩ resistor

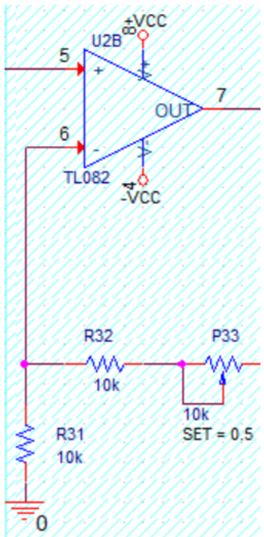


Figure 18 - The Voltage Amplifier

In *Figure 18* it is presented the voltage amplifier that I used in order to adjust the amplitude of the triangular signal between the limits that I was asked. The gain for this circuit, see (11), will be between 2 and 3 by adjusting the potentiometer P33, [1].

$$A_V = \left(1 + \frac{R32 + k \times P33}{R31}\right) \tag{11}$$

In order to obtain an amplitude of 4 V(more precise 3.9891 V) as presented in *Figure 19*, I need a gain of 2. It means that the division between the feedback resistance and the resistance of the resistor connected to ground should be equal to 1, therefore I choose R32 = R31 = 10 kΩ. To obtain an amplitude of up to 6 V(more precise 5.9716 V) as presented in *Figure 20*, I connected the potentiometer P33 with a value of 10 kΩ, so that when the set is on 1 (the whole value of the potentiometer is taken into account), the division between the feedback resistance (R32 + P33) and the resistance of the resistor connected to ground will be 2, and therefore the gain will be 3. When we adjust the potentiometer we can obtain values between 4 V and 6 V, see (11).

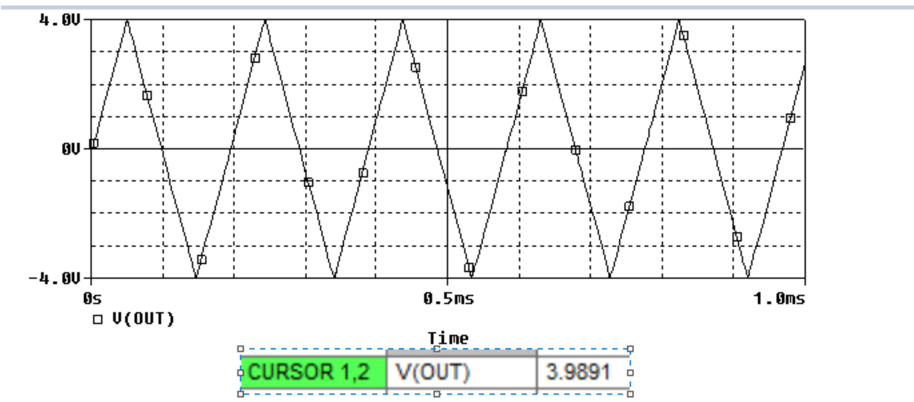


Figure 19 - The amplitude of the triangular signal when set (k)=0

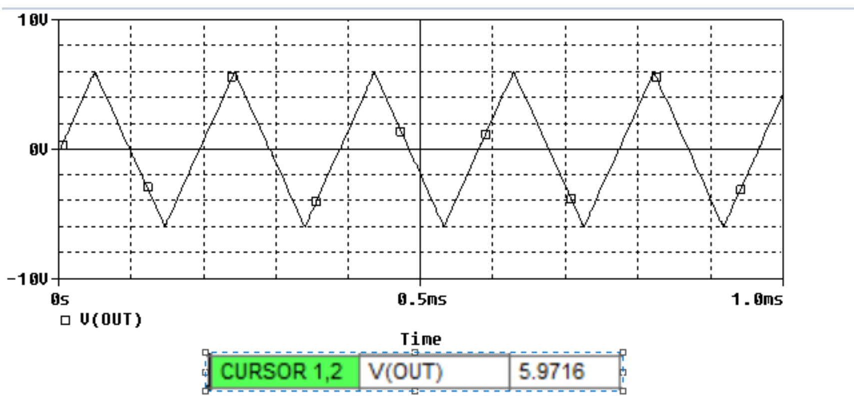


Figure 20 - The amplitude of the triangular signal when set (k)=1

3.3. Frequency adjustment

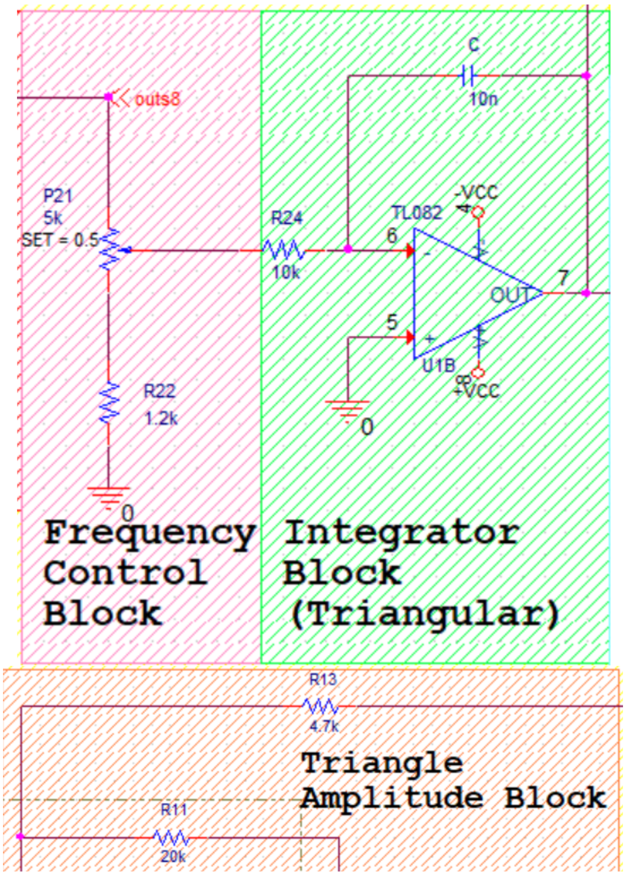


Figure 21 - How to set the frequency of the circuit

According to [1], the formulas to determine the highest and the lowest frequency that can be set in the circuit are:

$$f_{max} = \frac{1}{4 \times R23 \times C} \times \frac{R11}{R13} \tag{12}$$

$$f_{min} = \frac{1}{4 \times R23 \times C} \times \frac{R11}{R13} \times \frac{R22}{R22 + P21} \tag{13}$$

I choose C = 10 nF, R11 and R13 need to remain the same in order to maintain the 2 V amplitude of the triangular signal.

Therefore, in order to obtain a maximum frequency of 9.6 kHz:

$$9600\ Hz = \frac{1}{4 \times R23 \times 10^{-8}\ F} \times \frac{20\ k\Omega}{4.7\ k\Omega} \quad (14)$$

$$R23 = \frac{10^8}{4 \times 9600} \times 4.2\ [\Omega]\ \approx 10.9\ k\Omega \quad (15)$$

In order to use standardized values for the resistors and because of some parasitic effects in the circuit, the proper value for R23 will be 10 kΩ.

☑	Period(V(out))	104.07111u
☑	1/Period(V(out))	9.60881k

Figure 22 - The period and the frequency when set=0

To obtain the minimum frequency of 1.8 kHz (the theoretical value of R23 remains the same in the calculations):

$$1800\ Hz = \frac{1}{4 \times 10.9 \times 10^3\ \Omega \times 10^{-8}\ F} \times \frac{20\ k\Omega}{4.7\ k\Omega} \times \frac{R22}{R22 + P21} \quad (16)$$

$$\frac{R22 + P21}{R22} = \frac{10^3}{4 \times 10.9 \times 18} \times 4.2 = 5.35\ \approx \frac{6.2}{1.2} \quad (17)$$

Therefore it results that the numerator should be around 6.2 and the denominator around 1.2. Thus, I chose the value of R22 = 1.2 kΩ and of P21 = 5 kΩ in order to maintain the standardized values for the potentiometer and the resistor.

	Evaluate	Measurement	Value
	☑	1/Period(v(out))	1.82036k
	☑	Period(v(out))	549.34114u

Figure 23 - The period and the frequency when set=1

3.4. Class AB power amplifier design

For a load resistance this small, the output current of a regular operational amplifier would not be enough(20 up to 30 mA). Therefore I chose to use a class AB power amplifier to boost the current in the output.

3.4.1. The output current

The new current will be, according to Ohm's law:

$$I_{outmax} = \frac{Voutmax}{Rload} = \frac{6\ V}{25\ \Omega} = 240\ mA \tag{18}$$

$$I_{outmin} = \frac{Voutmin}{Rload} = \frac{4\ V}{25\ \Omega} = 160\ mA \tag{19}$$

3.4.2. Will the output voltage have distortions?

<u>For $V_{in} > 0$</u>

The first transistor (Q1) will be ON, while the second one (Q2) will be OFF. Therefore, according to Kirchhoff's Voltage Law, [3]:

$$V_{in} + V_{D1} = V_{out} + V_{BEn} \tag{20}$$

It results:

$$V_{in} + 0.6\ V = V_{out} + 0.6\ V => V_{in} = V_{out} \tag{21}$$

<u>For $V_{in} < 0$</u>

The first transistor (Q1) will be OFF, while the second one (Q2) will be ON. Therefore, according to Kirchhoff's Voltage Law:

$$V_{in} - V_{D2} = V_{out} - V_{BEp} \tag{22}$$

Finally:

$$V_{in} - 0.6\ V = V_{out} - 0.6\ V => V_{in} = V_{out} \tag{23}$$

Therefore, the distortions that we can observe using a class B power amplifier will not be present using a class AB one because of the biasing with diodes. As we can see in the Voltage

Transfer Characteristic presented below, in *Figure 24*. In the simulation profile, I made a DC sweep in which I varied the source Vin with a start value of 0 V, end of 6 V and an increment of 0.1 V. In the end we can see the voltage transfer characteristic Vout(Vin) in which it is clear that we have no distortions and the two voltages are equal.

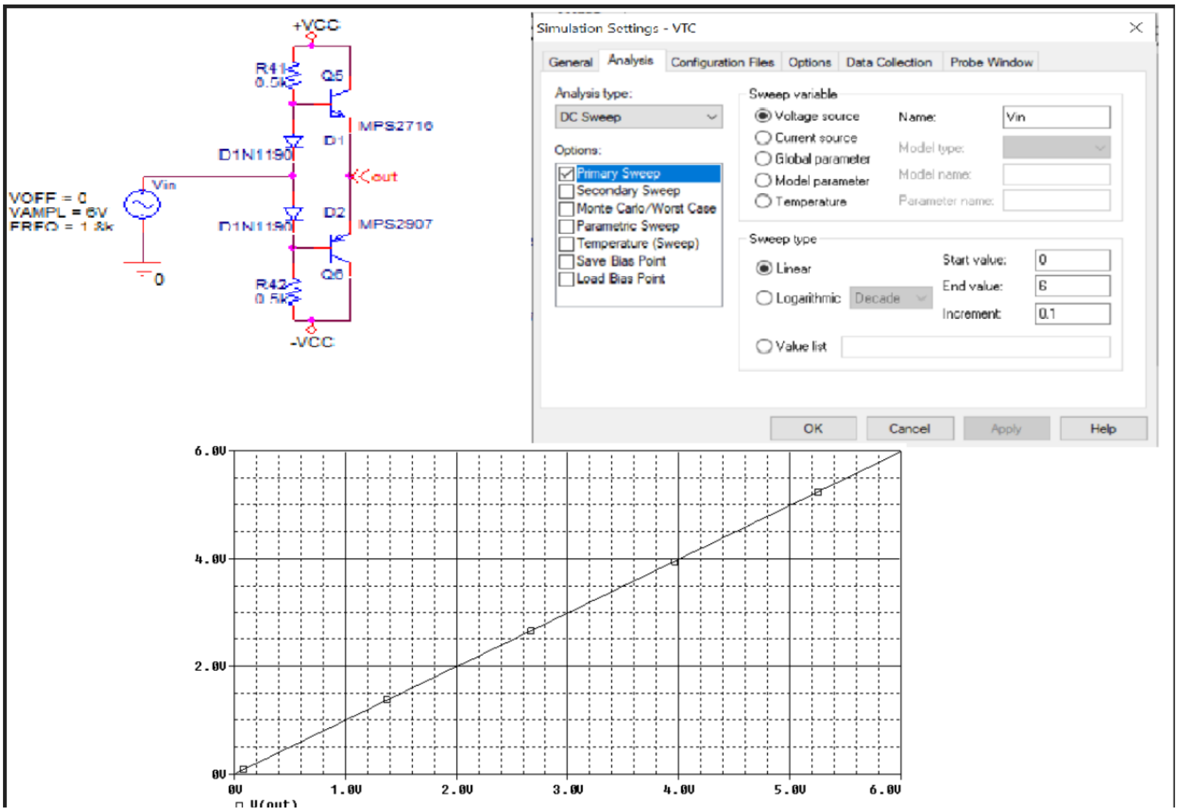


Figure 24 - Voltage Transfer Characteristic

3.4.3. The resistors

The resistors R41 and R42 should allow the currents in the diodes and in the bases of the transistors even for the maximum output current so, according to [3]:

$$I_{Csat} = \frac{V_{CC}}{2 \times R_{Load}} = \frac{15}{50} = 300\ mA \tag{24}$$

$$I_{bias} = 0.02 \times I_{Csat} = 0.02\ \times 0.3 = 0.006\ A \tag{25}$$

$$\mathrm{R41} = \mathrm{R42} = \frac{V_{CC} - 2 \times V_{BE}}{2 \times I_{bias}} = \frac{15\ V - 1.2\ V}{0.012\ A} = 1150\ \approx 1.2\ k\Omega \tag{26}$$

3.4.4. The efficiency of the class AB power amplifier

The average efficiency (denoted forward with η) will be, according to [1]:

$$\eta = \frac{P_O}{P_{PS}} \tag{27}$$

$$P_{PS} = P_{PS}^{+} + P_{PS}^{-} = \frac{2}{\pi} \times \frac{V_{CC} \times V_O}{R_L} \tag{28}$$

$$P_O = V_{Orms} \times I_{Orms} = \frac{V_O^2}{2R_L} \tag{29}$$

Therefore:

$$\eta = \frac{V_O^2}{2R_L} \times \frac{\pi}{2} \times \frac{R_L}{V_{CC} \times V_O} = \frac{\pi}{4} \times \frac{V_O}{V_{CC}}, \tag{30}$$

where Vo is the amplitude of the output signal.

The maximum efficiency (denoted forward with η_{max} of this amplifier will occur when $V_O = V_{CC}$, [3]:

$$\eta_{max} = \frac{\pi}{4} \times \frac{V_{CC}}{V_{CC}} = \frac{\pi}{4} \approx 78.5\% \tag{31}$$

The efficiency of **this circuit** will be, from (30):

$$\eta_{low} = \frac{\pi}{4} \times \frac{4\ V}{15\ V} = \frac{\pi}{4} = 20.9\% \tag{32}$$

$$\eta_{high} = \frac{\pi}{4} \times \frac{6\ V}{15\ V} = \frac{\pi}{4} = 31.4\% \tag{33}$$

4. Standardization

4.1. What I needed

In this circuit, I used 3 TL082 operational amplifiers. I chose to use this operational amplifier for its high slew rate (the rectangular signal need to have very low fall and rise times) and because it works well with ±15 V (max. rating ±18 V) voltage supply. I also used 2 BZ-075 Zener diodes with Zener voltage 7.5 V, 2 D1N1190 diodes for biasing the transistors in the power amplifier, 2 general purpose BJT transistors: MPS2716 (n-type) transistor and its pair MPS2907 (p-type) for the power amplifier; 1 capacitor of 10 nF, 7 resistors of different values, 2 potentiometers of 5 kΩ, respectively 10 kΩ and 2 DC voltage sources.

4.2. Datasheets

4.2.1. Operational Amplifier TL082

TEXAS INSTRUMENTS TL082-N

www.ti.com SNOSBW5C – APRIL 1998 – REVISED APRIL 2013

TL082 Wide Bandwidth Dual JFET Input Operational Amplifier

Check for Samples: TL082-N

FEATURES

- Internally Trimmed Offset Voltage: 15 mV
- Low Input Bias Current: 50 pA
- Low Input Noise Voltage: 16nV/√Hz
- Low Input Noise Current: 0.01 pA/√Hz
- Wide Gain Bandwidth: 4 MHz
- High Slew Rate: 13 V/µs
- Low Supply Current: 3.6 mA
- High Input Impedance: 10^{12}Ω
- Low Total Harmonic Distortion: ≤0.02%
- Low 1/f Noise Corner: 50 Hz
- Fast Settling Time to 0.01%: 2 µs

DESCRIPTION

These devices are low cost, high speed, dual JFET input operational amplifiers with an internally trimmed input offset voltage (BI-FET II™ technology). They require low supply current yet maintain a large gain bandwidth product and fast slew rate. In addition, well matched high voltage JFET input devices provide very low input bias and offset currents. The TL082 is pin compatible with the standard LM1558 allowing designers to immediately upgrade the overall performance of existing LM1558 and most LM358 designs.

These amplifiers may be used in applications such as high speed integrators, fast D/A converters, sample and hold circuits and many other circuits requiring low input offset voltage, low input bias current, high input impedance, high slew rate and wide bandwidth. The devices also exhibit low noise and offset voltage drift.

Figure 25 - TL082 Datasheet

Absolute Maximum Ratings (1)(2)

Supply Voltage	±18V
Power Dissipation (3)	(4)
Operating Temperature Range	0°C to +70°C
$T_{j(MAX)}$	150°C
Differential Input Voltage	±30V
Input Voltage Range (5)	±15V
Output Short Circuit Duration	Continuous
Storage Temperature Range	−65°C to +150°C
Lead Temp. (Soldering, 10 seconds)	260°C
ESD rating to be determined.	

Figure 26 - TL082 Maximum Ratings

4.2.2. Zener Diodes and Normal Diodes

Part #: BZ075

Part Category: Diodes
Manufacturer: New Japan Radio Co., Ltd.
Description: Zener Diode, 7.5V V(Z), 5%, 1W

SPECIFICATIONS	
Status	Active-Unconfirmed
Diode Type	ZENER DIODE
Configuration	SINGLE
Dynamic Impedance-Max	6.0 ohm
JESD-609 Code	e0
Moisture Sensitivity Level	2
Number of Elements	1.0
Operating Temperature-Max	175.0 Cel
Power Dissipation-Max	1.0 W
Reference Voltage-Nom	7.5 V
Sub Category	Voltage Reference Diodes
Surface Mount	NO
Terminal Finish	Tin/Lead (Sn/Pb)
Voltage Tol-Max	5.0 %
Working Test Current	30.0 mA

Figure 27 - BZ-075 Datasheet

D1N1190	35A, 600V, General Purpose Diode

Figure 28 - D1N1190 Specifications

4.2.3. The Transistors

PARAMETER	SYMBOL	MIN	MAX	UNIT	TEST CONDITIONS	
Collector-Base Breakdown Voltage	BV_{CBO}	-60		V	I_C=-10uA	I_E=0
Collector-Emitter Breakdown Voltage	LV_{CEO}	-40		V	I_C=-10mA	I_B=0
Emitter-Base Breakdown Voltage	BV_{EBO}	-5		V	I_E=-10uA	I_C=0
Collector Cutoff Current	I_{CBO}		-20	nA	V_{CB}=-50V	I_E=0
Collector Cutoff Current	I_{CBO}		-20	uA	V_{CB}=-50V T_A=150°C	I_E=0
Collector Cutoff Current	I_{CEX}		-50	nA	V_{CE}=-30V	V_{BE} = 0.5V
Base Current	I_B		50	nA	V_{CE}=-30V	V_{BE} = 0.5V
D.C. Current Gain	h_{FE}	35			V_{CE}=-10V	I_C=-100uA
D.C. Current Gain	h_{FE}	50			V_{CE}=-10V	I_C=-1mA
D.C. Current Gain	h_{FE}	75			V_{CE}=-10V	I_C=-10mA
D.C. Current Gain	h_{FE}	100	300		V_{CE}=-10V	I_C=-150mA
D.C. Current Gain	h_{FE}	30			V_{CE}=-10V	I_C=-500mA
Collector-Emitter Saturation Voltage	$V_{CE(sat)}$		-0.4	V	I_C=-150mA	I_B=-15mA
Collector-Emitter Saturation Voltage	$V_{CE(sat)}$		-1.6	V	I_C=-500mA	I_B=-50mA
Base-Emitter Saturation Voltage	$V_{BE(sat)}$		-1.3	V	I_C=-150mA	I_B=-15mA
Base-Emitter Saturation Voltage	$V_{BE(sat)}$		-2.6	V	I_C=-500mA	I_B=-50mA
Output Capacitance	Cob		8	pF	V_{CB}=-10V	I_E=0
Input Capacitance	Cib		30	pF	V_{EB}=-2V	I_C=0
High Frequency Current Gain	h_{fe}	2			V_{CE}=-20V f=100MHz	I_C=-50mA

Figure 29 MPS2716 Datasheet

General Purpose Transistors
ABSOLUTE MAXIMUM RATINGS(Ta=25ºC unless specified otherwise)

DESCRIPTION	SYMBOL	MPS2907	MPS2907A	UNITS
Collector Emitter Voltage	V_{CEO}	40	60	V
Collector Base Voltage	V_{CBO}	60	75	V
Emitter Base Voltage	V_{EBO}	5		V
Collector Current Continuous	I_C	600		mA
Power Dissipation @ Ta=25ºC	P_D	625		mW
Derate Above 25ºC		5		mW/ºC
Power Dissipation @ Tc=25ºC	P_D	1.5		W
Derate Above 25ºC		12		mW/ºC
Operating And Storage Junction Temperature Range	T_j, T_{stg}	-55 to +150		ºC
THERMAL RESISTANCE				
Junction to ambient	$R_{th(j-a)}$	200		ºC/W
Junction to case	$R_{th(j-c)}$	83.3		ºC/W

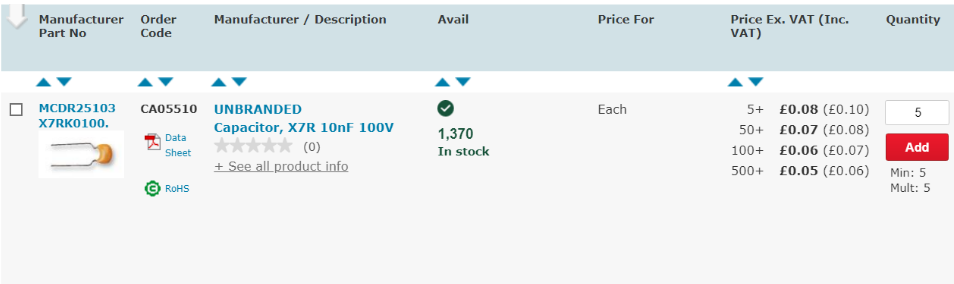
Figure 30 - MPS2907 Datasheet

4.2.4. Resistors, Potentiometers and Capacitors – Real world values

Ecobion Labs - Common E6 and E24 (bold) Resistor Values

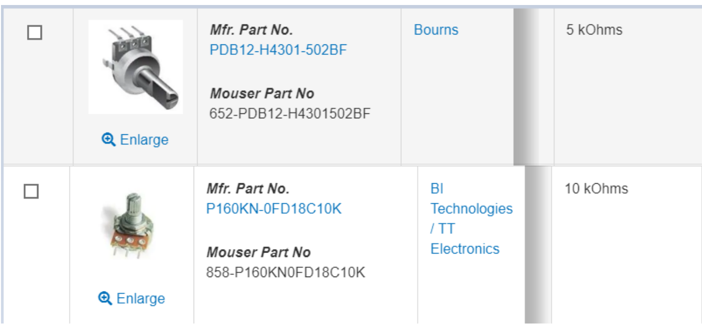
1	**10**	**100**	**1K**	**10K**	**100K**	**1M**	**10M**
1.2	1.2	1.2	1.2	1.2	1.2	1.2	
1.5	**15**	**150**	**1.5K**	**15K**	**150K**	**1.5M**	
1.8	18	180	1.8K	18K	180K	1.8M	
2.2	**22**	**220**	**2.2K**	**22K**	**220K**	**2.2M**	
2.7	27	270	2.7K	27K	270K	2.7M	
3.3	**33**	**330**	**3.3K**	**33K**	**330K**	**3.3M**	
3.9	39	390	3.9K	39K	390K	3.9M	
4.7	**47**	**470**	**4.7K**	**47K**	**470K**	**4.7M**	
5.6	56	560	5.6K	56K	560K	5.6M	
6.8	**68**	**680**	**6.8K**	**68K**	**680K**	**6.8M**	
8.2	82	820	8.2K	82K	820K	8.2M	

Figure 31 - Standard Resistors Values



Manufacturer Part No	Order Code	Manufacturer / Description	Avail	Price For	Price Ex. VAT (Inc. VAT)	Quantity
MCDR25103 X7RK0100.	CA05510 Data Sheet RoHS	UNBRANDED Capacitor, X7R 10nF 100V (0) + See all product info	1,370 In stock	Each	5+ £0.08 (£0.10) 50+ £0.07 (£0.08) 100+ £0.06 (£0.07) 500+ £0.05 (£0.06)	5 Add Min: 5 Mult: 5

Figure 32 - Capacitor real world value



Enlarge	Mfr. Part No. PDB12-H4301-502BF Mouser Part No 652-PDB12-H4301502BF	Bourns		5 kOhms
Enlarge	Mfr. Part No. P160KN-0FD18C10K Mouser Part No 858-P160KN0FD18C10K	BI Technologies / TT Electronics		10 kOhms

Figure 33 - Potentiometers real values

As we can see in the figures presented above, we can find all the parts we need for our project. We have got plenty of resistors values, including ours (25Ω, 1.2 kΩ, 4.7 kΩ, 10 kΩ, 20 kΩ).

4.2.5. Bill of Materials

```
Bill Of Materials          May 21,2020      15:58:01   Page1

Item    Quantity    Reference   Part    Value   Tolerance   Description Manufacturer    Vendor
____________________________________________________________

1   1   C   10n 10% Multilayer Ceramic Capacitors MLCC - SMD/SMT 100V .01uF C0G 1210 10% AEC-Q200   Vishay Intertechnology, Inc.    Mouser.com
2   2   Dz1,Dz2 BZ-075      Zener Diodes 7.5 Volt 500mW 2%  New Japan Radio Co., Ltd.   Mouser.com
3   2   D1,D2   D1N1190     Schottky Diodes & Rectifiers 100V 5A    MicroSim Corp.  Mouser.com
4   1   P21 5k      Potentiometers 5K 12.5MM SQ CONTROL Bourns, Inc.    Mouser.com
5   1   P33 10k     Potentiometers 10K LINEAR   Bourns, Inc.    Mouser.com
6   1   Q1  MPS2716     Bipolar Transistors - BJT 1A 100V 30W NPN   Micro Electronics, Ltd. Mouser.com
7   1   Q2  MPS2907     Bipolar Transistors - BJT 1A 100V 30W PNP   Micro Electronics, Ltd. Mouser.com
8   1   Rload   25  1%  Metal Film Resistors - Through Hole 3watts 25ohms 1%    Vishay Intertechnology, Inc.    Mouser.com
9   1   R11 20k 1%  Metal Film Resistors - Through Hole 0207 20Kohms 1% 50ppm CECC 06   Vishay Intertechnology, Inc.    Mouser.com
10  1   R13 4.7k    1%  Metal Film Resistors - Through Hole 0207 4.7Kohms 1% 50ppm CECC 06  Vishay Intertechnology, Inc.    Mouser.com
11  1   R22 1.2k    1%  Metal Film Resistors - Through Hole 0218 1.2Kohms 1% 50ppm  Vishay Intertechnology, Inc.    Mouser.com
12  1   R24 10k 1%  Metal Film Resistors - Through Hole 0149 10Kohms 1% 50ppm   Vishay Intertechnology, Inc.    Mouser.com
13  2   R31,R32 10k 1%  Metal Film Resistors - Through Hole 0210 10Kohms 1% 50ppm   Vishay Intertechnology, Inc.    Mouser.com
14  2   R41,R42 1.2k    5%  Metal Film Resistors - Through Hole 1.2K ohm 5% 1W  Bourns, Inc.    Mouser.com
15  2   U1,U2   TL082           Operational Amplifiers - Op Amps CONDITIONING & INTERFACES  Micro Electronics, Ltd. Mouser.com
```

Figure 34 - Bill of Materials

Table 1 - Components Details

Item	Quantity	Reference	Value	Tolerance	Description	Manufacturer	Vendor
1	1	C	10nF	10%	See in the picture	Vishay Intertechnology	Mouser.com
2	2	Dz1, Dz2	-	-	See in the picture	New Japan Radio	Mouser.com
3	2	D1, D2	-	-	See in the picture	MicroSim Corp.	Mouser.com
4	1	P21	5kΩ	-	See in the picture	Bourns, Inc.	Mouser.com
5	1	P33	10kΩ	-	See in the picture	Bourns, Inc.	Mouser.com
6	1	Q1	-	-	See in the picture	Micro Electronics	Mouser.com
7	1	Q2	-	-	See in the picture	Micro Electronics	Mouser.com
8	1	Rload	25Ω	1%	See in the picture	Vishay Intertechnology	Mouser.com
9	1	R11	20kΩ	1%	See in the picture	Vishay Intertechnology	Mouser.com
10	1	R13	4.7kΩ	1%	See in the picture	Vishay Intertechnology	Mouser.com
11	1	R22	1.2kΩ	1%	See in the picture	Vishay Intertechnology	Mouser.com
12	1	R24	10kΩ	1%	See in the picture	Vishay Intertechnology	Mouser.com
13	2	R31, R32	10kΩ	1%	See in the picture	Vishay Intertechnology	Mouser.com
14	2	R41, R42	1.2kΩ	5%	See in the picture	Bourns, Inc.	Mouser.com
15	3	U1, U2, U3	-	-	See in the picture	Micro Electronics	Mouser.com

5. Simulations and final results

5.1. Time domain analysis

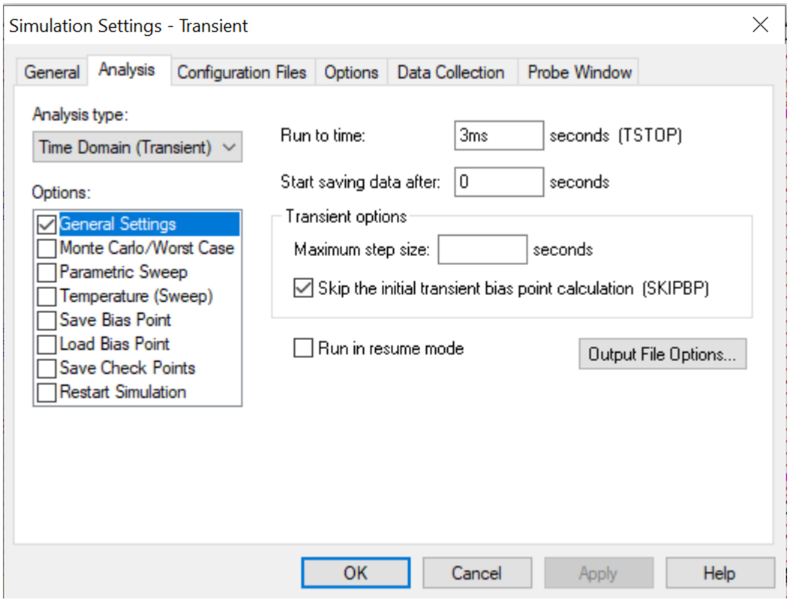


Figure 35 - Simulation profile for time domain analysis

The desired frequency have to be in the interval [1.8 kHz; 9.6 kHz], so the period of the signal will be in the interval [104 µs; 556 µs]. Therefore I decided to run the simulation to 3 ms, in order to see 5-6 periods of the signal when the frequency is 1800 kHz and about 30 periods of the signal when the frequency is 9600 kHz. The SKIPBP button is checked because I wanted to skip the transient regime of the signal.

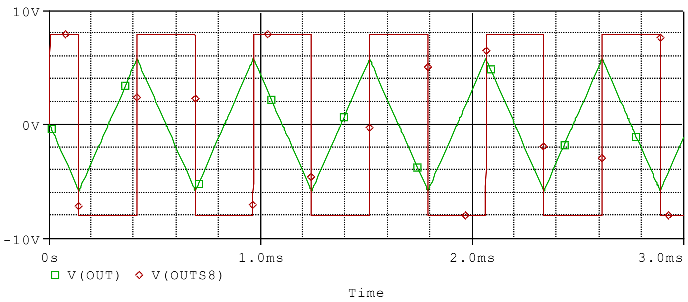


Figure 36 - Time domain analysis for the minimum frequency

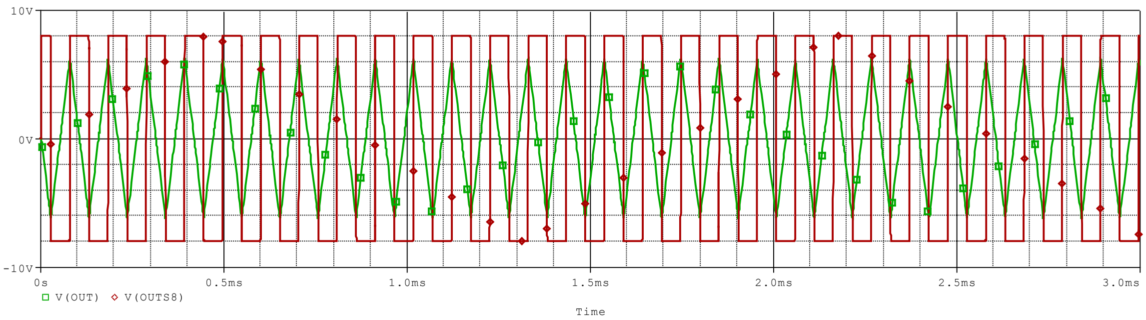


Figure 37 - Time domain analysis for the maximum frequency

5.2. Parametric analysis

This analysis is done in order to verify that the conditions imposed at first are respected: the amplitude of the triangular signal should vary between 4 and 6 V, and the frequency of the circuit should vary between 1.8 to 9.6 kHz.

5.2.1. The amplitude:

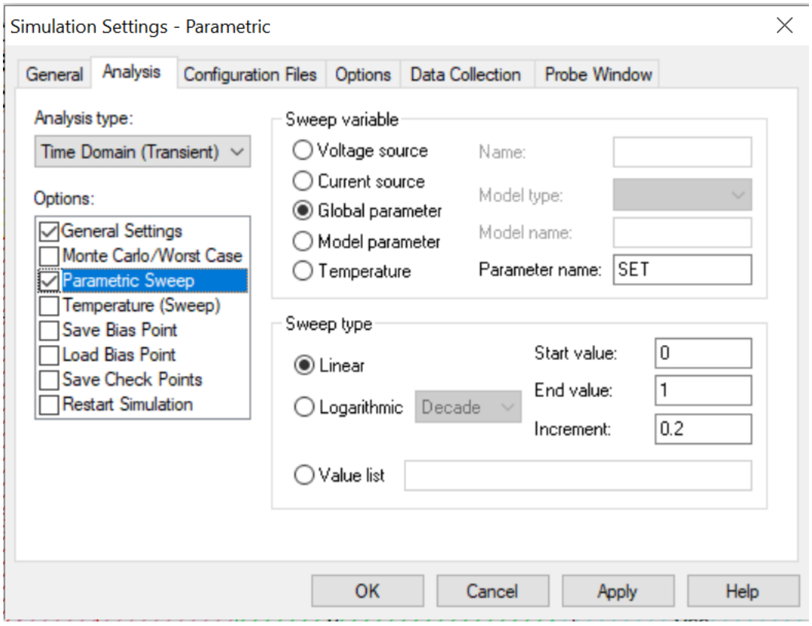


Figure 38 - Simulation profile for parametric analysis

For this I made a secondary sweep in which I chose to vary a parameter named "SET", that is placed as a value for the potentiometer P33 in the Voltage Amplifier Block, in order to see how the amplitude of the triangular signal varies as the wiper is moved from 0 to 1. The time domain analysis remain the same as above.

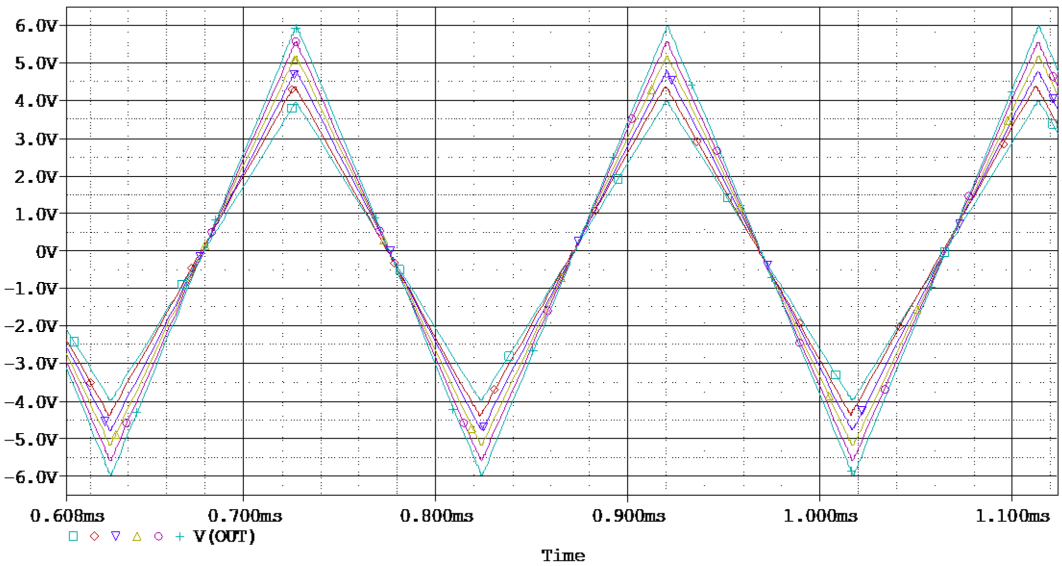


Figure 39 – The parametric sweep presenting the amplitude of the triangular signal plot

	Trace Color	Trace Name	Y1
		X Values	727.299u
	CURSOR 1,2	V(OUT)	3.9530
		V(OUT)	4.3357
		V(OUT)	4.7799
		V(OUT)	5.1771
		V(OUT)	5.5645
		V(OUT)	5.9579

Figure 40 - The values corresponding to each color in the picture above

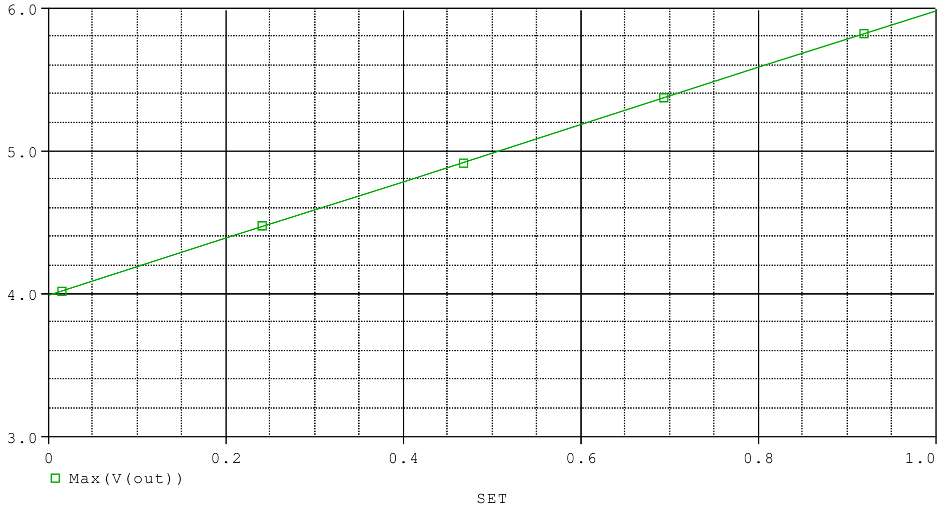


Figure 41 - The Performance Analysis of the triangular signal's amplitude

In *Figure 39* and *Figure 40* we can observe that the values of the amplitude of the triangular wave vary between almost 4 V(3.9530 V) and almost 6 V(5.9579 V). The error is present because of the losses in the circuit, but it is small enough. In *Figure 41* it is presented the performance analysis of the maximum of the function depending on the SET parameter of the potentiometer from the voltage amplifier. We can notice that the maximum vary between 4 V and 6 V as required for the project.

5.2.2. The frequency:

For this, I used the exact simulation profiles presented above, but now the SET parameter is placed as the value of the potentiometer P21. This sweep will vary the SET parameter from 0 to 1 with the same step of 0.2 in order to see how it adjust the frequency.

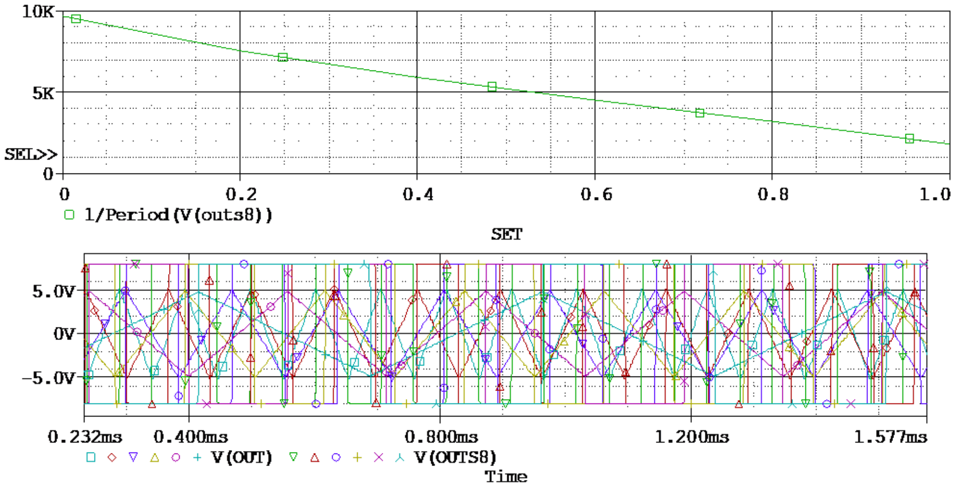


Figure 42 - The parametric sweep presenting the frequency

For a better understanding I used a **Performance Analysis** from the scope and plotted the frequency of the signal, as seen in *Figure 42*. We can observe that the frequency starts from almost 10 kHz at its highest (more precise 9.617 kHz, see *Figure 43*) and decreases until it reaches about 2 kHz (more precise 1.8213 kHz, see *Figure 44*).

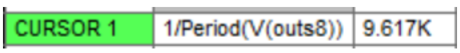


Figure 43 - Highest Frequency

Figure 44 - Lowest Frequency

5.3. Tolerances and Statistical Analysis

5.3.1. Why tolerances?

In real life applications, the components cannot have perfect values; therefore, the manufacturer always adds a tolerance for the product that tells us the maximum range of the error for the value of that product. This tolerance can affect our circuit performance, therefore when simulating a circuit we must take into consideration this parameter.

The components prices depend a lot of their tolerances, so when we choose a component we must know when it needs to have a more precise value and when not. Therefore I chose the components in the following order:

- The resistors (R11 and R13) which regulate the amplitude of the triangular signal with a tolerance of **1%**, because I need that amplitude to be as precise as possible.
- The resistors (R22 and R24) which regulate the frequency with a tolerance of **1%** because of the same reason, I need the frequency adjustment to be precise and because the tolerance for the capacitor will be bigger.
- The resistors (R31 and R32) which sets the gain for the voltage amplifier with a tolerance of **1%** in order to have an amplitude adjustment as close as the one required for the project.
- The resistors (R41 and R42) that should allow the currents through the diodes and the transistors with a tolerance of **5%** because their values don't need to be extremely

precise in order to make the circuit work, they are placed there in order to limit the current through the active components. A bigger tolerance doesn't affect the performance of the circuit.

- The load resistor (Rload) with a tolerance of **1%** in order to be as precise as possible according to the project requirements.
- The capacitor (C) from the integrator that also regulates the frequency of the signal with a tolerance of **10%**, because of the higher prices for the capacitors with smaller tolerances. This tolerance is almost a standard one for the cheap (almost medium) range capacitors.

The precise values and the tolerances can also be seen in *Figure 34 Bill Of Materials.*

5.3.2. Monte Carlo Analysis – Triangular Signal

The simulation profile for the primary sweep is the same as above (Time Domain).

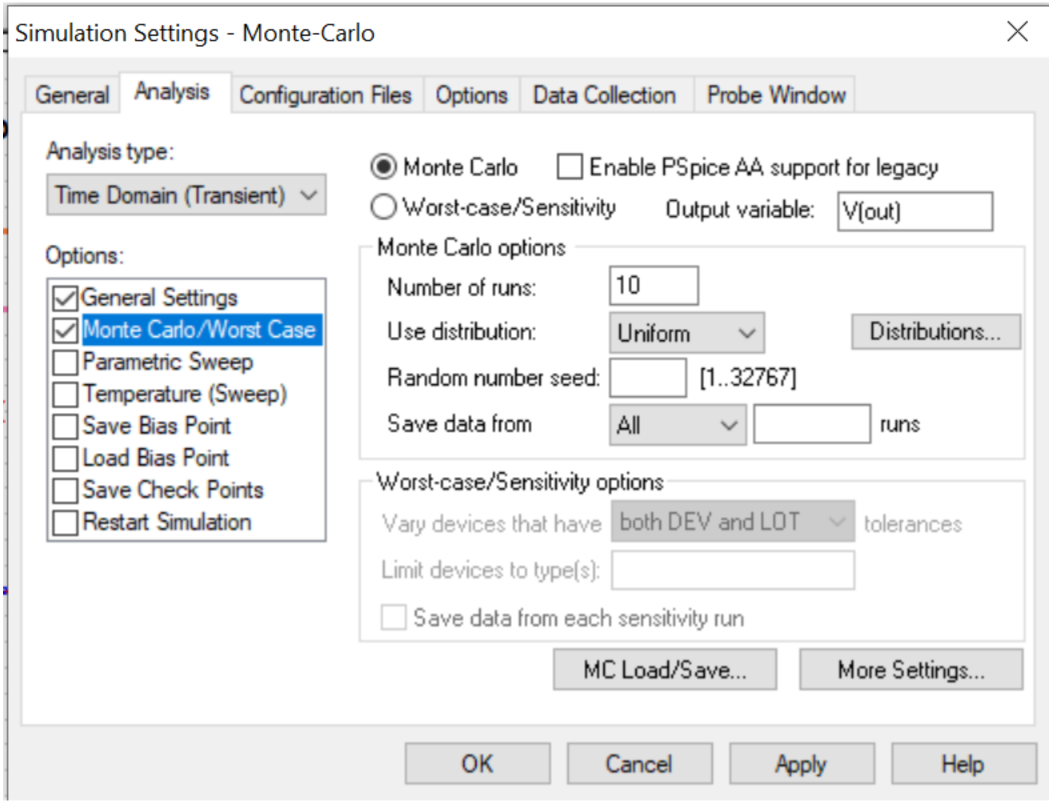


Figure 45 - The simulation profile for the Monte Carlo Analysis (Triangular Signal)

In *Figure 45* it is presented the simulation profile for the Monte Carlo Analysis, with the output variable V(out) representing the triangular signal. The number of runs is set to 10 because I want to see the results for 10 random samples.

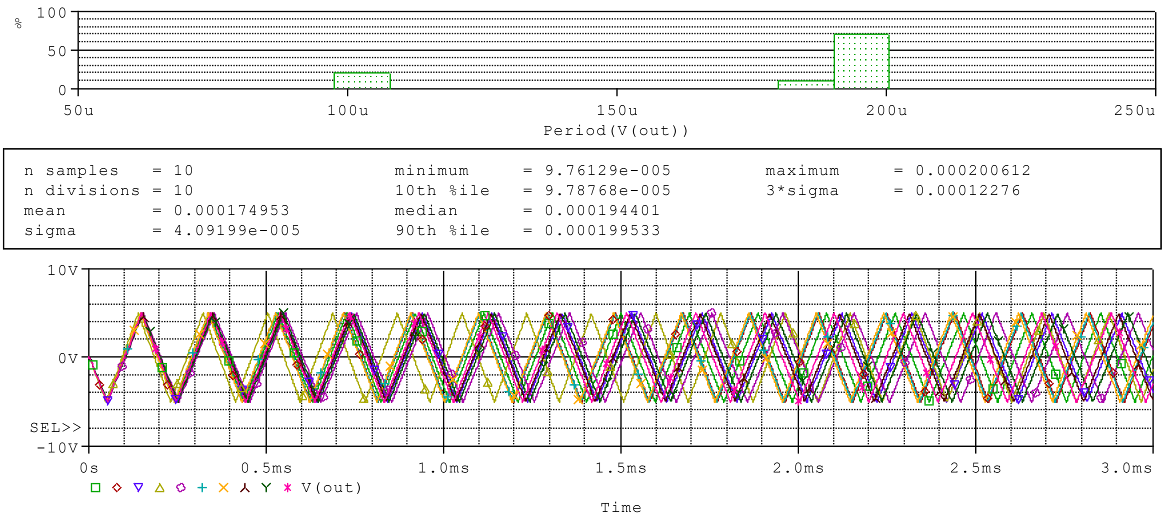


Figure 46 - The Monte Carlo Analysis for the triangular signal with the Period as measurement for the Performance Analysis

In *Figure 46* it is presented the Monte Carlo Sweep for the triangular signal with the Time Domain Analysis as a primary sweep. The Monte Carlo Sweep calculates random samples in order to obtain numerical results. It is the best way of analysing a circuit to see how it behaves at random components values variation, as presented in [2]. Above it is also presented the performance analysis about the period of the signal. In this analysis we can see that the period has a bigger deviation according to the tolerances around 200 μs (over 50%), but the limits for the project are maintained.

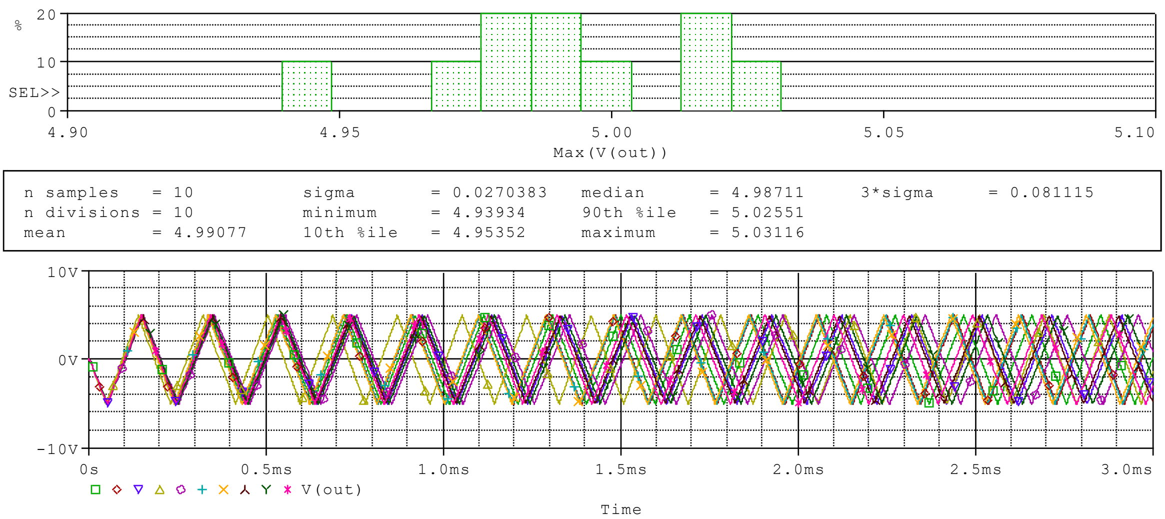


Figure 47 - The Monte Carlo Analysis for the triangular signal with the Max as measurement for the Performance Analysis

In *Figure 47*, the Performance Analysis is done with the Max function as the measurement. We can observe that the amplitude has a bigger deviation around 5 V (10-20%), but giving that the amplitude must be regulated between 4 V and 6 V, the limits are maintained.

5.3.1. Monte Carlo Analysis – Rectangular Signal

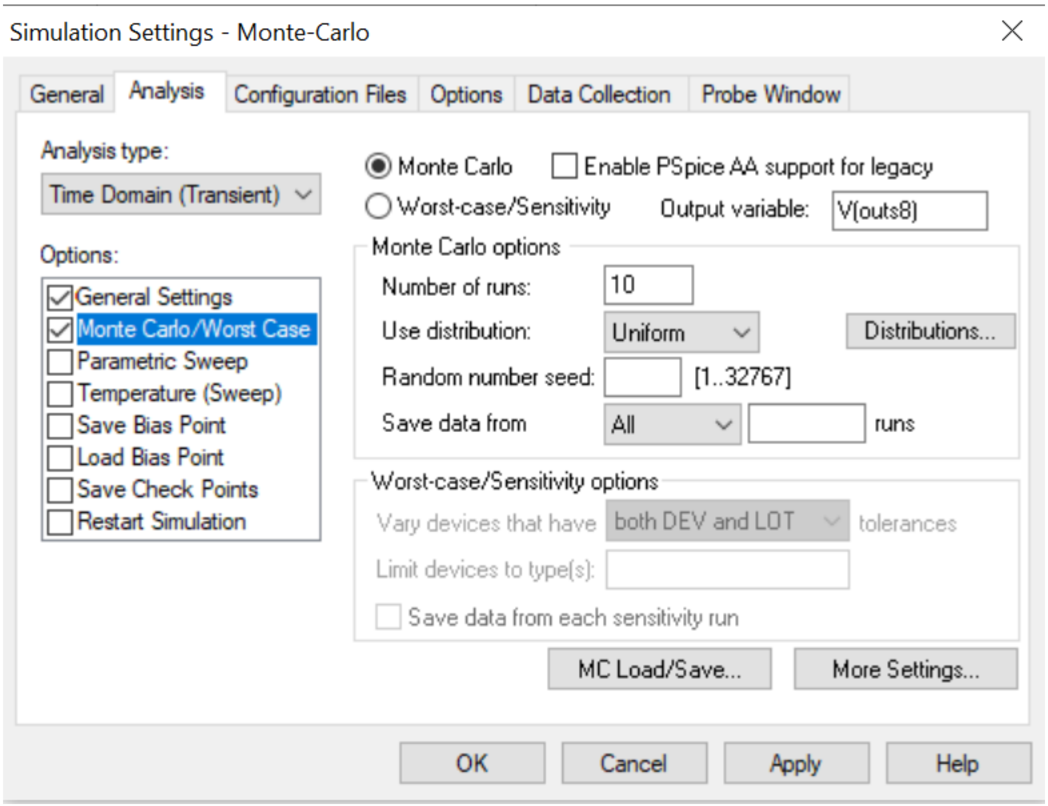


Figure 48 - The simulation profile for the Monte Carlo Analysis (Rectangular Signal)

In *Figure 48*, we can see that the simulation profile is the same as before, but now the output variable is the rectangular signal.

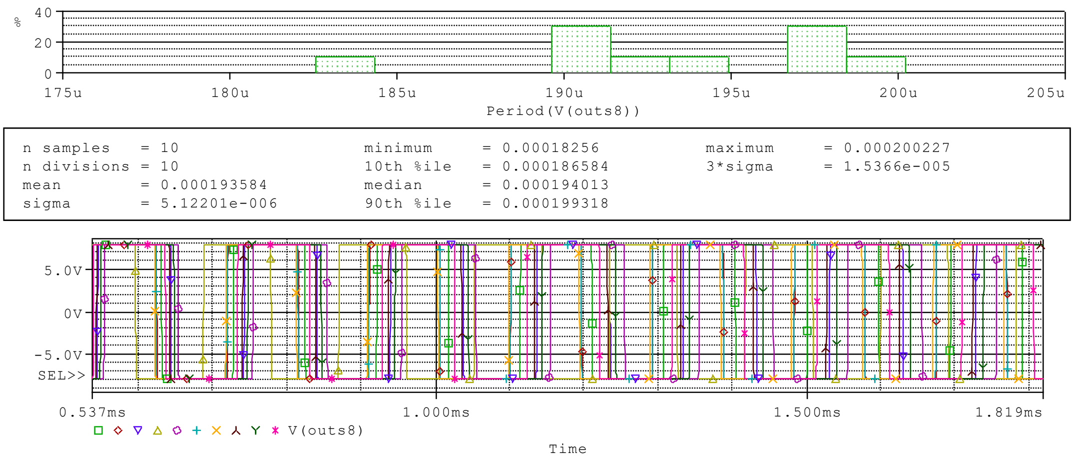


Figure 49 - The Monte Carlo Analysis for the rectangular signal with the Period as measurement for the Performance Analysis

In *Figure 49*, it is presented the Monte Carlo Sweep of the rectangular signal with the performance analysis of the period. It is clear that the bigger deviations in the period occur between 190 and 200 μs (around 30%), but the limits are maintained.

5.3.2. Worst-Case Analysis

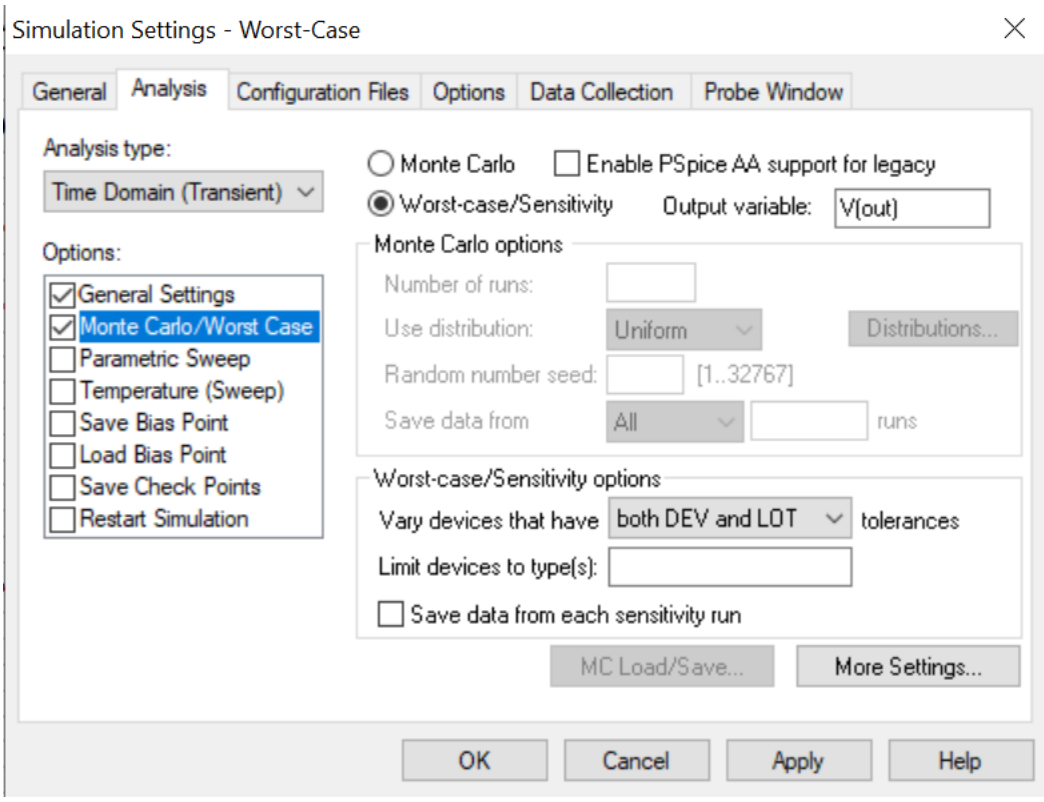


Figure 50 - The simulation profile for the Worst Case Analysis

The simulation profile is the same as before, but this time the Worst-Case/Sensitivity button is checked.

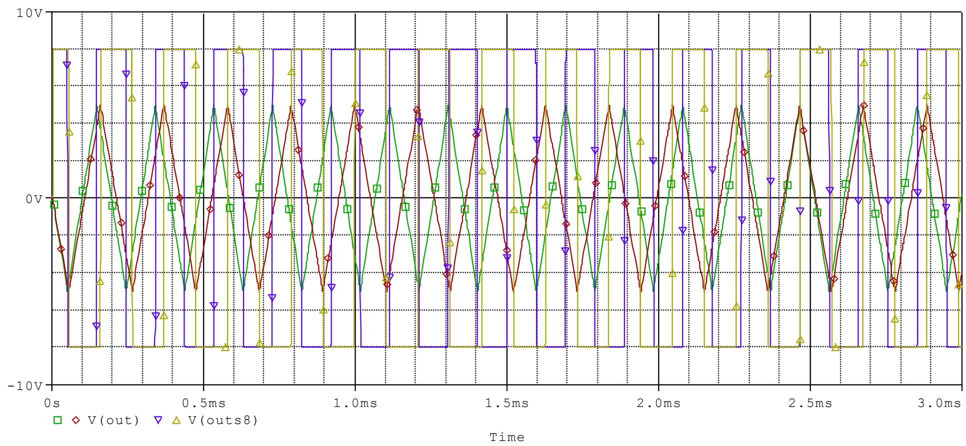


Figure 51 - The Worst Case Scenario

In *Figure 51*, we can observe how, in the worst case scenario, there will be a slightly big phase shift of the output signal.

```
                     WORST CASE ALL DEVICES

**********************************************************************


Device       MODEL        PARAMETER    NEW VALUE
C_C          C_C          C            1.1          (Increased)
R_R22        R_R22        R            1.01         (Increased)
R_R11        R_R11        R             .99         (Decreased)
R_R13        R_R13        R             .99         (Decreased)
R_R24        R_R24        R             .99         (Decreased)
R_Rload      R_Rload      R             .99         (Decreased)
R_R41        R_R41        R             .95         (Decreased)
R_R42        R_R42        R             .95         (Decreased)
R_R31        R_R31        R             .99         (Decreased)
R_R32        R_R32        R            1.01         (Increased)
```

Figure 52 - The Worst Case Analysis Output File

We cannot make a Worst-Case analysis without checking the output file in order to see and understand for what values of the components the worst-case scenario will happen (either increased or decreased value).

5.4. Conclusions/Final Results

By the end of the project, after running the simulations that I needed in order to demonstrate the functionality of the circuit, I am able to say that I am satisfied with the obtained results. The final results correspond to the project requirements and to the calculations that I made with a very low (maximum 3%) margin of error. The statistical analysis showed me how the real life components (with tolerances) could affect the functionality of the circuit and how much. The function generator is as required, with an adjustable frequency, a fixed rectangular signal's amplitude and an adjustable triangular signal's amplitude, all of them between the values mentioned in the project requirements. The circuit can also work with a load of 25 **Ω** as demanded.

6. References

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[11] Mouser Electronics, https://ro.mouser.com.