PWM Generator

Student: Veliciu Vlad

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Coordinator: Şl. dr. ing. Fizeșan Raul Traian

Faculty: Electronics, Telecommunications, and Information Technology

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Description and functionality of the circuit

Project requirements:

Design a PWM (Pulse width modulation) generator having the following parameters:

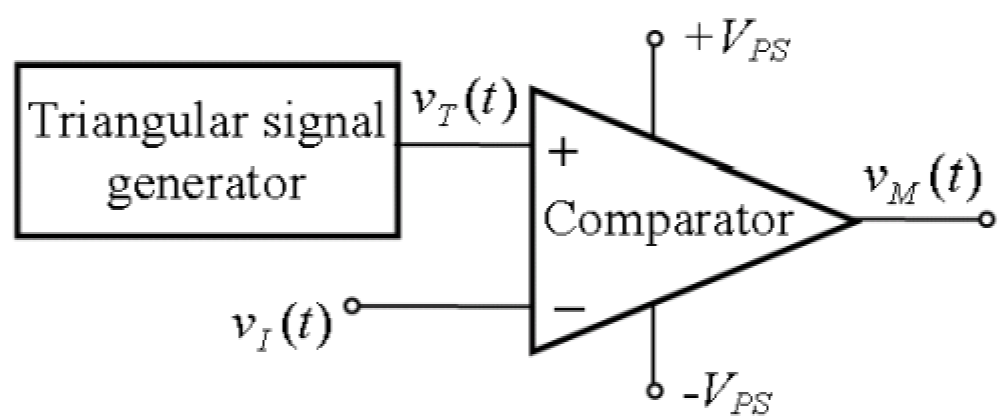
- Duty factor 1: 10%
- Duty factor 2: 50%
- Amplitude PWM 1: 3
- Amplitude PWM 2: 5
- F[Hz]: 12000

Description

Pulse width modulation (PWM) is a modulation technique that generates variable-width pulses to represent the amplitude of an analog input signal. The output switching transistor is on more of the time for a high-amplitude signal and off more of the time for a low-amplitude signal. The digital nature (fully on or off) of the PWM circuit is less costly to fabricate than an analog circuit that does not drift over time.[2]

PWM method is commonly used for speed controlling of motors, fans, etc (pulse width modulation controller). PWM signals may also be used to approximate time-varying analog signals. PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion. Pulse width modulation dc motor control is one of the popular circuits in Robotics.[1]

Schematic:



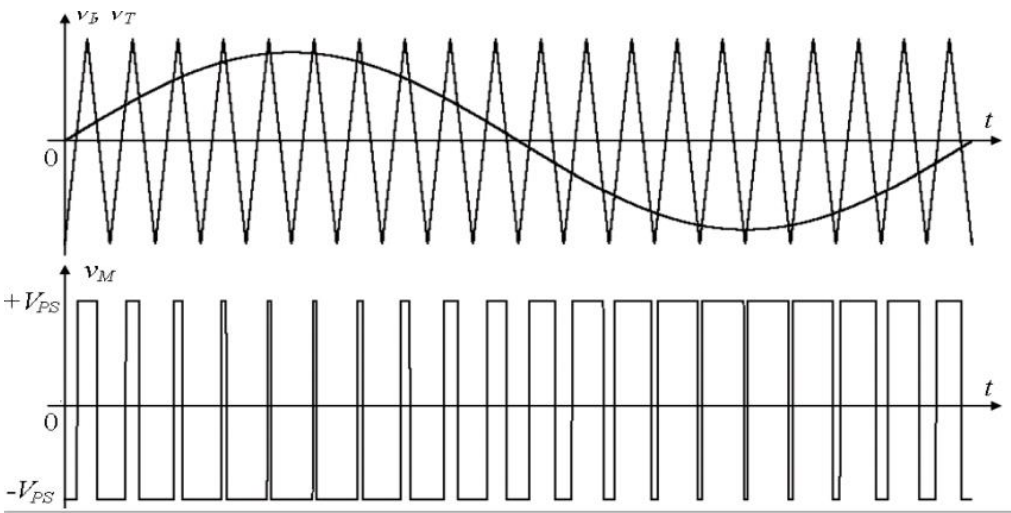
[4]

Working principle

- The op amp works as a comparator.
- It compares both the input voltages: the triangular waveform and the message signal (sine wave, DC signal, etc).

- The duration in which the instantaneous value of sine wave is above that of triangle, the op amp switches to -VPS. It’s because the message signal is connected to the inverting input of the op amp.
- When the message signal intersects the triangular wave, the switch happens. So, at every intersection the output waveform switches between the two power supplies of the op amp.
- Due to this fact a pulse waveform swinging between +VPS and –VPS is obtained.
- That is the pulse width changes according to the message signal (Width of the pulse is modulated)[1][3]

The waveforms for a PWM generator should look, for example, like those in the picture below, where vi(t) is the sine wave – the message signal, vt(t) is the triangular wave and vM(t) is the output voltage of the Pulse-Width Modulator. The frequency of the sine wave must be very small compared to the frequency of the triangular signal. If vi(t) is a pure DC signal, at the output, pulses with the same filling factor (duty cycle), are obtained (rectangular signal).[3]



In order to adjust the filling factor, the intersection points of the sine wave (message signal) with the triangular waveform must be controlled. In this way how much time does the output signal stay at high value in a period can be controlled.

To control the amplitude of the output signal, a voltage divider has to be designed, consisting of two resistors that have the voltage drop equal to the value of the power supplies, in such a way that the resistor that gives the output signal is a potentiometer (adjusts the amplitude of the output voltage). Then, a class B amplifier with global negative feedback has to be connected to the output to ensure that at the output of the entire circuit any type of impedance can be connected.

Advantages:

- Less effect of noise, very good noise immunity, cancelled out by the op amp working as a simple comparator.
- It is possible to reconstruct the PWM signal from a noise, contaminated PWM. Thus, it is possible to separate out signal from noise.[2]

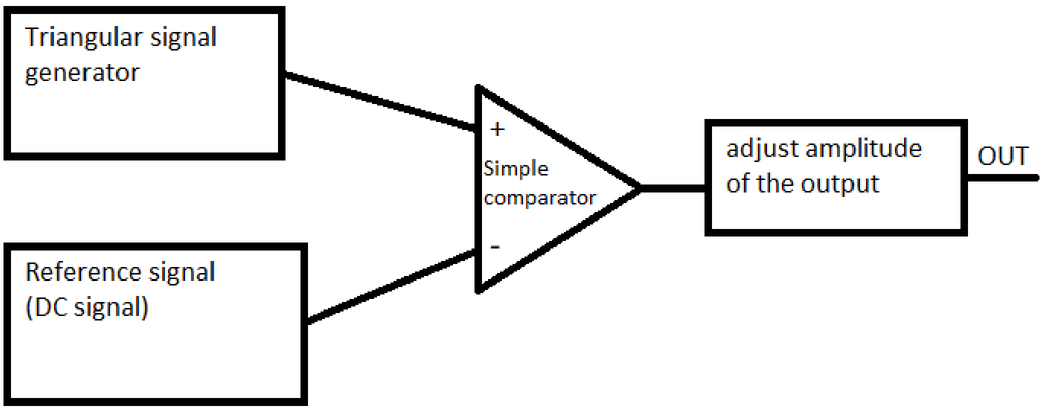
Parameters:

- Period (T): How long each complete pulse cycle takes
- Frequency (F): How often the pulses are generated. This value is typically specified in Hz (cycles per second). The frequency of the output signal is the same with the frequency of the triangular signal.
- Duty Cycle (D): The ratio of time in the period that the pulse is active or high (T on) to the total time of a cycle (T). The duty cycle is typically specified as a percentage of the full period.[1]

$$D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T}\ \%$$

As reference signal, a DC signal can also be used. In this way, the filling factor (duty factor) of the generated PWM signal can be easily controlled, only by adjusting the amplitude of the DC signal, with a voltage divider between a resistance and a potentiometer (from that the reference signal is collected, that will be used) from a power supply (VPS). Also, the same duty cycle at every period of the PWM signal will be obtained.

Block Diagram



Triangular Signal Generator:

- Generates a triangular signal that has the same frequency as the output signal
- Connected to the noninverting input of the simple comparator

Reference signal (DC signal):

- Generates a DC signal that will control the switch (from high to low and vice versa) at every intersection with the triangular signal in time
- Connected to the inverting input of the simple comparator
- Will adjust the filling factor (how long the pulses stay at high value)

Simple comparator:

- It's a noninverting simple comparator because the triangular signal is connected to the noninverting input
- Makes the switch between the two power supplies at a threshold controlled by the DC signal (reference signal). So, at every intersection of the two signals, a switch happens.

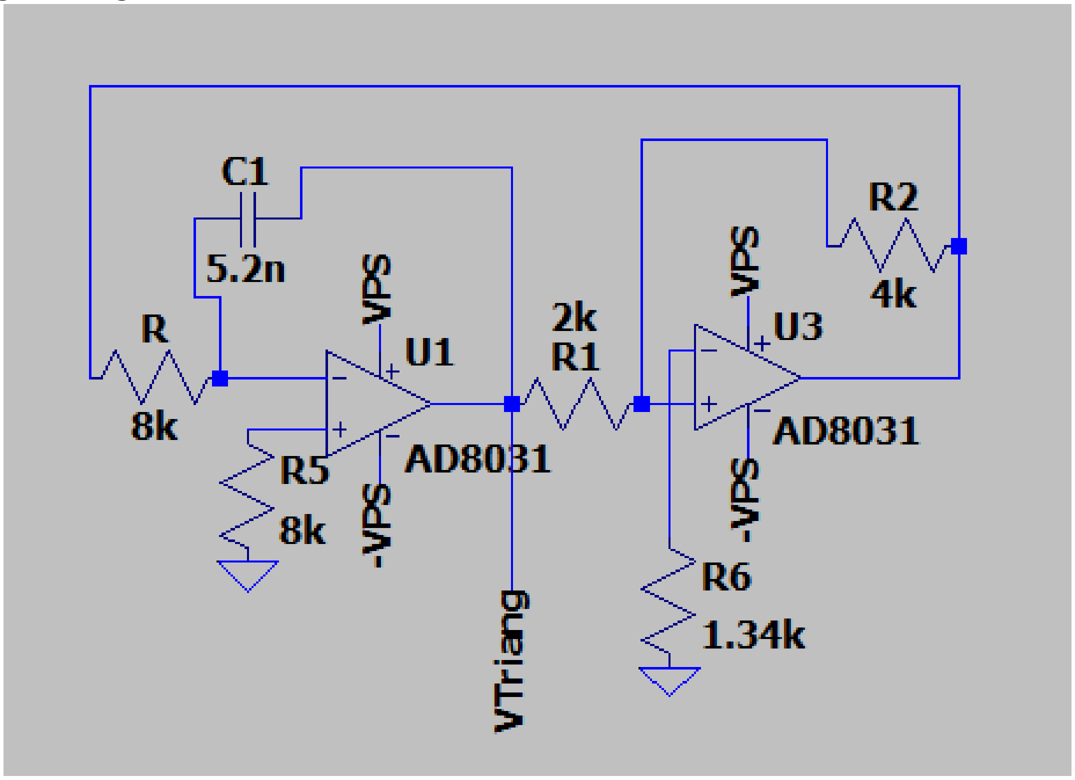
Adjust amplitude at the output circuit:

- Add a voltage divider circuit (2 resistors, one of them variable), to divide the voltage given by the comparator (which is equal to the power supplies)
- Collect the output from the variable resistor, to have an adjustable amplitude

- Connect the resulted voltage to a class B amplifier with global negative feedback, to ensure that at the output an impedance of any type can be connected without affecting the amplitude of the output voltage or any other components.

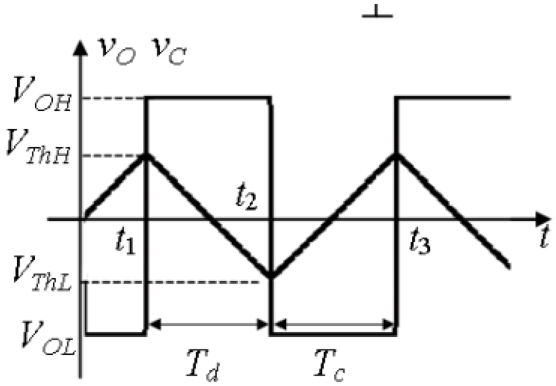
Electrical Schematic and theoretically computed nominal values for components

Triangular Signal Generator



VPS=6V, -VPS=-6V

From the topology of the circuit, there can be noticed that the capacitor C charges and discharges under a constant current (Ic = +/- VPS/R due to virtual ground at the inverting input of U1 due to the negative feedback and the non-inverting input connection to ground), so that the voltage on it will have a triangular shape -> triangular signal generator. (R5 and R6 have the role to balance the input of the opamps; it is not good to connect them directly to ground) [5]



[5]

$f = \frac{R_2}{4*R*C*R_1} = 12000$ – the frequency of the triangular signal[5]

Typically, C is in nF and R, R1, R2 in kΩ

$take\ R2 = x * 10^3, R = y * 10^3, C = z * 10^{-9}, R1 = b * 10^3$

$=> R_2 = 48000 * R * C * R_1$

$=> x * 10^3 = 48 * y * z * b$

$typically\ x = 2b\ (R2 = 2 * R1) =>$

$typically\ R_2 = 2 * R_1\ (necessary\ condition\ for\ oscillation;\ R_2 > R_1)$

$=> 2b * 10^3 = 48 * y * z * b\ \ => y * z = 41.6666 => take\ y = 8\ and\ z = 5.2$

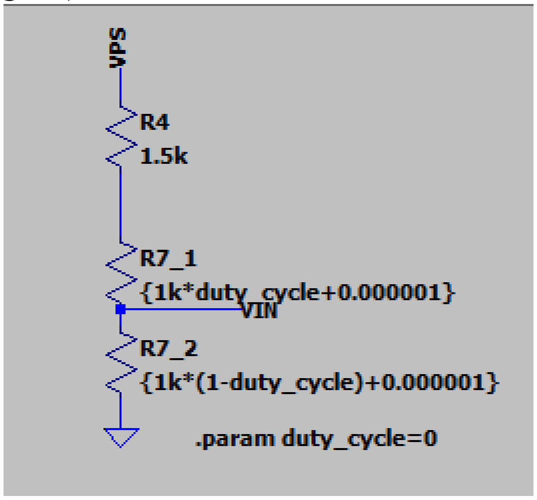
$=> \begin{cases} R_1 = 2k\Omega \\ R_2 = 4k\Omega \\ R = 8k\Omega \\ C = 5.2nF \end{cases}$ and R5=R=2kΩ; R6=R1||R2=1.34kΩ

The triangular signal generator controls the frequency of the output signal

The max and min values of the triangular signal are:

$V_{max} = V_{ThH} = -\frac{R1}{R2} * (-VPS) = 3V$ $\quad V_{min} = V_{ThL} = -\frac{R1}{R2} * VPS = -3V$ where VPS=VOH and -VPS=VOL

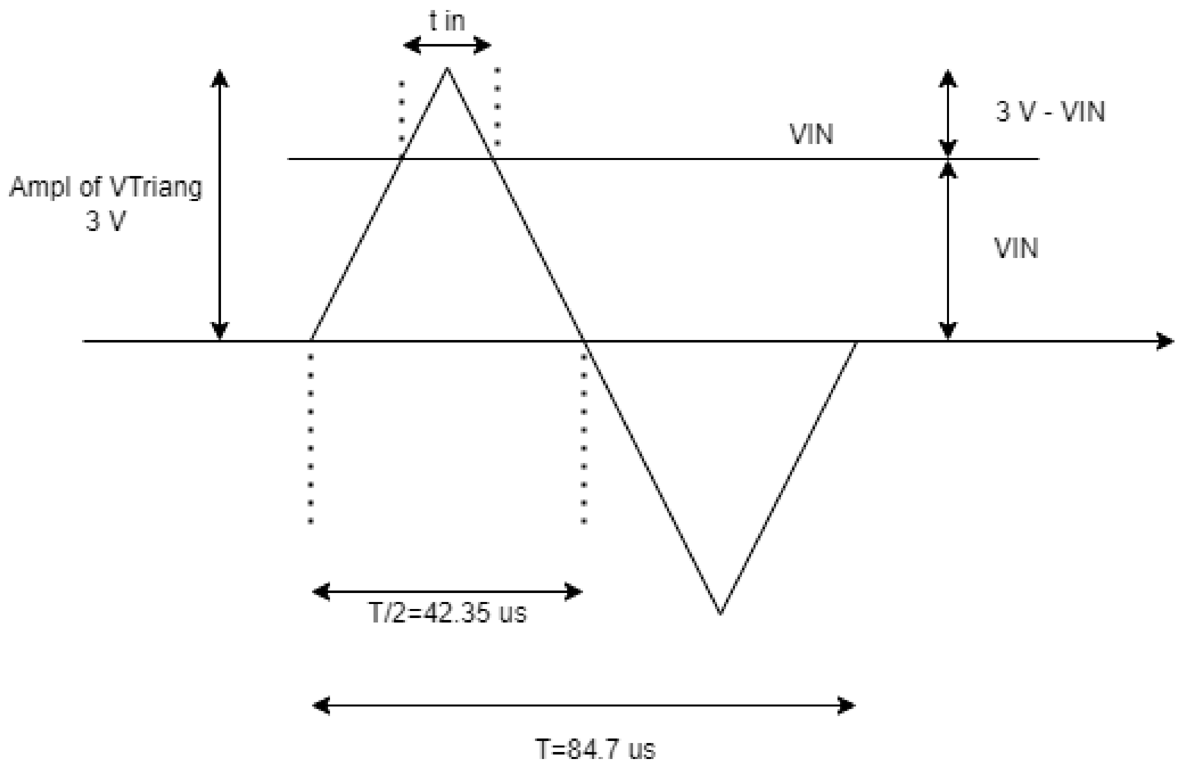
Reference signal (DC signal)



VPS=6V

To adjust the duty factor of the pwm generated signal, the amplitude of the VIN (DC signal) must be controlled in such a way that the duty cycle varies between 10% and 50%. To make this variation, a voltage divider between a fixed resistor (R4) and a variable resistor, potentiometer (R7) will be used. For that, the formula for calculating the duty cycle is known:

$D\ [\%] = \frac{T_{on}}{T} * 100$ where T_{on} is the time when the pwm signal is at high value. Consequently, the duty factor depends on the time (t in = T_{on}) the signal VIN, in this case, stays inside the triangle from the positive alternance (because in that case, the PWM signal is at high level), like in the picture below (knowing that the frequency of the triangular signal gives the frequency of the pwm signal, so their periods are also equal. The duty factor increases when VIN decreases):



For instance, to get the minimum duty cycle $D = 10\% = \frac{T_{on}}{T} * 100 => T_{on} = 0.1 * 84.7us = 8.47us\ where\ T = \frac{1}{f_{Triang}} = 84.7\ us$

$=> t_{in} = 8.47us$

So, by applying the similar triangles theorem, the result will be:

$$\frac{Ampl\ of\ V_{Triang}}{Ampl\ of\ V_{Triang} - VIN} = \frac{\frac{T}{2}}{t_{in}} \quad => \quad \frac{3\ V}{3\ V - VIN} = \frac{42.35\ us}{8.47\ us} \quad =>$$

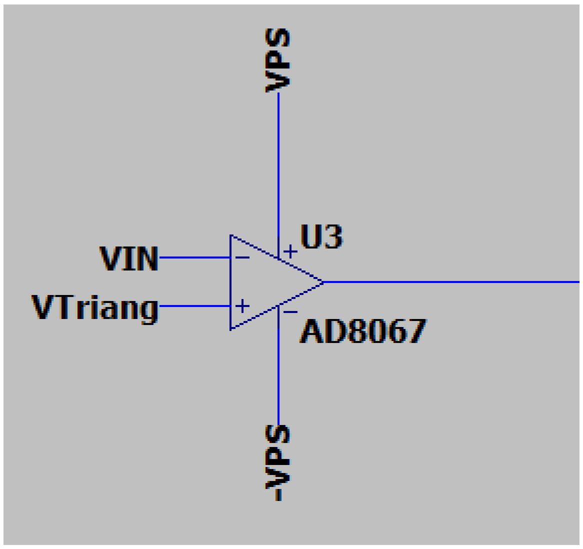
$$25.41 = 127.05 - 42.35 * VIN \quad => \ VIN = 2.4\ V$$

So, the maximum value of VIN is 2.4V. That means that the parameter *duty_factor* that controls the potentiometer, has to be 1:

$$\frac{R_7}{R_7 + R_4} * VPS = 2.4\,V => \frac{R_7}{R_7 + R_4} = 0.4\ and\ take\ R_7 = 1k\Omega => R_4 = 1.5k\Omega$$

In the same logic, to get the maximum duty cycle, 50%, $T_{on} = T/2$, so VIN=0V. Consequently, the parameter *duty_factor* must be 0.

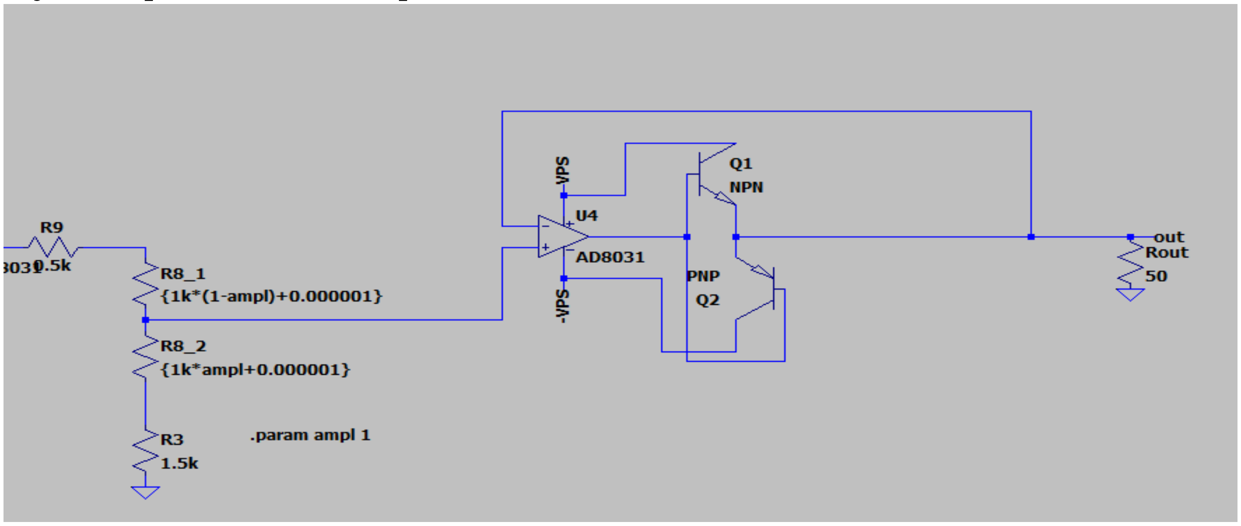
Simple comparator



VPS=6V; -VPS=-6V

The simple comparator compares VTriang (the triangular signal) connected to the noninverting input with VIN (the reference voltage) connected to the noninverting input. At every intersection of VIN with VTriang, a switch of the output signal happens. This signal can take values only at -VPS and +VPS. The AD8067 rail-to-rail is used here because it has more precision than AD8031, as there is needed here to have at the output a rectangular signal with the amplitude that goes very narrow to the value of the power supplies. In this way, the adjustment of the amplitude will be made correctly.

Adjust amplitude at the output circuit



VPS=6V

This circuit is for adjusting the amplitude of the output signal (through the potentiometer R8 and the resistance R9, as the simple comparator provides an output signal with an amplitude of 6V) and for ensuring that for every load that will be connected to the output of the generator, the desired amplitude of the signal will always be obtained (the load doesn't influence the output signal), a class B amplifier with global negative feedback is used, as this type of amplifier has neglectable distortions. The n-type transistor will be active for the positive alternance of the voltage, while the p-type for the negative alternance. Transistors are used to ensure that at the output any type of impedance can be put, as they will amplify, if necessary, the output current from the OpAmp (max 15mA for this type), in order to ensure the same amplitude of the voltage even for a low impedance without affecting the circuit or the OpAmp.[6]

Typically, the values of R3, R8 and R9 are in kΩ.

In order to obtain an amplitude of 5V (VPS is 6V)=> use the whole potentiometer (parameter *ampl*=1) and to obtain 3V (parameter *ampl*=0) =>

$$\frac{R_3}{R_3+R_8+R_9} * 6 = 3 => \frac{R_3}{R_3+R_8+R_9} = 0.5 \; and \; R_8 = 1k => R_3 = 1 + R_9$$

$$\frac{R_8 + R_3}{R_3 + R_8 + R_9} * 6 = 5 \; => 6 + 6 * R_3 = 5 * R_3 + 5 + 5 * R_9$$

$$=> 1 + 1 + R_9 = 5 * R_9 \; => \; R_9 = 0.5k\Omega \; and \; R_3 = 1.5k\Omega$$

So, at the output will be obtained the same voltage that is taken from the potentiometer (at the output of the simple comparator).

The voltage follower ensures that at its output (that it's connected to the inverting input through the negative feedback), the same voltage, that is applied to the non-inverting input (the voltage collected from the potentiometer), is obtained. It is used an AD8031 op amp that, that, for low impedances, acquires the highest amplitude possible (5V). It is more comfortable for it to work with a power supply of 6V, instead of 5V, as it will attenuate the output voltage too much from its desired value, and also since the transistors will need a certain voltage drop Vce to function properly. And that is why a 6V power supply in the class B amplifier configuration is used. (the power supplies should be greater than the desired amplitude at the output)

The class B amplifier with global negative feedback is more efficient than other power amplifier, as is has very low distortions:[6]

$$\begin{cases} v^{+} = v^{-} \\ v^{+} = voltage\ from\ potentiometer \Rightarrow voltage\ from\ potentiometer = v_{out} \\ v^{-} = v_{out} \end{cases}$$

$if\ v_{output\ of\ opamp\ U5}\ \epsilon\ (-0.6V; 0.6V)\ where\ V_{Thn} = 0.6V\ and\ V_{Thp} = -0.6V$

$\Rightarrow both\ transistors\ are\ off \Rightarrow there\ is\ no\ negative\ feedback$

$\Rightarrow OpAmp\ acts\ like\ a\ simple\ comparator$

$v_{output\ from\ U5} = a * v_d\ where\ v_d = v^{+} - v^{-} = voltage\ from\ potentiometer - v_{out}$

$where\ v_{out} = 0 \Rightarrow v_d = voltage\ from\ potentiometer$

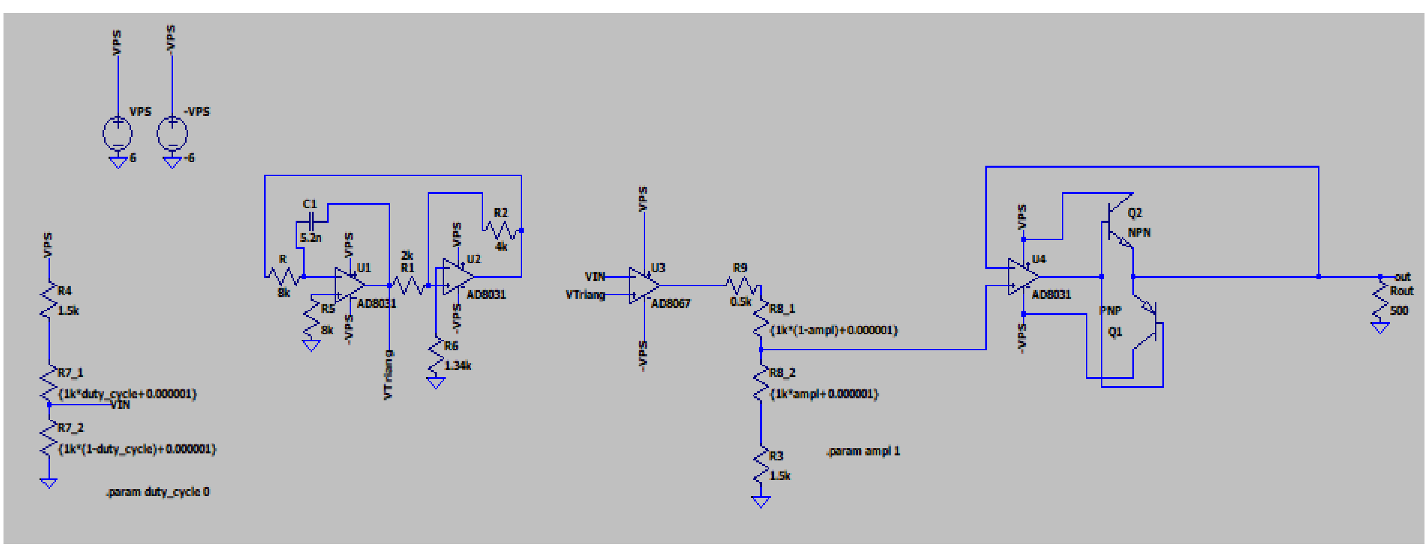
$v_{output\ of\ U4} = a * v_d = 10000 * v_d\ where\ a - open\ loop\ gain\ of\ the\ OpAmp$

$\Rightarrow -0.6 < a * v_d < 0.6$

$\rightarrow voltage\ from\ potentiometer\ \epsilon\ (-0.06mV; 0.06mV); for\ these\ values\ the\ output\ is\ 0$

- ⇨ Neglectable distortions

Schematic with theoretically computed values



Choosing standard components

Op Amps

The type of OpAmp, that is used in the circuit is AD8031, as it is a rail-to-rail amplifier. This means, it can give at the output a voltage that is almost equal to the value of the power supplies, with a negligible difference only, having a voltage output swing that gets very close to the values of the power supplies. The slew rate is relatively high (30V/us) compared to the common value of 10V/us. This means that the OpAmp stabilizes the output voltage in a short time as a response to a sudden change in the input voltage (as it is the case here, when the voltage switches from a low value to a high value, transition that needs to happen in a short time). Also, it is suitable to be used in the triangular signal generator, as the triangular signal has a slope of 177 mV/us. The bandwidth (54-80 MHz) is also suitable for this circuit, as the frequencies of the output signal, as well as that of the triangular signal, are 12kHz. Also, it is a low power amplifier, so it provides a very high accuracy and a very low power consumption, suitable for using in power amplifier circuits, as well as in signal generator circuits (as it is the case here, triangular signal generator), because of its precision. [8]

Consequently, the model I have chosen, that has these characteristics, is AD8031ARTZ-REEL7. In the circuit there will be 4 such OpAmps used. I have chosen to supply the OpAmps with a voltage of +/-6V, in order for the class B amplifier with global negative feedback to function properly, as the circuit needs to provide a maximum amplitude of 5V. This couldn't be achieved with a power supply of +/-5V for any impedance that will be connected to the output, as the class B amplifier with global negative feedback cannot function properly (it tries to give 5V to a low impedance while being supplied with 5V; that's why the supply voltage has to be increased). [8]

A much precise OpAmp is used as a simple comparator, the rail-to-rail AD8067 (has a higher slew rate of 640V/us). It is more expensive than the AD8031, but it is necessary to use it to generate a rectangular signal, as this signal has a high slope, so a quick stabilization at the high and low level is needed in order to generate this signal. The model's name is AD8067ARTZ-REEL7. [7]

Passive components and transistors

Start with the most difficult to find component, the capacitor.

- The capacitor

A component with the nominal value as that calculated theoretically (5.2 nF) is too hard to find and consequently too expensive. So, a value of 5.1nF is chosen, that is more accessible; for instance, CC0805KRX7R9BB512, that has a tolerance of 10%. It also has a good voltage rating for this circuit.

- The resistances and transistors

The resistances that are used in the triangular signal generator should have a low tolerance, as the triangular signal has a fixed value of 12kHz. Consequently, ERJ-1RHD2001C is chosen for the resistance R1 (2k) with the tolerance 0.5% (has a good voltage rating: 15 V and at the triangular generator only 3V is needed and a low power rating: 50 mW). As it is difficult to find a resistor of 4 kΩ for R2, a resistor of 4.02 kΩ can be find with a lower tolerance of 0.05% (RG1608P-4021-W-T5). In order to keep the frequency as close to 12kHz as possible, a resistor of 8.06 kΩ is chosen (ERJ-6RBD8061V) with a tolerance of 0.5% for R and R5, instead of one of 8 kΩ, because this type of resistor is difficult to find. For R6 a resistor of 1.35 kΩ is chosen (RT0603DRE071K35L) with a tolerance of 5%.

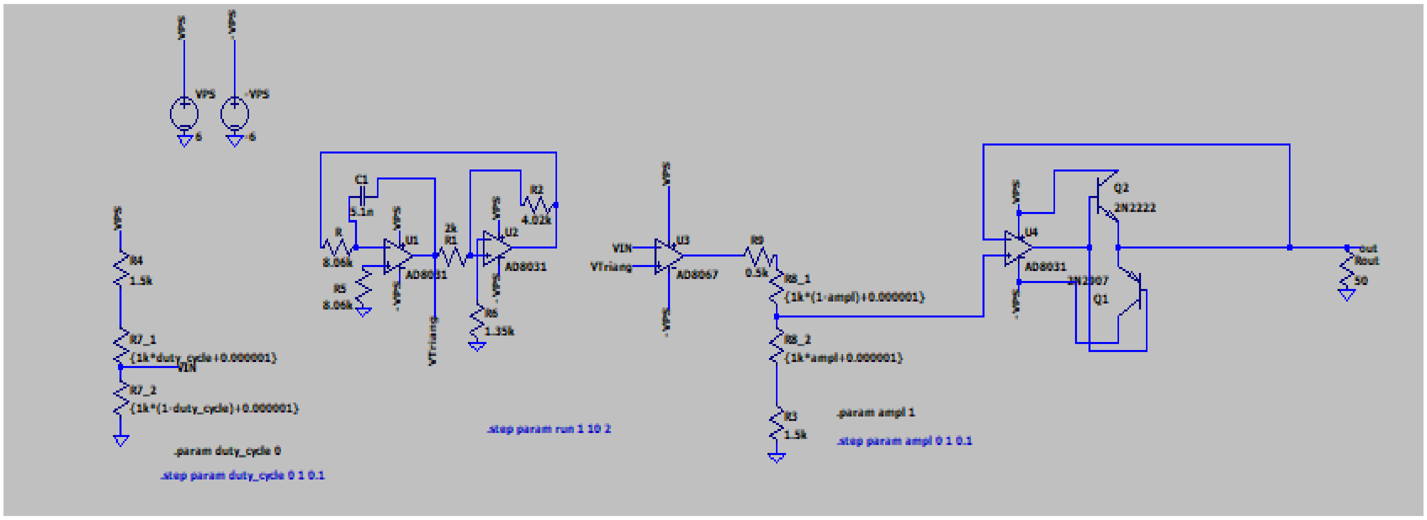
So, the frequency of the triangular signal and of the pwm signal will change. In the next chapter there will be explained how the frequency and the amplitude of the triangular signal are affected by measuring and doing analysis.

For the resistance R4 and the potentiometer R7 that provides VIN (which contributes to the variation of the duty cycle), there can be chosen elements with not so low tolerance, with the condition that the variation interval will be respected with little difference. Consequently, for R4 a resistor of 1.5kΩ is chosen (302-1.5K-RC) with a tolerance of 1% and for R7 a potentiometer of 1kΩ with a tolerance of 20% (P160KN-0QC15B1K). In the next chapter the influence of these tolerances on the duty cycle will be affected.

For the resistance R9 a resistor of 0.5kΩ with a low tolerance of 0.1% is chosen (RN732ATTD5000B25) because this resistance controls the voltage that will be given to the potentiometer R8 and also the maximum amplitude of the pwm generated signal (that should be 5V). For the potentiometer R8 choose a value of 1 kΩ with a tolerance of 20% (P160KN-0QC15B1K) and for the resistance R3 a resistor of 1.5 kΩ with a tolerance of 1% (302-1.5K-RC). In the next chapter the variation of the amplitude depending on the tolerances will be presented.

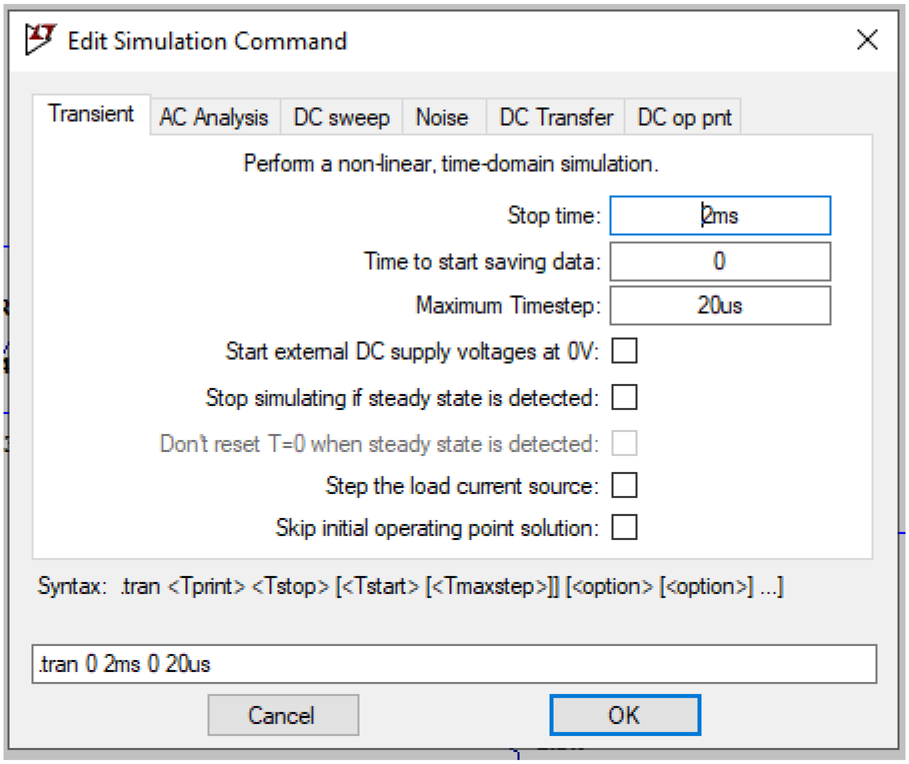
For the transistors that compose the class B amplifier, for the n-type transistor a BJT 2N2222 is chosen because it has a maximum collector current 0.6 A and a DC current gain of 100. The high collector current ensures the possibility to put low impedances at the output of the pwm generator, keeping the amplitude of the voltage at the desired level (provides the necessary current through the impedance without affecting the rest of the circuit and by amplifying the output current of the opamp). It has a threshold voltage of 0.65V, so a normal value for this parameter, keeping a low level of distortions of this class B amplifier with global negative feedback that are neglectable. The product that corresponds to this transistor is 2N2222A. In the same logic, for the p-type transistor is made a similar choice. The model's name would be 2N2907A, having the same maximum collector current as the n-type transistor, 600mA. In this way, the circuit can work correctly for a minimum impedance of 8.33Ω (=5V/600mA) for an amplitude of 5 V (at the output around 4.7V in this case, out of 5V, will be obtained), which is not the case if a voltage follower is used, where the minimum output impedance for which the circuit works correctly is limited by the output current of the OpAmp that is used (typically 20mA; the AD8031, 15mA). [10]

<u>The circuit with standard nominal values</u>

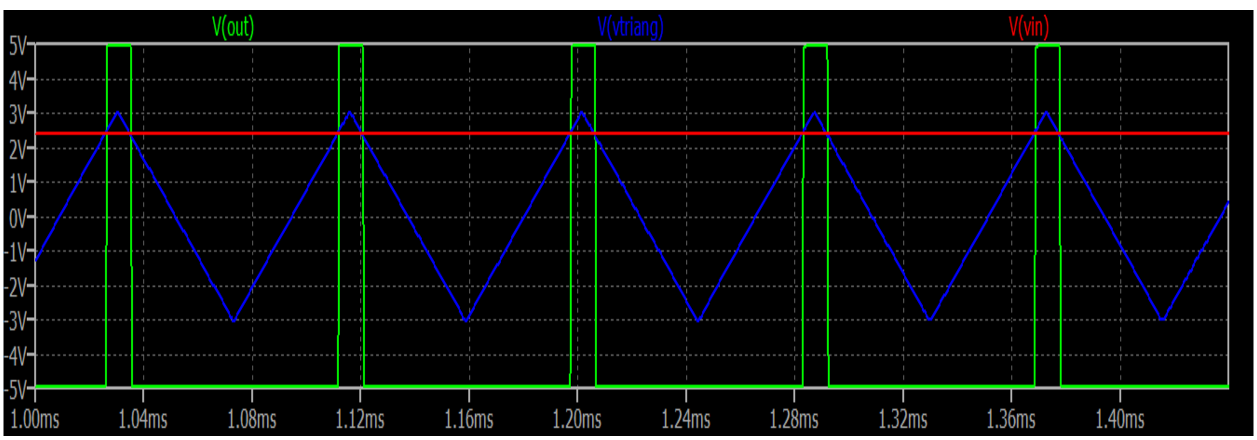


Simulations and Analysis

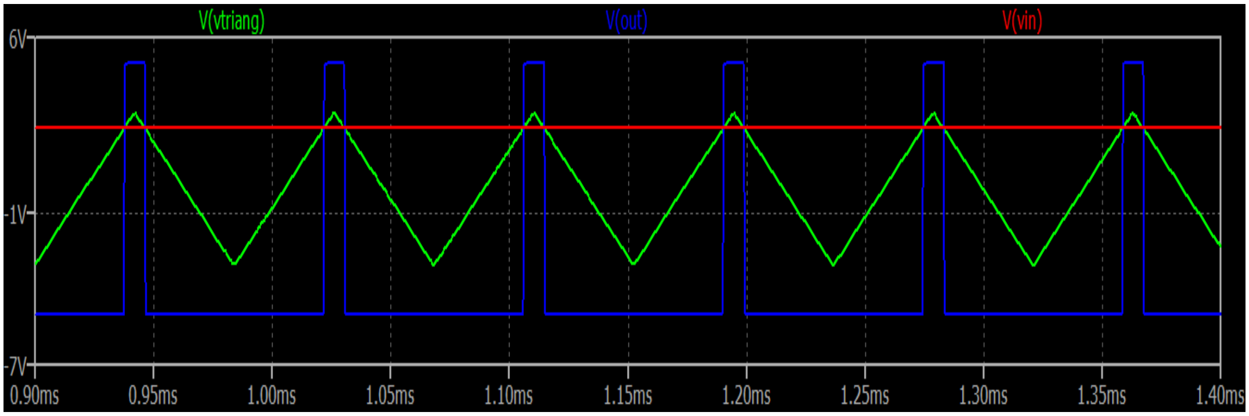
Time-domain simulation



(simulation profile)



(with the computed values)



(with the standard nominal values)

This simulation in time shows how the pwm generator works: at every intersection of VIN (red waveform) which is at 2.4V (minimum duty cycle) with VTriang, Vout switches form high to low, and it is at high value (5 V in this case, so maximum amplitude) when VIN is inside the triangle form the positive side. (points: signal compound out of 100 points per period)

Remark: Since the components that are in the triangular signal generator are slightly modified, the frequency of the output signal and the amplitude of the triangular signal will also be modified. To see this, the frequency and the amplitude of the triangular signal are measured with *.meas* command. To do this, some time moments will be measured first: time moment t1 when V(out) passes through 0 at the rising edge and t3 when V(out) passes through 0 at the next (consecutive) rising edge and also the frequency as 1/(t3-t1), like in the figure below:

```
.meas tran t1 V(out) when V(out)=0 rise=2
```

```
.meas tran t3 V(out) when V(out)=0 rise=3
```

```
.meas tran freq param 1/(t3-t1)
```

```
t1: v(out)=0 AT 0.000769187
```

```
freq: 1/(t3-t1)=11874.7
t3: v(out)=0 AT 0.0008534
```

(the results)

So, the frequency will be 11.8kHz instead of 12kHz and the amplitude of the triangular signal will be 3.028V:

```
.meas tran amplVTriang max V(VTriang)
```

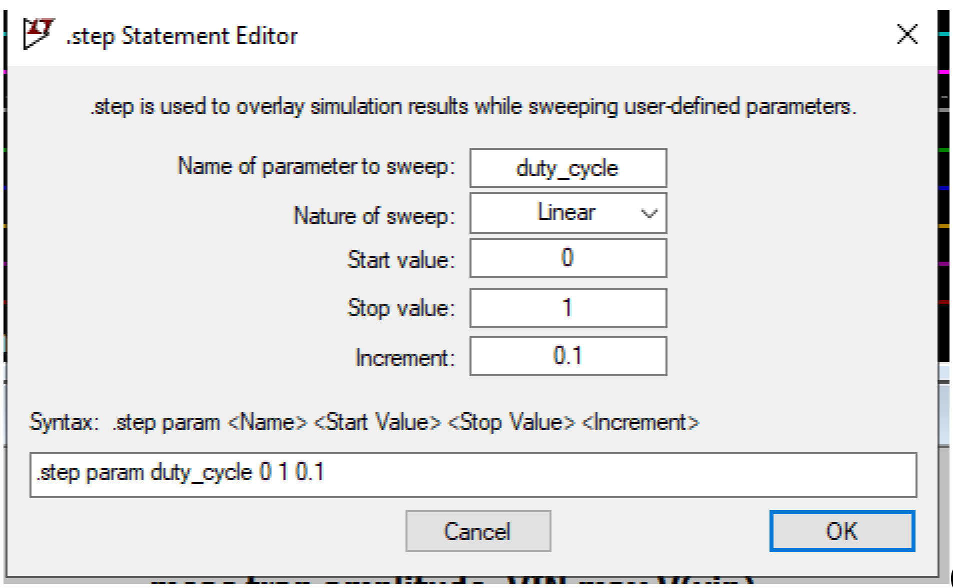
```
amplvtriang: MAX(v(vtriang))=3.02858 FROM 0 TO 0.003
```

Parametric analysis – varying duty cycle

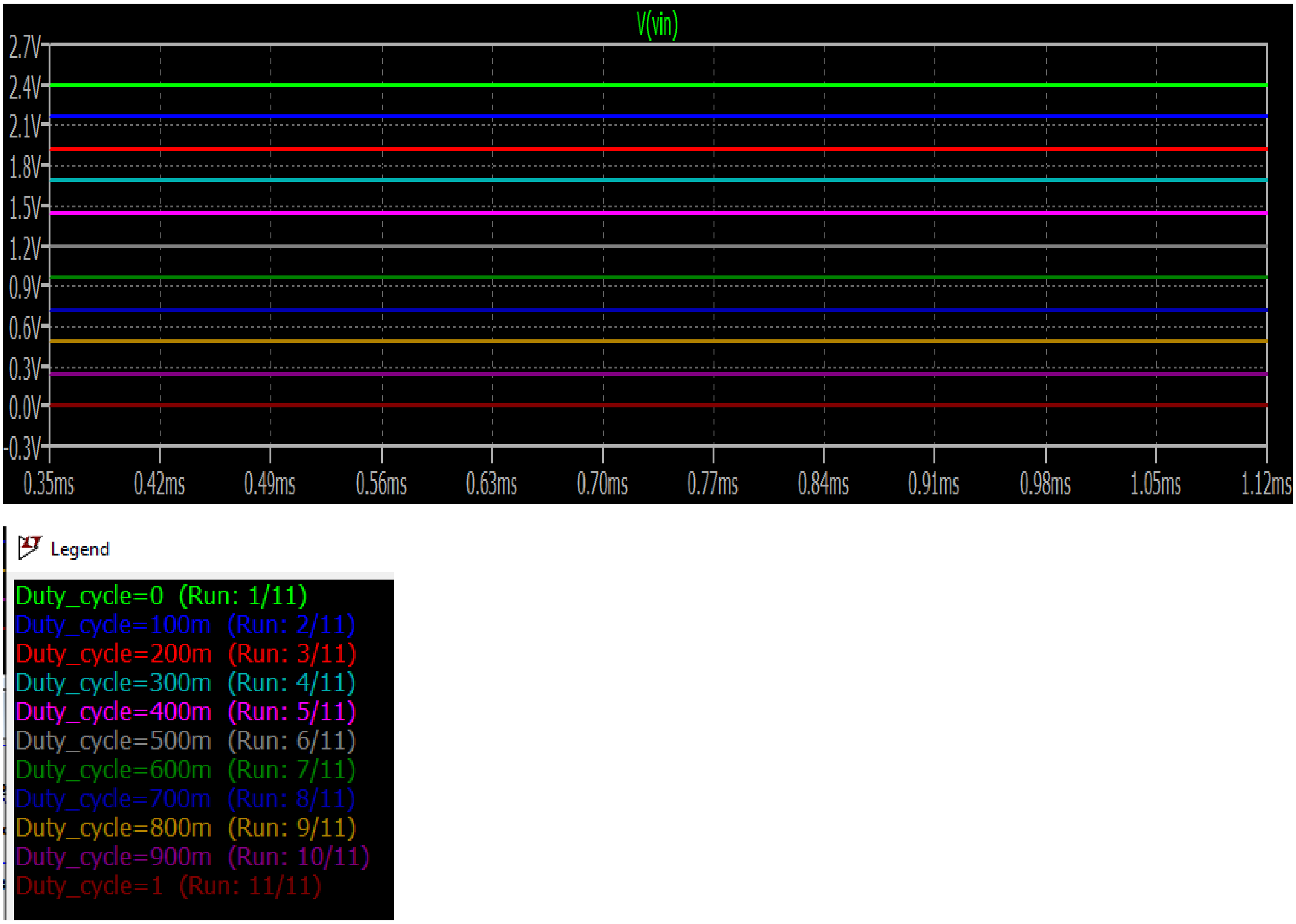
- Varying the parameter *duty_cycle* from 0 to 0.5 with a step of 0.1 (duty cycle: 10%-50%, VIN: 0V-2.4V and amplitude of Vout: 5V)

- Theoretical results:

duty_cycle	VIN [V]	Duty cycle [%]
0	2.4	10
0.1	2.16	14
0.2	1.92	18
0.3	1.68	22
0.4	1.44	26
0.5	1.2	30
0.6	0.96	34
0.7	0.72	38
0.8	0.48	42
0.9	0.24	46
1	0	50



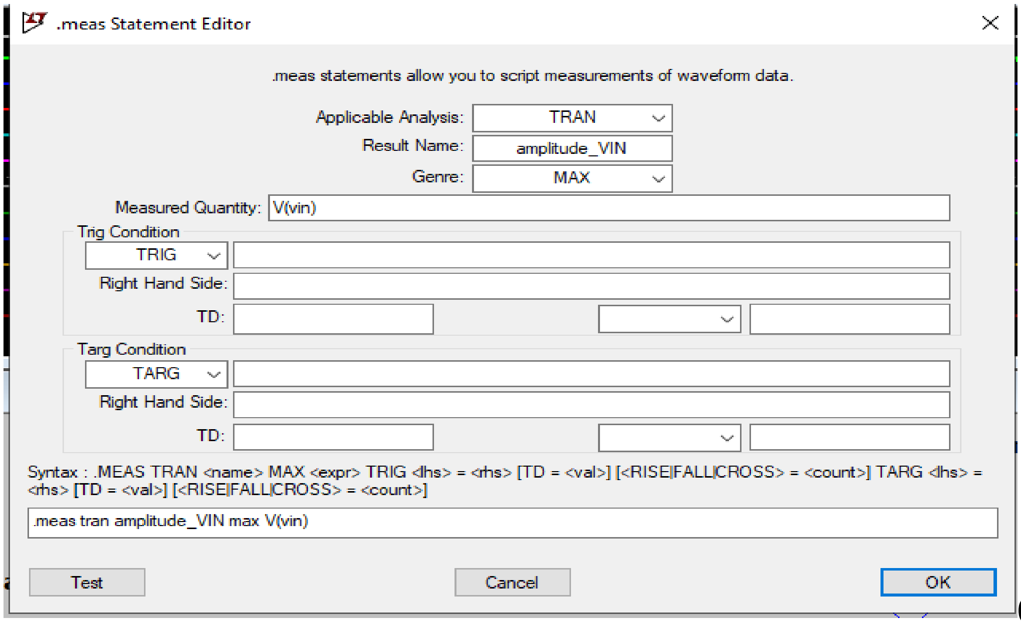
(simulation profile)



(Vin varies between 0V and 2.4V. Parametric analysis with transient analysis as secondary analysis)

- Performance analysis:

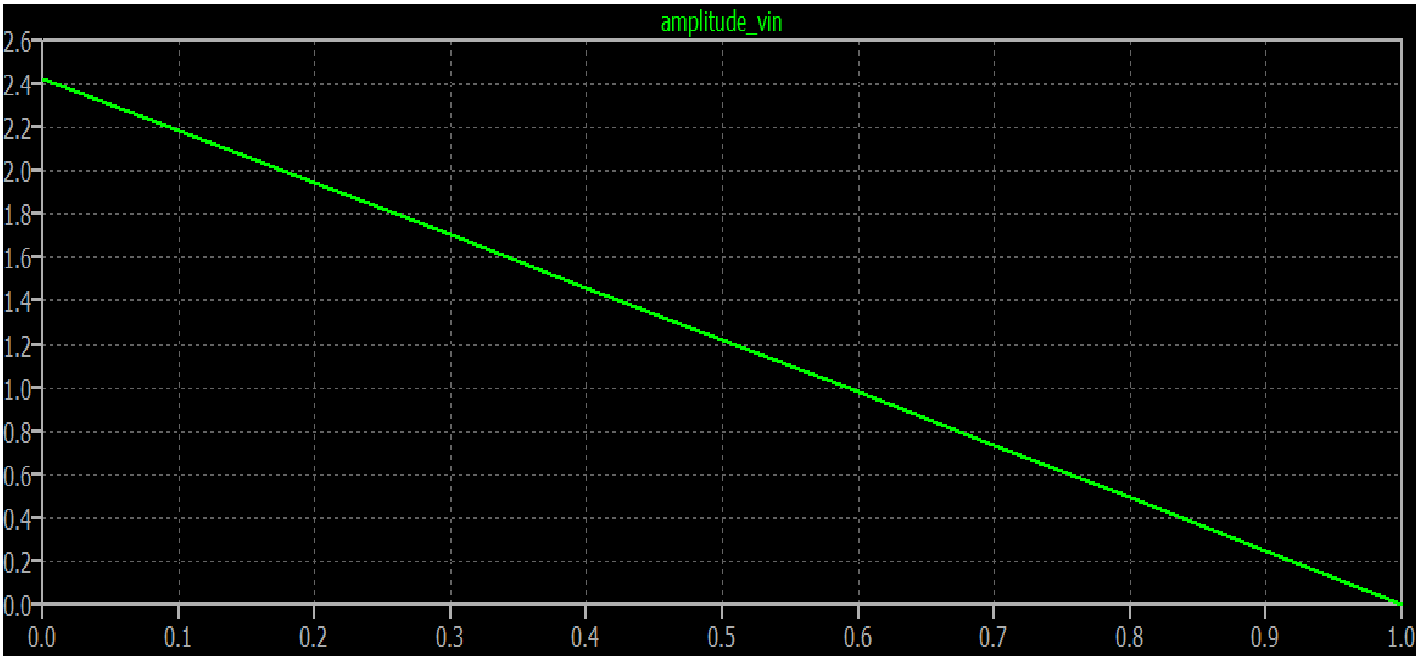
Using *.meas* the amplitude of Vin depending on the variation of the potentiometer R7 can be measured:



(command *.meas*)

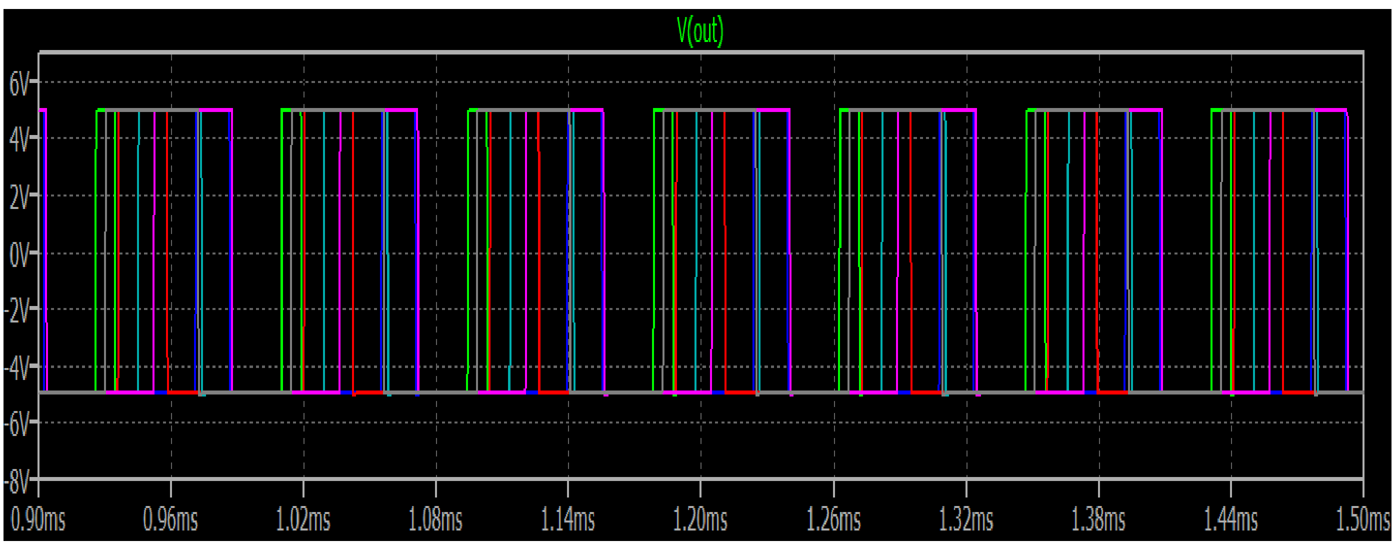
```
.step duty_cycle=0
.step duty_cycle=0.1
.step duty_cycle=0.2
.step duty_cycle=0.3
.step duty_cycle=0.4
.step duty_cycle=0.5
.step duty_cycle=0.6
.step duty_cycle=0.7
.step duty_cycle=0.8
.step duty_cycle=0.9
.step duty_cycle=1


Measurement: amplitude_vin
  step       MAX(v(vin)) FROM   TO
     1       2.4281      0      0.004
     2       2.1871      0      0.004
     3       1.94584     0      0.004
     4       1.70486     0      0.004
     5       1.4634      0      0.004
     6       1.22162     0      0.004
     7       0.979349    0      0.004
     8       0.736253    0      0.004
     9       0.49233     0      0.004
    10       0.247037    0      0.004
    11       2.47882e-009      0      0.004
```

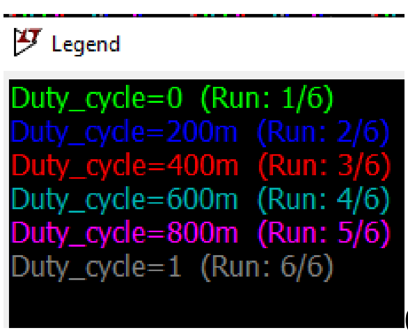
(measurement results)



(VIN decreases when more of the potentiometer is used – percentage use on the horizontal axis and on the vertical axis, the value of VIN)

The variation of the duty cycle at Vout is presented next:





(variation of the duty cycle at Vout; step size=0.2)

- Performance Analysis

Using *.meas* command the variation of the duty cycle in this interval can be measured. To do this, some time moments will be measured first: time moment t1 when V(out) passes through 0 at the rising edge, t2 when V(out) passes through 0 at the falling edge and t3 when V(out) passes through 0 at the next (consecutive) rising edge, like in the figure below:

```
.meas tran t1 V(out) when V(out)=0 rise=2

.meas tran t2 V(out) when V(out)=0 fall=2

.meas tran t3 V(out) when V(out)=0 rise=3
```

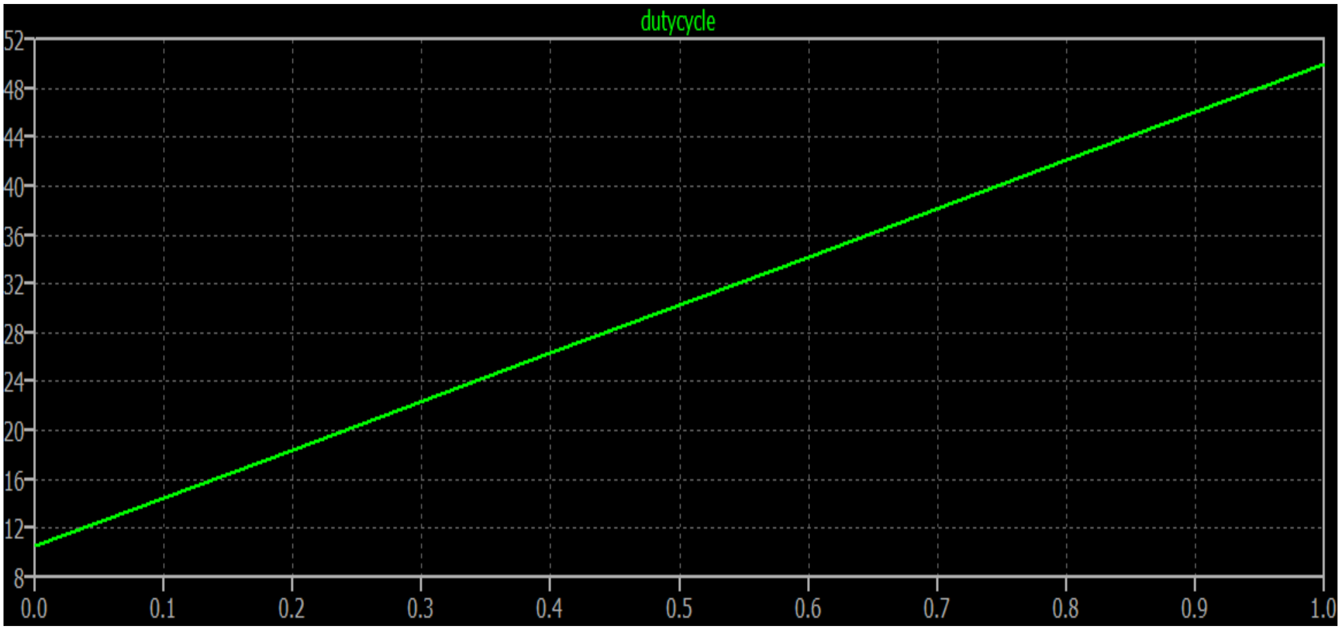
Next, the duty cycle based on these values must be calculated, where Ton=t2-t1, T=t3-t1 and the duty cycle=Ton/T.

```
.meas tran dutyCycle param (t2-t1)/(t3-t1)*100
```

Running the parametric analysis (with the transient analysis in the background) and measuring the duty cycle, the result will be:

```
.step duty_cycle=0
.step duty_cycle=0.2
.step duty_cycle=0.4
.step duty_cycle=0.6
.step duty_cycle=0.8
.step duty_cycle=1
```

```
Measurement: dutycycle
  step       (t2-t1)/(t3-t1)*100
     1       10.5331
     2       18.4294
     3       26.3119
     4       34.2078
     5       42.1109
     6       50.0053
```



(duty cycle vs percentage of potentiometer use)

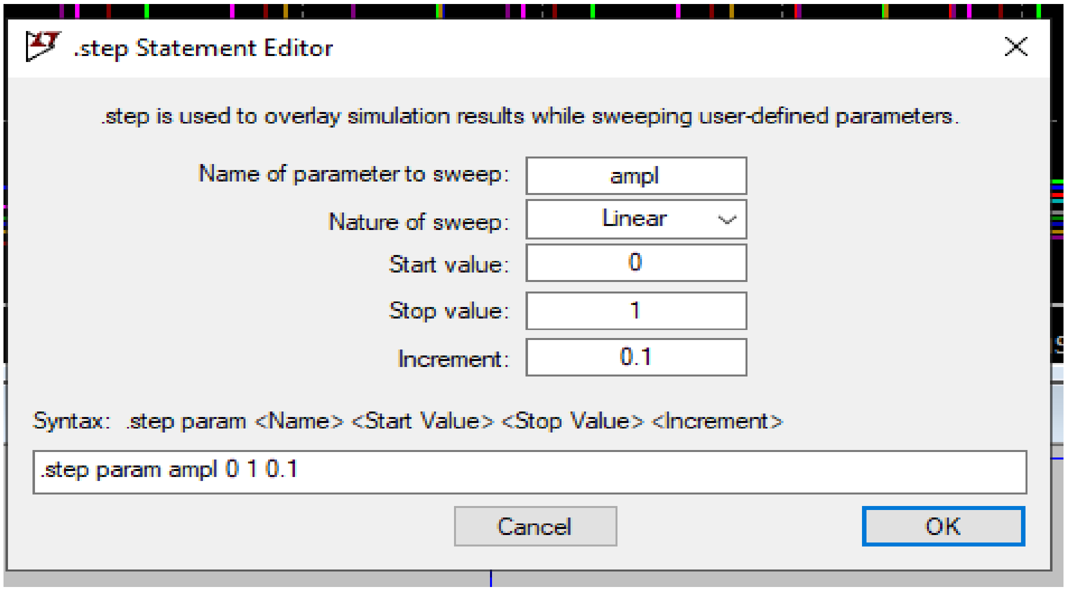
So, the duty cycle varies linearly with the adjustment of the potentiometer from 10.53% and 50%. 10.53% instead of the desired minimum duty cycle of 10% comes from the fact that the amplitude of the triangular signal is not 3V but 3.02V.

Parametric analysis – varying the amplitude

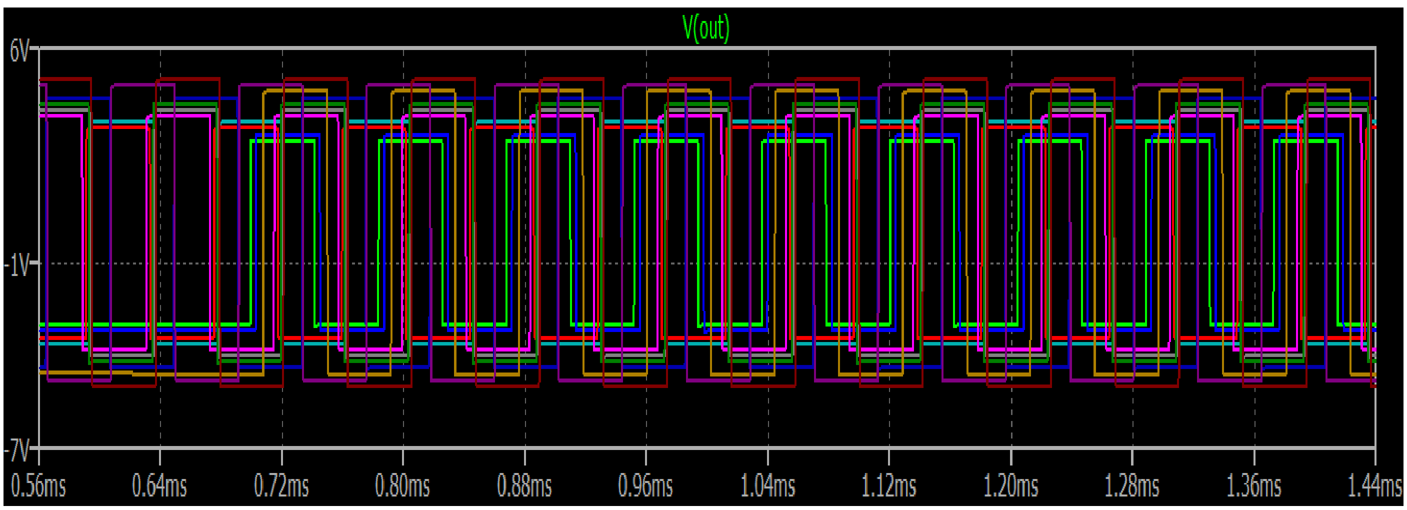
- Varying the parameter *ampl* from 0 to 1 with a step of 0.1 (Amplitude of Vout: 3V-5V and duty cycle: 50%), then a parametric analysis is done (and plot the result using the time-domain analysis: *.tran 0 3ms 0 20us*). Theoretical results:

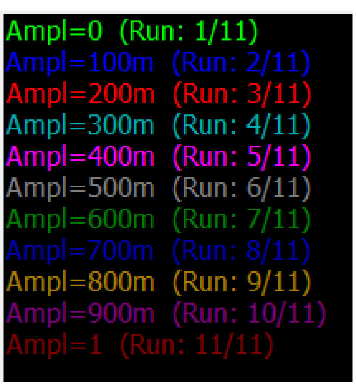
ampl	Amplitude of Vout [V]
0	3
0.1	3.2
0.2	3.4
0.3	3.6
0.4	3.8
0.5	4

ampl	Amplitude of Vout [V]
0.6	4.2
0.7	4.4
0.8	4.6
0.9	4.8
1	5



(simulation profile)

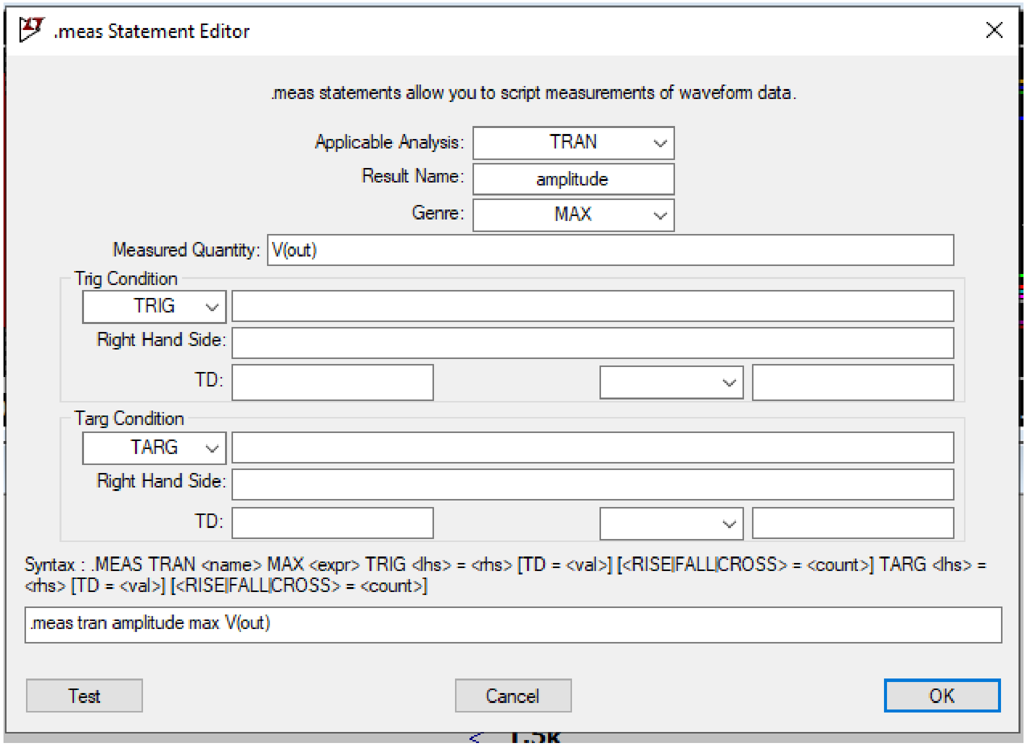




(parametric analysis with transient analysis as second analysis. We can see the variation of the amplitude between 3V and 5V)

- Performance analysis:

Using the *.meas* statement, the program will measure the values for the amplitude of the output signal and how these vary with the value of the potentiometer R8 (should be a linear variation)

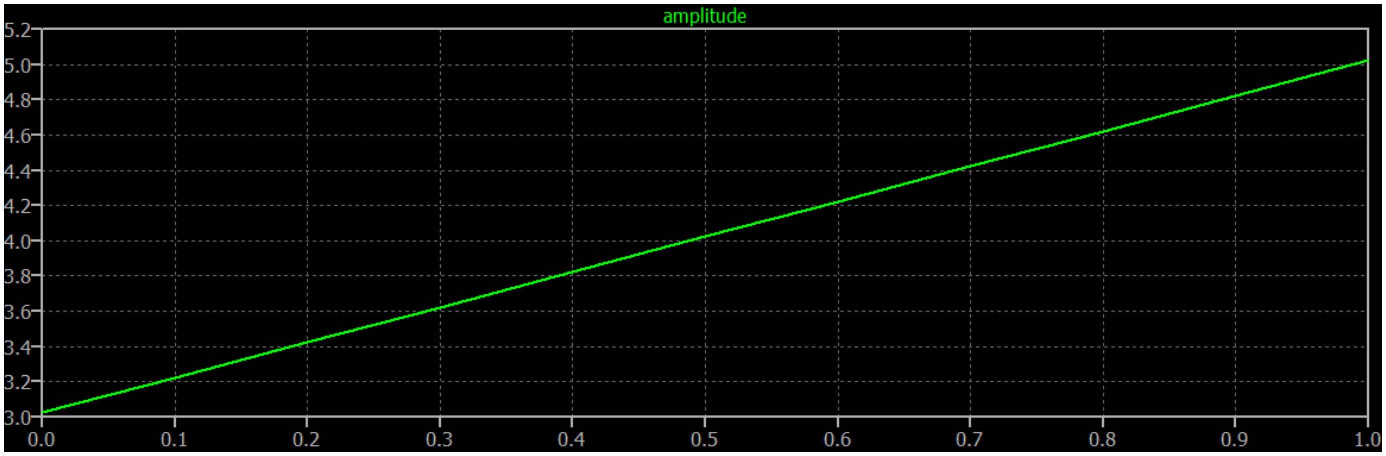


(command for measuring the amplitude of Vout)

```
.step ampl=0
.step ampl=0.1
.step ampl=0.2
.step ampl=0.3
.step ampl=0.4
.step ampl=0.5
.step ampl=0.6
.step ampl=0.7
.step ampl=0.8
.step ampl=0.9
.step ampl=1
```

```
Measurement: amplitude
  step       MAX(v(out)) FROM   TO
     1       3.02491      0     0.003
     2       3.22457      0     0.003
     3       3.4241       0     0.003
     4       3.6239       0     0.003
     5       3.82346      0     0.003
     6       4.02306      0     0.003
     7       4.22308      0     0.003
     8       4.42312      0     0.003
     9       4.62299      0     0.003
    10       4.82242      0     0.003
    11       5.02311      0     0.003
```

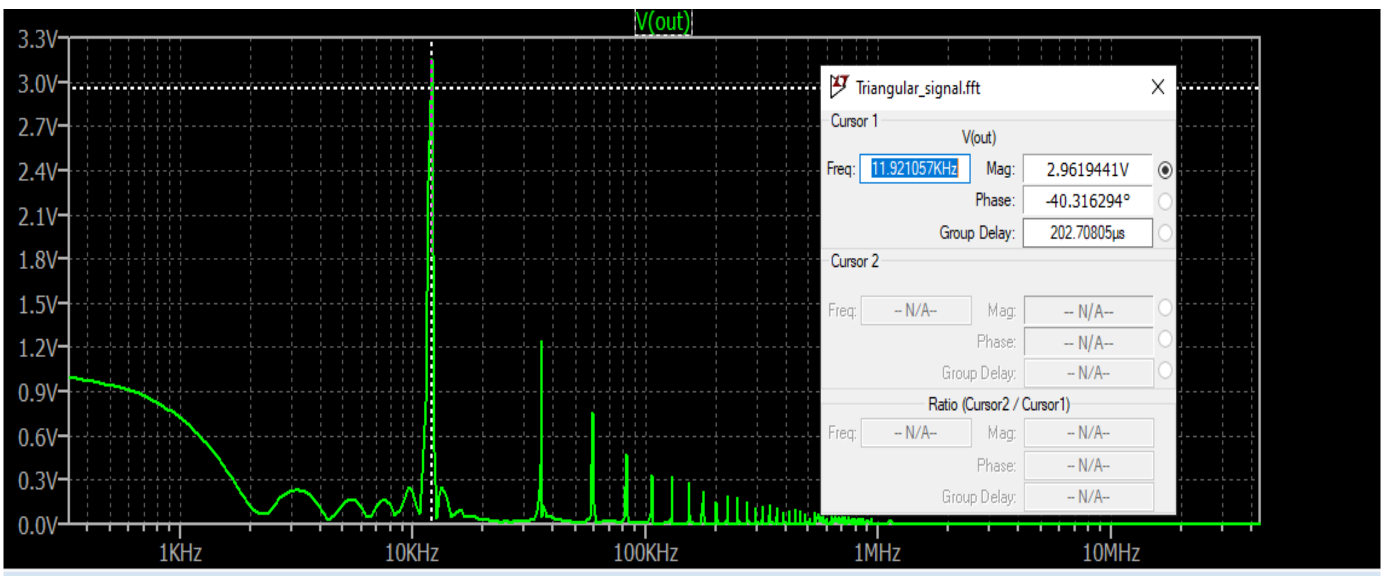
(results of the measurements – very close to the desired ones)



(variation of the amplitude depending on the percentage of the used potentiometer - linear variation between 3.02V and 5.02V)

FFT (Fast Fourier Transform)

- Analysis done to demonstrate that the output signal is rectangular.
- Output voltage spectrum:



At the working frequency of approx. 12kHz the harmonic is the biggest one (the central harmonic) and the spectrum is a sinc function, so it corresponds to the spectrum of the rectangular signal. (Ampl of Vout=5V and duty cycle= 50%)

The spectrum of a periodic rectangular signal:

$$Spectrum = \frac{2}{T} * A * \tau * sinc(\pi * n * f * \tau);\ T - period, A - amplitude, f - frequency, \boldsymbol{\tau} - duration\ of\ a\ triangle\ pulse. [9]\ \tau = T/2\ in\ this\ case:$$

$$Spectrum = \frac{2}{T} * 5 * \frac{T}{2} * \frac{\sin\left(\pi * n * \frac{1}{T} * \frac{T}{2}\right)}{\pi * n * \frac{1}{T} * \frac{T}{2}} => 5 * \frac{\sin\left(\pi * n * \frac{1}{2}\right)}{\pi * n * \frac{1}{2}}$$

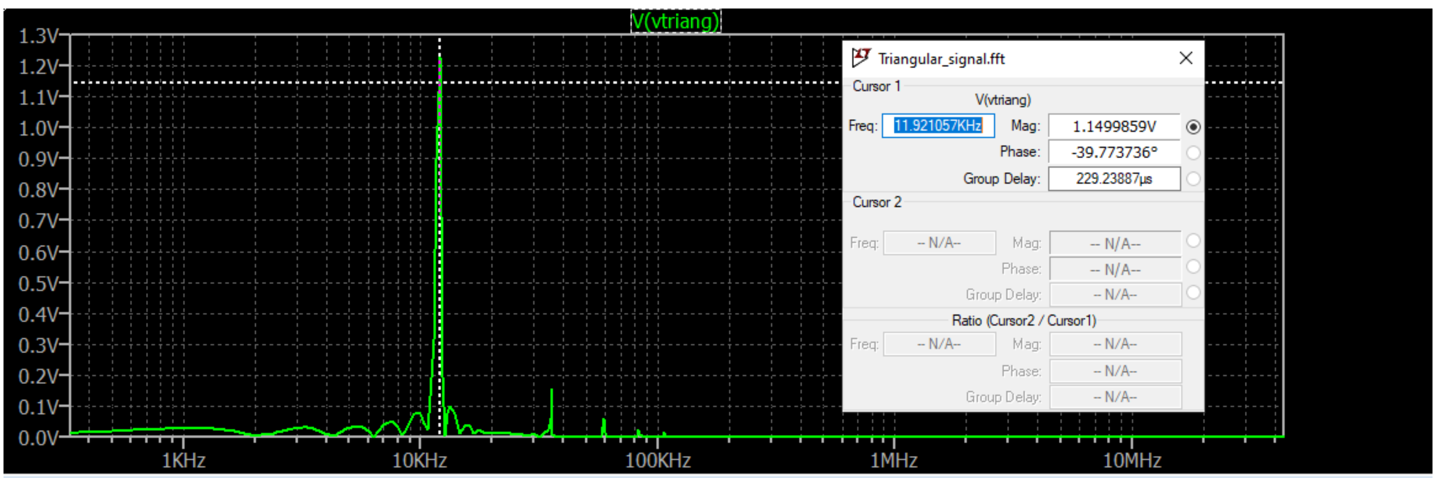
$$So, for\ the\ first\ harmonic\ (n = 1\ at\ f = 12kHz) =>$$

$5 * \frac{\sin\left(\frac{\pi}{2}\right)}{\frac{\pi}{2}} = 3.18\ V$ (corresponding to the measurement on the graphic)

The spectrum has to be discrete (consisting of harmonics at multiple of f) because the signal is periodic in time.

So, knowing the graph of the spectrum and the formula that gives the spectrum (so, the value of every harmonic), it has been proved that the signal is a rectangular one with the central frequency of about 12kHz.

- Triangular signal spectrum:



The central frequency is at about 12kHz and there can be seen also other, much smaller, harmonics and multiples of this frequency.

The formula of the spectrum for a periodic triangular signal is:

$$Spectrum = \frac{2}{T} * A * \frac{\tau}{2} * sinc^2\left(\pi * n * f * \frac{\tau}{2}\right);\ T - period, A - amplitude, f - frequency, \boldsymbol{\tau} - duration\ of\ a\ triangle\ pulse. [9]\ \tau = T\ in\ this\ case:$$

$$Spectrum = \frac{2}{T} * 3 * \frac{T}{2} * sinc^2\left(\pi * n * \frac{1}{T} * \frac{T}{2}\right) => 3 * \frac{sin^2\left(\pi * n * \frac{1}{2}\right)}{\pi^2 * n^2 * \frac{1}{4}}$$

$$So, for\ the\ first\ harmonc\ (n = 1\ at\ f = 12kHz) =>$$

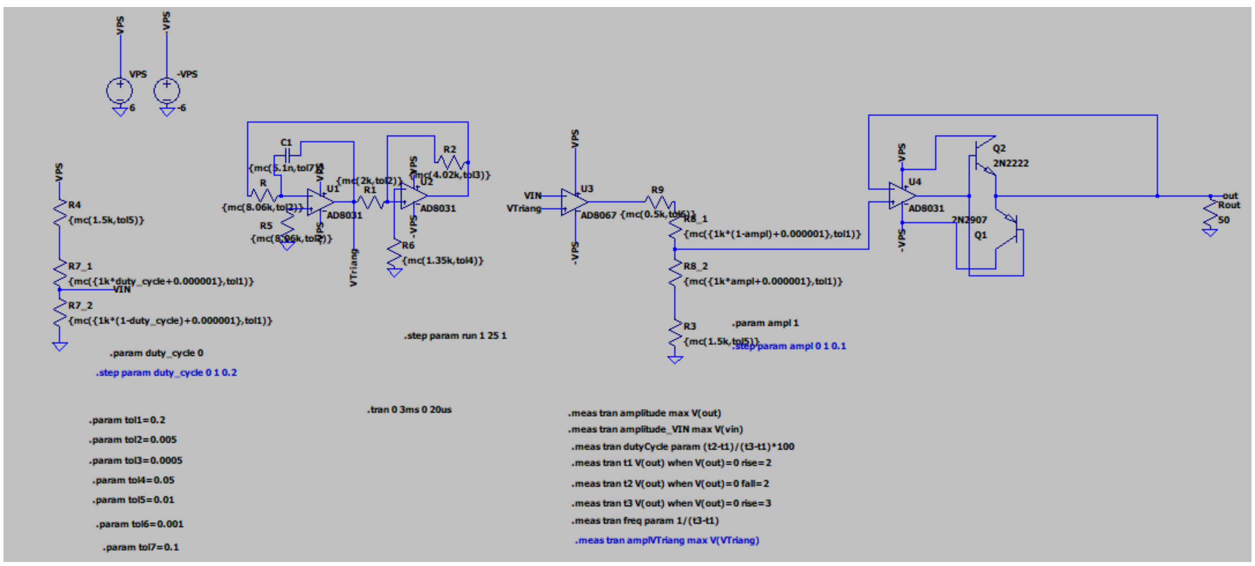
$3 * \frac{sin^2\left(\frac{1}{2}\right)}{\pi^2 * \frac{1}{4}} = 1.21\ V$ (corresponding to the measurement on the graphic)

The spectrum has to be discrete (consisting of harmonics at multiples of f) because the signal is periodic in time.

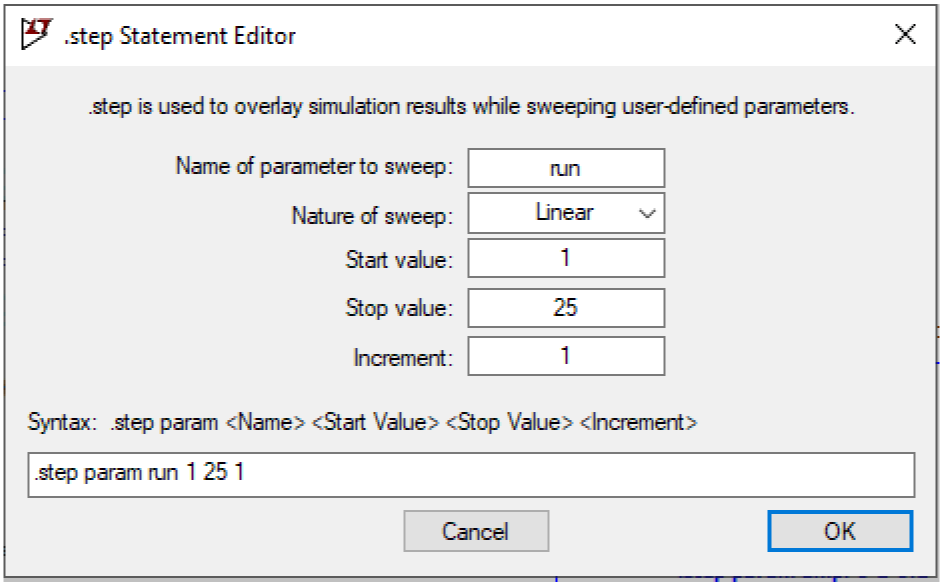
So, knowing the graph of the spectrum and the formula that gives the spectrum (so, the value of every harmonic), it has been proved that the signal is a triangular one with the central frequency of about 12kHz.

Monte Carlo analysis

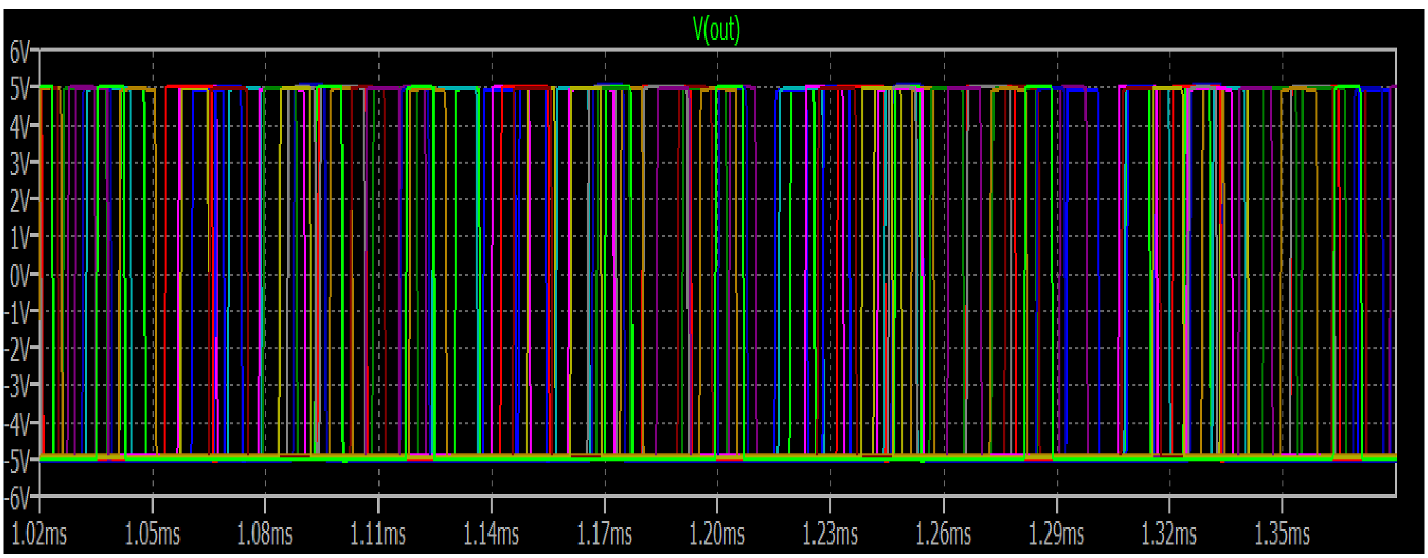
- Adding tolerances to the components and see their behavior (for a desired amplitude of the output signal of 5V and a duty cycle of 10%)



(the circuit with tolerances of all components)



(simulation profile to run monte carlo; big number of runs to get a better overview of the impact of the tolerances on the functioning of the circuit)



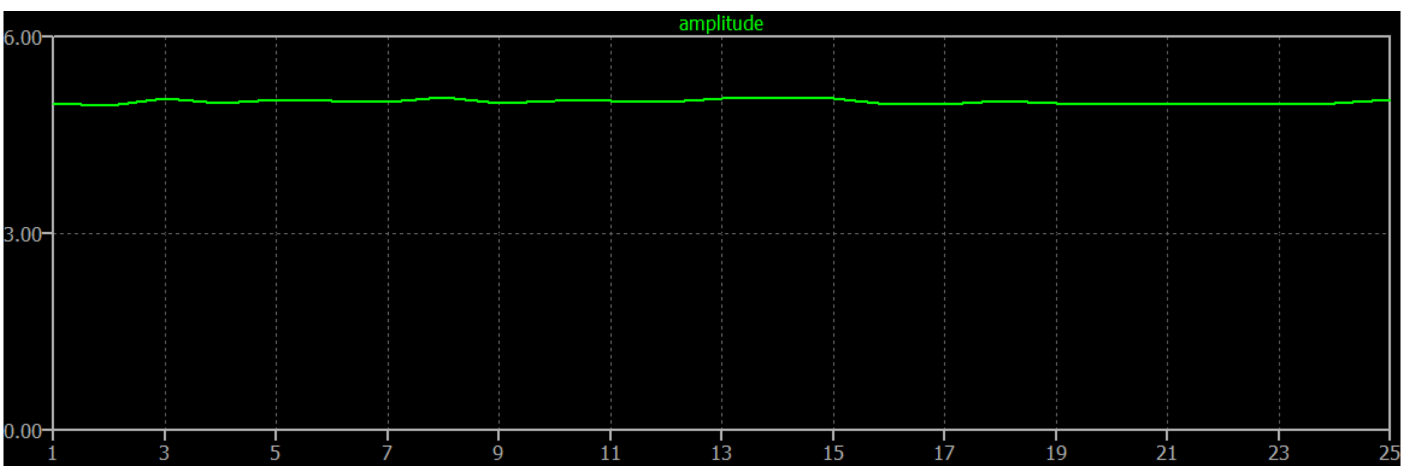
(Variation of Vout in time after monte carlo analysis)

With the *.meas* command the amplitude of the output signal is measured (the method to measure the amplitude of Vout was define previously) and get:

Measurement: amplitude

step	MAX(v(out))	FROM	TO
1	4.97972	0	0.003
2	4.94851	0	0.003
3	5.06044	0	0.003
4	4.98574	0	0.003
5	5.04318	0	0.003
6	5.02049	0	0.003
7	5.0102	0	0.003
8	5.07626	0	0.003
9	4.98081	0	0.003
10	5.02197	0	0.003
11	5.01704	0	0.003
12	5.01154	0	0.003
13	5.06504	0	0.003
14	5.0568	0	0.003
15	5.0548	0	0.003
16	4.97602	0	0.003
17	4.96657	0	0.003
18	5.01807	0	0.003
19	4.99153	0	0.003
20	4.97668	0	0.003
21	4.96407	0	0.003
22	4.99487	0	0.003
23	4.97531	0	0.003
24	4.99166	0	0.003
25	5.03834	0	0.003

So, the minimum amplitude is 4.94V and the maximum amplitude 5.07V, an acceptable range of variation. In the graphic from below there can be seen that this variation is tolerable for the functioning of the circuit, an amplitude that has very little variation from its desired value of 5V is obtained:



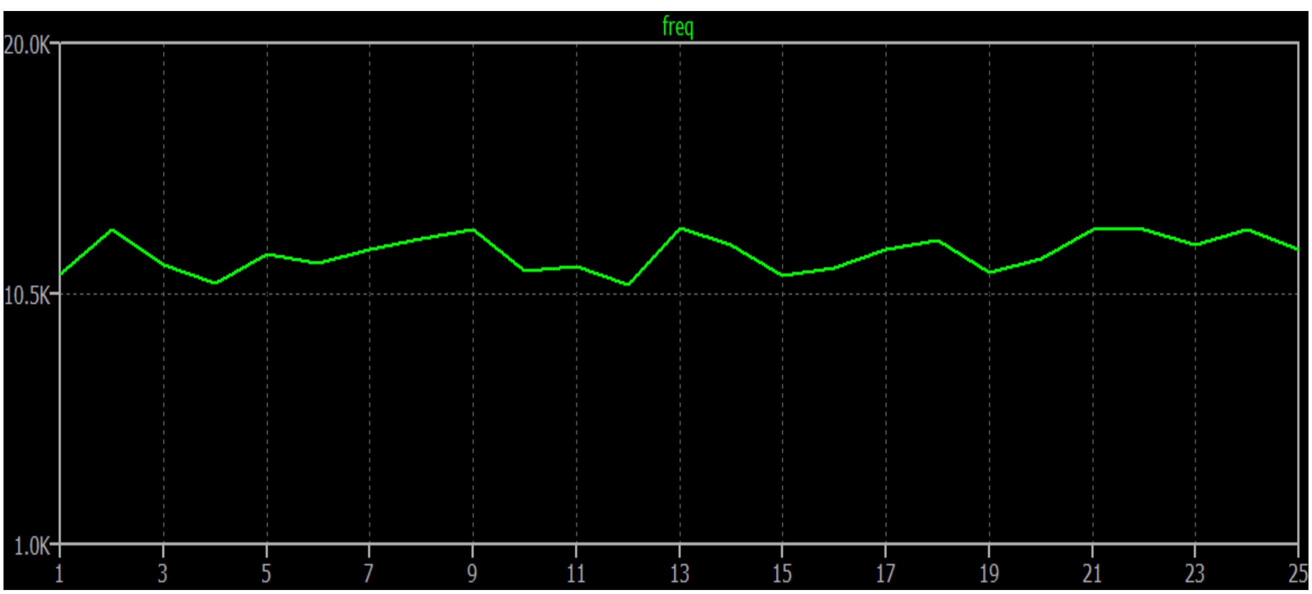
(amplitude of Vout vs simulation run)

In the same manner, the variation of the frequency of the signal is obtained (method to measure the frequency was defined previously):

Measurement: freq

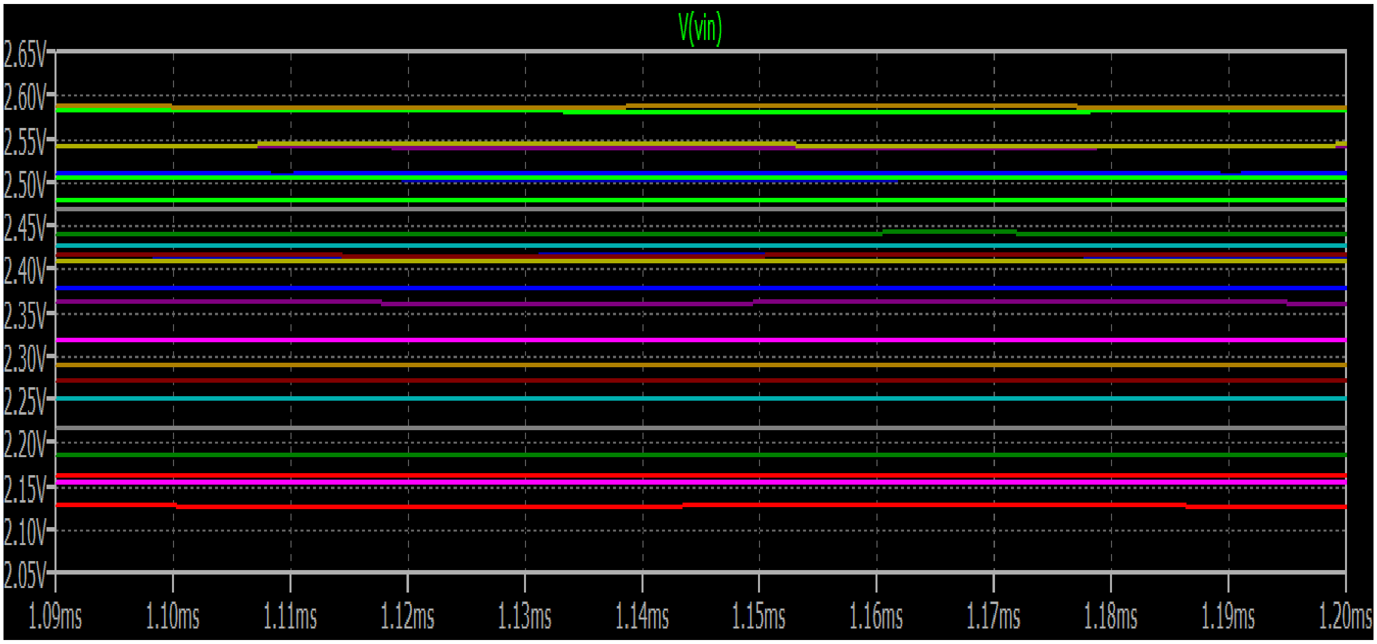
step	1/(t3-t1)
1	11240.9
2	12923
3	11618.2
4	10887.1
5	12011.2
6	11647.1
7	12167.4
8	12603.7
9	12964.6
10	11400.7
11	11525.3
12	10872.7
13	13014.1
14	12390.9
15	11212.8
16	11486.4
17	12194.1
18	12544.4
19	11313.3
20	11852.1
21	12975.5
22	12956.7
23	12393.7
24	12943.7
25	12188.7

So, the frequency has a variation from 10.88kHz to 13kHz; variation that is caused mainly by the big tolerance of the capacitor (10%). This interval could be reasonable, but if a more precise frequency is wanted, a capacitor with a smaller tolerance, that is more expensive, could be used. The graph from below shows this frequency variation:



(frequency of Vout vs simulation run)

Next the variation of VIN, that controls the duty cycle, is presented:

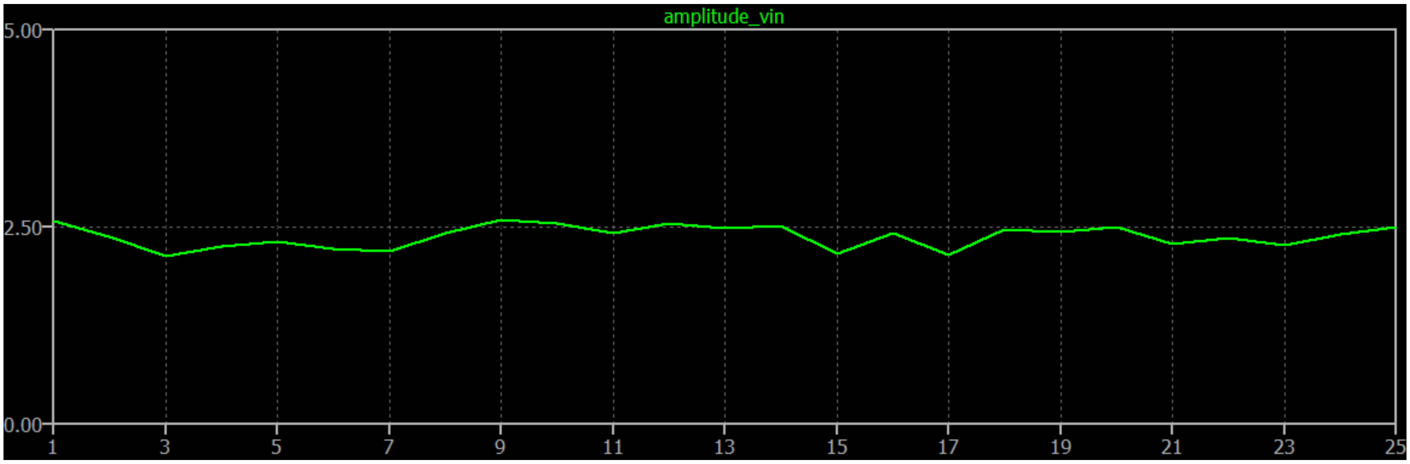


(monte carlo analysis with transient analysis as second analysis)

Using the *.meas* command, the amplitude of VIN can be measured (how to measure VIN was defined previously) and the results are:

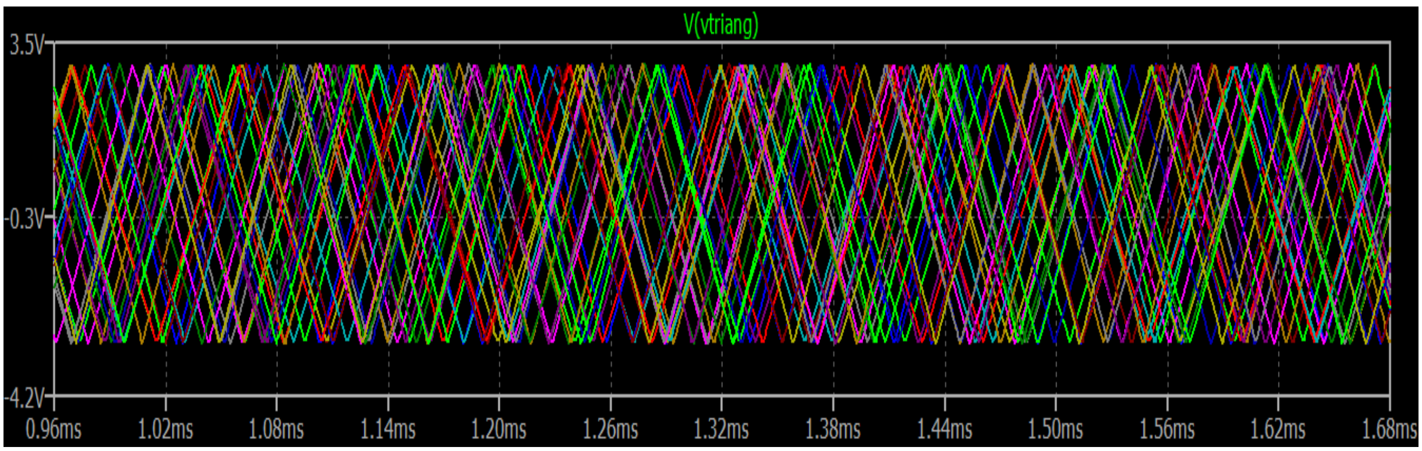
```
Measurement: amplitude_vin
  step       MAX(v(vin)) FROM    TO
     1       2.58201     0       0.003
     2       2.37917     0       0.003
     3       2.12769     0       0.003
     4       2.25183     0       0.003
     5       2.31838     0       0.003
     6       2.21652     0       0.003
     7       2.1864      0       0.003
     8       2.41645     0       0.003
     9       2.5875      0       0.003
    10       2.54048     0       0.003
    11       2.41642     0       0.003
    12       2.54343     0       0.003
    13       2.47975     0       0.003
    14       2.51017     0       0.003
    15       2.16227     0       0.003
    16       2.42737     0       0.003
    17       2.15433     0       0.003
    18       2.4687      0       0.003
    19       2.44167     0       0.003
    20       2.50436     0       0.003
    21       2.29078     0       0.003
    22       2.36177     0       0.003
    23       2.27157     0       0.003
    24       2.4092      0       0.003
    25       2.50593     0       0.003
```

Therefore, VIN varies between 2.15V and 2.587V from the desired value of 2.4V (variation that is caused mainly by the tolerance of the potentiometer – 20%). The graph from below shows this variation of VIN:



(VIN vs simulation run)

Next, the effect of the tolerances on the triangular signal, more specific its amplitude, in order to see how the relationship between Vin and the amplitude of VTriang affects the duty cycle of the output signal:



(variation of VTriang in time with monte carlo analysis)

Using *.meas* command the amplitude of the triangular signal can be measured (how to do this was presented previously) and get:

Measurement: amplvtriang

step	MAX(v(vtriang))	FROM	TO
1	3.01278	0	0.003
2	3.03612	0	0.003
3	3.02816	0	0.003
4	3.01741	0	0.003
5	3.04429	0	0.003
6	3.04071	0	0.003
7	3.03807	0	0.003
8	3.04757	0	0.003
9	3.03975	0	0.003
10	3.02539	0	0.003
11	3.03713	0	0.003
12	3.01857	0	0.003
13	3.01987	0	0.003
14	3.0373	0	0.003
15	3.0094	0	0.003
16	3.01524	0	0.003
17	3.03701	0	0.003
18	3.01909	0	0.003
19	3.03644	0	0.003
20	3.03519	0	0.003
21	3.04675	0	0.003
22	3.04163	0	0.003
23	3.02106	0	0.003
24	3.03333	0	0.003
25	3.03539	0	0.003

So, there is a very small variation of the amplitude of the triangular signal.

The relationship between the amplitude of the triangular signal, VIN, frequency and the duty cycle is:

$$\frac{Ampl\ of\ V_{Triang}}{Ampl\ of\ V_{Triang} - VIN} = \frac{\frac{T}{2}}{T_{on}}\ and\ D = \frac{T_{on}}{T} * 100\ (from\ previously)$$

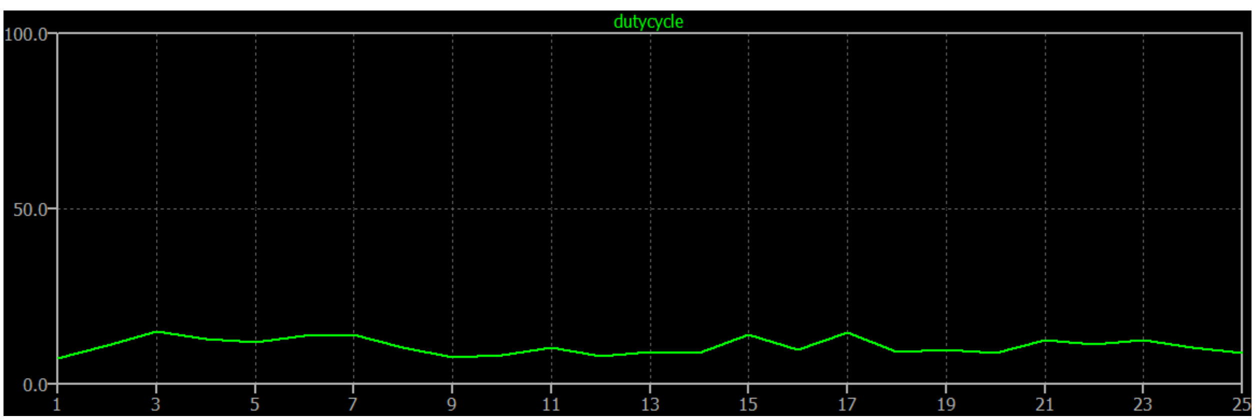
Consequently, the duty cycle will be affected by the amplitude of the triangular signal, VIN and frequency (T=1/f) and next the variation of the duty cycle due to these parameters will be presented.

The variation of the duty cycle of the output signal can be measured (the method to do this was defined previously) and the following result is obtained:

Measurement: dutycycle

step	(t2-t1)/(t3-t1)*100
1	7.29721
2	10.98
3	15.0103
4	12.8232
5	12.0783
6	13.7083
7	14.1473
8	10.5212
9	7.61386
10	8.17925
11	10.3711
12	8.0144
13	9.13187
14	8.85669
15	14.216
16	9.89731
17	14.6631
18	9.30119
19	9.94969
20	8.91091
21	12.5533
22	11.3232
23	12.5211
24	10.4702
25	8.89681

So, the duty cycle will vary between 7.29% and 15% (caused by the variation of VIN and the variation of the amplitude of the triangular signal) out of the desired value of 10%. Therefore, a resonable variation intervall of the duty cycle is obtained, that is shown in the graphic from below:



(duty cycle vs simulation run)

In conclusion, the chosen components have very little impact on the functioning of the circuit, so they can be use to build a pwm generator with the specified design parameters.

Bill of materials

Nr Crt	Model name	Description	Units	Comp	Price per unit [RON]	Total price [RON]
1	AD8031ARTZ-REEL7	Operational Amplifiers - Op Amps SOT23 SINGLE LOW POWER OP AMP	3	U1, U2, U4	8.86	26.58
2	AD8067ARTZ-REEL7	Precision Amplifiers High Gain Band Width High Perf Fast FET	1	U3	18.32	18.32
3	CC0805KRX7R9BB512	Multilayer Ceramic Capacitors MLCC - SMD/SMT 50V 5100pF X7R 0805 10%	1	C1	0.09	0.09
4	ERJ-1RHD2001C	Thick Film Resistors - SMD 0201 chip resistor (R=2k)	1	R1	0.08	0.08
5	RG1608P-4021-W-T5	Thin Film Resistors - SMD 1/10W 4.02K Ohm .05% 0603 25ppm	1	R2	0.77	0.77
6	ERJ-6RBD8061V	Thick Film Resistors - SMD 0805 Resistor 0.5% 50ppm 8.06KOhm	2	R, R5	0.08	0.08
7	RT0603DRE071K35L	Thin Film Resistors - SMD 1/10W 1.35K Ohms .5%	1	R6	0.05	0.05
8	302-1.5K-RC	Thick Film Resistors - SMD 1/10WATT 1.5KOHMS	2	R4, R3	0.005	0.01
9	P160KN-0QC15B1K	Potentiometers 1/5W 1K Ohms 20% 16mm ROTARY POT	2	R7, R8	2.53	5.06
10	RN732ATTD5000B25	Thin Film Resistors - SMD 500Ohm,0805,0.1%,25p	1	R9	0.52	0.52
11	2N2222A	Bipolar Transistors - BJT Bipolar Transistor, TO-92, 40V, 600mA, NPN	1	Q2	0.39	0.39
12	2N2907A	Bipolar Transistors - BJT Bipolar Transistor, TO-92, 60V, 600mA, PNP	1	Q1	0.39	0.39
TOTAL						52.34

Conclusions

This PWM generator is based on the idea of “building” a rectangular signal of variable duty cycle and amplitude by comparing two signals: one triangular and one DC and at every intersection point in time domain of the DC signal with the triangular signal, a switch of the rectangular signal from low level to high level (or vice-versa) happens. This is performed by a simple comparator that has connected to its inverting input the DC signal and to its non-inverting the triangular signal. Consequently, the frequency of the resulted rectangular signal is the frequency of the triangular signal. The variation of the duty cycle is performed by a circuit with a potentiometer based on a voltage divider out from the voltage of the power supplies, that gives the DC signal, and so the intersection points with the triangular signal can be controlled. In a similar way is the amplitude varied, but by connecting the voltage divider circuit (also with a potentiometer) at the output of a simple comparator, that gives a signal with the amplitude equals with the voltage of the power supply. From the potentiometer we collect the output signal that is passed through a class B amplifier with global negative feedback that has a unity gain. This is done to be able to connect at the output also low impedances without affecting the performance of the circuit.

The components that are chosen to build this circuit and their tolerances have a small impact on the performance of the circuit (demonstrated in the previous chapters), although they produce a variation of the parameters of the circuit (amplitude, frequency, duty cycle), this variation is in an acceptable interval. So, they are suitable to be considered when build such a circuit with the given parameters.

The circuit was designed in LTSpice, as well as the simulations and analysis were done with the help of the same simulator.

References

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