Circuit Theory and Electronics Fundamentals 2020/2021

Integrated Masters in Aerospace Engineering, Técnico, University of Lisbon

Third Laboratory Report

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1 Introduction

The objective of this laboratory assignment is to study and implement an AC/DC converter circuit while, at the same time, trying to maximize the figure of merit M. The AC/DC converter circuit can be separated into two circuits: an Envelope Detector circuit, that takes a (relatively) high-frequency amplitude modulated signal as input and provides an output (the demodulated envelope of the original signal), and a Voltage Regulator circuit, designed to automatically maintain a constant voltage. The circuit can be seen in Figure 1.

The implementation of the AC-DC converter circuit was made according to the theoretical or simulation principles we were based on, with the construction of two simillar circuits with just a few differences in the components value (such as the resistance of some resistors and the capacitance of the capacitors) and also in the components number (such as the number of diodes). These small adjustments were made in order to compensate the changes in the behaviour of the electric circuits components verified while implementing both the theoretical circuit in GNU Octave and the simulation circuit in NGSpice.

In Section 2, a theoretical introduction is made in order to contextualize all the main principles that sustain our construction and analysis of the circuit. A theoretical AC-DC coverter is built and carefully analysed in Section 3, where the results are obtained in GNU Octave. Also, in Section 4, another AC-DC converter is constructed and analysed by simulation through the use of NGSpice to simulate the real electric circuit behaviour. The results of the simulation of Section 4 are then compared to the theoretical results obtained in Section 3 and the comparative results are expressed in Section 5. The figure of merit, calculated according to the components used to build the simulation circuit, can also be found in Section 5. The conclusions of this study are outlined in the final part of the report, in Section 6.

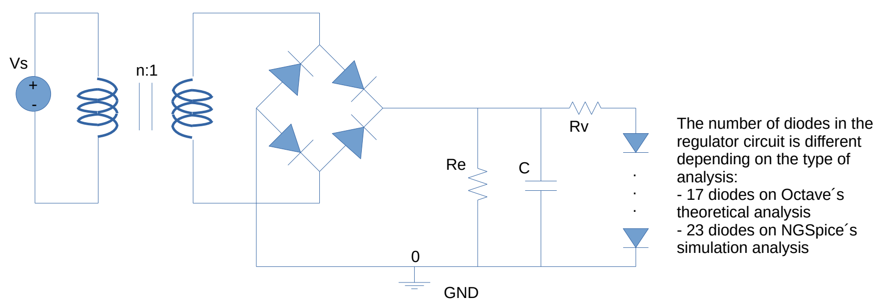


Figure 1: Third laboratory circuit.

2 Theoretical Introduction

Electric power is transported on wires either as a direct current (DC) flowing in one direction at a non-oscillating constant voltage, or as an alternating current (AC) flowing backwards and forwards due to an oscillating voltage. AC is the dominant method of transporting power because it offers several advantages over DC, including lower distribution costs and simple way of converting between voltage levels thanks to the invention of the transformer. AC power that is sent at high voltage over long distances and then converted down to a lower voltage is a more efficient and safer source of power in homes.

AC to DC Converters are one of the most important tools in power electronics because a lot of real applications are based on this type of conversions. The AC current to DC current conversion process is known as rectification. This rectifier converts the AC supply into the DC supply at the load end connection. Normally, transformers are used to adjust the AC source to get the step down transformer to reduce the voltage amplitude, so that there is a better operation range for the DC supply.

The output voltage of the full-wave rectifier is not constant, it is always oscillating and thus can't be used in real-life applications. That's why it is required a DC supply with a constant output voltage. This need can be fulfilled by using an adequate filter with an inductor or a capacitor (envelope detector circuit) to make the output voltage smooth and constant.

This capacitor is connected in parallel to the load resistance in a linear power supply. The capacitor is used to increase the DC voltage and to reduce the ripple voltage of the output obtained. This capacitor is also called a reservoir or smoothing capacitor and it is generally followed by a voltage regulator which eliminates the remaining ripples so that the required output can be achieved.

While the rectifier conducts and the potential is higher than the charge across the capacitor, the capacitor stores the energy from the transformer. However, when the output of the rectifier falls below the charge across the capacitor, the capacitor naturally discharges its energy into the circuit. As the rectifier conducts current only in the forward direction, all the energy discharged by the capacitor will flow into the load. There are other types of filters, such as the half wave rectifier, studied in the theoretical classes. However, the efficiency of the full-wave rectifier is double that of a half-wave and the ripple voltage is lower using this four diodes bridge rectifier.

Finnaly, a voltage regulator is a circuit that creates and maintains a fixed output voltage, regardless of changes to the input voltage or load conditions. A simple voltage regulator can be made from a resistor in series with a diode or a series of diodes. The voltage regulators keep the voltages from a power supply within a range that is compatible with the other electrical components.

3 Theoretical Analysis

In this section, we can find the results of an AC-DC converter build according to theoretical principles in order to be the subject of a theoretical analysis. The numeric results or graphics are presented alongside the formulae and methods used to calculate them. All of the results were obtained usig GNU octave and the section is organized in four different subsections, dividing the converter into two circuits - the envelope detector circuit in Subsection 3.1 and the voltage regulator circuit in Subsection 3.2 - and analysing the final values of the ripple voltage - in Subsection 3.3 - and the output DC level - in Subsection 3.4.

3.1 Envelope Detector Circuit

We start by defining some of the parameters needed in the composition of an envelope detector circuit, suchs as the resistance of resistor R and the capacitance of the capacitor C. It is important to point out that, in this specific envelope circuit used in the theorical approach, we considered the diodes to be the ideal model. We also present the voltage source v_S characteristic values, such as the frequency f (and the period T, as the inverse frequency value) and the amplitude A.

$$\begin{cases} f = 50Hz \\ A = 14V \\ R = 1000\Omega \\ C = 100\mu F \end{cases}$$

$$\begin{cases} T = \frac{1}{f} = 1/50s \\ \omega = 2\pi f = 100\pi rad/s \end{cases}$$

The voltage source v_S produces a sinusoidal wave and is defined by the following expression: $v_S = Acos(\omega t)$.

The envelope detector circuit includes a full-wave bridge rectifier, whose voltage output $v0_{rect}$ corresponds to the absolute value of the voltage source v_S.

$$v0_{rect} = \begin{cases} v_S, & v_S \geq 0 \\ -v_S, & v_S < 0 \end{cases}$$

Finally, the envelope detector circuit voltage v_0 is the highest between $v0_{rect}$, the full-wave bridge rectifier voltage, and the voltage $v0_{exp}$ induced when the capacitor C discharges through the resistor R and described by the following equation: $vO_{exp} = Acos(\omega t_{OFF})e^{(\frac{-(tON-tOFF)}{RC})}$.

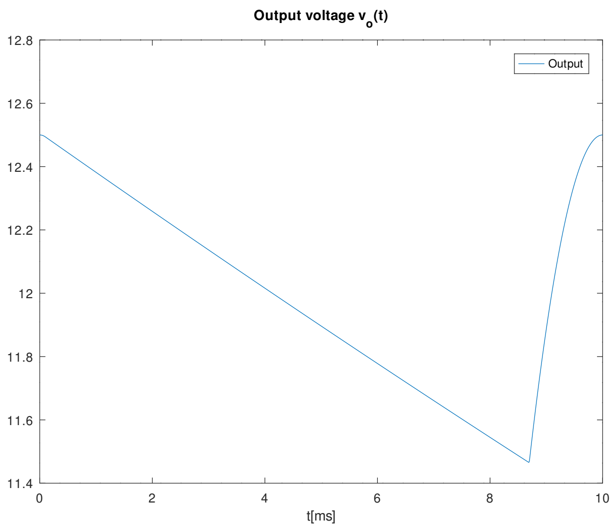


Figure 2: The final envelope detector circuit voltage v_0 during a half-period interval.

where t is expressed in miliseconds (ms) along the x-axis
and v_0, the envelope output voltage, is expressed in Volts (V) along the y-axis.

3.2 Voltage Regulator Circuit

The voltage regulator attenuates oscillations in the input signal without frequency dependence and takes advantage of the non-linear characteristic of the N diodes included in the positive voltage limiter.

We start by defining some of the parameters needed in the composition of a voltage regulator circuit, suchs as the resistor R_2 value and the number of diodes n of the voltage limiter. We also present the diode's characteristic values, such as the emission coefficient η, the reverse saturation current I_S, the thermical voltage v_T and the diode voltage v_D.

$$\begin{cases} N = 17 \\ R_2 = 10k\Omega = 10000\Omega \\ \eta = 1 \\ v_t = 0.025V \\ v_d = 0.706V \\ I_s = 1 \times 10^(-14) \end{cases}$$

The voltage analysis of the regulator applies the incremental analysis method, separating the DC and incremental components.

The diode incremental resistance is calculated using the following expression: $r_d = \frac{\eta v_t}{I_s e^{(\frac{v_d}{\eta v_t}}}$.

Applying the voltage divider rule, the AC increment v_{out} is defined using the following relation: $vout = \frac{Nr_d}{Nrd+R2} vO$.

It is easy to understand that a large value of the resistor R_2 will maximize the denominator and make it significantly bigger than the numerator ($Nrd + R2 >> Nr_d$), which makes the whole quotient tend to zero ($\frac{Nr_d}{Nrd+R2} \longrightarrow 0$). While we minimize the AC increment, we are at the same time increasing the precision of the DC voltage, as pretended when building an AC-DC converter.

On the other hand, the DC voltage V_{OUT} is obtained multypling the diode voltage v_d by the number of diodes N used in the voltage regulator circuit: $V_{OUT} = Nv_d$.

The final voltage of the regulator circuit v_{OUT} is obtained adding the results of the incremental analysis and the DC analysis: $v_{OUT} = v_{out} + V_{OUT}$.

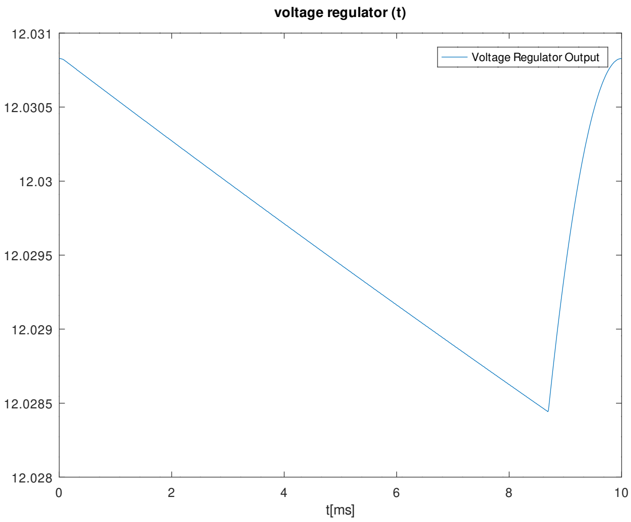


Figure 3: The final voltage v_{OUT} of the voltage regulator circuit during a half-period interval.

where t is expressed in miliseconds (ms) along the x-axis
and v_{OUT}, the voltage of the regulator, is expressed in Volts (V) along the y-axis.

3.3 Voltage Ripple

The voltage ripple can be improved using a full-wave rectifier circuit in the envelope detector circuit.

The value of the voltage ripple v_{ripple} can be calculated relating the maximum and the minimum values of the final voltage of the regulator circuit v_{OUT}, using the following expression: $v_{ripple} = max(v_{OUT}) - min(v_{OUT})$.

The Output Voltage RIPPLE is	0.00238568 V

3.4 The Output DC Level

The t_{ON} is calculated using the Newton-Raphson iterative method, starting with a function obtained through the following equation: $Acos(\omega t_{ON}) = Acos(\omega t_{OFF})e^{(\frac{-(t_{ON}-t_{OFF})}{RC}})$.

The DC level output average is obtained integrating the sinusoidal and exponential functions during a half-period interval. The calculations are shown below.

$t \in [0, t_{OFF})]$
$$\int_0^{t_{OFF}} = \frac{Nr_d}{Nr_d+R_2}\frac{A}{\omega}sin(\omega t_{OFF}) + Nv_d t_{OFF}$$

$t \in [t_{OFF}, t_{ON}]$
$$\int_{t_{OFF}}^{t_{ON}} = \frac{Nr_d}{Nr_d+R_2}(-ARCcos(\omega t_{OFF})(e^{\frac{-(tON-tOFF)}{RC}} - 1)) + Nv_d(t_{ON} - t_{OFF})$$

$t \in [t_{ON}, \frac{T}{2}]$
$$\int_{t_{ON}}^{\frac{T}{2}} = \frac{Nr_d}{Nr_d+R_2}\frac{A}{\omega}(sin(\omega\frac{T}{2}) - sin(\omega t_{ON})) + Nv_d(\frac{T}{2} - t_{ON})$$

$$\overline{V} = \frac{\int_0^{t_{OFF}} + \int_{t_{OFF}}^{t_{ON}} + \int_{t_{ON}}^{\frac{T}{2}}}{\frac{T}{2}}$$

The Output Voltage AVERAGE LEVEL is	12.0224 V

The Output DC Level accuracy can be evaluated through comparing the final voltage of the circuit v_{OUT} and the $12V$ constant function.

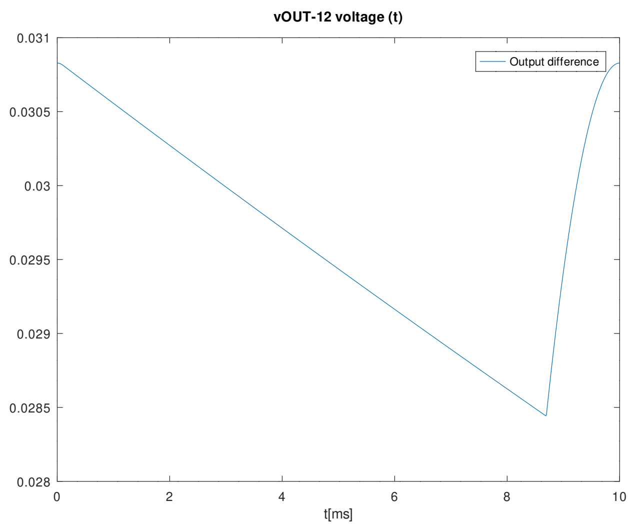


Figure 4: The voltage $(v_{OUT} - 12)$ during a half-period interval.

where t is expressed in seconds (s) along the x-axis
and $(v_{OUT} - 12)$, the output voltage difference, is expressed in Volts (V) along the y-axis.

4 Simulation Analysis

In this section, we can find the results of each topic required in the simulation analysis. The numeric results or graphics are presented alongside a short explanation of the interpretation of the problem. All of the results were obatined usig NGSpice and the section is divided in two different subsections.

In this part of the lab, we tried to build the circuit in such a way that it would be as similar as possible as the one used in the Octave theoretical part. The most important difference between both approaches is that in Ngspice we had to use more diodes in the regulator circuit than in Octave. This is because while in Octave we used the standard diode voltage $(0.7V)$, requiring 17 diodes, in Ngspice that wasn't possible because diodes have varying voltages. Given that, our Ngspice voltage regulator circuit is made of 23 diodes.

Another difference from the Octave model, is that the ideal diode model used in the envelope circuit is not possible to replicate in Ngspice. However, this does not affect the final results because the transformer conversion factor was updated to compensate the fact that there is going to be a voltage drop in the envelope circuit diodes.

4.1 Envelope Circuit Output

For this envelope circuit we used the following values:

$$\begin{cases} f = 50Hz \\ n = 13.5304V \\ R = 50k\Omega \\ C = 150\mu F \end{cases}$$

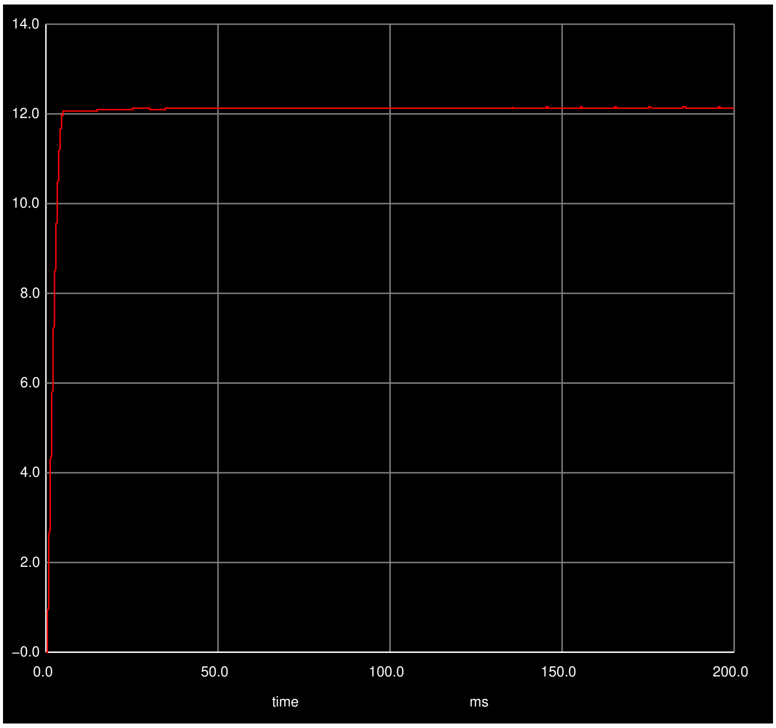


Figure 5: The final envelope detector circuit voltage v_0 during 10 periods

In the graphic above, it is possible to see that, even though it is not the final result of the whole converter, it is already very close to $12V$. It is important to note that, if we zoom in, there will be a certain level of ripple that may affect our desired result, given that the signal hasn't gone throught the voltage regulator yet. Still on this topic, a particularity of Ngspice is the rising line at the very beginning which clearly stands for some transient the software uses.

4.2 Circuit Output

In this part the total output of the circuit is analysed. The voltage regulator had its resistor set with a value of $10Ohms$ and a total number of 23 diodes.

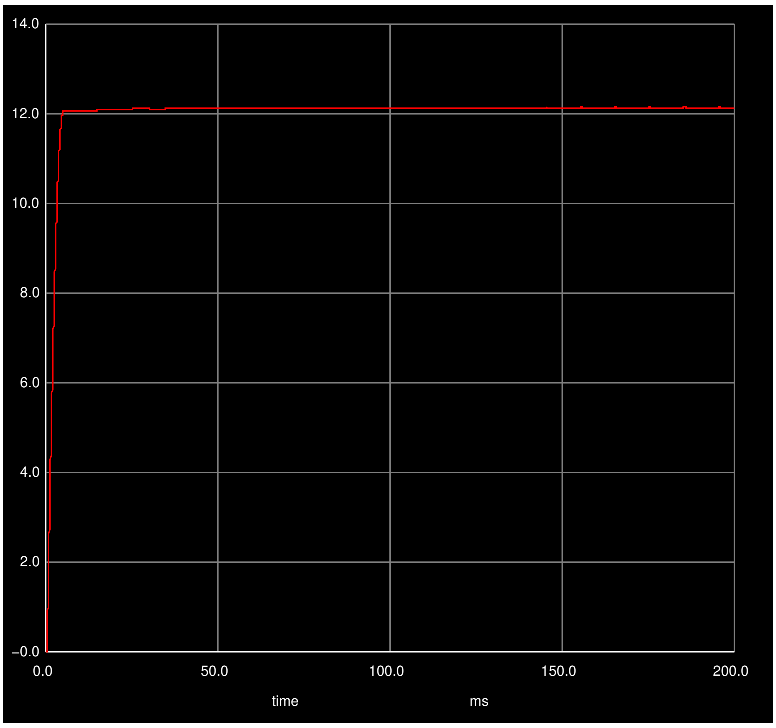


Figure 6: The final output voltage v_0 during 10 periods

In the graphic above, the output voltage is represented. Looking at it is enough to understand that the final voltage is very close to the desired $12V$, however the difference that remains will be discussed below.

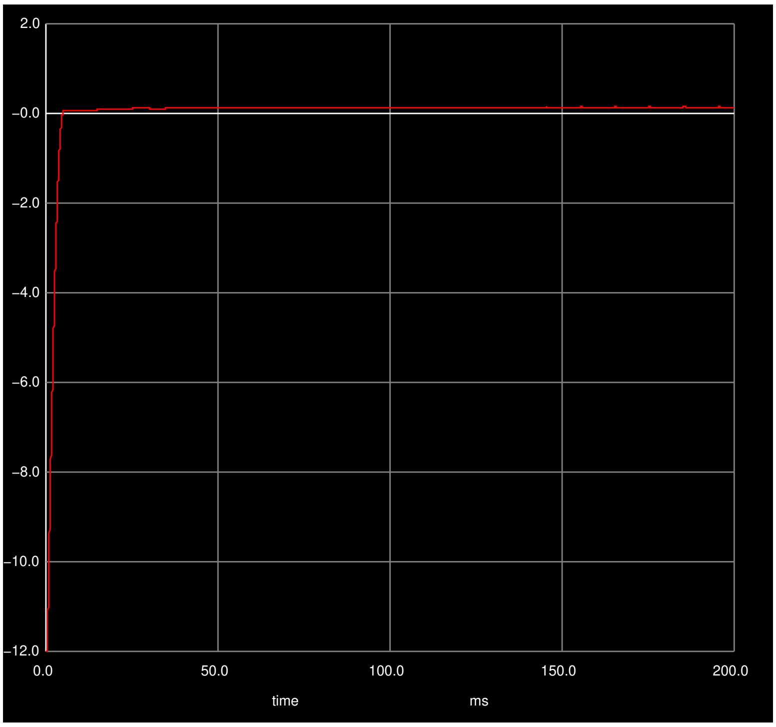


Figure 7: The final output voltage v_0 subtracted by 12 during 10 periods

The graphic above essentialy shows the ripple of the circuit, which is basically how much the output voltage deviates from $12V$ and, once again, the results are pretty satisfying, with the line being very close to zero for most of the 10 periods. Still, below we can find a table with more accurate ripple data at a numerical level, which will confirm the theory that the simulation was well-succeeded.

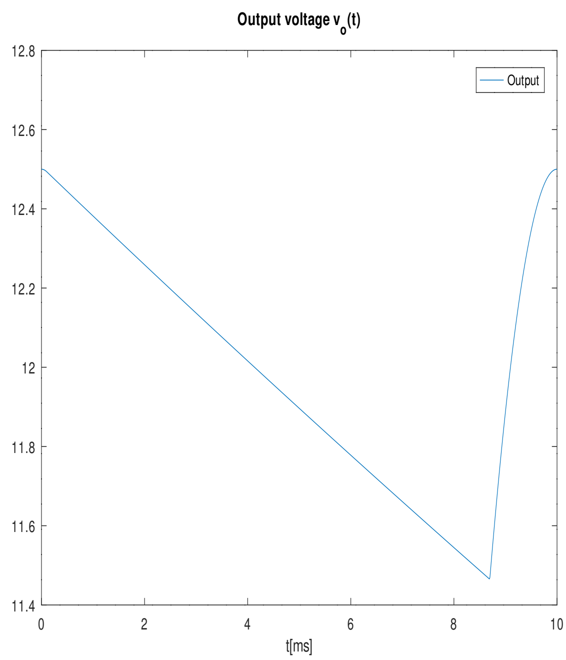
Data	**Value**
max	1.214333e+01
min	1.212654e+01
ripple	1.679523e-02
average	1.200008e+01

Table 1

From the table above, we can see that the average has a pretty good result being pratically $12V$. When it comes to the ripple, it also has a very good result, with an order of significance in the hundredths.

5 Relative Error and Graphic Analysis

5.1 Envelope Detector Circuit

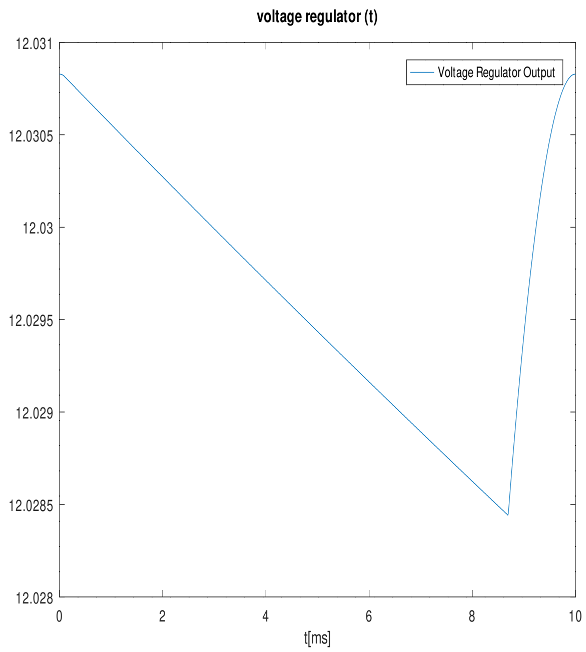


(a) Octave

(b) Ngspice

In first set of graphics, we have the comparation of the envelope circuits. The graphics do match our expectations in terms of results, with both already having very close numbers to $12V$, although with some differences between them, mainly when it comes to the ripple.

5.2 Voltage Regulator Circuit

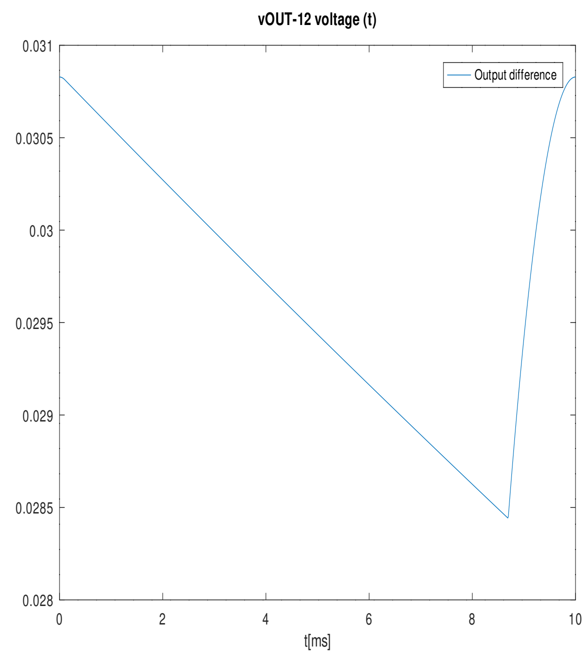


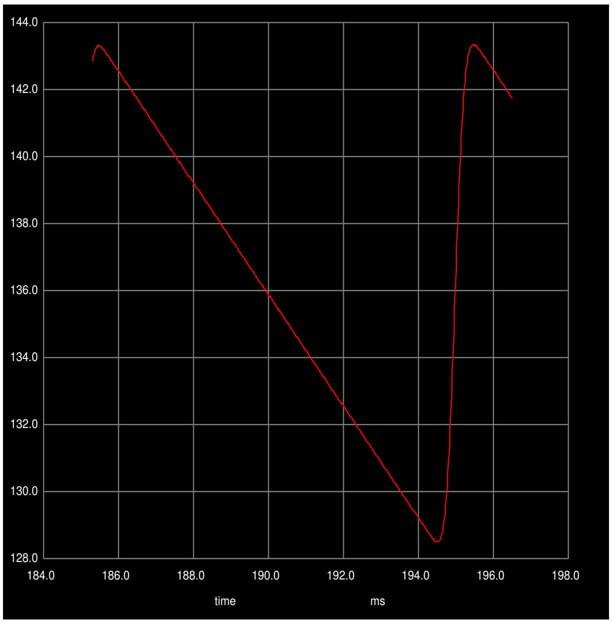
(a) Octave

(b) Ngspice

In this second set of graphics, we have the comparation of the output between Octave and Ngspice. Once again, the results are very sastisfying.

5.3 DC Output Level





(a) Octave

(b) Ngspice. It is importanto to note that this graphic is in mV

In this last set of graphics, we have the comparation between the output difference (relative to $12V$) obtained by Octave and Ngspice, which also correspond to what was required (as close to zero as possible).

5.4 Relative Errors

Comparation of various data between Octave and Ngspice			
DATA	Octave	Ngspice	Percentual Relative Error
Max	12.030828	12.143330	0.935111
Min	12.028443	12.126540	0.815545
Voltage Ripple	0.002386	0.016795	604.000781
Average Output Voltage	12.022394	12.000080	0.185602

In the table above, we have the comparation between Octave and Ngspice of the maximum output values, the minimum output values, the voltage ripple and the average. The percentual relative error is also included to make the interpretation of these values easier. With the exception of the Voltage Ripple, it is safe to say that all the values are very good. When it comes to the voltage ripple, while it is true that the relative error is of 5 times of difference, it is important to note that they are still very small values. The possible explanation for this discrepancy is that Ngspice uses a diode model which does not have fixed parameters (Namely V_D), making it very hard to match the Octave results.

5.5 Figure of Merit

Figure of Merit	
Merit Figure	0.292314

To end our report, we present the figure of merit. It is important to remind that this figure is obtained upon the devices and values used in Ngspice and not the ones used in Octave. During our work, we struggled a bit trying to understand what the ideal value would be, given that we did not have any reference however, we did our best to make it as high as possible.

6 Conclusion

In this third laboratory assignment, all the major goals of the project were achieved. We concluded with success a further interaction with a new software (Ubuntu), with a simulation software (Ngspice), with a computational language program (GNU Octave) and with a text report editor (LaTeX). The construction and analysis of the circuit was also finished with success through simulation and theoretical interpretation, which allowed a good comparative analysis between the differences presented in the behaviour of a simulated and theoretical electric circuit.

In fact, this assignment allowed us to build two AC-DC converters which were able to transform the current and achieve an output voltage as close to $12v$ as possible. Even though we needed to construct two different electric circuits according to the simulation or theoretical principles we were based on, both of them were succesfuly implemented and achieved the pretended output voltage. The simulation results about the output voltage matched the theoretical results precisely. This accuracy was confirmed by the matemathical calculation of relative errors, which were proved to be really small. Also, the comparative analysis of graphics ploted by both theoretical and simulation tools confirmed the similarity of the results, obtained successfully and with notorious precision.