Circuit Theory and Electronics Fundamentals

Aerospace Engineering, Técnico, University of Lisbon

3rd Laboratory Report

João Martins 95806
Gonçalo Martins 95793
António Lopes 95771

May 6, 2021

Contents

1 Introduction

The objective of this laboratory assignment is to design and analyse an AC/DC converter. In order to do this, we chose the envelope detector circuit, as well as the voltage regulator circuit. The architecture of our circuit can be seen in the following picture.

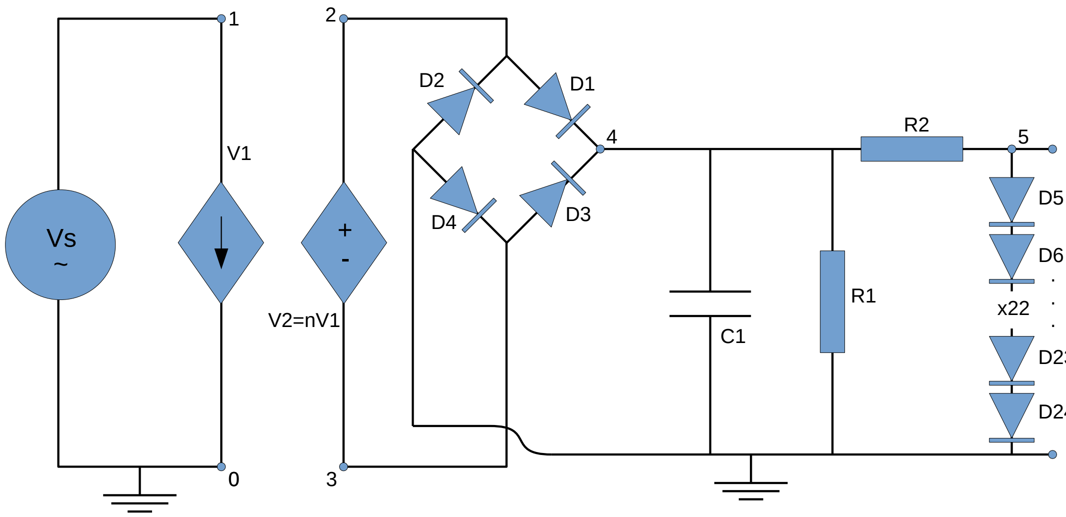

Figure 1: AC/DC converter

One way to get a stable DC output voltage is, in the first hand, to use a full wave rectifier - this circuit allows us to use every half-period of the input voltage. As we can see, diodes 1 and 4, as well as diodes 2 and 3 work in pairs, in order to allow us using the full lenght of the wave. In the other hand, to reduce the voltage output variations, we used a capacitor.

Finally, in order to maintain the DC component in the desired value, and to minimize the AC component, we used a series of diodes (because once they get activated, their output voltage is constant, no matter what the supply voltage or current are), in series with a resistor.

2 Theoretical Analysis

In this section, the circuit shown in the previous figure is analysed theoretically.

Our approach begins with getting a smaller value for the voltage input in our circuit. As such, we used a transformer, with a ratio of turns in the primary and secondary circuits of $\frac{1}{10}$. As a consequence, because the input voltage amplitude is $V_s = 230V$, this value will be lowered to $V_r = \frac{230}{10}V$, so that the circuit can then approximate to 12V. Although we already have a better value for the voltage input, it still is an AC input that needs to be converted to DC. In order to do this, we proceeded as described next.

Firstly, we used a full wave rectifier. As we said before, this circuit allows us to use the full length of the wave, converting the initial AC signal in an equal amplitude unidirectional current. Therefore, the wave format remains unchanged if the voltage is positive and gets reflected if the voltage is negative.

Secondly, we used a parallel of a capacitor and a resistor, in order to reduce the variaton of the voltage output, and make it closer to a DC one. This circuit is called an envelope detector, and it works based on the charge and discharge proccesses of the capacitor - when the diodes of the full-wave rectifier are on, the capacitor charges up, and when they turn off, the capacitor discharges through the resistor (in order to make things more clear, we're calling $v_O(env)$ to the voltage drop in R_1 terminals).

In order to compute the output of this process, we needed to know when the capacitor starts and stops discharging (t_{off} and t_{on}, respectively). As one might guess, and based on what has been said, t_{off} corresponds to the instant in which the diodes become off ($t_{off} = \frac{1}{\omega} \cdot atan(\frac{1}{\omega R_1 C})$) and if $t < t_{off}$, $v_O(env) = v_R$. On the other hand, t_{on} corresponds to the instant in which the diodes become on (ton is obtained by solving the equation $Asin(\omega ton) = Asin(\omega t_{off}) \cdot e^{-\frac{ton - t_{off}}{R_1 C}}$) and if $t < t_{on}$, $v_O(env) = Asin(\omega t_{off}) \cdot e^{-\frac{t - t_{off}}{R_1 C}}$. The ripple voltage is given by max(v_O(env)-min($v_O(env)$) and it's value is shown in the table bellow, as well as the average voltage output value. As we can see, the value of the ripple voltage is very low, which is very good.

Ripple Envelope	3.605573e-04 V
Average Envelope	2.299982e+01 V

Table 1: Ripple and average value for the envelope detector (all values are in Volt)

Thirdly, we used a series of 22 diodes, in series with a resistor (voltage regulator circuit) in order to "get rid" of the AC component and make the DC component 12V. This makes the current an almost perfect 12V DC, because the diodes have a constant voltage output, no matter what the current or voltage inputs are. If we compute the minimum value of $v_O(env)$, we can conclude if it sufices to turn the diodes on (this happens when $min(v_O(env)) \geq nv_{ON}$, being v_{ON} the minimum voltage required to activate one diode).

At this point, we have the DC component of the voltage, so we need to calculate and minimize the AC component. This is achieved by making incremental analysis. In incremental analysis, we can replace each diode by a resistor with resistance r_d, and we get $v_o = \frac{n \cdot r_d}{n \cdot r_d + R_2} \cdot (v_O(env) - V_O(env))$. As we can see, if $R_2 \gg n \cdot r_d$, $v_o \approx 0$.

Putting all this things together, we get a final output voltage $v_O = V_O + v_o$, and the average of the signal must be approximatly 12V. The values of the ripple and average output voltage for the voltage regulator can be seen in the following table. As we can see, the value of the ripple voltage is very low, which is very good. Although the average voltage output is indicated as being 12V exactly, it isn't exactly 12V, because of the approximation made by octave's output - the deviation is so small, that this value is rounded to exactly 12V.

Ripple regulator	9.535195e-06 V
Average regulator	1.200000e+01 V

Table 2: Ripple and average value for the voltage regulator (all values are in Volt)

In the following picture, the output voltage of the full-wave rectifier, output voltage of the envelope detector and output voltage of the voltage regulator are plotted. Here we have a more visual perception of the values shown in the previous tables. The ripple of the final output (blue line) is even lower than the ripple of the envelope detector's output (green line) but as this value was already very low, it is not noticeable and the output looks like a straight line (although it isn't). In the last two plots we can see by the sacale used that the ripple in both the envelope detector and the voltage regulator are in fact very small.

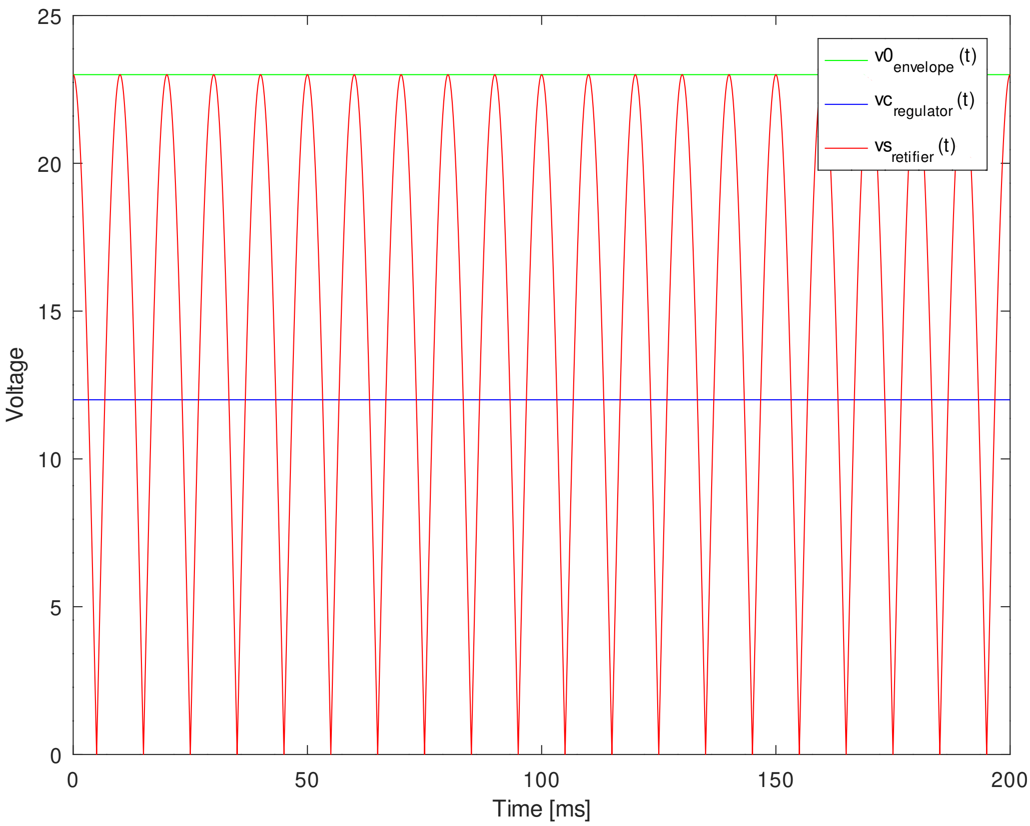

Figure 2: Input voltage of the secondary circuit, output voltage of the envelope detector and output voltage of the voltage regulator

Lastly, the parameters used can be seen in the following table. The method through which we obtained this values will be explained in the next section.

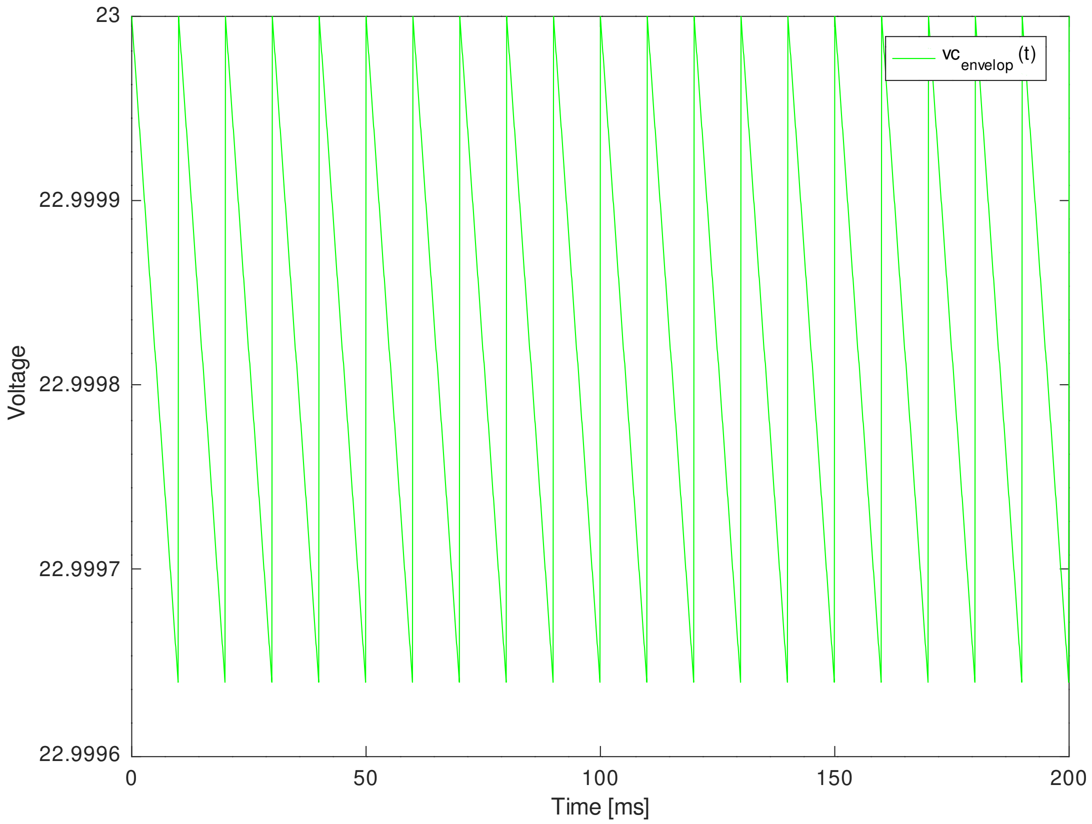

Figure 3: Ripple of the voltage output in the envelope detector

R1	9.843700e+04 Ohm
R2	6.774100e+05 Ohm
C	7.347694e-03 F
n transformador	1.000000e+01
nº diodos (voltage regulator)	2.200000e+01

Table 3: Parameters used in the circuit

3 Simulation

In this section, we used NGspice in order to simulate the conceived AC/DC converter. In order to simplify the circuit, we had to make some changes.

Firstly, the transformer was replaced by an ideal model that consists in a pair of dependent sources (a current one in the primary circuit, and a voltage one in the secondary circuit). It should be noted that the values of the parameter n (parameter of dependency of the dependent sources), the capacitance of the capacitor and the resistance of the resistors were adjusted through an optimization using simulink, in order to get an output voltage that is as close to 12V and as stable as possible, as well as maximize the figure of merit. Although the optimization was run, it's important to mention that the value of R2 had to be adjusted through trial and error. This happened because it's very dificult to simulate a diode in simulink and because of this, the simulink's output was violating KVL for the loop of the voltage regulator. As such, we forced the value of R2 to be defined as $R2 = \frac{\frac{230}{n}-12}{I_s(e^{\frac{12}{\eta V_t k}}-1)}$, and we only allowed simulink to change k in this formula, which is the number of diodes. By using this method, the optimization allowed

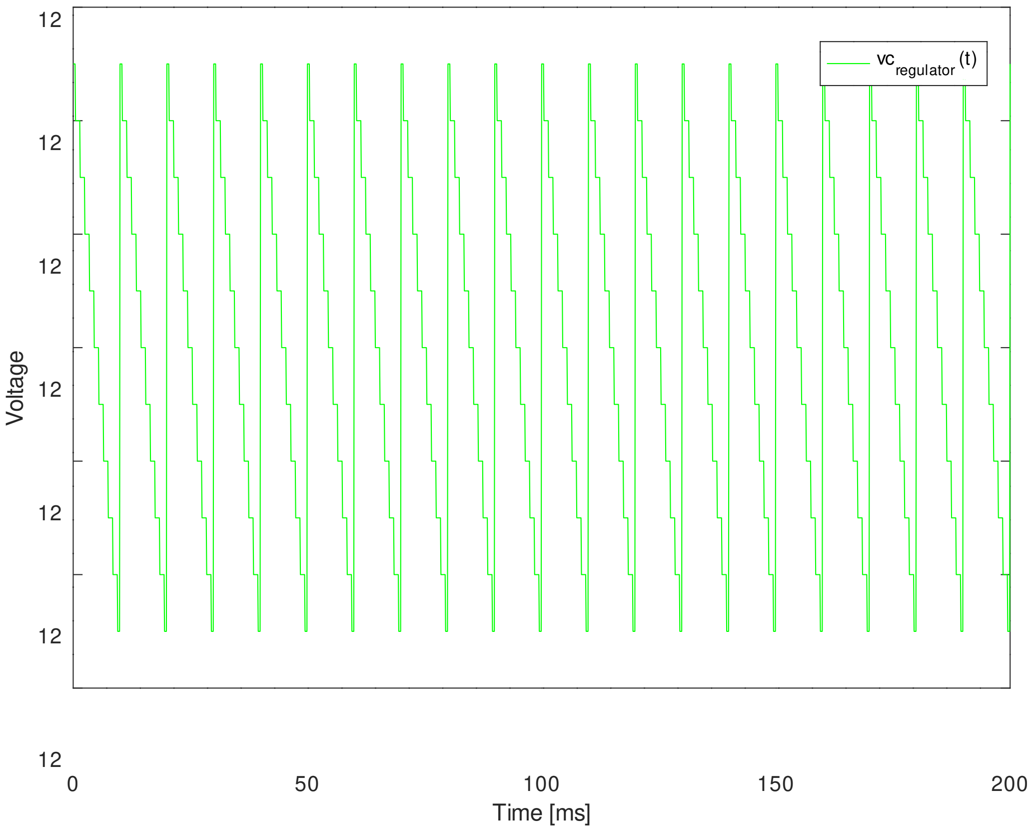

Figure 4: Ripple of the voltage output in the voltage regulator

us to know how many diodes we had to use. Despite this, when the values obtained where used in NGspice, the output voltage of the entire circuit was something about 12,3V, so we had to change the value of R2 through trial and error, in order to lower this value to the desired 12V. This correction only had to be done in the DC value, because the ripple value was already pretty good.

In the tables below, the values of the ripple and the mean value of the voltage output for the envelope detector and the voltage regulator are shown.

maximum(v(4))-minimum(v(4))	6.149354e-03
mean(v(4))	2.176133e+01

Table 4: Ripple and mean value for the envelope detector (all values are in Volt)

maximum(v(5))-minimum(v(5))	3.387254e-04
mean(v(5))	1.200000e+01

Table 5: Ripple and mean value for the voltage regulator (all values are in Volt)

Considering this values, we have to mention that, in our case, the value indicated for the ripple in both cases is not actually the ripple. This happens because NGspice can't calculate the ripple in any other way that isn't maximum(v(x))-minimum(v(x)). As such, because our ripple is really small, the voltage decrease due to energy dissipation has a greater impact on the output than the ripple itself, and the value indicated for the ripple in both tables is actually the initial value minus the last value of the voltage output. This effect is more noticeable in the plots bellow.

In the following pictures, the first one shows the plots for the input of the secondary circuit of the transformer (v(2)-v(3)), the output voltage of the envelope detector (v(4)), the output voltage of the voltage regulator (v(5)), and the value of v(5)-12 (in order to show that it is a line close to zero - not completely straight because of the diodes, that are not linear components). Here we can see that the envelope detector does, in fact, decrease the ripple value, and the voltage regulator keeps the output voltage approximately constant. In the last two plots, we have a more detailed prespective of the output, of both the envelope detector and the voltage regulator, and the effect explained before is well noticeable - if we look carefully, we can identify a small ripple but, as said, the decrease of the voltage output due to energy losses has a stronger effect that the ripple itself.

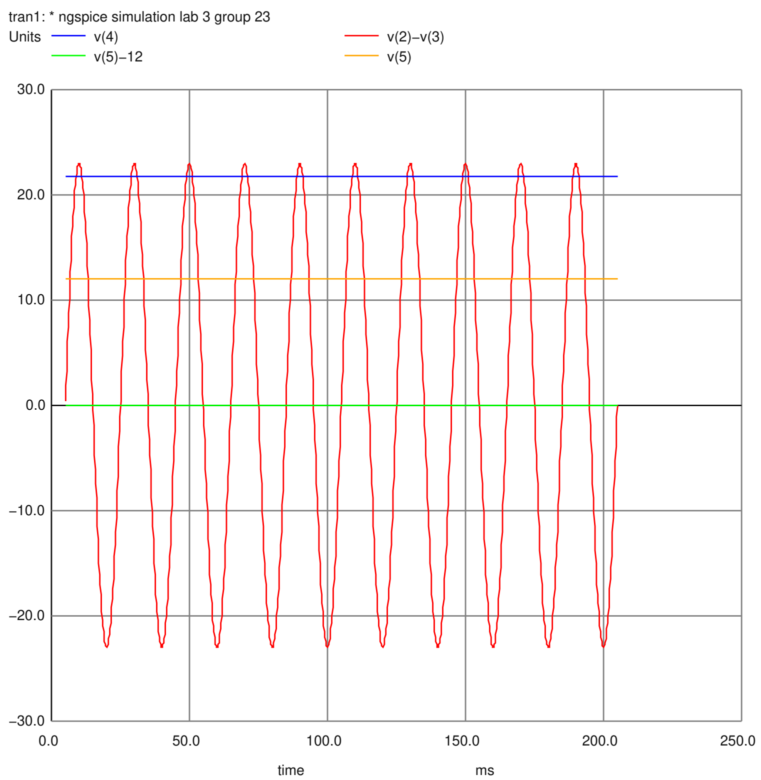

Figure 5: Input voltage of the secondary circuit (v(2)-v(3)), output voltages of the envelope detector (v(4)) and voltage regulator (v(5)), and v(5)-12

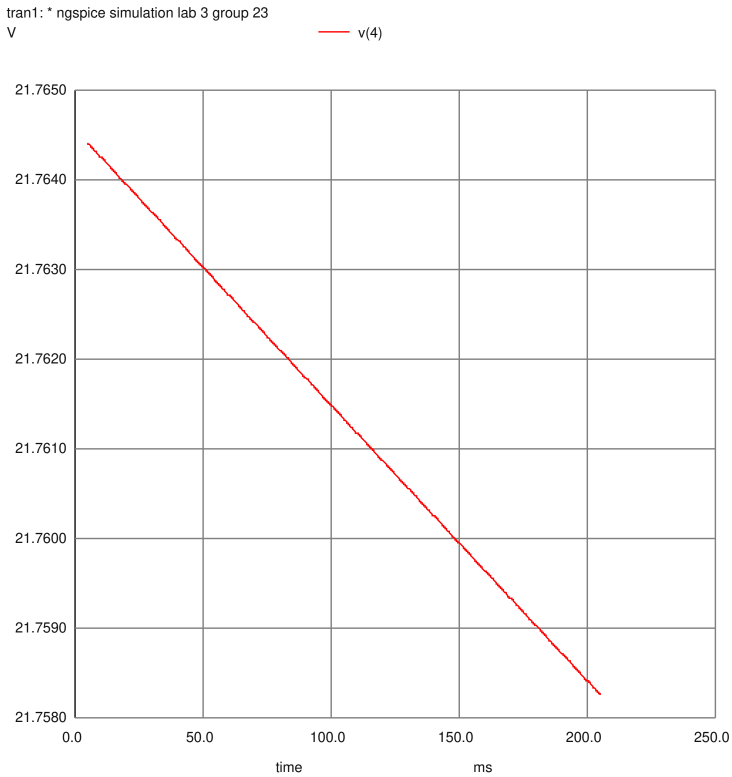

Figure 6: Output voltage of the envelope detector

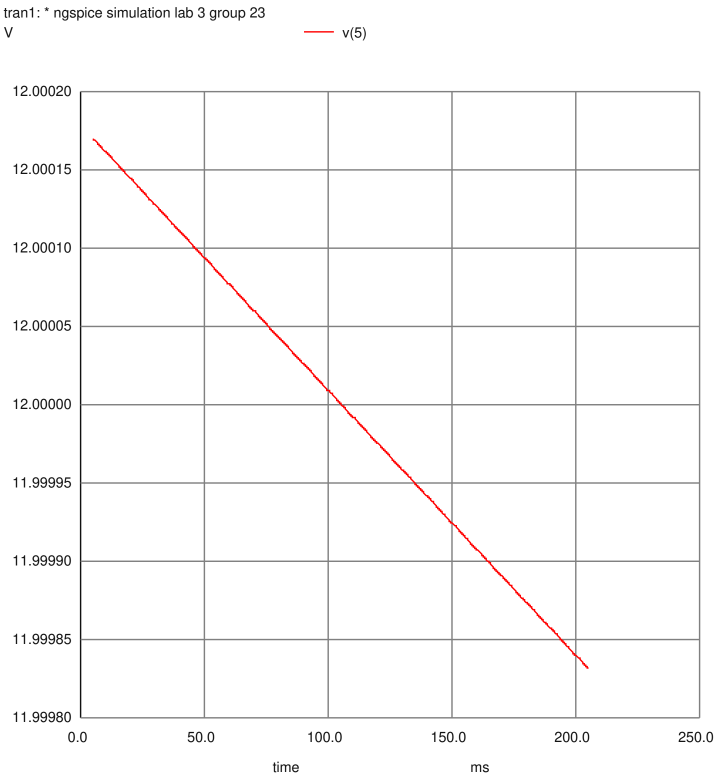

Figure 7: Output voltage of the voltage regulator

4 Data comparison

In this section, we're going to make a comparison between the values obtained for the ripple and average voltage output values obtained when using both Octave and NGspice. Also, weŕe going to compute the figure of merit of our solution.

Firstly, we're going to analyse the ripple and average voltage output of the envelope detector (v(4)).

maximum(v(4))-minimum(v(4))	6.149354e-03
mean(v(4))	2.176133e+01

Table 6: Ripple and mean value for the envelope detector obtained with NGspice (all values are in Volt)

Ripple Envelope	3.605573e-04 V
Average Envelope	2.299982e+01 V

Table 7: Ripple and mean value for the envelope detector obtained with Octave (all values are in Volt)

By observing the table above, we can see that de values are quite different. This happens essentially because the diode is a non-linear component which has a quite complex model in NGspice, and while making the calculations using otave, we took an approximation of the behavior of this component. In addition, as said before, the value indicated as beig the ripple in NGspice, is not actually the ripple. However, the values are close enough so we can conclude that our approximation is good reasonable.

Secondly, we're going to compare the ripple and average voltage output of the voltage regulator (v(5)).

maximum(v(5))-minimum(v(5))	3.387254e-04
mean(v(5))	1.200000e+01

Table 8: Ripple and mean value for the voltage regulator obtained with NGspice (all values are in Volt)

Ripple regulator	9.535195e-06 V
Average regulator	1.200000e+01 V

Table 9: Ripple and mean value for the voltage regulator obtained with Octave (all values are in Volt)

As in the previous situation, this values are a little bit different. The discrepancies observed can be explained in the same way we did for the envelope detector. In a similar way, we can say that our approximation is good enough mainly because the output voltage is very close to 12V.

Lastly, the figure of merit of our solution is shown for both octave and NGspice

Cost	8.126141e+03 MU
Merit	1.168081e+01

Table 10: Cost and figure of merit (Octave)

1/(8126.1415*((maximum(v(5))-minimum(v(5)))+abs(mean(v(5)-12))+10e-6))	3.522025e-01

Table 11: Figure of merit (NGspice)

As said before, this formula was optimized using simulink, in order to maximize the figure of merit. The values obtained for NGspice and Octave are very different because, as explained, the value shown as ripple in NGspice is not actually the ripple.

5 Conclusion

In this laboratory assignment, the goal of conceiving an AC/DC converter was achieved. As seen in the whole report, the theoretical results (obtained using Octave) didn't exactly match the simulated ones (obtained using NGspice) because of the non-linearity of the diodes (as predicted), but overall the final result was pretty decent and it's good enough to validate the model used in the theoretical analysis.