Laboratory 3: AC/DC Converter

Msc. Aerospace Engineering, Técnico, University of Lisbon

Circuit Theory and Electronics Fundamentals

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1 Introduction

The goal of this laboratory assignment is to model and analyse an AC/DC converter circuit, by designing both Envelop Detector and Voltage Regulator circuits.

It was chosen a full-wave bridge rectifier circuit, using 4 diodes, $D_{i=1,2,3,4}$. Furthermore, it was used 1 diode, D_e, 2 resistors, R_e and R_v, a capacitor, C, and 17 aditional diodes. The circuit described is portrayed in Figure-1.

Throughout the report it is presented a theoretical analysis, a simulation of the circuit and its analysis as well as a comparison of the obtained results.

In Section 2, it is executed an incremental analysis by separating the AC and DC components, in order to do a theoretical analysis of the circuit, using the Octave maths tool. In Section 3, it is executed an analysis of the circuit using the Ngspice tool to simulate it. In Section 4, reults obtained with both Octave and Ngspice are displayed side-by-side, in order to compare the results. Lastly, in Section 5, it is performed a conclusion, bearing in mind the results from both the theoretical analysis and the simulation, from Section 2 and Section 3, respectively.

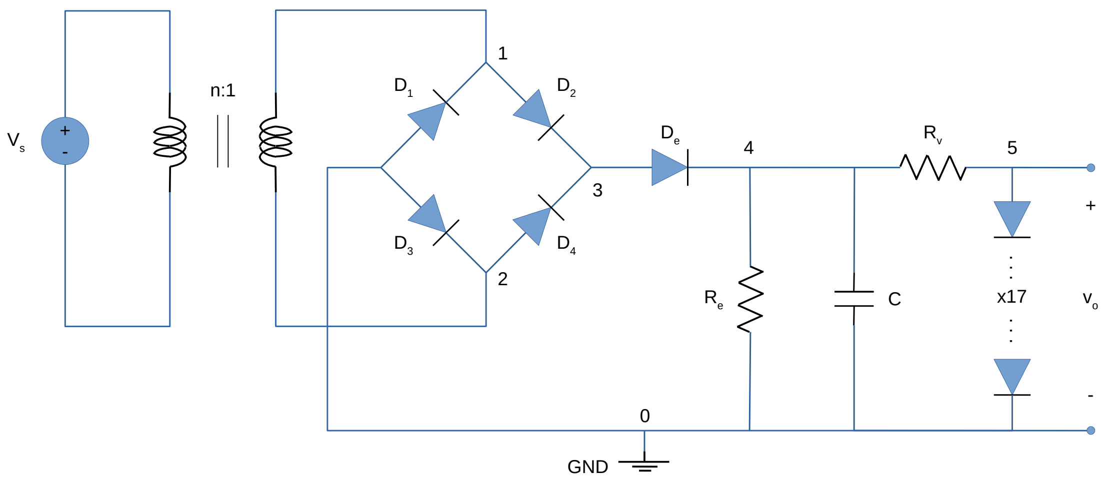

Figure 1: Circuit

2 Theoretical Analysis

In this section, we will analyse our theoretical model of the AC/DC converter in terms of the DC output voltage V_O and the deviation from this DC value, the AC component v_o. Our goal is to maximize the merit function given by:

$$M = \frac{1}{cost * (ripple(v_O) + average(v_O - 12) + 10^{-6}} \tag{1}$$

With cost given by:

$$M = \frac{\text{Sum of the resistors}}{1000} + \frac{Capacity}{10^{-6}} + Num_{diodes} * 0.1 \tag{2}$$

To maximize it we should obtain small deviations from V_O (small riplle) and obtain a V_O closer to $12V$, wich is the output voltage required. At the same time, we must reduce the cost of the circuit, by reducing the number of components and their values. We concluded that the following values were the ones that maximize this function: $C = 920\mu F$, $R_e = 920k\Omega$, $R_v = 3.3k\Omega$.

2.1 Transformer and full wave bridge rectifier

For the first part of the circuit we used a transformer that converts the input voltage $v_S = 230cos(\omega t)V$, with $\omega = 2\pi * 50$, to a voltage with the same frequency and a amplitude of $230.1V$. Thus, the number of spirals for the transformer was $N = \frac{N_1}{N_2} = 1.000434783$.

After that, we introduced a full wave rectifier circuit that converts the negative values to positive ones, so the peaks of the sinusoidal voltage appear with the double of the original frequency. Thus, the voltage that enters the envelope detector is $v_3 = |230.1cos(\omega * t)|$. To do that, we use a circuit with 4 diodes (between nodes 0, 1, 2 and 3) which ensures that the output voltage is always positive, because they only conduct current in the forward active region.

In that way, one can reduce the ripple in the envelope detector circuit, as we will se in the next chapter.

2.2 Envelope Detector

The main purpose of the envelope detector is to obtain a voltage that follows the peaks of the input voltage, achieving much smaller AC components. We can distinguish 2 phases of operation, considering the ideal diode model:

- When the diode is on, the envelope voltage v_4 is equal to v_3. This happens for $T_{ON} < t < T_{OFF}$, every period.
- When the diode is off, it blocks the current, and the voltage in the capacitor starts discharging throuth the resistor R_e. The equation to compute the voltage when the diode is off is:

$$v_4 = 230.1 * (2\omega T_{OFF}) * \exp{(-\frac{t - T_{OFF}}{R_e C})} \tag{3}$$

For computing T_{OFF} we used the equation

$$T_{OFF} = \frac{1}{2\omega} * \arctan(\frac{1}{2\omega * R_e * C}) \tag{4}$$

Then we can solve the implicit equation for T_{ON}:

$$v_3(T_{ON}) = 230.1 \cos(2 * \omega * T_{OFF}) \exp{(-\frac{T_{ON} - T_{OFF}}{R_e * C})} \tag{5}$$

Notice that the envelope output voltage is defined by branches. We computed the DC value of v_4 as $V_4 = mean(v_4)$, and the ripple is the maximum deviation $ripple_envelope = max(v_4) - min(v_4)$. This ripple is reduced by doubling the frequency in the full wave bridge rectifier, because the difference between T_{ON} and T_{OFF} is shorter. In this table we present the values for the DC component and the ripple:

Name	Value (V)
$Ripple_{envelope}$	0.002714
$Average_{envelope}$	230.098644

Table 1: Output DC voltage and ripple for the envelope detector.

The next plot shows the rectified voltage, v_3, and the envelope output voltage covering the peaks, v_4.

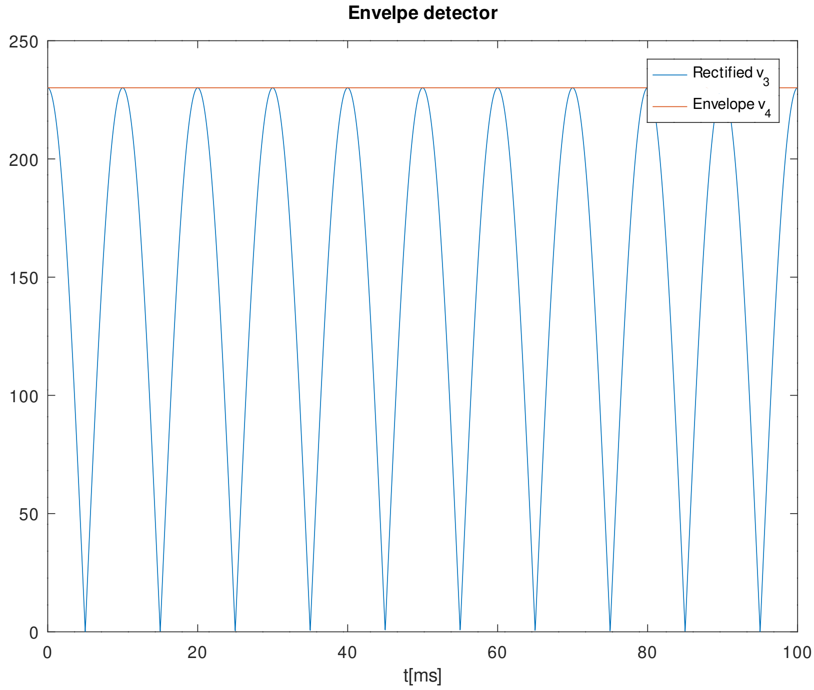

Figure 2: Rectified and envelope voltages in function of time.

2.3 Voltage regulator

The next stage is the voltage regulator, composed by 17 diodes and a resistor R_v. The diodes impose a DC output voltage, V_O, close to 12V, that was our goal to maximize the merit equation 2. By using a large resistor, we apply a voltage division in incremental terms. Therefore, one can reduce the AC component of the output voltage, v_4, and his ripple. We did an operating point and incremental analysis on this part of the circuit, assuming that the AC component of v_4 is already small.

To compute the operating point, we circulate the mesh composed by the diodes and the resistor R_v and obtained the following equation (using only the DC component of the voltages):

$$-V_4 + IS * Id * R2 + V_O = 0 \tag{6}$$

Where Id is the DC component of the current that passe throuth the diodes, giver by:

$$I_d = I_S * \exp\left(\frac{V_O}{17 * \eta * V_T}\right) \tag{7}$$

I_S, η and V_T are constants for the diode model used. Solving this implicit equation with Newton-Raphson methods one can obtain the DC output V_O, which we want to be close to 12V.

Then we compute V_{ON}, which is the threshold voltage to achieve the active region of an ideal diode model, that can be estimated as $V_{ON} = \frac{V_O}{17}$. Using this method instead of chosing a fixed V_{ON}, one can reproduce with less error the DC output given by the simulation.

For the incremental analysis, we computed the incremental resistor of the 17 diodes:

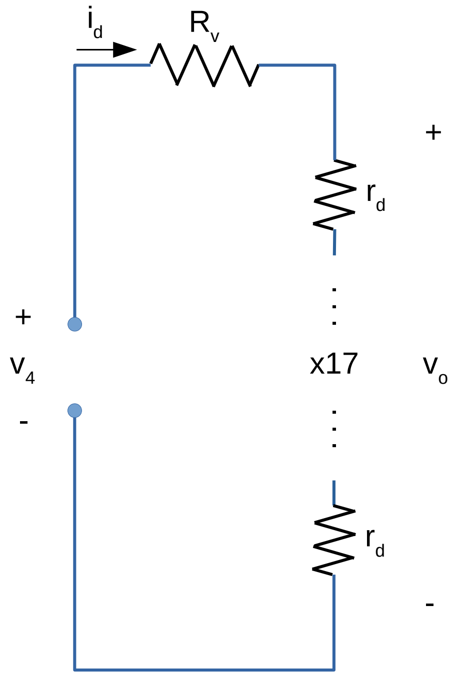

Figure 3: Circuit model used for incremental analysis.

$$r_d = \frac{\eta * V_T}{I_S * \exp\left(\frac{V_{ON}}{\eta * V_T}\right)} \tag{8}$$

Then we applied a voltage divisor to compute the AC component v_o for every time step of the v_O output voltage:

$$v_O(t) = \frac{17 * rd}{17 * rd + R_v} * (v_4(t) - V_4) \tag{9}$$

Those are the $ripple = max(v_O) - min(v_O)$ and the DC output, V_O, obtained with the same input values values we used in the simulation:

Name	**Value [V]**
$Ripple_{regulator}$	0.000004
$Average_{regulator}$	11.742371

Name	**Value [V]**
Merit	0.002073

Table 2: Output DC voltage and ripple for the voltage regulator. Merit obtained with theoretical analysis.

As we will see in the next chapter, this value of merit is much smaller than the one obtained with the simulation in ngspice, in part because of simplifications in the models used.

Next we show some plots of the voltages obtained:

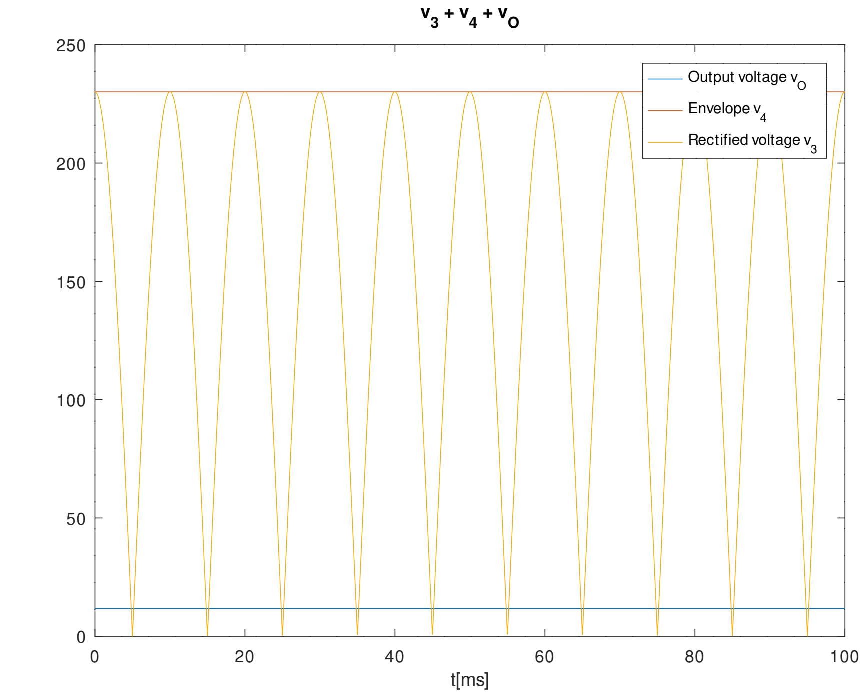

Figure 4: v_O, v_4 and the rectified voltage in function of time.

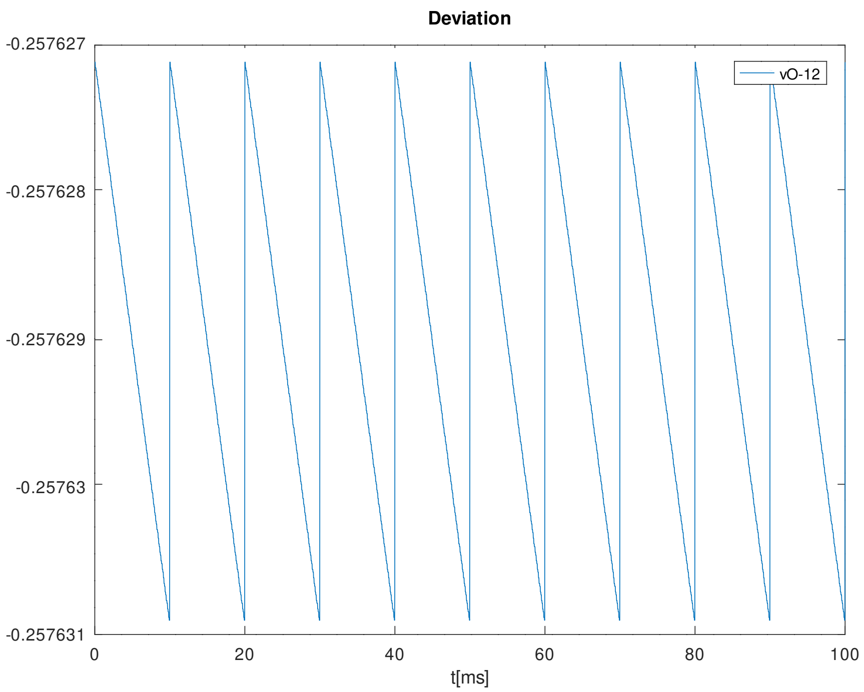

Figure 5: Deviation of v_O from the 12V in funtion of time.

3 Simulation Analysis

3.1 AC/DC Converter Simulation

In this section we simulate an AC/DC COnverter for 10 periods. It is our goal to understand how the values of each component affects the precision and the quality of the output voltage. This circuit transforms a variable voltage into a voltage with a DC component as closest as one can get to the pretended value, reducing, at the same time, the oscilation around that value.

Important note: Beyond modelling and analysing the circuit provided, one of the goals of this laboratory assignment is to maximize the merit, which is computed according to the following formula:

$$M = \frac{1}{\text{cost} * [\text{ripple}(v_0) + \text{average}(v_0 - 12) + 10^{-6}]} \tag{10}$$

Therefore, it was our intention to obtain the best value for this parameter,using each of the variables in order to maximize it, wich means that we have not tried to improve each of those separately, but as a all. In order to do it we used the values indicated in the begginig of Section 2 which resulted in the merit value bellow:

Merit	Value
1/(((950300)/1000+(920e-6)/1e-6+(22)*0.1)*(maximum(v(5))-minimum(v(5))+abs(mean(v(5))-12)+10e-6))	2.178736e+00

Table 3: Merit Calculation

3.2 Output Voltage Level and Ripple

In order to measure the output voltage level, we have used Ngspice's *average* function to determine its mean value. Beyond that it was from our interest to determine the ripple on the voltage. To do it, we have used Ngspice's *max* and *min* functions, which have allowed us to compute the amplitude of the oscilation. Beyond this, we also computed the V_{ON} value used by Ngspice's diode model. The results obtained are shown in the tables bellow:

Variable	Value [V]
maximum(v(5))-minimum(v(5))	1.597796e-04
mean(v(5))	1.199992e+01

Table 4: Output Voltage Level, Ripple in Volts[V]

V_{ON}	Value [V]
mean(v(5))/17	7.058779e-01

Table 5: V_{ON} in Volts[V]

3.3 Envelope Detector and Voltage Regulator - Output Voltages and Ripple

In this section, it is presented the plots regarding both envelope detector and voltage regulator output voltages and ripple. The values for each one of this 'subcircuits' are shown in the following tables:

Variable	**Value [V]**
maximum(v(4))-minimum(v(4))	7.852210e-02
mean(v(4))	2.276490e+02

Table 6: Envelope Detector - Output Voltage and Ripple in Volts[V]

Variable	**Value [V]**
maximum(v(5))-minimum(v(5))	1.597796e-04
mean(v(5))	1.199992e+01

Table 7: Voltage Regulator - Output Voltage and Ripple in Volts[V]

Next, we present the plot regarding the results obtained:

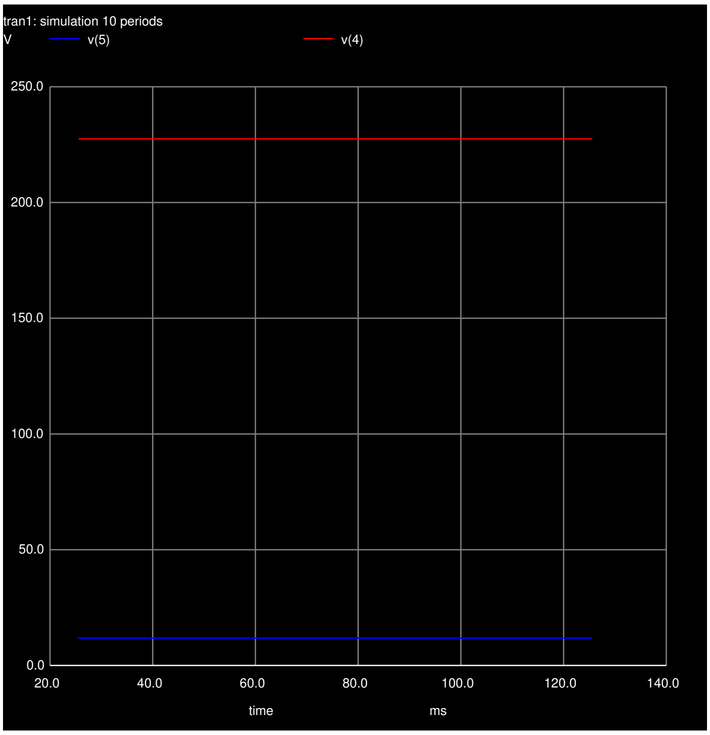

Figure 6: Total solution of the voltage source and the capacitor

As one can conclude from the plot analysis, the ripple suffers a significant reduction from the envelope detector to the the voltage regulator. This last circuit has the same output voltage as the ac/dc converter as a all. That is why table 7 is equal to table 4 in Subsection 3.1.

3.4 Final Result

As mentioned in Subsection 3.1 our goal is to obtain a voltage as stable as possible as well as closest as possible to 12V. Therefore, in this subsection we present a plot where the difference beetwen the output voltage and the pretended result is shown.

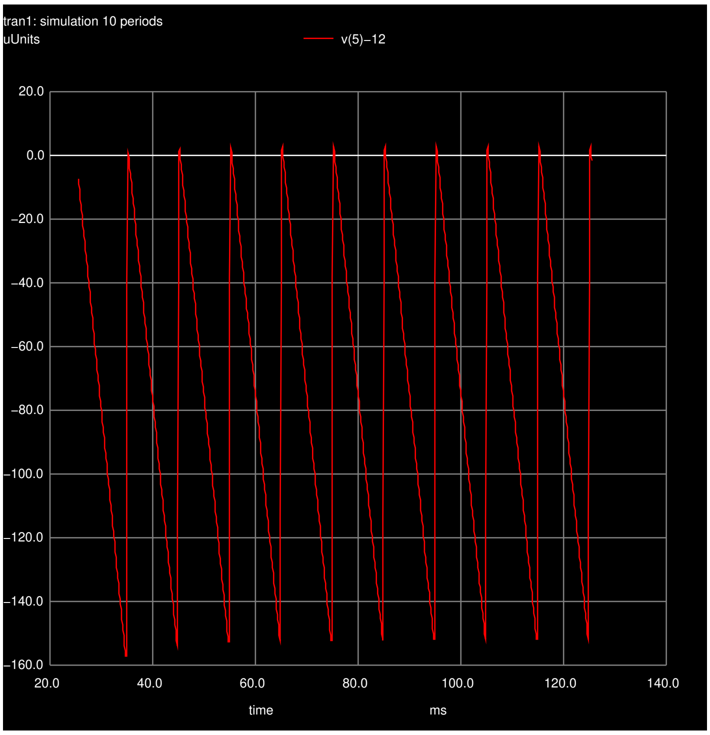

Figure 7: Total solution of the voltage source and the capacitor

As one can see, we were able to complete this laboratory objective, since we ended up with a voltage which as a DC component really close to 12V and with a minimum AC component.

4 Comparison between Octave and Ngspice results

Table 8 shows, on the left, the ripple voltage and the average output voltage of the evelope detector, which corresponds to the voltage on node 4, found by Octave, and, on the right, the same variables, but with the simulation results, by Ngspice, all for the circuit under analysis.

Name	Value [V]
$Ripple_{envelope}$	0.002714
$Average_{envelope}$	230.098644

Name	Value [V]
maximum(v(4))-minimum(v(4))	7.852210e-02
mean(v(4))	2.276490e+02

Table 8: Results for the ripple and average output voltages of the envelope detector.

By analysing the result from both the theoretical and simulated models is possible to observe differences in values. These discrepancies are, in its majority, due to the non-linearity of the diodes. Due to this complexity, we are forced to use a simplistic model in our calculations (the ideal model of the diode), through Octave, while Ngspice uses a more complete model for the analysis of this circuit. With this, discrepencies in values are expected.

Beyond the envelope detector, it can also be compared the ripple voltage and the average output voltage of the voltage regulator, corresponding to the voltage on node 5. The results from Octave, on the left, and NGspice, on the right, can be observed in Table 9.

Name	Value [V]
$Ripple_{regulator}$	0.000004
$Average_{regulator}$	11.742371

Name	Value [V]
maximum(v(5))-minimum(v(5))	1.597796e-04
mean(v(5))	1.199992e+01

Table 9: Results for the ripple and average output voltages of the voltage regulator.

Similarly to the envelope detector, discrepancies can also be found on the ripple and average output voltages of the voltage regulator, by reasons metioned above. The ripple value for the theoretical analysis is much smaller than the one obtained in ngspice, however, the DC value is closer to 12V in the ngspice calculations. The differences in the ripple are expected since we are using a simple incremental analysis to calculate the AC component.

5 Conclusion

After the theoretical analysis, the simulation and the results' comparison, it can be concluded that, despite the objective of the work, the design and analysis of a AC/DC converter circuit, presented in Figure-1, has been accomplished.

There were performed both a theoretical and a simulation analysis, where the non linearity of some components became noticeable. This laboratory assignment allowed us to constact with a more realistic and complex problem in a way that its goal forced us to integrate all of our knowledge acquired untill this moment, and made us understand what is in stake when we need to use models to aproximate a circuit. It became clear thet Ngspice is a powerfull tool in circuit solving, representing a good resource in a possible future problem in the industry context. Concluding, we were able to achieve the proposed objective and became more aware of the real context of the applications of this course lectures.