AC/DC converter

Circuit Theory and Electronics Fundamentals

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Contents

1 Introduction

The objective of this laboratory assignment is to create a circuit that converts alternate current into direct current. This is achieved using an envelope detector and a voltage regulator, which consist, respectively, in a rectifier, a resistor and a capacitor, and in a resistor and a limiter. The rectifier used is a bridge rectifier, and the limiter used is composed by a group of diodes connected in series. The starting schematic of the circuit is present on the following figure (Figure 1):

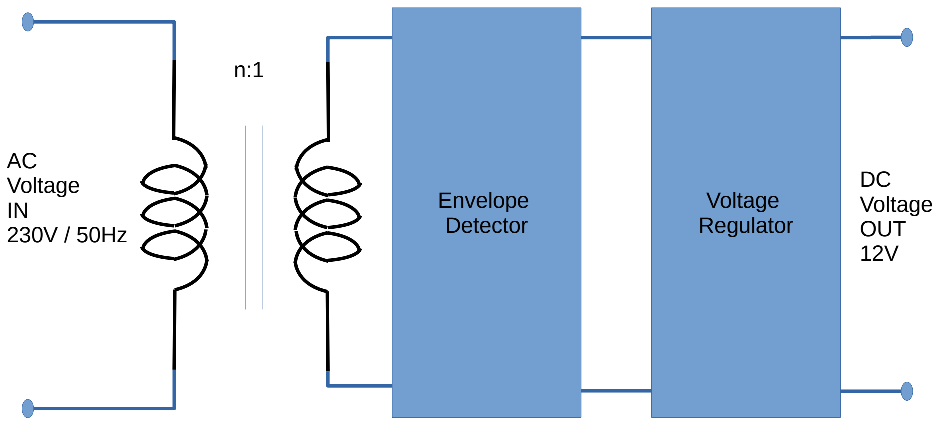


Figure 1: AC/DC converter circuit

In Section 2, a theoretical analysis of the circuit is presented. In Section 3, the circuit is analysed by simulation, and the results are compared to the theoretical results obtained in Section 2. The conclusions of this study are outlined in Section 5.

2 Theoretical Analysis

In this section, the circuit shown in Figure 1 is analysed theoretically.

The theoretical output values of the envelope detector and the voltage regulator will be calculated using *Octave*. These values can be obtained with the aid of the Kirchhoff laws, the diode equations and its simplified models.

First the circuit must be divided into:

- **Voltage source**: The circuit is connected to mains voltage, this means the voltage source as an amplitude of 230 V and a frequency of 50 Hz;
- **Transformer**: The circuit cannot work the supplied voltage, so it must be transformed into a lower voltage, with the aid of a transformer;
- **Envelope detector**: This component is responsible for rectifying the current and for the initial voltage smoothing;
- **Voltage regulator**: Since the desired output is a horizontal line, additional smoothing is required to ensure the best results possible.

With all these parts, the final circuit can be drawn as shown in Figure 2.

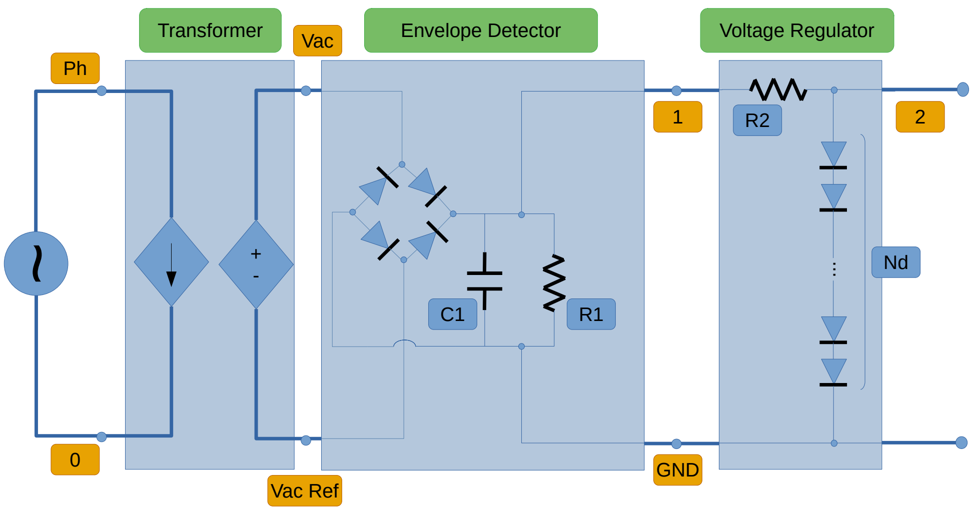


Figure 2: AC/DC converter circuit

2.1 Envelope Detector Analysis

The envelope detector consist of a rectifier, a resistor and a capacitor.

The rectifier used is the bridge rectifier, which is a type of full-wave rectifier. Ideally, this should mean that its output (v_O) is the module of its input (v_S): $v_O = |v_S|$.

However, the voltage needed to activate the diodes (V_{ON}) has to be taken into account as there are no ideal components in the real world. Therefore, $v_O = |v_S| - 2V_{ON}$ since we have 2 diodes connected in series in both ways, as seen in Figure 3.

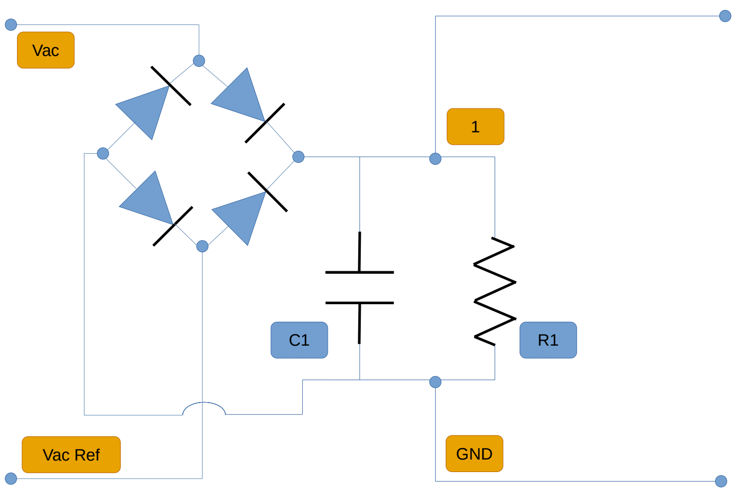


Figure 3: Envelope detector

Now that the voltage is positive, a capacitor and a resistor are used to smooth the wave in order to make it as close to a line as possible. For this to be possible, an instant (t_{OFF}), where the diodes are turned off, has to be established. This way, the current isn't allowed to pass through the diodes making the capacitor the only voltage source in the circuit. t_{OFF} can be calculated using equation 1, which was solved approximately using *Octave*.

$$\frac{A \cdot cos(\omega \cdot t_{OFF}) - 2V_{ON}}{R} = C \cdot A \cdot \omega \cdot sin(\omega \cdot t_{OFF}) \tag{1}$$

As known, a capacitor supplies an exponentially decaying voltage according to equation 2.

$$v_O(t) = (A \cdot sin(\omega \cdot t_{OFF}) - 2V_{ON}) \cdot e^{-\frac{t - t_{OFF}}{RC}} \tag{2}$$

Therefore an instant where the diodes are turned back on (t_{ON}) also needs to be implemented. This instant is the one where the voltage supplied by the capacitor intercepts the rectified voltage, and it can either be calculated using similar methods to the ones used to calculate t_{OFF} or by intercepting the voltage graphics.

2.2 Voltage Regulator Analysis

The voltage regulator (Figure 4) consists of a resistor and a limiter, which itself is composed by multiple diodes connected in series. This component takes advantage of the non-linear diode characteristics to attenuate oscillations in the input signal whilst not being frequency dependent.

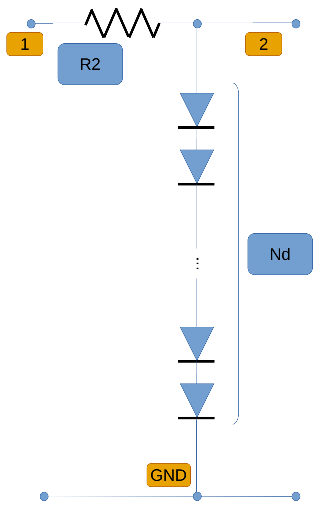


Figure 4: Voltage Regulator

The limiter's function is to regulate the voltage to the desired voltage output (in this case it would be 12V). This is done by varying the number of diodes (N) used, once that the limit will be approximately N times the voltage needed to activate the diodes (V_{ON}). Since the voltage regulator is connected to the envelope detector, the output of the limiter (V_o) depends on the output of the envelope detector (V_{env}) according to equation 3:

$$V_o(t) = \begin{cases} N \cdot V_{ON} + v_o, & V_{env} \geq N \cdot V_{ON} \\ V_{env}, & V_{env} < N \cdot V_{ON} \end{cases}, \tag{3}$$

being v_o the incremental output voltage.

The resistor has various functions, such as to prevent the overheating of the diodes. As these are not ideal diodes, the limit set by them will not be perfect, so the resistor will also have a smothering effect on the voltage output, reducing v_o, and therefore making the output as close as possible to a line (DC). The incremental voltage v_o can be approximately described by equation 4:

$$v_o = \frac{N \cdot r_d}{N \cdot r_d + R_2} \cdot v_{env} \quad , \tag{4}$$

where v_{env} is the incremental voltage of the envelope detector's output.

Although there is equation 3, equation 5 was used to calculate V_o using *Octave*.

$$i = I_S \cdot (e^{\frac{v}{\eta \cdot V_T}} - 1) \tag{5}$$

where i is the current passing trough the diode, I_S is the reverse saturation current, v is the voltage across the terminals of the diode, η is a constant from the material of the diode (this value is 1 for the diodes currently in use) and V_T is the thermal voltage from the diode.

This action goes against the model used before, but it offers the best results without great approximations. To calculate the output voltage, the KVL equation can be written based on the input voltage from the envelope detector (V_{env}), the Resistor (R) and the number of diodes (N) as seen in equation 6. To simplify the circuit, the diodes in series where replaced by one with $\eta_t = \eta \cdot N$.

$$V_o + R \cdot I_S \cdot (e^{\frac{v}{N \cdot V_T}} - 1) - V_{env} = 0 \tag{6}$$

2.3 Final results

With all these equations solved with some arbitrary values for the inputs, the following graph can be obtained using *Octave* (Figure 5):

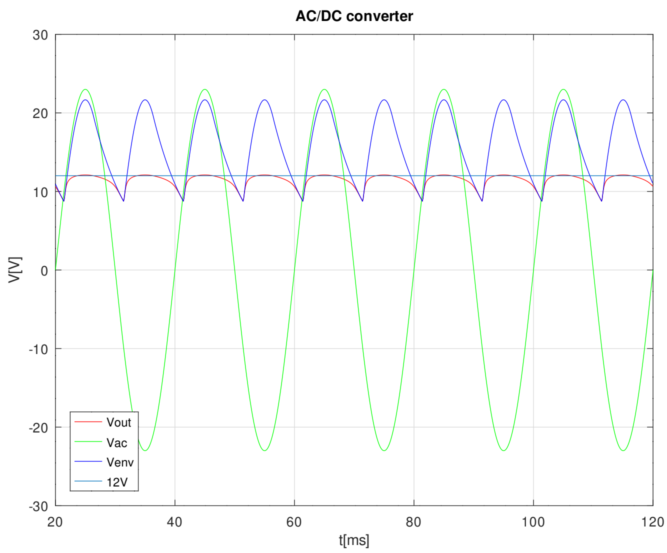


Figure 5: *Octave* output

In order to make a better analysis, a closeup at the voltage ripple and average voltage can be seen in Figure 6:

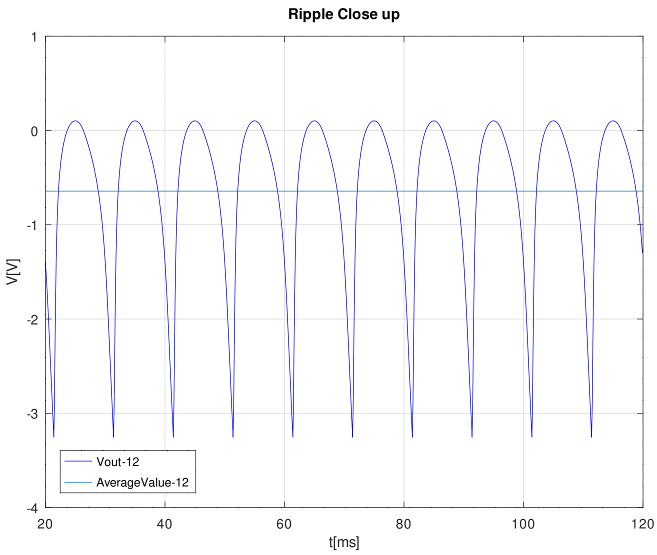


Figure 6: *Octave* output closeup

In this graphic we can see the output parameters from *Octave*. Ideally the ripple and the average voltage value $((mean(v(2)) - 12))$ should be as close to 0 as possible, the cost (in Monetary Units, mu) should be as low as possible and the merit should be as high as possible.

Name	**Value**
$V_{Ripple}(V)$	3.355507e+00
$V_{average}(V)$	11.356762
$V_{deviation}(V)$	6.432375e-01
$Cost(MU)$	9.200000

Table 1: Output parameters from *Octave*

As seen in both graphics and in table 1, the results aren't great. This was made on purpose in order to facilitate their analysis. In section 3 the results will be optimised in order to get as close to the ideal values as possible.

3 Simulation Analysis

3.1 Initial Input

This section discusses the circuit simulation, performed using *Ngspice*.

This circuit was entered into the *Ngspice* simulation environment. This tool is used to simulate analog electronic circuits and predict circuit behaviour. This *Ngspice* simulation begins by defining the base circuit, visible on image 7. The circuit can be subdivided into the following components:

- Voltage source;
- Transformer;
- Envelope detector;
- Voltage regulator.

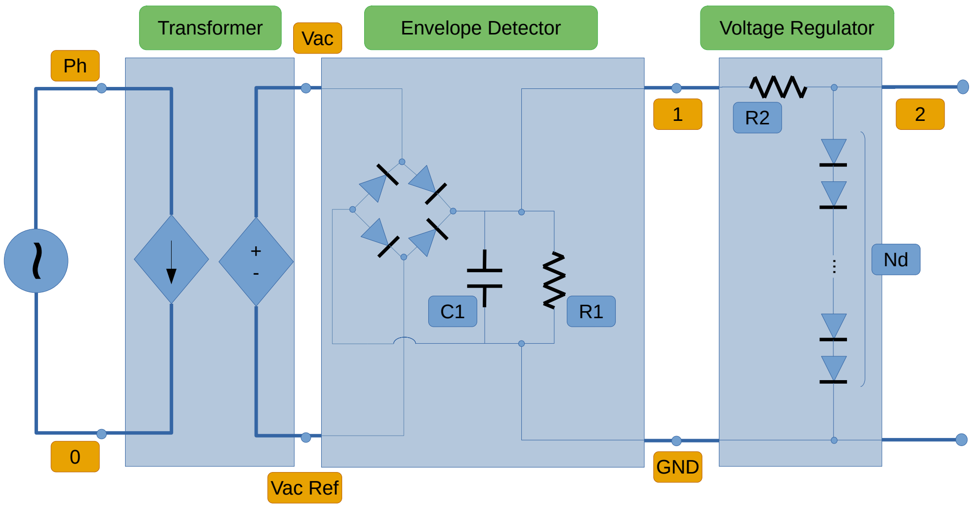


Figure 7: *Ngspice* circuit

After having the base circuit description, the parameters have been chosen by trial and error. The final values are present on the following table (table 2):

Name	**Value**
Tranformer Windings	2.000000
Number of Diodes	18.000000
C1(μF)	1600.000000
R1($K\Omega$)	1000.000000
R2($K\Omega$)	64.915200

Table 2: Input Parameters

With this process it was discovered that:

- The number of winding of the transformer (n) was not changed a lot, this value was only to reduce the input voltage to a one with more manageable values. A higher n means a lower voltage on the circuit (but a higher current).
- Increasing the Capacitor C_1 and the Resistor R_1, reduces the ripple and brings the voltage average slightly upwards;
- The number of diodes (on the voltage regulator) is directly responsible for the average voltage. The number of diodes changes the voltage at which the limiter cuts the current, this value is (approximately) the result from the product of V_{ON} and the number of diodes in series;
- Changing the Value for the Resistor R_2 has a dramatic impact on the average voltage, a small increase, decreases the average voltage by a substantial amount. This was used to fine tune the average voltage without influencing the ripple very much.

Even though we want the best output possible, the price of the components has to be taken into consideration. The method utilised for optimising the output results was trial and error. The parameters were changed until the merit stopped increasing. This resulted in an expensive circuit, but with great results on the output.

3.2 Results

With the parameters honed in, the following graph (Figure 8) is obtained, containing the voltage input and output on both the envelope detector and the voltage regulator:

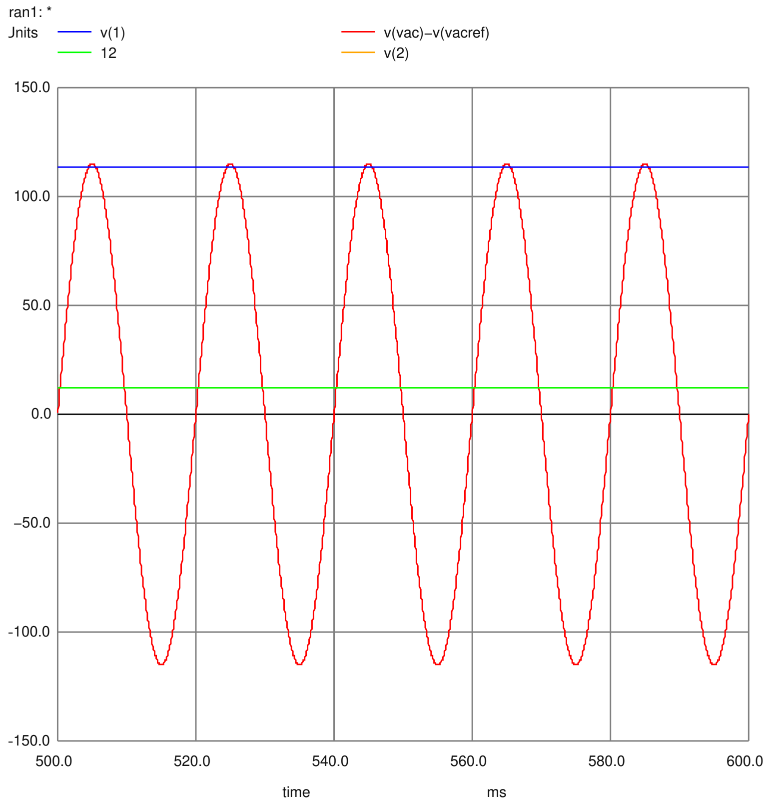


Figure 8: *Ngspice* Output

Since the voltage ripple and the voltage deviation (from 12V) are what is going to be analysed, a closed up graph at these aspects was plotted (Figure 9):

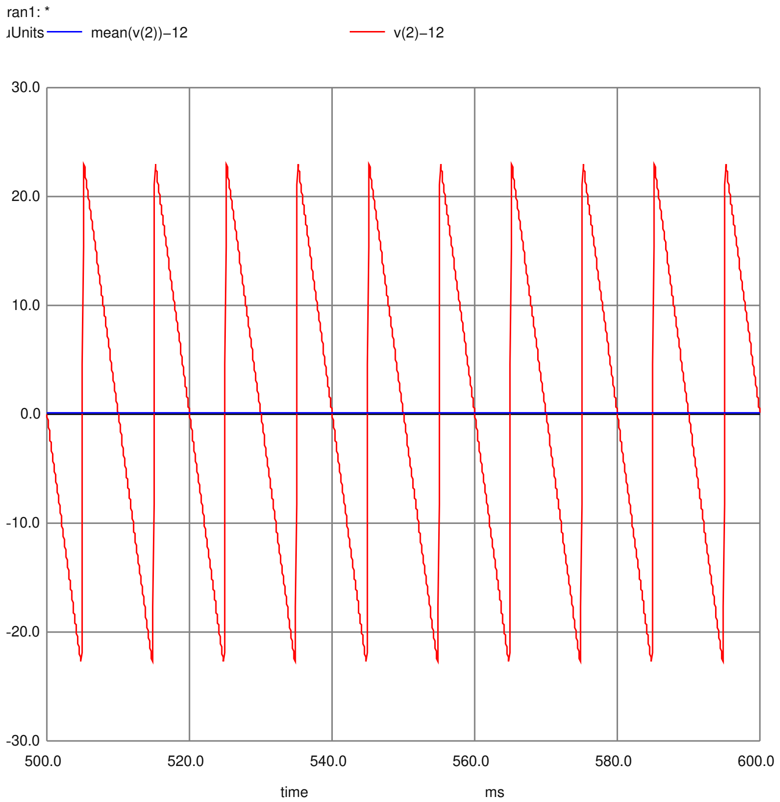


Figure 9: *Ngspice* Output Close up

The quality of the output from this simulation can be analysed through the values shown in the next table (Figure 3).

Name	**Value**
ripple	4.569616e-05
abs(mean(v(2))-12)	8.412735e-08
cost	2.667115e+03
merit	8.014849e+00

Table 3: Output Parameters

As it can be seen, the ripple as well as the mean voltage average have values which are very close to 0. However, in order to reach those values expensive components are needed, thus the high value for the cost (mu). Since the rate at which the ripple and the mean voltage average decreased was higher than the rate at which the cost (mu) increased, a high merit value was obtained.

4 Result Analysis

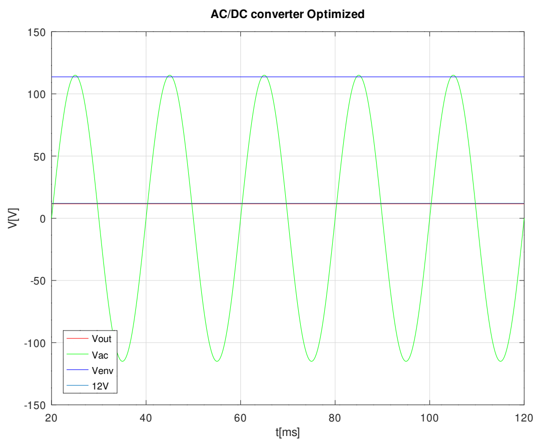
In this section the results will firstly be analysed and then compared, identifying the differences between the calculated results and the simulation results.

The *Octave* graph with optimised parameters will be presented and discussed in this section. This final graph (Figure 10a) can be obtained by introducing these optimised parameters on the previous *script*.

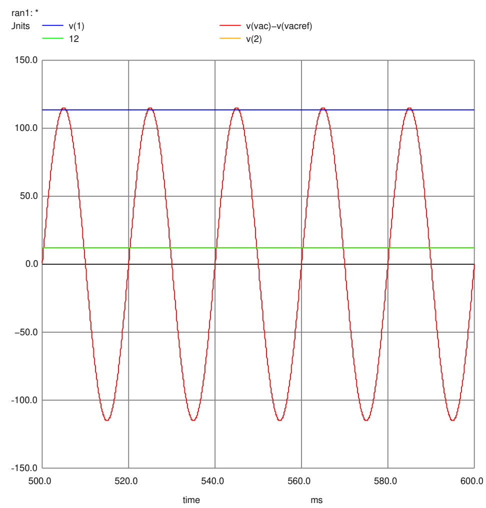
Note: When running the simulation it is possible to notice that it takes a while to plot the graphics. This is due to the fact that the number of time instants used is very high. If it were lower, the graph of the exponentially decaying voltage (from the capacitor) would not intercept the module of the sinusoidal voltage's (output of the bridge rectifier) graph. In turn, that would increase the error by making an approximation in order to force this interception, which looked like a vertical line when analysing the ripple's graph up close.

4.1 Graphs

4.1.1 Outputs overview



(a) Octave

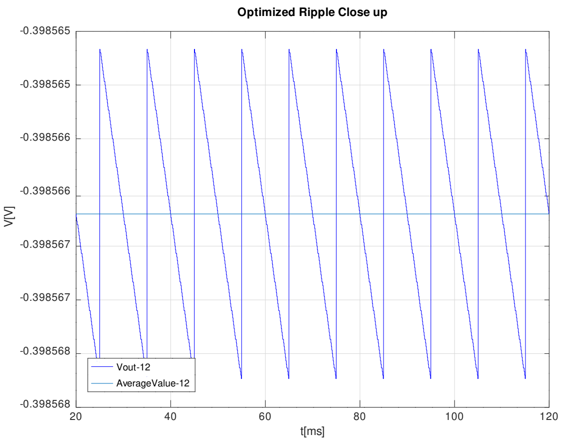


(b) Ngspice

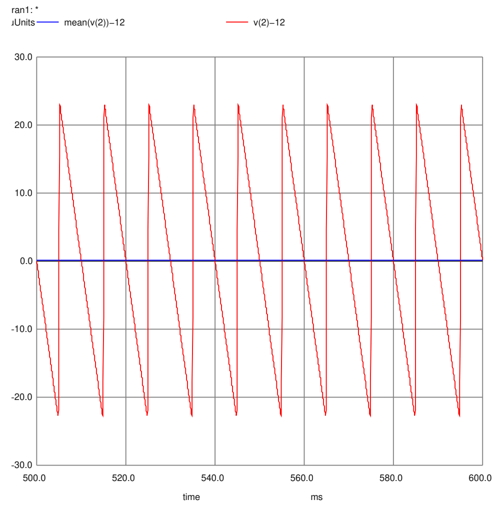
Figure 10: General voltage output

In these graphs we can see that the results match almost identically, as expected. However there is a very slight deviation from 12 V on the Figure 10a. This does not happen on the one Generated using *NGSpice*, it matches 12 volts almost perfectly.

4.1.2 Outputs closeup overview



(a) Octave



(b) Ngspice

Figure 11: Voltage ripple and average close up

Similarly to what happened on the previous graph, we can clearly see that the mean voltage deviation on the *Octave* graph differs a lot from the pretended $0V$ (This means the average voltage is not close to $12V$), this does not happen on the *Ngspice* version, it matches perfectly. On the voltage ripple, the differences are not that severe, but it is present.

These are expected since on *Octave*, approximations were used, which deteriorate the results.

4.2 Tables

Table 4: Output parameters

(a) Octave

Name	**Value**
$V_{Ripple}(V)$	3.114541e-06
$V_{average}(V)$	11.601433
$V_{deviation}(V)$	3.985667e-01
$Cost(MU)$	2667.115200

(b) Ngspice

Name	**Value**
ripple	4.569616e-05
abs(mean(v(2))-12)	8.412735e-08
cost	2.667115e+03
merit	8.014849e+00

Looking at these tables it is possible to confirm what was said before. While the ripple only differs in one order of magnitude from the simulation values to the theoretical ones, the mean voltage deviation differs in five orders of magnitude (where the simulation values are the smallest).

As previously stated, the differences came from approximations such as the diode model approximation, since the diode equation (equation 5) was not solved. Instead, V_{on} was used to calculate the voltage output at the envelope detector. The most probable source of error was overestimating V_{on}, since the values at the output, on this section, are bellow of what was expected from *Ngspice*. This happens because $V_o = V_s - 2V_{on}$, where V_o is the output voltage and V_s is the input one.

Another source of error may come from the computation of the voltage exponential decay, from the capacitor after the bridge rectifier. It was calculated using equation 1 and 2, which means that t_{off} depends on V_{on} and therefore might be different from the real one. $v_O(t)$ may differ too, due to the dependencies on t_{off} and V_{on}.

5 Conclusion

In this laboratory assignment, the main objectives were achieved: we were able to analyse the working principle of an AC/DC converter, as well as understanding the various circuit architectures to solve this problem. We were also able to work with circuits containing diodes.

In order to analyse the circuit, *Octave* was used to compute the theoretical values and *Ngspice* was used to simulate the circuit shown in Figure 2. To obtain the theoretical values, Kirchhoff Laws were used as well as the V_{on} model for the diode values. After that, a plot was made with the values of V_o (voltage output) over time, obtaining a near horizontal line (DC) at 12 volts.

With the theoretical values in, the circuit was simulated and the same plot was made, showing similar results. The input values were then optimised in order to achieve the best simulation output possible. With this, the objective of the laboratory was achieved and we were able to successfully build an AC/DC converter.