Circuit Theory and Electronics Fundamentals

Integrated Master in Aerospace Engineering, Técnico, University of Lisbon

Lab3: AC/DC converter circuit

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1 Introduction

The objective of this laboratory assignment is to develop a circuit, containing a transformer, a envelope detector and a voltage regulator. The AC input voltage amplitude is 230V and the frequency is 50 Hz. The main goal is to obtain a DC output voltage of 12V, meaning that the voltage ripple as to be as small as possible. The circuit created and analysed in this assignment can be seen in Figure 1.
In order to evaluate how successfully our goal has been achieved, we calculate the merit M of our work, using the following expression:

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

where the cost is given by cost = cost of resistors + cost of capacitors + cost of diodes, knowing that each kOhm costs 1 monetary unit (MU), each μF costs 1 MU and each diode costs 0,1 MU. In Section 2, a theoretical analysis of the circuit is presented, using Octave. In Section 3, the circuit is analysed by simulation using ngspice. The conclusions of this study are outlined in Section 4. In addiction, the results are compared to the theoretical results obtained in Section 2.

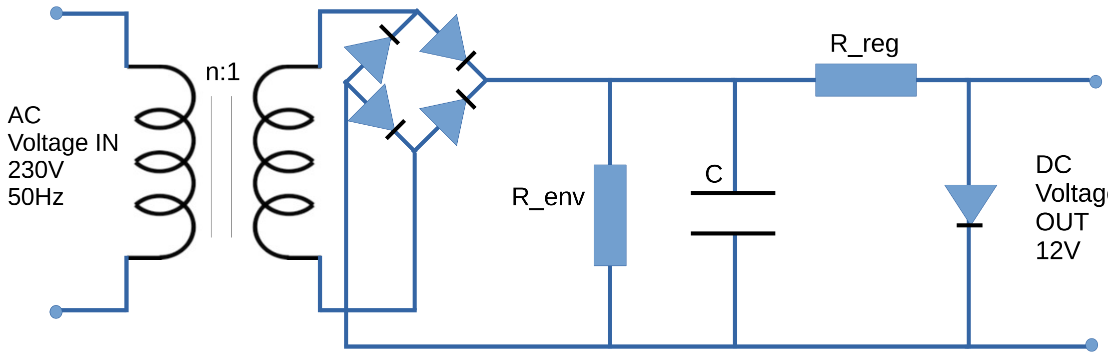

Figure 1: Circuit analysed.

2 Theoretical Analysis

In this section, the circuit shown in Figure 1 is analysed theoretically.
At first, we are going to explain the theoretical models we used to compute the outputs of the envelope detector and the voltage regulator. After that, we will present plots of these outputs and the deviation of the output DC voltage from 12 Volts. Finally, we are able to compute the outuput DC level and the voltage ripple.

2.1 Envelope detector

The transformer of this circuit has a ratio of n:1 between the primary and secondary circuits, where n is greater than 1, meaning that:

$$Amplitude_{secondary} = \frac{V_{PRIMARY}}{n} \tag{2}$$

For the envelope detector, the input voltage is the one in the secondary circuit:

$$v_{SECONDARY} = \frac{V_{PRIMARY}}{n} cos(wt) \tag{3}$$

For this circuit, we have choosen a full-wave bridge rectifier circuit, that is composed by four diodes, a resistance and a capacitor. The output voltage in the envelope detector,$vo_{ENVELOPE}$, is the absolute value of the input voltage, in this case, $v_{SECONDARY}$, assuming the ideal model for diodes. When the diode is on, $v_{SECONDARY}$ > $vo_{ENVELOPE}$ and when the diode is off $v_{SECONDARY}$ < $vo_{ENVELOPE}$. From t = 0 until t = t_{off}, the diode is on and at t_{off} the diode goes off, therefore, in this period of time:

$$vo_{ENVELOPE} = |v_{SECONDARY}| \tag{4}$$

To compute t_{off}, we used the following equation, where w = 2πf:

$$t_{off} = \frac{1}{w} atan(\frac{1}{wR_{enve}C}) \tag{5}$$

From t = t_{off} until the diode is on again:

$$vo_{ENVELOPE} = A_{secondary}|cos(wt)|e^{-\frac{t-t_{off}}{R_{enve}C}} \tag{6}$$

When the diode turns on again:

$$vo_{ENVELOPE} = |v_{SECONDARY}| \tag{7}$$

Also, at this moment, since full-wave rectifier circuit makes the output voltage the absolute value of the input voltage, the period of this circuit becomes half of the original period, reducing the time constant and our cost, therefore:

$$t_{off}new = t_{off} + \frac{1}{2f} \tag{8}$$

2.2 Voltage Regulator

The voltage regulator is composed by a resistance and a limiter circuit. A limiter circuit is a serie of diodes, that, in this case, is a positive voltage limiter. Our goal is that the DC voltage, in the serie of diodes, is 12V. For the voltage regulator circuit, we have to separate the DC analysis and the incremental analysis. At first, for the DC analysis, when $VO_{ENVELOPE} \geq$ 12:

$$VO_{REGULATOR} = 12; \tag{9}$$

On the other side, when $VO_{ENVELOPE}$ < 12:

$$VO_{REGULATOR} = VO_{ENVELOPE}; \tag{10}$$

Moving on to the incremental analysis, if $vo_{ENVELOPE} \geq$ 12:

$$vo_{regulator} = \frac{n_{diodes} r_d}{n_{diodes} r_d + R_{reg}} (vo_{ENVELOPE} - average(vo_{ENVELOPE})) \tag{11}$$

where n_{diodes} is the number of diodes of the voltage regulator and r_d is given by the following expression:

$$r_d = \frac{\eta V_T}{I_s e^{\frac{v_{on}}{\eta V_T}}} \tag{12}$$

where V_T is the thermal voltage (0,025 V), η is the material constant (1), I_s is the reverse saturation current (1*10^{-14}) and v_{on} is given by the following equation:

$$v_{on} = \frac{12}{n_{diodes}} \tag{13}$$

On the other side, if $vo_{ENVELOPE}$ < 12:

$$vo_{regulator} = vo_{ENVELOPE} - average(vo_{ENVELOPE}) \tag{14}$$

2.3 Results and plots obtained

To calculate n from the transformer ratio n:1, we made an approximation using the diode equation to compute the current flowing in the diodes and in the resistance of the voltage regulator:

$$i = I_s(e^{\frac{12}{\eta V_T n_{diodes}}} - 1); \tag{15}$$

Then, we calculated the voltage regulator input voltage and calculated n, using that. After, with this approximation, we adjust n in Ngspice, in order to obtain a lower ripple.
Therefore, the following table shows the values we choose for the circuit parameters.

Table 1: Values of the circuit parameters

n_{diodes}	1.80000000e+01
n	2.24101600e+00
C	4.00000000e-04
R_{env}	4.00000000e+05
R_{reg}	5.70000000e+04

With this parameters, we have obtained the following values:

Table 2: Results obtained

$average(v_O)$	1.20000000e+01
$Ripple$	1.32079202e-05
$average(\|v_O - 12\|)$	3.55271368e-15
$cost$	8.59200000e+02
$Merit$	8.19172230e+01

At last, the following plots show our results graphically.

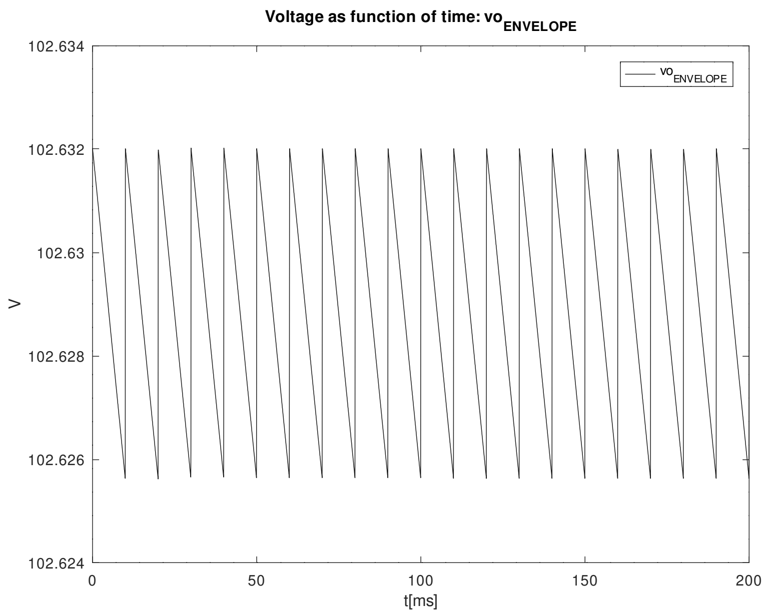

Figure 2: $vo_{ENVELOPE}$ in Volts.

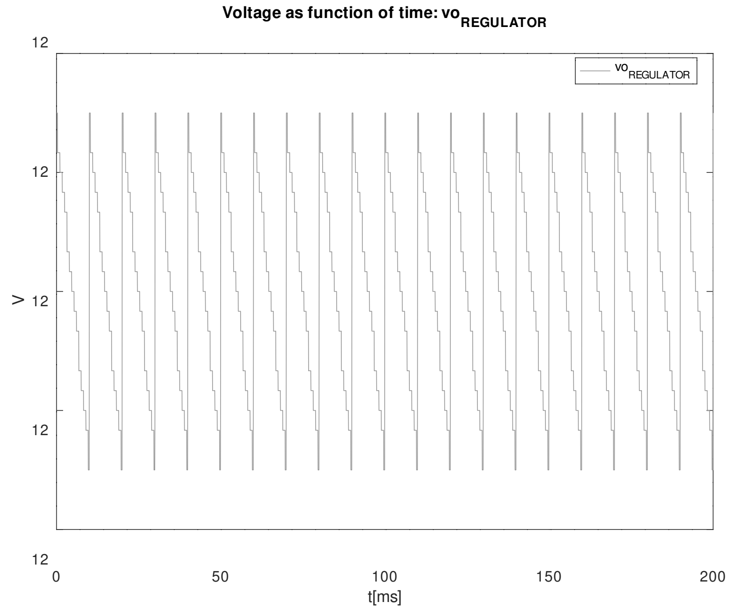

Figure 3: $vo_{REGULATOR}$ in Volts.

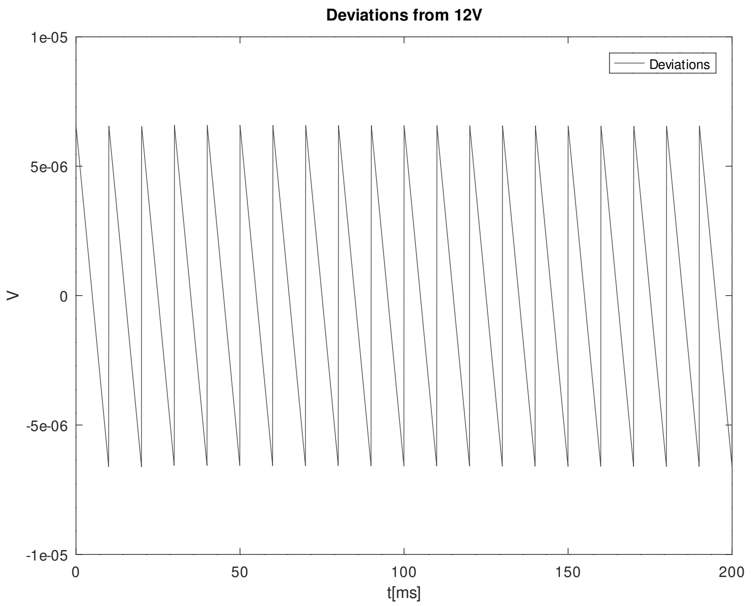

Figure 4: Deviations of $vo_{REGULATOR}$ from 12 Volts.

3 Simulation Analysis

This section covers circuit simulation in ngspice, in the transient analysis was performed and the following graphs were plotted along with a table, that contains the results of this simulation.

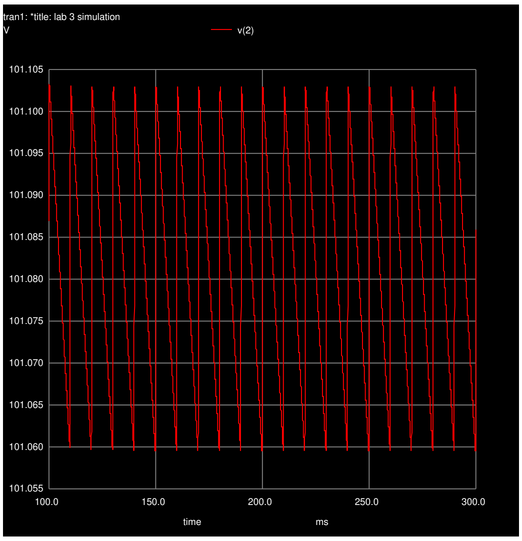

Figure 5: Output voltage for the envelope detector (Volts).

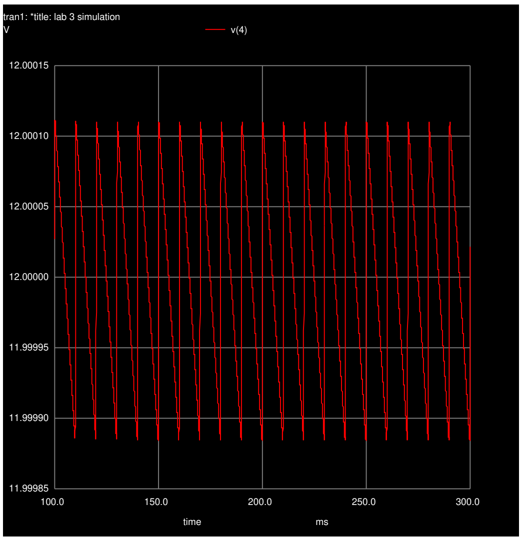

Figure 6: Output voltage for the voltage regulator (Volts).

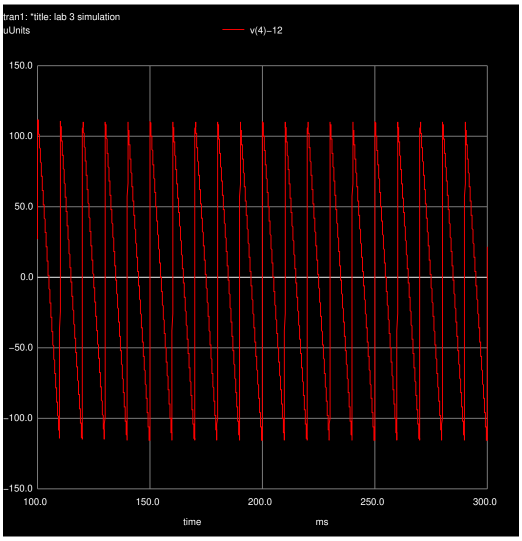

Figure 7: v_O - 12 (Volts).

Name	Value
ndiodes	1.800000e+01
n	2.241016e+00
c1	4.000000e-04
renv	4.000000e+05
rreg	5.700000e+04

Name	Value [A or V]
vavrg	1.200000e+01
ripple	2.267899e-04
mean	2.420788e-06
cost	8.592000e+02
merit	5.055688e+00

Table 3: Parametres used (right) and results obtained (left) in the simulation.

4 Conclusion

In order to analysis the similarities or discrepancies in the theoretical analysis and the simulation, the following tables made with ngspice and octave are presented.

Name	Value
vavrg	1.200000e+01
ripple	2.267899e-04
mean	2.420788e-06
cost	8.592000e+02
merit	5.055688e+00

Name	Value
$average(v_O)$	1.20000000e+01
$Ripple$	1.32079202e-05
$average(\|v_O - 12)\|)$	3.55271368e-15
$cost$	8.59200000e+02
$Merit$	8.19172230e+01

Table 4: Simulation (right) and Theoretical (left) results obtained.

Comparing the values obtained in Octave and Ngspice, the most significant discrepancy observed is the ripple value, where the octave's ripple is about 10 times lower than the simulation's ripple. This is due to the fact that the model used for diodes in ngspice is significantly more complex than the model used in octave. Also, we can observe a huge difference in the orders of magnitude of the $|v_O$ - 12| value, since ngspice's value is about 10^9 greater than the octave's. This can be explained by the difference in the precision of ngspice and octave floating points. However, since they are both very small values, this difference is negligible. Therefore, this explains the fact that the merit in simulation (5.055688) is lower than the merit in the theoretical analysis (81.9172230). Actually, the octave's merit has no meaning, because it is in the simulation that we are interested, since it is the best approximation of the reality. As for the graphs, the results obtained through ngspice and octave are very similar. Taking all this into account, both analysis were still able to create a circuit that transforms the input AC Voltage of 230V and a frequency of 50Hz into an output DC voltage of 12V, even if the octave's model is not the best representation for the reality.