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 **??**, 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 **??** 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.

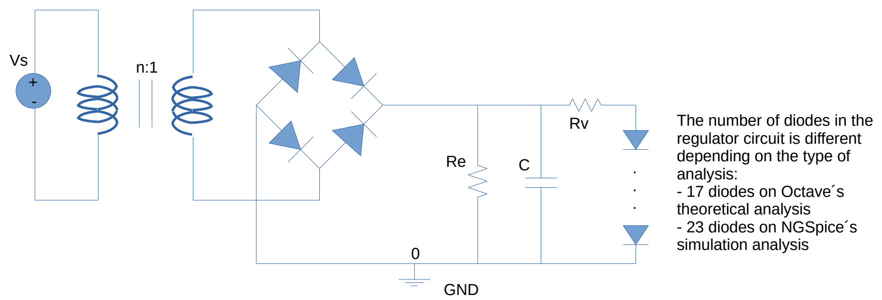

Figure 1: Third laboratory circuit.

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

This theoretical analysis has, as its main purpose, showing how this circuit would behave in theory. this section is divided in two, given that this circuit, as explained in the theoretical introduction, is mainly composed of the two different stages - the gain stage and the output stage. However, there will also be a third subsection which will include the frequency response analysis for the whole circuit.

3.1 The Gain Stage

As already explained in the very first section of this report, the final objective of this lab assignment is to make an amplifier. Given so, this stage will have, as its main goal, to get a voltage gain as high as possible. In this subsection, the OP analysis of circuit will be made (DC current) and the gain, plus the input and output impedances, will be calculated.

3.1.1 OP Analysis

The first subject being analyzed is how does the circuit behave when the current is continuous (DC). This part is crucial when it comes to the study of the rest of the topics, such as the impedances, given that the incremental parameters of the transistors will be calculated based on the values obtained in the OP analysis.

$$\begin{cases} R_{B1} = \\ R_{B2} = \\ R_B = \frac{R_{B1}R_{B2}}{R_{B1}+R_{B2}} \\ V_{BEON} = \approx 0.7V \\ I_E = (1+\beta_F)I_B \\ V_E = R_E I_E \\ V_C = R_C I_C \\ V_O = V_{CC} - V_C \end{cases}$$

3.1.2 Voltage Gain

In order to compute the voltage gain, the values of transistor's incremental parameters are required, given by the expressions below:

$$g_m = \frac{I_C}{V_T} \tag{1}$$

$$r_\pi = \frac{\beta_F}{g_m} \tag{2}$$

$$r_o \approx \frac{V_A}{I_C} \tag{3}$$

$$\frac{v_o}{v_i} = -g_m(R_C||r_o)\frac{r_\pi||R_{B1}||R_{B2}}{R_S + r_\pi||R_{B1}||R_{B2}}v_S \tag{4}$$

In which v_S is the voltage supplied by the source.

3.1.3 Input and Output Impedances

Yet another very important property of this stage to be studied are the impendances, both the input and output ones. The relevance of the impedance, specially the output one, is that it gives an indication about the type of components that can be connected to it. Thus, through deductions made in the theoretical class, the final expressions that give the required values are the following:

$$Z_I = R_{B1}||R_{B2}||r_\pi \tag{5}$$

$$Z_O = R_C||r_o \tag{6}$$

And so, the final results for this stage were obtained:

Gain Stage Computations	
Data	Values
Voltage Gain	-202.010493
Input Impedance	523.575168
Output Impedance	730.963158

Analyzing the table above with detail, there are two specific values that are of great interest to this report: the voltage gain and the output impedance. When coming to the voltage gain, this stage had as its major function, to obtain a very high value, to amplify the sound as much as possible. It can be said that this objective was fulfilled. Looking now at the output impedance, a value of 730.96ω was computed. This value creates a problem: this stage has an astonishingly high output impedance value to be connected to an 8ω speaker. Given so, there is only one way to keep both the present Gain Stage and the 8ω speaker, which is by adding an intermediate stage which will lower the output impedance while maintaining the voltage gain. This intermediate stage is the output stage and its computations are going to be presented right next.

3.2 The Output Stage

As it can be seen from the output impedance obtained in the previous stage, it has a very high value to be connected to the 8Ω of the speaker in the end of the circuit. Therefore, the reasoning of this stage is precisely to solve that issue: to force the output impedance of the amplifier to have a reasonable value to be connected to an 8Ω speaker.

3.2.1 OP Analysis

Just like it was done for the Gain Stage, the operating point analysis for the output stage is also required. The fact that, such as the Gain Stage, this present stage also has a transistor, makes this analysis specially important given that the transistor's incremental parameters depend on the values obtained in this subsection. To do it, the following equations are going to be used.

$$\begin{cases} V_{CC} = 12V \\ V_{BEON} =\approx 0.7V \\ R_E = \omega \\ R_E I_E + V_{BEON} + V_I - V_C C = 0 \\ V_O = V_{CC} - R_E I_E \\ V_O = V_I + V_{BEON} \end{cases}$$

3.2.2 Voltage Gain

As it was previously explained, the main justification for the existence of this Output Stage is to make the output impedance compatible with the 8Ω speaker. Given so, the voltage gain of this stage is expected to be 1, because it should simply transport the voltage gain of the previous stage to the already mentioned speaker.

It will be more convenient to work with admitances, therefore:

$$g_\pi = \frac{1}{r_\pi} \tag{7}$$

$$g_E = \frac{1}{R_E} \tag{8}$$

$$g_o = \frac{1}{r_o} \tag{9}$$

By using the Kirchhoff Current Law (KCL), the expression for the voltage gain of this output can be deduced:

$$\frac{v_o}{v_i} = \frac{g_m}{g_\pi + g_E + g_o + g_m} \tag{10}$$

3.2.3 Input and Output Impedances

Of all the computations already made for this stage, the impedances are certainly the most important ones. As it was already mentioned, the output impedance of this stage is supposed to be compatible with the 8Ω speaker so, by using the expressions deducted in class, the formulas that follow next were obtained:

$$Z_I = \frac{g_\pi + g_E + g_o + g_m}{g_\pi(g_\pi + g_E + g_o)} \tag{11}$$

$$Z_O = \frac{1}{g_\pi + g_E + g_o + g_m} \tag{12}$$

This way, the final results for this stage were obatined:

Output Stage Computations	
Data	Values
Voltage Gain	0.990747
Input Impedance	78634.698490
Output Impedance	3.171596

From looking at the table the results are, overall, very good. Starting by the voltage gain, as mentioned in the theoretical explanation about this stage, it should have a value of 1, which is very well approximated by the 0.99 obtained. Besides that, when it comes to the impedances, the attention should go to the output one, given that it is the one that is going to connect to the speaker. And so, for this impedance, we get an amazing value of 3.17ω, which is more than perfect to connect to the 8ω speaker.

3.3 Frequency Response Analysis

Something that is of great interest to analyze an amplifier is how its voltage gain will vary accordingly with the frequency. As a consequence of that, this subsection will look forward to study the frequency response of the whole circuit, varying the frequency from an initial value of $10Hz$ to a final value of $10MHz$. It is important to add that, in this final topic of the theoretical analysis, a total number of 10 points per decade will be considered.

When varying the frequency, at some point, the voltage gain will have a constant value and thus have a graphical representation similar to a an upland. This way, there will be two frequency, commonly referred to as the cut-off frequencies, that will delimit the already mentioned upland, which will correspond to a gain approximately $3dB$ lower than the constant voltage gain. However, the graphical representation of the frequency response in this report will be somewhat different from the what was just described. In this report, the higher cut-off frequency will be considered as infinite and, when it comes to the lower cut-off frequency, even though it will be calculated, the shape of the graph line for points lower than it will not. The reason why the choice to ignore the graph of the points located between $10Hz$ and the lower cut-off frequency was made is simply because of the difficulty of its computation, added to the fact that they are of no interest to the amplifier. This will result in a graphic made of a single constant function that will vary from the lower cut-off frequency to $100MHz$.

Similarly to what was done in the previous subsections, the formula already deduced in the theoretical classes to compute the value of the constant voltage gain value mentioned in the previous paragraph is presented:

$$\frac{v_o(f)}{v_i(f)} = \frac{g_B + g_{m2}}{g_B + g_{e2} + g_{o2} + g_{m2}} \times Av_{GainStage} = = \frac{g_B + g_{m2}}{g_B + g_{e2} + g_{o2} + g_{m2}} \frac{(r_\pi || R_{B1} || R_{B2})}{(R_S + r_\pi || R_{B1} || R_{B2})} v_S(-g_m(R_C || r_o) \tag{13}$$

Just as a side note, the variables included in the previous formula, such as g_{e2}, g_{o2} and g_{m2} are relative to the output stage while the ones that do not have the ”2” belong to the Gain Stage.

Yet another formula of extreme importance to this topic is the one that will calculate the value of the lower cut-off frequency:

$$f_{Lower\ Cut-Off} = \frac{1}{min[Z_{I1}C_I, Z_{O2}C_O, 1/g_{m1}C_E]2/pi} \tag{14}$$

4 Simulation Analysis

In this section, we can find the results of the topics 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 obtained using NGSpice and the section is divided in three different subsections.

4.1 Output Voltage Gain

The output stage of the common collector amplifier allows the circuit to be compatible with the speaker impedance limits. It is possible to analyse the output voltage of this second part of the amplifier circuit relating it with the variation of the frequency. The NGSpice analysis results in the plot shown below.

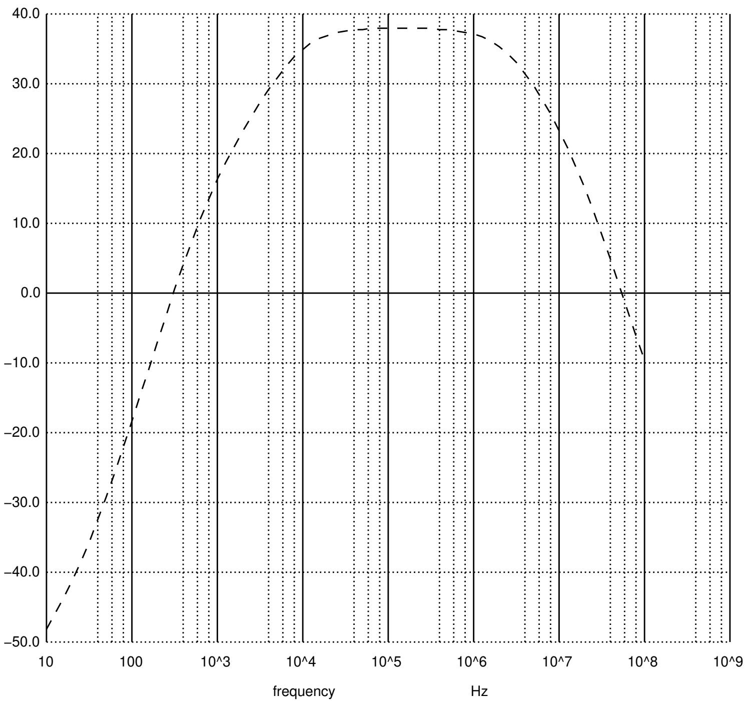

Figure 2: The Output Voltage of the Output Stage of a Common Collector Amplifier.

where f is expressed in Hertz (Hz) along the x-axis
and $v_{dB_{out}}$, the output voltage of the amplifier, is expressed in in Volts (V) using a decibel scale along y-axis.

The interpretation of the graphic allows us to see that the output voltage tends to become constant when closer to its maximum values. In fact, it is possible to compute the output voltage gain as an approximation of the maximum output voltage level.

NGSpice Formula	Output Voltage Gain (V)
vdb(out)[40]	3.793151e+01

4.2 Bandwidth and Cut-Off Frequencies

Also from the intepretation of the plot presented in the previous usbsection, we can calculate the cut-off frequencies. In this case, since we are using an electric circuit simulation tool like NGSpice, we are able to compute values for two existing cut-off frequencies. They are calculated as 3dB cut off frequencies, which means that their correspondent output voltage is the same and it is 3dB lower than the maximum output voltage level. From the lower and upper cut-off frequencies it is possible to calculate the bandwidth.

Variable	Frequency Value (Hz)
f1	1.004524e+04
f2	2.189576e+06
f2-f1	2.179531e+06

where f_1 is the lower cut-off frequency,
af_1 is the upper cut-off frequency and
$f_2 - f_1$ is the bandwith (the difference between the upper and lower cut-off frequencies).

4.3 Input and Output Impedances

NGSpice Formula	Input Impedance Value (Ω): a, b from $Z_{in} = a + bj$
v(in2)[40]/(v(in)[40]-v(in2)[40])*100/1000	6.077977e-01,-1.08849e-01

NGSpice Formula	Output Impedance Value (Ω)

NGSpice Formula	Output Impedance Value (Ω)

NGSpice Formula	Output Impedance Value (Ω)

5 Relative Error and Graphic Analysis

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.