Mathematical analysis of physical stability in the design of bipolar amplifiers through a computer tool

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Mathematical analysis of physical stability in the design of bipolar amplifiers through a computer tool

L Ramírez-Carvajal[1], **K Puerto-López**[1], **and J Ramírez-Mateus**[1]
[1] Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: luiseduardorc@ufps.edu.co

Abstract. This article presents a computer tool that allows to carry out a mathematical analysis of the physical stability of the bipolar transistor in the design of amplifiers. The tool allows to introduce the values of voltage gain, output impedance and input impedance, current gain of transistors and power supplies, to give as a result the values of the resistances. It also allows modifying the transistor operating point and graphing in real time the behavior of the load line and the output signal of the amplifier. Different designs were made with the tool and the results obtained were compared with academic software approved by the scientific community. The errors in all variables evaluated were less than 1.5%. The results are important for semiconductor physics, taking into account that they reaffirmed the directly proportional relationship between the stability of the transistor in its amplification state and the power required to operate. Finally, we conclude that the computer tool allows us to design amplifiers with bipolar transistors with precision and, depending on the need or application of the amplifier, the operating point Q is located in the load line to obtain an output signal without distortion and with the least power dissipation.

1. Introduction

The discovery of the transistor was one of the most important advances in electronics, not only because of the reduction in size and power consumed by the circuits, but also because of the techniques and research that began to emerge [1]. These have had different approaches over time: their semiconductor nature [2], modeling and/or characterization [3], applications [4], design [5], among others. This is possible because its physical characteristics allow it to be an element with several applications, because it has 3 working regions: cutting, amplification and saturation; and depending on the application, it is polarized by locating the Q point in one of these regions [6]. For amplification, for example, the polarization circuits must ensure that the bipolar transistor is located at a point on its "charge line" and in its active zone [7]. Authors such as Horenstein [8], Hambley [9] and Sedra [10], among others, advise placing this point in the center of the charge line to ensure the physical stability of the transistor. However, the power dissipation is a very important factor because in excess, it can cause heating of the transistor [11], and this is not taken into account in these procedures nor was found a tool that allows a concise study of the location of the operating point in the design of bipolar amplifiers.

Savant, Roden and Carpenter address this issue adequately. They claim that if the input signal is very small, power is wasted, since the power dissipated will be greater than that needed to generate an output signal without distortion, and propose a design procedure that takes into account the location of the operating point on the load line [12]. It was then required to corroborate this postulate and develop a tool for the analysis and design of transistor amplifiers that would allow to have an output signal without distortion with the lowest power dissipation to avoid energy waste and heating of the device.

Taking into account the above, we developed a methodology for the mathematical analysis of the physical stability of the bipolar transistor in its amplification state, which allows the analysis of the load lines and the power dissipated in the transistor during the design process. This methodology was represented through a flow diagram and codified, with the purpose of developing a computer tool taking into account the good results that these have brought in different areas of knowledge such as: computer assisted manufacturing processes [13], fluid mechanics [14], neural networks [15], radio communications [16], artificial vision [17], among others.

With the developed tool, circuits were designed and simulated in a software of academic use endorsed by the scientific community. The tests made to the tool and the research in general showed excellent results that are expected to be of impact to the scientific community and to the experimental field of the design of amplifiers with bipolar transistors.

2. Materials and methods

A descriptive and applied methodology was used which can be seen in Figure 1.

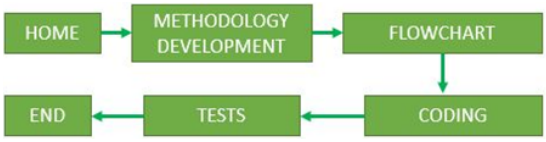


Figure 1. Methodology used in the project.

When consulting sources of information on bipolar transistor amplifier design, most recommend placing the Q operating point in the middle of the load line. However, Savant, Roden and Carpenter [10], proposes a procedure to carry out the design without this condition. Based on this procedure, a design methodology was developed for the study of the operating point Q and the power dissipation in order to confirm the postulate made by the authors, which is divided into 3 parts.

- It is not necessary to locate the point of operation in the middle of the load line for maximum excursion
- If the input signal is small, setting the operating point to 0.5 wastes power
- It is recommended to use 90% of the load line, approaching 5% to the cut zone or 5% to the saturation zone, *i.e*., locate the Q point in a range greater than 0.05 or less than 0.95.

The methodology developed was represented through a flow chart that of Figure 2.

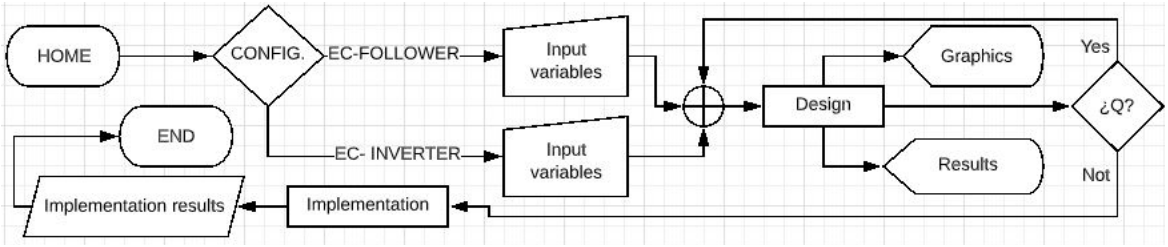


Figure 2. Flowchart.

Figure 3 shows the graphic interface developed through the use of free programming language and it is composed of 5 modules. A start module where the configuration to be designed is chosen, a design module where the process is carried out whose results are observed in the "Q operation point" module; this module has a sliding bar that allows modifying the Q point in a range from 0 to 1, being 0, "cut" and 1, "saturation". As the slider moves, the load lines and the output signal vs. input signal are drawn in real-time in the "Graphics" module; moreover, an implementation module allows you to enter resistance values and do the analysis of the circuit. This tool to be useful for the design of bipolar amplifiers and the compression of physical phenoms of electricity and electronics.

The computer tool allows amplifiers with bipolar transistors were designed starting with Q at 0.02 (cut-off region) and increasing 0.02 until reaching the amplification zone, then starting at 0.48 to 0.54 to evaluate the vicinity of the maximum power point and finally from 0.92 to saturation. These designs were simulated in the software of academic use endorsed by the scientific community to calculate the errors and thus be able to compare the two tools.

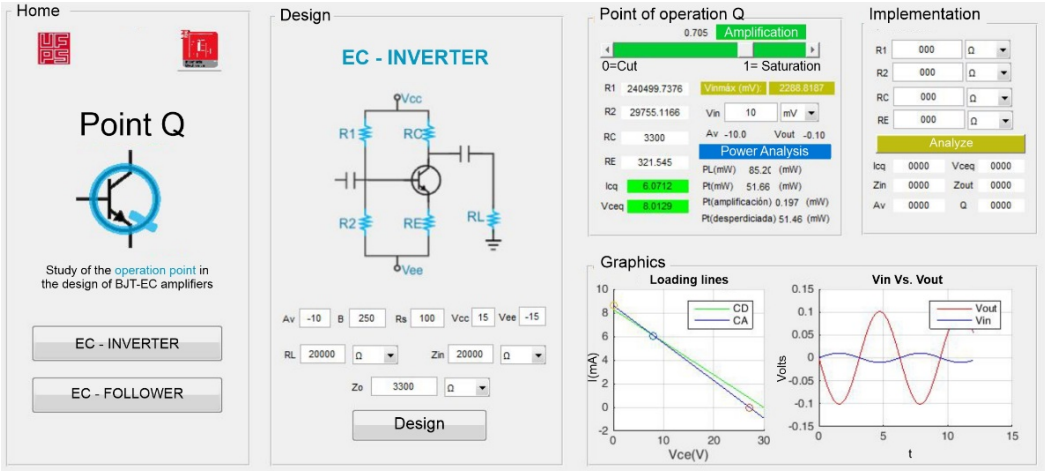


Figure 3. Graphical interface of the computer tool.

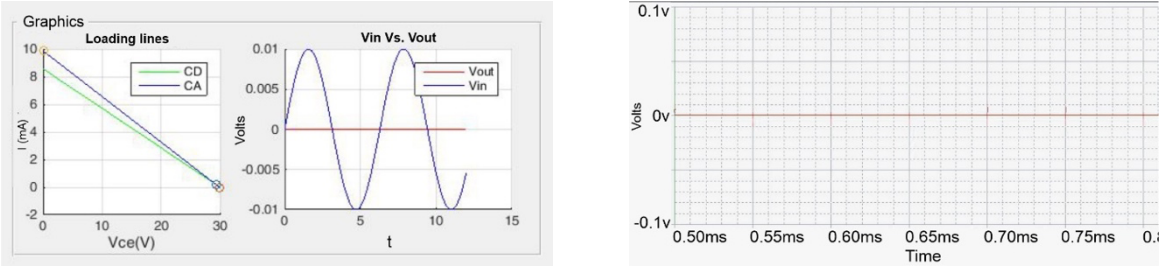
3. Results and discussion

Understanding the physical behavior of the semiconductor was important in addressing the research, as the goal was to optimize a design process. Therefore, information gathering was not only based on obtaining a procedure with mechanically applied steps and equations, but also on understanding the physical impact caused on the transistor. This was achieved thanks to the sweep we made between the different states it presents (cut, amplification and saturation).

The results presented below confirm the postulate made by Savant, Roden, and Carpenter [10], since although physically the semiconductor is at its point of maximum stability by placing the point of operation Q in the center of the load line, as recommended by most authors; it is also true that this point is the one of maximum power consumption, placing it there, without it being necessary, can lead the transistor to waste energy, therefore, the ideal is not to place it in the center of the load line but to bring the semiconductor to the appropriate state to achieve both objectives (stability and optimal power consumption). The input variables were: Av = -10, Zin = 100 Ω, Zout = 3.20 KΩ, B = 250, Vcc = 15 V, Vee = -15 V, RL = 100 Ω, and Rs = 20 KΩ (Figure 3), and the results obtained are report to following.

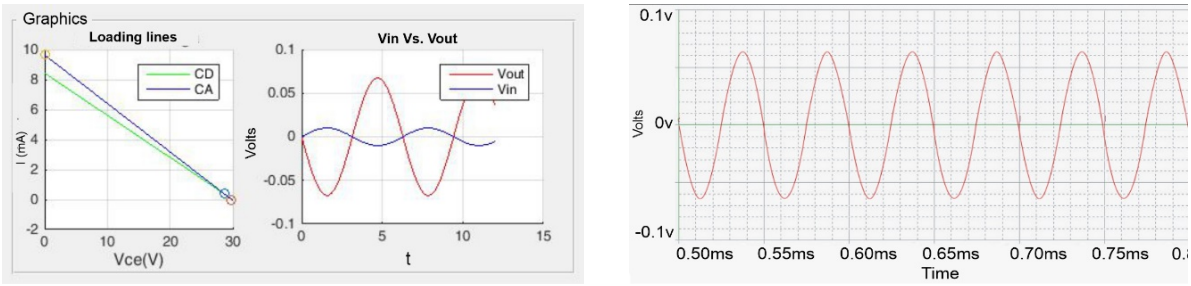
3.1. Passing from the cut-off region to the amplification region

Figure 4 shows the results for Q at 0.02; in Figure 4(a) is reports the graphics of the design tool, and in Figure 4(b) is shown the output signal. Likewise, the Figure 5 shows the results for Q at 0.04, in Figure 5(a) is reports the graphics of the design tool, and in Figure 5(b) is shown the output signal.



(a) (b)

Figure 4. (a) graphics and (b) output signal for Q in 0.02.



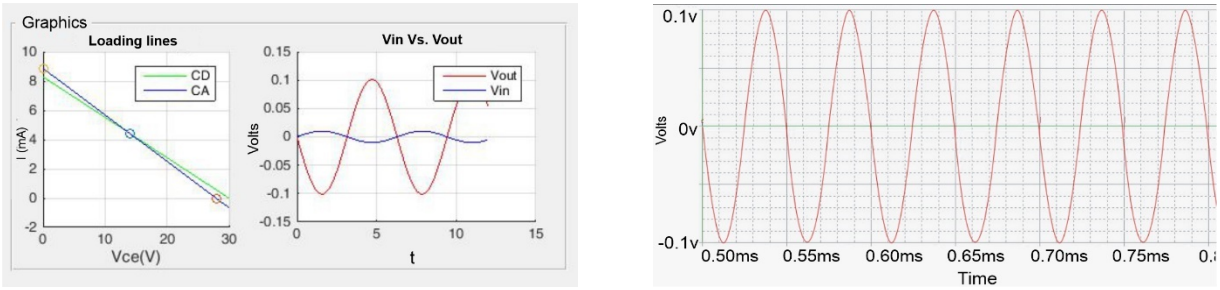
(a) (b)

Figure 5. (a) graphics and (b) output signal for Q in 0.04.

The change between the cut-off region and the saturation region shows a high sensitivity in the manipulation of the operating point, taking into account that this has a range of 0 to 1 and that between 0.02 and 0.04, 55% of the required amplification is reached, and at 0.06, the amplifier has already reached 90%.

3.2. Passing from the cut-off region to the amplification region

Figure 6 shows the results from Q to 0.50; in Figure 6(a) is reports the graphics of the design tool, and in Figure 6(b) is shown the output signal.

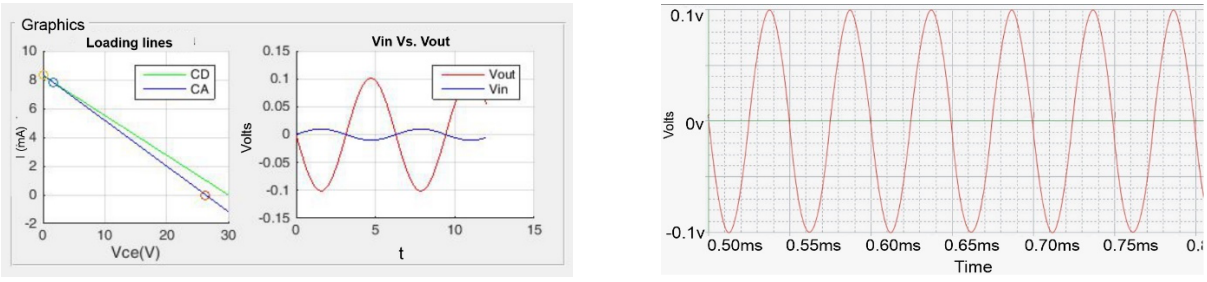


(a) (b)

Figure 6. (a) graphics and (b) output signal for Q in 0.50.

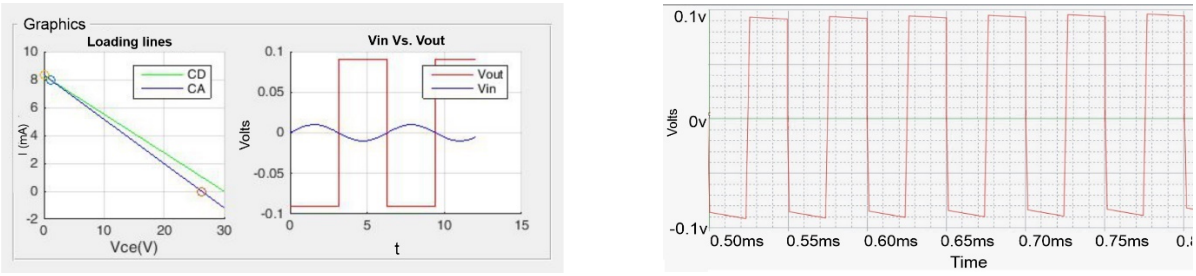
3.3. Passing from the cut-off region to the amplification region

Figure 7 shows the results for Q at 0.94; in Figure 7(a) is reports the graphics of the design tool, and in Figure 7(b) is shown the output signal. Likewise, Figure 8 shows the results for Q at 0.96, in Figure 8(a) is reports the graphics of the design tool, and in Figure 8(b) is shown the output signal. Here it can be seen that between 0.94 (Figure 7) and 0.96 (Figure 8) the change in the physical state of the transistor occurred, going from the amplification region to the saturation region.



(a) (b)

Figure 7. (a) graphics and (b) output signal for Q in 0.94.



(a) (b)

Figure 8. (a) graphics and (b) output signal for Q in 0.96.

Table 1 shows the errors between the two tools for a 10 mV input. These were less than 1.5% for all variables evaluated. The average error for the currents was 1.04%, for the voltages 0.95%, for the transistor powers 0.98% and for the gains 0.81%.

Table 1. Design tool vs. simulation software.

Q	Ic (mA)		e%	Vce (V)		e%	Pt (mW)		e%	Av		e%
	Design	Sim		Design	Sim		design	Sim		Design	Sim	
0.02	0.19	0.19	1.22	29.31	29.57	0.89	0.00	0.00	0.00	0.00	0.00	0.00
0.04	0.38	0.39	1.34	28.62	28.90	0.98	3.36	3.39	0.93	-6.72	-6.80	1.24
0.06	0.57	0.58	1.32	27.94	28.10	0.56	9.11	9.17	0.65	-9.11	-9.22	1.23
0.08	0.75	0.76	1.02	27.27	27.45	0.67	14.33	14.51	1.23	-9.56	-9.67	1.13
0.48	4.26	4.27	0.24	14.56	14.74	1.23	62.09	62.98	1.42	-10	-10.11	1.11
0.50	4.42	4.47	1.11	13.96	14.15	1.33	62.12	62.39	0.43	-10	-10.02	0.24
0.52	4.59	4.64	1.02	13.36	13.42	0.43	61.95	62.29	0.54	-10	-10.07	0.67
0.54	4.75	4.80	1.03	12.77	12.90	0.98	61.59	62.34	1.21	-10	-10.04	0.43
0.92	7.69	7.80	1.40	2.11	2.14	1.24	21.99	22.26	1.22	-10	-10.05	0.46
0.94	7.84	7.96	1.49	1.58	1.60	1.40	18.37	18.61	1.31	-10	-10.08	0.76
0.96	7.99	8.06	0.90	1.05	1.06	0.88	14.61	14.81	1.34	-10	-10.11	1.12
0.98	8.13	8.16	0.40	0.52	0.52	0.75	10.72	10.88	1.45	-10	-10.13	1.27

Table 2, we can see; according to the input signal (Vin), the operating point (Q) and the power in the transistor (Pt), how much is the value of the power required for an output with maximum linearity (Preq), and how much is the value of the wasted power (Pwast). Here we can see that placing the operating point near or equal to 0.50, power is wasted if the input signal is small. For example, the table shows that by setting the operating point to 0.50 the power in the transistor is 62.12 mW, If the input is 1 mV, 0.23 mW is required to operate, wasting 61.89 mW of power, equivalent to 99.62% of the power in the transistor, and if the input is 2 V, the power required is 47.42 mW, wasting only 14.70 mW, equivalent to 23.66% of the power in the transistor.

Table 2. Results of the power dissipation.

Zone	Q	Pt (mW)	Vin = 10 mV		Vin = 100 mV		Vin = 1 V		Vin = 2 V	
			Preq (mW)	Pwast (mW)	Preq (mW)	Pwast (mW)	Preq (mW)	Pwast (mW)	Preq (mW)	Pwast (mW)
Close to cutting	0.04	3.36	0.01	3.35	0.64	2.72	1.28	2.08	2.57	0.79
	0.06	9.11	0.03	9.08	1.73	7.38	3.47	5.64	6.95	2.16
	0.08	14.33	0.05	14.28	2.73	11.60	5.47	8.86	10.94	3.39
Half of the line of load	0.48	62.09	0.23	61.86	11.84	50.25	23.69	38.40	47.39	14.70
	0.50	62.12	0.23	61.89	11.85	50.27	23.71	38.41	47.42	14.70
	0.52	61.95	0.23	61.72	11.82	50.13	23.64	38.31	47.29	14.66
	0.54	61.59	0.23	61.36	11.75	49.84	23.51	38.08	47.02	14.57
Close to saturation	0.92	21.99	0.08	21.91	4.19	17.80	8.39	13.60	16.78	5.21
	0.94	18.37	0.07	18.30	3.51	14.86	7.01	11.36	14.02	4.35

We can also observe that the power in the transistor (Pt) is higher the closer to the center of the load line is the point of operation. For example, Table 2 shows that when the operating point is set at 0.50, the transistor power is 62.12 mW, if set at 0.06, is 9.11 mW, and if set at 0.94, is 18.37 mW.

4. Conclusions

The study carried out with the tool is relevant to semiconductor physics, taking into account that it shows results on the relationship between transistor stability and energy consumption. The research concluded that the power wasted in a bipolar transistor amplifier is directly proportional to the proximity of the operating point of the half of load line and inversely proportional to the magnitude of the input signal. It is confirmed that it is advisable to use 90% of the load line for amplification, locating the operation point higher than 0.05 and lower than 0.95.

The analysis was evidenced that the gain errors were lower according to the proximity of the operating point at 0.50, reaffirming that this is the point of maximum stability, and also, that it is the point of maximum power, which allows inferring that the greater linearity required in the output signal, the greater the power consumption. The tool allows to locate the operating point Q according to the input signal. This is useful for designing voltage amplifiers with bipolar transistors depending on the need or application, since it allows physical stability in the operation of the transistor and obtaining a distortion-free output signal with the least power dissipation. The tool developed is useful in the implementation because it allows to change the by commercial or real values and analyze the circuit, showing data of polarization, input impedance, output impedance and gain.

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