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Computer-aided design software for multi-stage amplifiers with bipolar transistors and field effect

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Abstract. The following article presents computer-aided design software for multi-stage amplifiers with bipolar transistors and field effect. It is composed of two units: a design and analysis unit that allows for step-by-step introduction of polarization and small signal values, the type of transistor to be used (bipolar or field effect) with their respective characterization values: current gain, thermal voltage, activation voltage, and saturation current, to result in the configurations and values of the resistors; and a theoretical unit that contains complete information on multi-stage amplifiers. A n-stage amplifier design method was developed, represented through a flowchart, and coded using a freely usable programming language. With the software, designs were made and simulated in a computational tool for academic use endorsed by the scientific community. The result for all variables evaluated was an average error of less than 2%. The research concludes that this software allows an effective design process of multi-stage amplifiers with bipolar transistors and field effect in a short time, it also allows changing the resistance values obtained for commercial values and calculating the error when implementing the circuit being a useful tool in the experimental area.

1. Introduction

The transistor plays an important role in technological progress. Its discovery was the driving force behind electronics, since it was not only of enormous importance due to the decrease in size and power consumed by circuits, but also due to the new techniques and researches that were developed [1] from it and that have been deriving in the technological boom in which we find ourselves today.

A transistor is a device that controls the flow of a signal by means of a second signal of much lower intensity. The control signal can be a current or voltage signal, these can be connected and form a complex system called a multi-stage amplifier, where each constitutes a stage [2].

Designing a multi-stage amplifier composed of bipolar junction transistor (BJT) and/or Junction field-effect transistor (JFET) transistors is quite an arduous process. Students consult existing procedures by researching the bibliography of the micro-curriculum of the subject and the formulas guides provided by the professor and develop their own compendium of design equations, but in the end quite high mathematical and experimental errors are presented. The whole procedure requires to be reviewed and be redone from the point where the first error occurred until the expected results are obtained. Higher education institutions are in continuous evaluation to improve their academic processes; they have always sought to ratify the relevance of their mission by finding mechanisms and strategies that allow them to give a new profile to their main functions [3]. The “Universidad Francisco de Paula Santander”, Colombia, for example, develops pedagogical practices oriented to a permanent exercise of change incorporating the latest scientific advances and the updating of thematic contents.



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The focus is on contributing to the continuous improvement of its quality and productivity [4]. For this reason, it is necessary to create a tool that allows students to carry out an effective design process strengthening their knowledge in this area and encouraging them to research through interaction with a product of the same that offers good results in their academic process.

Computer aided design (CAD) can be understood as the "application of information technology to the design process" [5]. Focusing the definition, we understand by a CAD system, a computer system that automates the design process. The success in the use of CAD systems lies in the reduction of time invested in scanning cycles. This is mainly due to the use of interactive graphic systems, which allow modifications to be made to the model and changes in the design to be observed immediately [6].

Research on the subject, such as that carried out by Bernal and Rodríguez [7], Rojas, Zuluaga and Rodríguez [8] Alvarez and Marcon [9], Mejía [10], Rengifo, Morales and Gonzales [11], Feria and Zúñiga [12], Veytia, Lara and García [13] and Rojas and Rojas [14], has shown that computational tools and CAD systems have improved the quality of displaying the results of design processes and have allowed professionals related to these technologies to improve their productivity, quality and opportunity. Then they can devote more time to improving designs. It additionally produces good results for education, such as encouraging students and teachers to learn new forms of education that generate knowledge using various technological resources, thus being able to achieve the objectives set in an interactive and friendly manner.

2. Materials and methods

This research was carried out by means of a descriptive and applied methodology that can be seen in the following Figure 1.

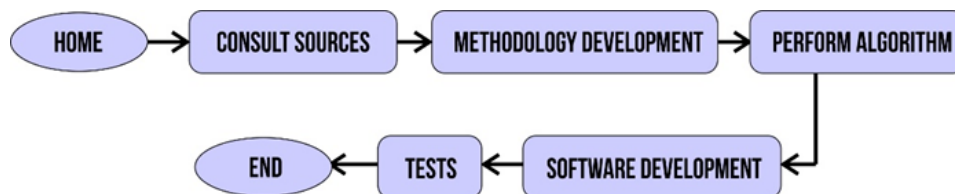


Figure 1. Diagram of the methodology used in the project.

2.1. Consult sources: Dataset

Authors Savant and Carpenter [15], Boylestad and Nashelsky [16], Hambley [2], Horensteins [17] and Sedra and Smith [18] were consulted for the purpose of analyzing the design procedures they propose.

2.2. Methodology development

Variables describing the behavior of a multi-stage amplifier were identified: activation voltage (V_p), saturation current (I_{dss}), drainage current (I_d), gate-source voltage (V_{gs}), conductance (K), transconductance (G_m), voltage gain (A_v), resistance ϕ (r_π), input impedance (Z_{in}), output impedance (Z_{out}), source gate resistance (R_1), earth gate resistance (R_2), drainage resistance (R_D), source resistance (R_S), collector current (I_c), base current (I_b), transmitter current (I_e), collector-emitter voltage (V_{ce}), thevenin resistance (R_{th}), thevenin voltage (V_{th}), current gain (β), thermal voltage (V_t), transconductance (G_m), ϕ resistance (r_π), collector resistance (R_C), emitter resistance (R_E) and power supplies (V_{DD} or V_{CC} and V_{EE}), with them and the respective equations and a design methodology was developed.

2.3. Algorithm

The algorithm was performed and represented in a flow diagram as shown in Figure 2.

2.4. Software development

Through the use of Java language and the NetBeans programming tool, a computer-assisted design software was created that is composed of three main units: start unit, theoretical unit and design and

analysis unit. The start unit can be seen on the left side of Figure 3, where you can choose whether to consult theory or make a design process.

By clicking on the "Unidad teórica" button, you can access the theoretical unit shown on the right side of Figure 3, where you can consult information on multi-stage amplifiers, bipolar transistors, field effect transistors, polarization, configurations, small signal analysis, analysis equations and design equations. In addition, by means of the "Unidad de diseño y análisis" button on the starting unit; you can access the design unit shown on the left side of Figure 4.

This unit allows the input of system variables: voltage gain, input impedance and output impedance, load resistance, power supplies, current gain, activation voltage and saturation current of the transistors and carries out the design process whose results can be displayed stage by stage in a text field choosing each stage through a selector.

The tool allows you to enter commercial resistance values and calculate results with the "Analizar" button. It also allows to graph the schematic of each stage and to show output voltage as a function of time by means of the "Graficar" button, which opens a window that is observed in the right part of figure 4. In the text field "Av implemented" the value of the gain obtained in implementation is introduced and with the button "e%" the implementation error is calculated and shown.

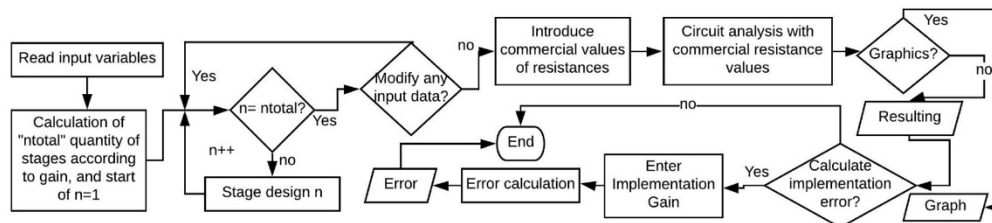


Figure 2. Design flowchart.



Figure 3. Star Unit and theoretical unit.

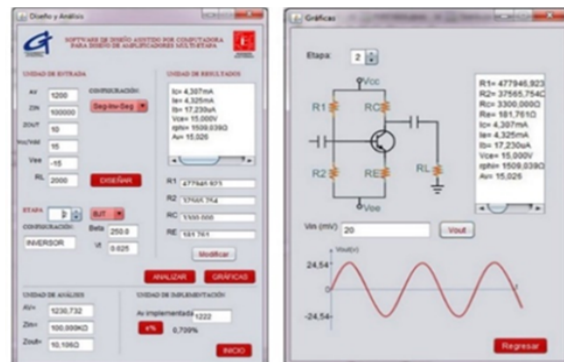


Figure 4. Design and analysis unit and graphics window.

2.5. Software tests

Designs were made with the software and the results obtained were simulated in a computer tool endorsed by the scientific community to be compared by calculating errors in the different variables.

3. Results and discussion

Two design tests were carried out and the results obtained were as follows.

3.1. 4-Stage amplifier with bipolar junction transistor

The variables described in Table 1 were entered into the developed software. The result is shown in Figure 5. A four-stage schematic with a gain of 327.10. When simulating this circuit in another computational tool endorsed by the scientific community, the gain obtained was 326.1 for a percentage error of 0.3%.

Table 1. Input values design 1.

Variable	Value	Variable	Value
A_v (voltage gain)	330	V_{cc} (voltage source)	12 V
Z_{in} (input impedance)	100000 Ω	V_{dd} (voltage source)	-12 V
Z_{out} (output impedance)	10 Ω	R_L (load resistance)	1500 Ω

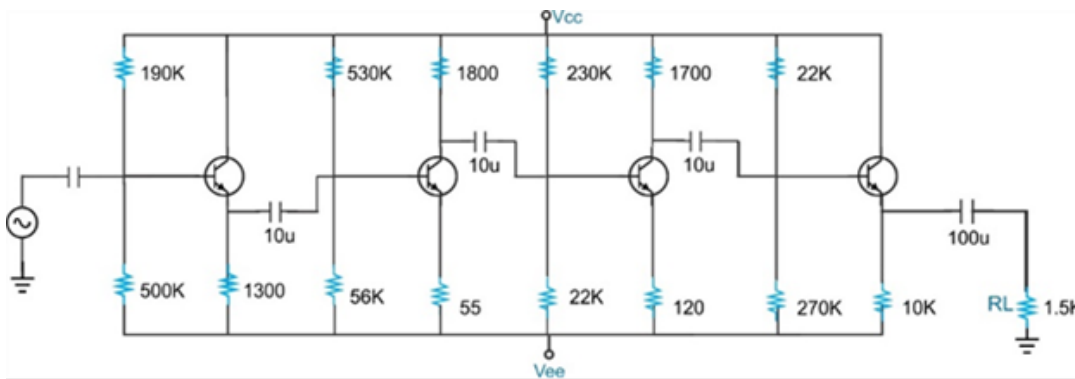
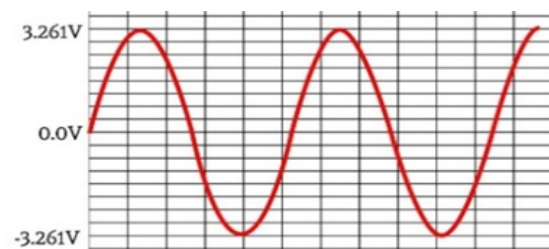
**Figure 5.** Four-stage schematic.

Table 2 shows the design, simulation and error values for the variables: Collector current (I_c), collector-emitter voltage (V_{ce}), resistance r_π and voltage gain of each stage (A_{vi}).

Table 2. Design vs simulation.

	Stage 1			Stage 2		
	Design	Simulation	e%	Design	Simulation	e%
I_c	8.94 mA	8.85 mA	0.54	5.79 mA	5.74 mA	0.80
V_{ce}	12.33 V	12.23 V	0.80	13.25 V	13.09 V	1.20
R_π	727.09 Ω	720.03 Ω	0.97	1120 Ω	1104 Ω	1.40
A_{vi}	0.99	0.99	0.01	-26.27	-26.05	0.80
	Stage 3			Stage 4		
	Design	Simulation	e%	Design	Simulation	e%
I_c	6.45 mA	6.36 mA	1.30	2.11 mA	2.09 mA	0.90
V_{ce}	12.25 V	12.01 V	1.20	2.78 V	2.76 V	0.70
R_π	1007 Ω	997.13 Ω	0.98	3075 Ω	3031 Ω	1.40
A_{vi}	-12,59	-12,48	0.80	-0.99	0.98	0.20

Figure 6 shows the output signal 1 obtained in the computer-aided design software and Figure 7 shows the output signal 1 obtained in the simulation software. Figure 6 and Figure 7 present similar outputs in amplitude and linearity.

**Figure 6.** Output Signal 1 in computer aided design software.**Figure 7.** Output signal 1 in simulation software.

3.2. 6-stage amplifier with bipolar junction transistor and junction field-effect transistor

The variables described in Table 3 were entered into the developed software. Figure 8 presents a more complex circuit than Figure 5 because it contains bipolar and field effect transistors.

Table 3. Input values design 2.

Variable	Value	Variable	Value
Av (voltage gain)	850	Vcc/Vdd (voltage source)	12V
Zin (input impedance)	250000 Ω	Vdd (voltage source)	-12V
Zout (output impedance)	10 Ω	RL (load resistance)	1500 Ω

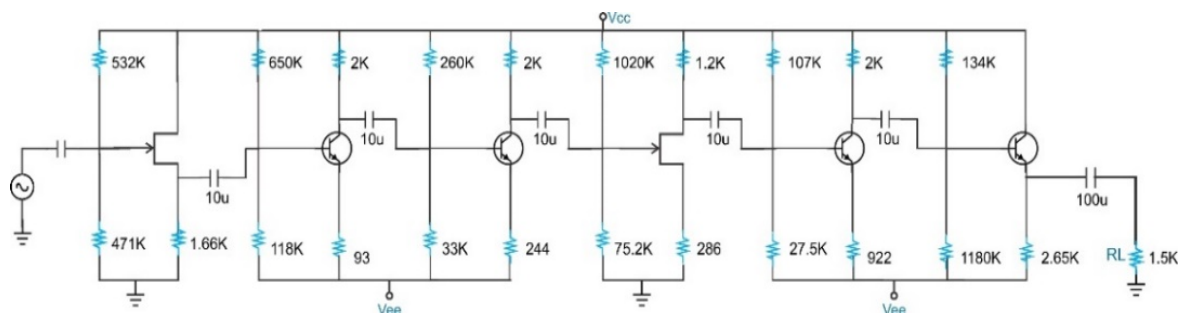


Figure 8. Six-stage schematic.

Table 4 and Table 5 show the design, simulation and error values for the following variables: Collector current (I_c), collector-emitter voltage (V_{ce}), resistance r_π , drainage current (I_d), source drainage voltage (V_{ds}), source gate voltage (V_{gs}), transconductance (g_m) and gain of each stage (A_{vi}).

Table 4. Design vs simulation, BJT stages.

	Stage 2			Stage 3		
	Design	Simulation	e%	Design	Simulation	e%
I_c	5.85 mA	5.80 mA	0.76	5.25 mA	5.18 mA	1.23
V_{ce}	11.73 V	11.52 V	1.75	12.20 V	12.01	1.50
R_π	1109 Ω	1095 Ω	1.24	1236 Ω	1213 Ω	1.80
A_{vi}	-18.58	-18.48	0.54	-7.78	-7.74	0.40
	Stage 5			Stage 6		
	Design	Simulation	e%	Design	Simulation	e%
I_c	4.05 mA	3.99 mA	1.40	6.60 mA	6.48 mA	1.76
V_{ce}	12.14 V	11.92 V	1.76	6.47 V	6.34	1.92
R_π	1603 Ω	1583 Ω	1.20	984 Ω	973 Ω	1.10
A_{vi}	-2.098	-2.09	0.36	0.99	0.99	0.35

Table 5. Design vs simulation, JFET stages.

	Stage 1			Stage 4		
	Design	Simulation	e%	Design	Simulation	e%
I_d	3.63 mA	3.57 mA	1.44	4.57 mA	4.50 mA	1.34
V_{ds}	5.97 V	5.88 V	1.50	5.19 V	5.11 V	1.67
V_{gs}	-0.39 V	-0.38 V	0.56	-0.48	-0.48 V	0.60
g_m	9 mA	8.80 mA	1.87	9 mA	8.90 mA	0.11
A_{vi}	0.99	0.99	0.10	-2.85	-2.84	0.22

Figure 9 shows the output signal 2 obtained in the computer-aided design software and Figure 10 shows the output signal 2 obtained in the simulation software.



Figure 9. Output signal 2 in computer aided design software.

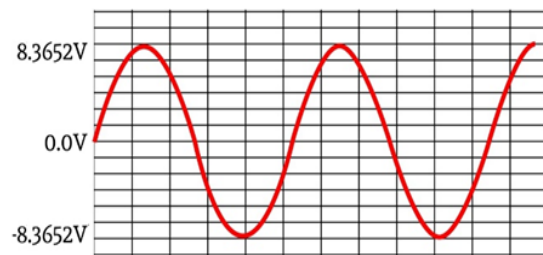


Figure 10. Output signal 2 in simulation software.

Multi-stage amplifiers are approached from 2 types of analysis: "Polarization" and "small signal". Polarization refers to the electrical characteristics of voltage and current in the time domain while "small signal" is a type of analysis that allows us to address these systems in the frequency domain [16]. The variables "collector currents, emitter-collector voltages, drainage currents, drain-source voltages and gate-source voltages" allow us to evaluate the results in polarization and the variables "resistance $r\pi$ and voltage gains" allow us to evaluate the results in "small signal". When calculating the average errors of these variables between the software and the simulation, the following results were obtained (Table 6).

Table 6. Average errors.

	Variable	error%
Polarization analysis	Collector currents	1.08
	Emitter-collector voltages	1.35
	Drainage currents	1.39
	Drain-source voltages	1.58
	Gate-source voltages	0.58
Small-signal analysis	Resistances $r\pi$	1.26
	Voltage gains	0.52

4. Conclusions

In all the tests carried out, the maximum excursion to the start was presented. Low errors were obtained in the two types of analysis: polarization and small signal. In polarization the highest error was 1.58% and in small signal was 1.26%. None of the mean errors in all the evaluated variables was higher than 2%, which allows inferring that the developed software is exact in comparison with the simulator endorsed by the scientific community.

The software presented in this article is an innovative tool, as it not only performs circuit analysis as in simulation software, but also performs two procedures: Design and analysis.

By allowing resistor values to be modified for commercial or real values, analyzing the circuit again, and entering the value of the gain obtained by implementing the circuit to calculate the error, it makes the software a useful tool in the experimental area.

The software is an academic tool because it has theoretical unity and allows to strengthen the knowledge about multi-stage amplifiers. This allows it to be a virtual guide with a friendly graphical interface that encourages the learning process.

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