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Dissipation Minimization of Two-stage Amplifier using Deep Learning

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Abstract: Designing electrical circuits and devices is usually based on expertise in electronics and the thorough use of numerical software tools. This procedure can be time-consuming, and the designer has only one solution. This paper introduces a new approach focused on new concept design and optimization of specific circuits using symbolic expressions. The primary amplifier circuit, realized by a deep learning module, changes the value to reduce power dissipation. The control signal of the deep learning module is output from an amplifier that depends on the statistics of the input signal value.

Keywords: Artificial intelligence, Total-power-consumption, Optimization algorithm based on statistics, Knowledge based system.

1 Introduction

Most of the signals that are processed on modern devices are digital, i.s., represented by quantized values: 1D (one dimensional) is a signal in discrete equidistant intervals of time or space (as a function of a single independent variable such as music or speech), 2D (two-dimensional) is a signal that depends on two variables (such as images represented as 2D arrays, called pixels as the smallest element of a raster image), 3D (three-dimensional) are digital signals such as images at discrete equally spaced time intervals.

There are only analog signals in nature. Analog signals have continuously changing values and are constantly changing with independent time or space. If space is the independent variable, we call it time for simplicity. The number of values of an analog signal is infinite. Therefore, it is impossible to process analog

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signals with digital systems because infinite space cannot be represented by a finite set of values. The only possibility is to use mathematical expressions to represent analog signals as functions. Instead of continuously changing the amplitude, we use mathematical expressions to provide a jump in some cases of the independent variable. We call those signals continuous or, in jargon, continuous-time signals, signals that exist at every moment in time.

A 1D continuous time signal arises at some point and disappears after some time. 2D image signal has limited space (horizontal and vertical dimensions). The 3D digital signal is limited space and also time-limited.

The exact properties of the analog signal cannot be discovered. Fortunately, this is not necessary in practice. As a rule, an analog signal has added noise. Therefore, the properties of an analog signal can be determined with a certain error. This means that we can use some approximations of the original signal unless the total error significantly affects the signal properties. Therefore, the mathematical approximation with a continuous signal is quite acceptable for determining the properties of the signal.

Instead of using mathematical derivations, we can make devices that process an analog signal with added noise in real-time. In that case, we do not take into account that the signal is time-limited.

To design analog circuits, we can use stringent procedures. For example, the design can be in the time domain, but it is more convenient to use the frequency domain.

In this paper, we start with an existing analog circuit schematic and derive properties in the time and frequency domain. Some constitutive elements can be represented by symbols as long as it is unnecessary to optimize some system parameters.

The paper is organized as follows. The following Section presents a symbolic schematic transformation of a known analog circuit. Various transform schemes derive properties in the time or frequency domain. In Section 3, the automatic symbolic solution of the system is performed directly from the corresponding scheme. In Section 4, mixed numerical symbolic optimization is presented. Note that some elements and parameter values are represented as integers treated as symbolic values. In Section 5, the symbolic derivation of the system parameters is illustrated. The knowledge of the analog system is embedded in the deep learning module, as shown in Section 6. In the deep learning module, we add additional circuits, such as a peak detector, to generate a control signal to change the value of some elements as required (reducing the overall power consumption). Finally, we added some references explaining some parts of the proposed method.

2 Symbolic Schematic Transformation

In this section, we demonstrate that automated symbolic schematic transformation is the primary initial step for using Deep Learning (DL) to optimize some properties of electric circuits. The same electric circuit has to be differently analyzed [1] depending on the operation type, such as (1) the direct current (DC) mode of operation, (2) the small signal model (SSM), and (3) the large signal mode (LSM) of operation. We can derive (1) the power consumption from the DC mode, (2) the linear property such as the operational amplifier (opamp) gain from the SSM model, or (3) the distortion from the LSM mode. In classic circuit analysis, each mode of operation is separately analyzed and designed. However, the modern circuit design requires optimization concerning input signal that is possible only using DL since the input signal can vary during the exploitation period. For example, when the input signal does not exist, (1) the power dissipation has to be reduced to the minimum in the DC mode of operation, (2) the linear property has to be achieved in the SSM mode of operation, and (3) the harmonic distortion has to be keeping to the acceptable level in the LSM mode of operation.

The power consumption of the bipolar transistor amplifier depends on resistor values computed to offer a load line (LL) below acceptable power consumption and the operating point (OP) between the cutoff region and the saturation region. The total power consumption (TPC) also depends on the value of the collector resistance. The TPC can be reduced by moving the OP closer to the saturation region. The OP for the minimal TPC and the minimal collector value is located at the intersection of the LL and collector current. In the static state, without an input signal applied, the OP should correspond to the minimal TPC.

On the other way, the OP for linear amplification should be located near the center of the LL, but in that case, the TPC is larger. In the dynamic case, when a significant input signal is applied, the OP should be moved so that the positive and negative alternations of the input signal cannot be distorted at the increased TPC. An increase and decrease in the input signal alterations cause a corresponding increase and decrease in the TPC.

If the opamp gain is too large, overdriving can occur even with a properly selected OP. When the output can be nonlinearly distorted, the transistor gain should be reduced to keep the linear operation of the amplifier. Note that the nonlinear distortion can be tolerated in some applications, especially when the rest of the overall circuit has an appropriate filtering function.

Suppose we know a schematic of an electric circuit that we would like to optimize. The circuit we analyze (the amplifier that consists of two-stage direct-coupled active transistor components) is shown in Fig. 1.

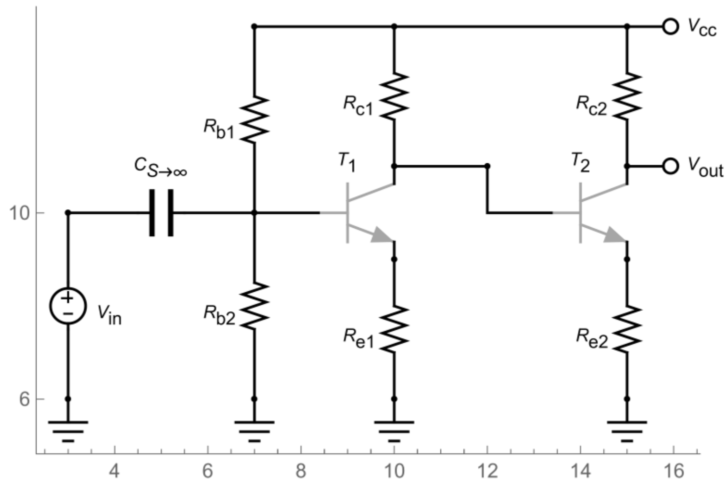


Fig. 1 – *Two-stage direct-coupled amplifier.*

For circuit analysis, it is appropriate to redraw the schematic with symbols suitable for automated equations settings. We use existing software [2] and appropriate GUI [3]. Fig. 2 shows the automatically redrawn schematic for determining OP, where the bipolar transistor is replaced with equivalent voltages V_{BE} (between Base and Emitter) and V_{CE} (between Collector and Emitter). Notice that voltages V_{BE} and V_{CE} should be larger than 0V.

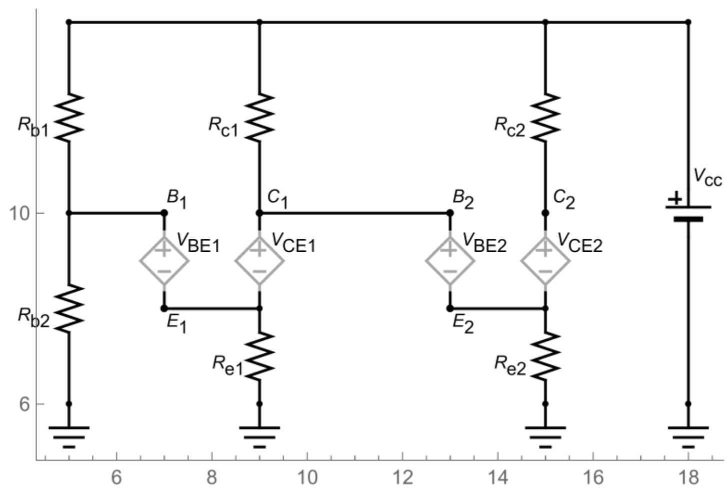


Fig. 2 – *Schematic for determining OP.*

Assuming that OP is correctly computed, the automatically redrawn schematic for SSM is shown in Fig. 3. The equivalent symbols for SSM transistors are used. The automated schematic transformation is the primary first step in the optimization since it prevents errors in manual redrawing. In addition, the automated symbolic transformation prevents errors in manual system description settings.

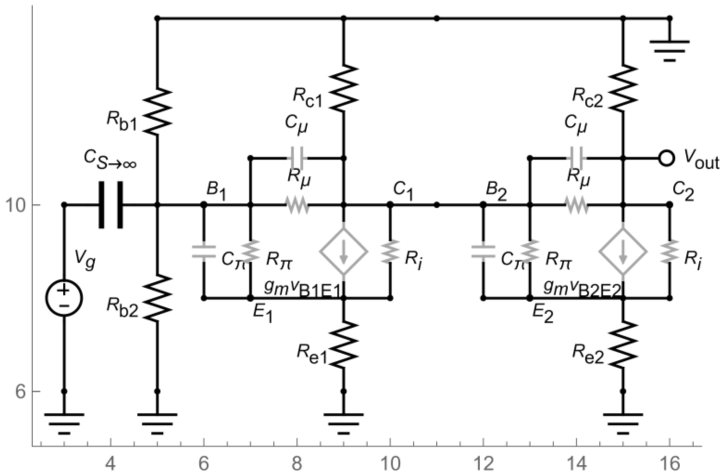


Fig. 3 – *Two-stage direct-coupled amplifier.*

3 Symbolic System Solving

In this paper, the circuit-system solving derives all node voltages in terms of element values and applied voltages in symbolic form. This is an almost impossible task for manual solving. Instead of presenting equations and voltage responses regarding the applied voltages (input voltages such as V_{in}, supply voltages such as V_{cc} in Fig. 1), we present all responses obtained by the software. The total power consumption (TPC) is computed as:

$$\mathrm{TPC} = V_{\text{cc}} \frac{\left[\begin{gathered} -\beta(1+\beta)(R_{\text{b1}}+R_{\text{b2}})R_{\text{e2}}V_{\text{BE1}} - R_{\text{b1}}R_{\text{b2}}V_{\text{BE2}} \\ -(1+\beta)(R_{\text{b1}}+R_{\text{b2}})R_{\text{e1}}V_{\text{BE2}} \\ +\big(R_{\text{b1}}(R_{\text{b2}}+R_{\text{e1}}+\beta R_{\text{e1}})+(1+\beta)R_{\text{b2}}(R_{\text{e1}}+\beta R_{\text{e2}})\big)V_{\text{cc}} \\ +(R_{\text{c1}}+R_{\text{e2}}+\beta R_{\text{e2}})\big(-R_{\text{b2}}V_{\text{BE1}}+(R_{\text{b2}}+R_{\text{e1}}+\beta R_{\text{e1}})V_{\text{cc}}\big) \\ +\beta^2(R_{\text{b1}}+R_{\text{b2}})(R_{\text{c1}}V_{\text{BE1}}-R_{\text{e1}}V_{\text{BE2}}) \\ -\beta\big(R_{\text{b2}}R_{\text{e1}}+R_{\text{b1}}(R_{\text{b2}}+R_{\text{e1}})\big)(V_{\text{BE2}}-V_{\text{cc}}) \\ +\beta^2\big(-R_{\text{b2}}R_{\text{c1}}+(R_{\text{b1}}+R_{\text{b2}})R_{\text{e1}}\big)V_{\text{cc}} \end{gathered}\right]}{\big(R_{\text{b1}}R_{\text{b2}}+(1+\beta)(R_{\text{b1}}+R_{\text{b2}})R_{\text{e1}}\big)(R_{\text{c1}}+R_{\text{e2}}+\beta R_{\text{e2}})}. \tag{1}$$

The output voltage V_{c2} for operating point (OP) is computed as:

$$V_{c2} = \frac{\left[\begin{array}{c} \left(R_{e2} + \beta(R_{c2} + R_{e2})\right) \cdot \\ \left(-\beta(R_{b1} + R_{b2})R_{c1}V_{BE1} + R_{b1}R_{b2}V_{BE2} + (1+\beta)(R_{b1} + R_{b2})R_{e1}V_{BE2}\right) + \\ + V_{cc}R_{b1}(-\beta R_{c2} + R_{c1})(R_{b2} + R_{e1} + \beta R_{e1}) \\ + R_{b2}V_{cc}\left[R_{c1}R_{e1} + \beta^2\left(-R_{c2}R_{e1} + R_{c1}(R_{c2} + R_{e2})\right)\right. \\ \left. + \beta\left(-R_{c2}R_{e1} + R_{c1}(R_{e1} + R_{e2})\right)\right] \end{array}\right]}{((R_{b1}R_{b2} + (1+\beta)(R_{b1} + R_{b2})R_{e1})(R_{c1} + R_{e2} + \beta R_{e2}))}. \quad (2)$$

4 Mixed Numeric-Symbolic Optimization

In many systems [4], designing a robust system insensitive to element changes is possible. Using sensitivity analysis [5], we can determine which system parameter or element value has the most significant influence on the parameter that can be optimized. This way, we collect knowledge on a system used for deterministic or heuristic optimization. Once we find which system transistor parameter or element values are of small influence on the optimization parameter, we can choose numeric values and reduce the complexity of the optimization function.

The other way of selecting the parameter that we chose for optimization is the accessibility to change the value of the parameter. In this paper, we are choosing the emitter resistances because they are connected to the common node of the battery supply. Figs. 4 and 5 illustrate the influence of resistor values on TPC and voltage swing at OP.

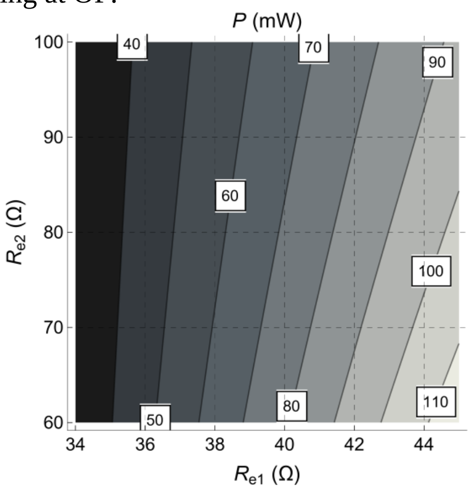


Fig. 4 – *Parametric plot of TPC in terms of the emitter resistances.*

Note that the numeric values of all other parameters and values should be represented by integer values treated as symbolic values in computer algebra systems.

Many other possibilities for using embedded knowledge of systems for deterministic or heuristic optimization with statistical inputs, such as financial engineering, are presented in [6].

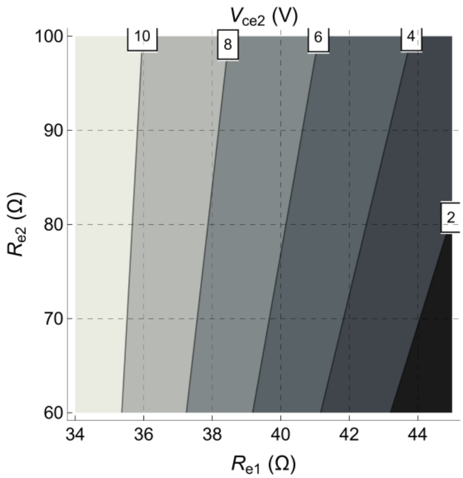


Fig. 5 – *Parametric plot of the output voltage at OP in terms of the emitter resistances.*

5 Symbolic Derivation of System Parameters

When the system parameters are derived as closed-form solutions in terms of the values of the constituent elements (values of resistors, capacitors, supply voltages, DC transistor parameters), other system parameters can be derived in the dynamic mode of operation, such as the gain in SSM and LSM, assuming that the mode of operation is linear, see Fig. 3.

Automatically deriving the gain in terms of all symbolic values is too complex, and even manually rewriting the final expression is difficult to achieve without errors. Fig. 6 shows the denominator of the derived gain expression as the `TreeForm`.

A visual check of the meaning of the expression without errors is possible by replacing all values as integers, symbolically simplifying the expression, and finally expressing it in a suitable form, such as a plot of the gain in terms of the frequency, see Fig. 7. By solving equations, we can efficiently compute 3dB gain edge frequencies ($f_{3\text{dB}} = 7.41548 \times 10^5$ and $f_{3\text{dB}} = 5.0265 \times 10^{11}$). The edge frequencies cannot be precisely calculated using numerical solvers.

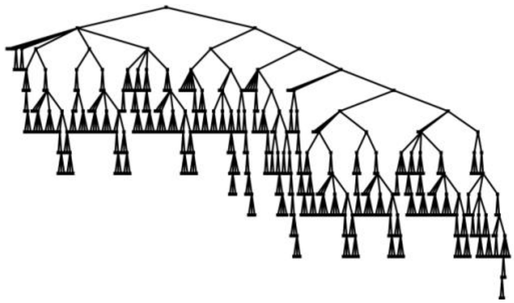


Fig. 6 – `TreeForm` *of the denominator of the gain in SSM.*

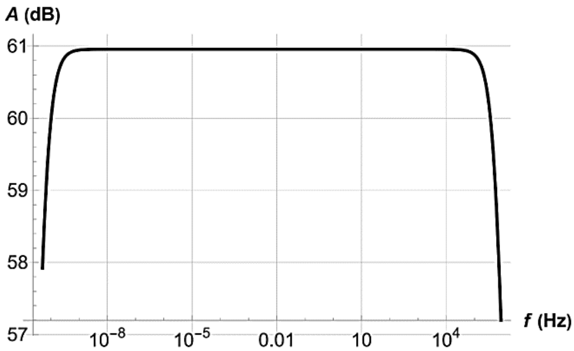


Fig. 7 – *Gain of the amplifier.*

In LSM, we would like to avoid clipping signal peaks caused by saturation and cutoff transistor regions. Therefore, a reduction of the gain is possible simultaneously with the optimization of TPC, see Fig. 8.

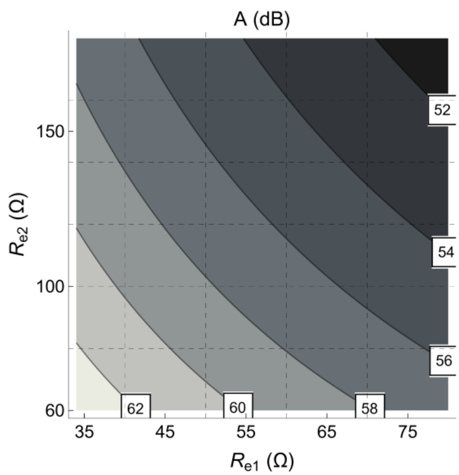


Fig. 8 – *Parametric plot of the gain in terms of the emitter resistances.*

6 Deep Learning Module

The derived knowledge of the electrical circuit can be incorporated as a separate module. Then, deep learning can optimize parameters such as reducing the TPC, increasing the output voltage swing depending on the correct choice of OP, or reducing the harmonic distortion by reducing the opamp gain. Optimization can be done by changing the value of the emitter resistance using the derived expression of TPC, OP position, or gain. Instead of a deterministic approach, we can use statistical knowledge like in financial engineering [6]. The control signal is the peak detector of the output voltage, as shown in Fig. 9.

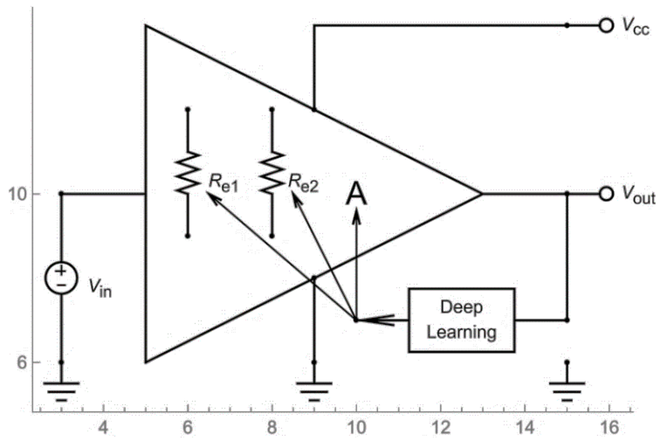


Fig. 9 – *Two-stage Optimization using DL amplifier.*

More details on stochastic process identification are presented in [7]. Numerical and symbolic processing in modern electronics was presented at a conference on energy efficiency [8]. Reduction of operations using fast calculation and simulation methods is shown in [9, 10]. The International Journal of Reasoning-based Intelligent Systems presents a design based on sub-circuits as parts of more complex systems [11]. Also, the textbook [12] presents basic knowledge about analog and digital systems transformations.

All derivations in this paper are performed using a symbolic processing platform based on the Wolfram language [13]. This proprietary software is accessible on the Raspberry Pi hardware platform and comes bundled with Raspbian (see [14 – 16]). Mathematica is a computer programming platform used in science, mathematics, computer science, and engineering and is generally used for coding university-level projects.

Once the effects of emitter resistance on TPC and output voltage are known, the control signal incorporates the knowledge of how to change the resistance to minimize dissipation and distortion.

Fig. 10 shows OP in terms of R_{e1} which can be used for determining the output voltage swing without distortion. For example, for R_{e1} = 39.5 Ω, the output voltage has approximately 6V amplitude for the sinusoidal input signal without distortion. Distortion occurs when the output voltage exceeds the supply voltage or tends to become negative between the cutoff and saturation regions. Therefore, the preferred solution is to use R_{e1} = 39 Ω or R_{e1} = 40 Ω.

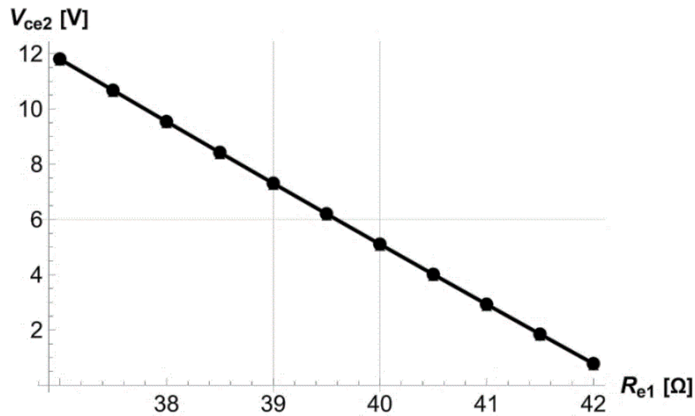


Fig. 10 – *Output voltage swing in terms of* R_{e1}.

Fig. 11 shows the collector current of the output stage OP in terms of R_{e1}. Notice that the output signal is without distortion for R_{e1} = 39 Ω and the sinusoidal input signal. Therefore, the preferred solution is to use R_{e1} = 39 Ω or R_{e1} = 40 Ω.

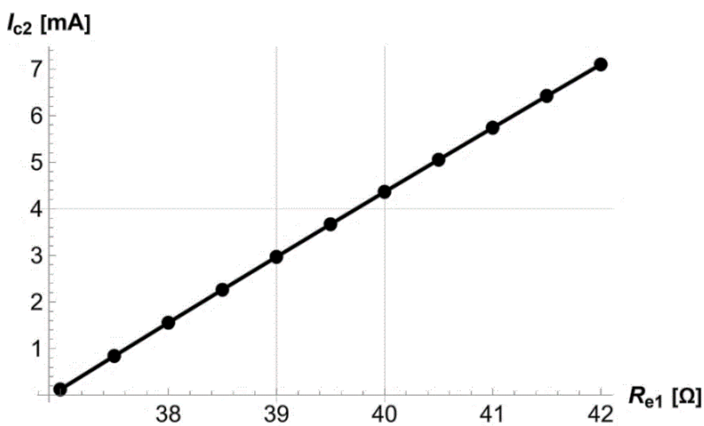


Fig. 11 – *Collector current of the output stage in terms of* R_{e1}.

Fig. 12 shows the TPC in terms of R_{e1}. For a maximal output voltage swing, that is, for R_{e1} = 39 Ω or R_{e1} = 40 Ω, the TPC is between 60 mW and 80 mW. If the output voltage swing is lower, we can move OP so that R_{e1} = 37 Ω with lower TPC.

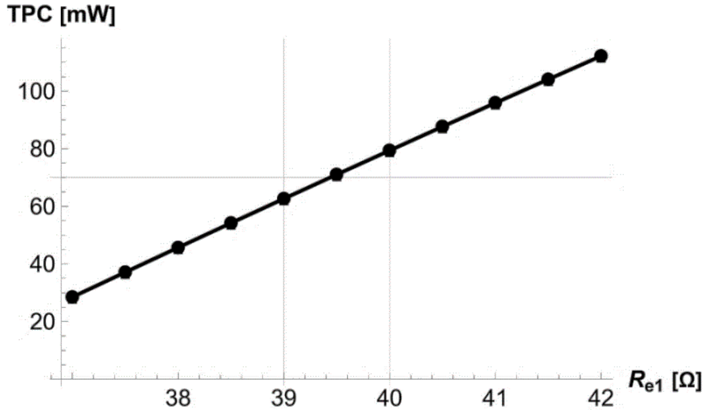


Fig. 12 – *TPC in terms of* R_{e1}.

Note that in the saturation region, V_{ce2} cannot be less than 0.2 V, and in that case, TPC = 90 mW and I_{c2} = 7.5 mA. This means that an OP close to the saturation region is not a good position for the OP.

Fig. 13 shows the OP in terms of R_{e1} that can be used for determining the output voltage swing without distortion. The smallest TPC is in the cutoff region when the collector current is also small, so the output voltage approaches the supply voltage. Therefore, we choose R_{e1} = 36 Ω for the smallest TPC when the input signal does not exist, say in amplifier hibernation.

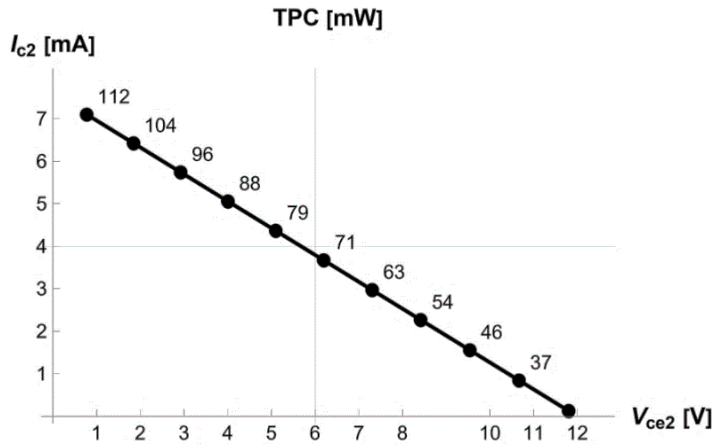


Fig. 13 – *Operating point on load line and TPC.*

Fig. 14 shows the changes in R_{e1} in different modes. For the largest output voltage fluctuation, switches S1 and S2 are open so that R_{e1} = 39 Ω. On the other hand, switches S1 and S2 are closed for hibernation mode, so R_{e1} = 36 Ω and the TPC is the smallest possible.

For low amplitude input signal, switch S1 will be open, and S2 will be closed, so R_{e1} = 37 Ω and TPC are smallest, and operation is without distortion. For a larger amplitude input signal, switch S1 will be closed, and S2 will be open, so R_{e1} = 38 Ω. While for a very large amplitude input signal, switches S1 and S2 will be open, so R_{e1} = 39 Ω.

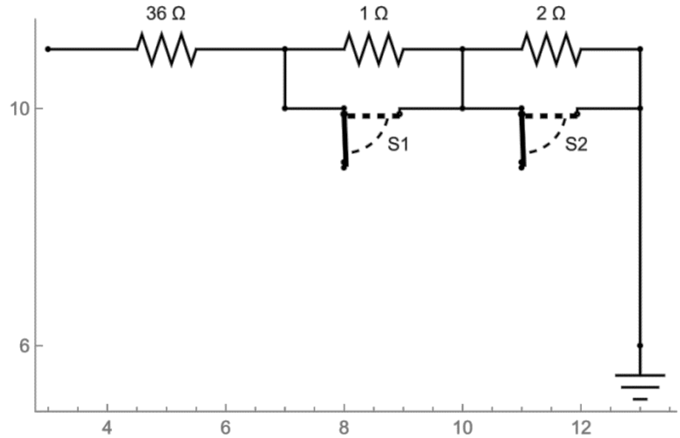


Fig. 14 – *Variable resistance of R_{e1}.*

For extremely high amplitude of the input signal, which will lead to cutting off the output signal and, therefore, distortion, the amplifier gain should be reduced using a peak detector, as shown in Fig. 15.

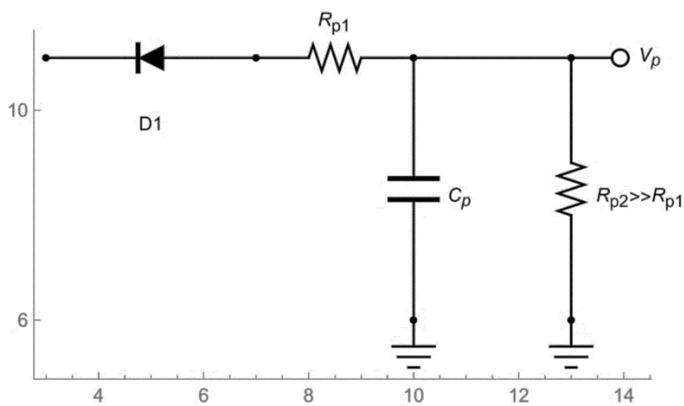
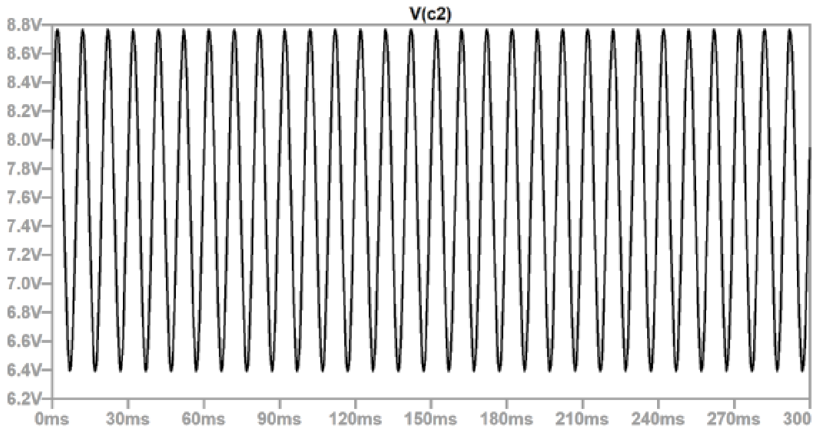


Fig. 15 – *Peak detector.*

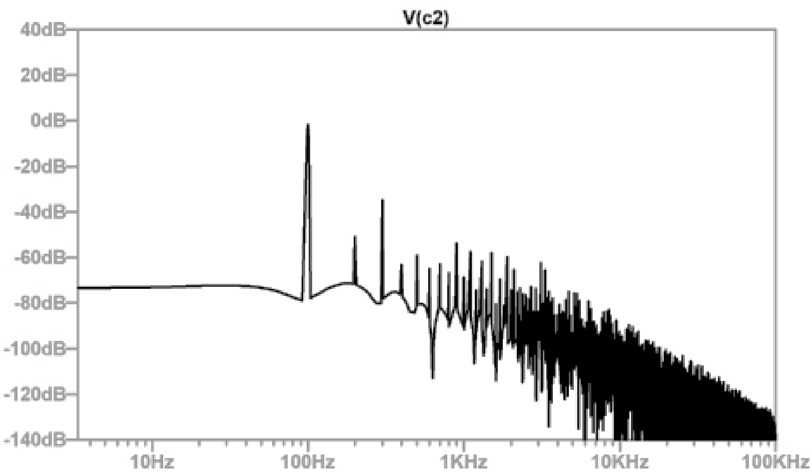
7 Tests with Numeric Software

Once the solution is complete, we can test the circuit with professional numerical software such as SPICE [16]. This software uses transistor models with actual manufacturing properties.

The Fast Fourier Transform (FFT) of the output signal for R_{e1} = 40 Ω shows little distortion, with the third harmonic being 30 dB below the primary signal, see Figs. 16 and 17.

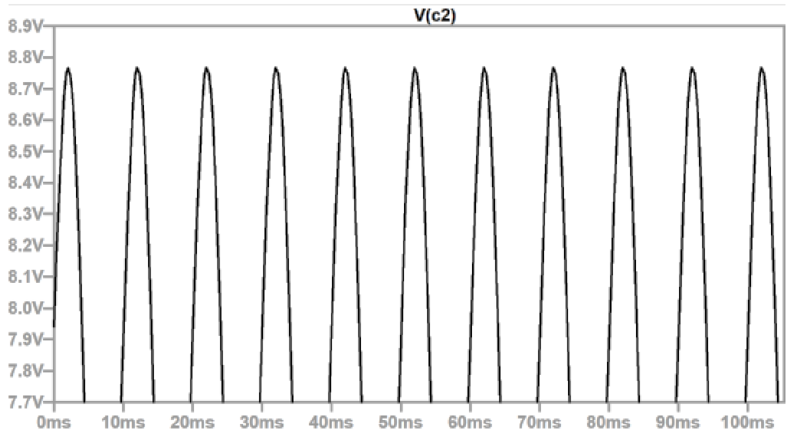


(a)

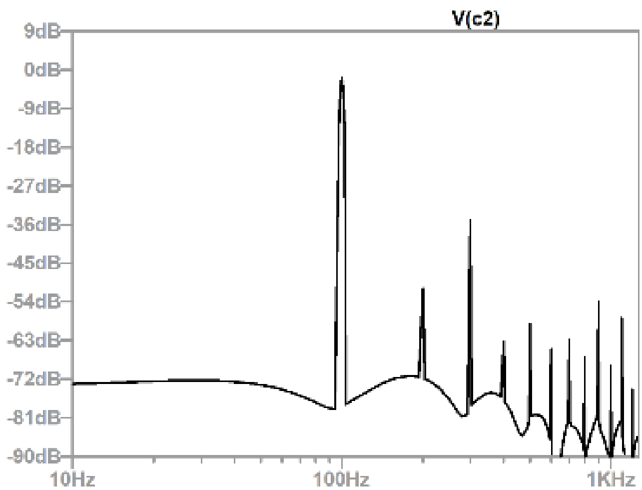


(b)

Fig. 16 – *Full sinusoidal response for R_{e1}= 40 Ω:*
(a) *time response;* (b) *frequency response.*



(a)



(b)

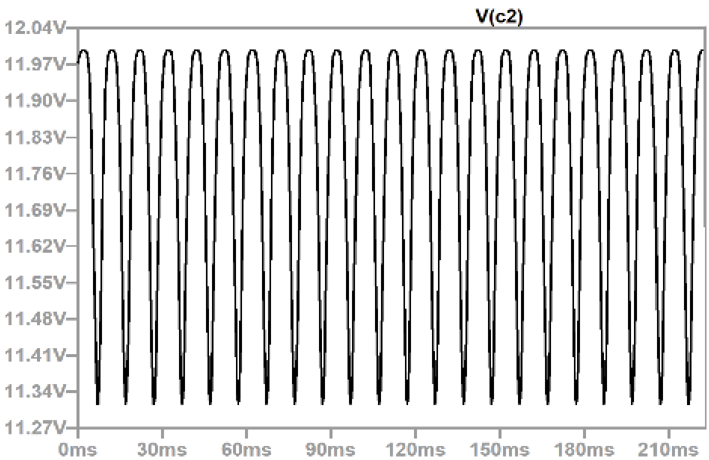
Fig. 17 – *Enlarged sinusoidal response for R_{e1} = 40 Ω:*
(a) *time response;* (b) *frequency response.*

The Fast Fourier Transform (FFT) of the output signal for R_{e1} = 36 Ω shows large distortion, with the second harmonic being 6 dB below the primary signal, see Figs. 18 and 19.

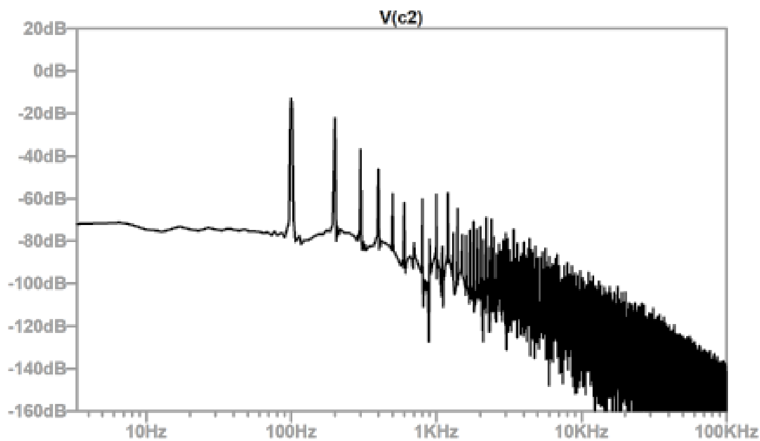
The main reason for the large distortion is that for R_{e1} = 36 Ω, OP is close to the cutoff region. As a result, the amplitude of the maximal sinusoidal output signal is smaller than the minimal sinusoidal output signal.

Using the peak detector on the output signal concerning OP will show that OP should be shifted to OP by R_{e1} = 39 Ω. The statistical properties of the input signal can be used to identify when appropriate emitter resistances should be used.

Deep learning can be used to change resistor values and thereby optimize dissipation depending on the input signal. Using knowledge of the probability of the input signal and the peak-to-peak voltage value of the expected output signal in linear mode operation, in advance it can be used to optimally select resistor values to minimize dissipation and distortion.

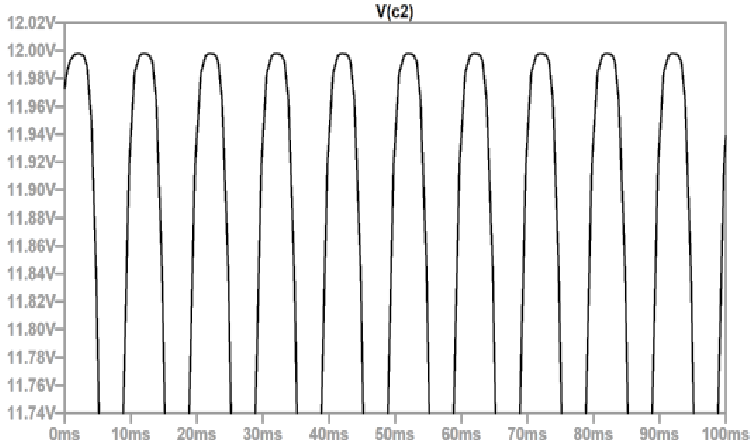


(a)

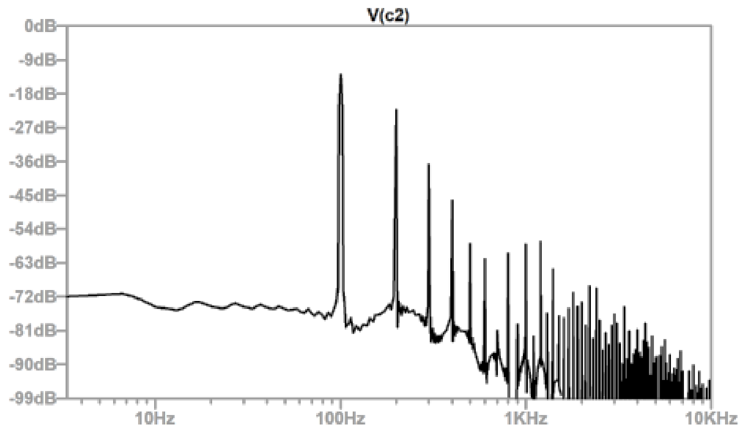


(b)

Fig. 18 – *Full sinusoidal response for* R_{e1}= *36 Ω:*
(a) *time response;* (b) *frequency response.*



(a)



(b)

Fig. 19 – *Enlarged sinusoidal response for* R_{e1} = 36 Ω*:*
(a) *time response;* (b) *frequency response.*

7 Conclusion

Classical electrical engineering education and training rely on manual demonstrations, experiments, and mathematics. The design is so complex that it is tough to evaluate the optimization of several parameters (dissipation, distortion) concerning the constituent elements. This is more complex if we add a deep learning module to minimize dissipation and distortion when the input signal changes over time. The entire process is automated and starts with an initial circuit description.

8 References

[1] D. R. Patrick, S. W. Fardo: Electricity and Electronics Fundamentals, 2nd Edition, River Publishers, London, New York, 2008.

[2] M. D. Lutovac, D. V. Tošić: SchematicSolver - Symbolic Signal Processing, Version 2.3, LMAAM, Belgrade, 2014.

[3] M. Lutovac-Banduka, D. Milosevic, Y. Cen, A. Kar, V. Mladenovic: Graphical User Interface for Design, Analysis, Validation, and Reporting of Continuous-Time Systems Using Wolfram Language, Journal of Circuits, Systems, and Computers, Vol. 32, No. 14, April 2023, pp. 1 – 14.

[4] M. Lutovac: The Design of Analog and Digital Filters using Computer Algebra Systems, Academic Mind, Belgrade, 2011. (in Serbian)

[5] M. M. Lutovac, V. Pavlovic, M. D. Lutovac: Automated Knowledge Based Filter Synthesis Using Gegenbauer Approximation and Optimization of Pole-Q Factors, Elektronika Ir Elektrotechnika, Vol. 19, No. 9, October 2013, pp. 97 – 100.

[6] V. Mladenović, M. Lutovac: Symbolic Processing for System Development using Computer Algebra, Faculty of Technical Sciences Čačak, Čačak, 2020. (in Serbian)

[7] V. Mladenović, M. Lutovac, D. Debeljković: Stochastic Process Identification – part 1, Faculty of Technical Sciences Čačak, Čačak, 2016. (in Serbian)

[8] M. Lutovac, V. Mladenovic: Contemporary Electronics with LTSpice and Mathematica, Proceedings of the International Scientific Conference of IT and Business-Related Research, Belgrade, Serbia, April 2015, pp. 134 – 138.

[9] V. Mladenović, D. Milosevic, M. Lutovac: An Operation – Reduced Calculation Method for Solving Complex Communication Systems, Studies in Informatics and Control, Vol. 26, No. 2, June 2017, pp. 213 – 218.

[10] V. Mladenović, D. Milosevic, M. Lutovac, Y. Cen, M. Debevc: An Operation Reduction Using Fast Computation of an Iteration-Based Simulation Method with Microsimulation-Semi-Symbolic Analysis, Entropy, Vol. 20, No. 1, January 2018, p. 62.

[11] Lj. D. Milić, M. D. Lutovac, J. D. Ćertić: Design of First–Order Differentiator Utilising FIR and IIR Sub-Filters, International Journal of Reasoning-based Intelligent Systems, Vol. 5, No. 1, July 2013, pp. 45 – 48.

[12] M. D. Lutovac, D. V. Tošić, B. L. Evans: Filter Design for Signal Processing Using MATLAB and Mathematica, Publishing House of Electronics Industry, Beijing, 2006.

[13] S. Wolfram: An Elementary Introduction to the Wolfram Language, 2nd Edition, Wolfram Media, Champaign, 2017.

[14] S. Wolfram: Wolfram Language & Mathematica Free on Every Raspberry Pi!, 2022, Available at: https://www.wolfram.com/raspberry-pi/

[15] P. Harney: New Wolfram Mathematica Free Resources for your Raspberry Pi, 2019, Available at: https://www.raspberrypi.org/blog/new-wolfram-mathematica-resources-2019/

[16] G. Halfacree: The Official Raspberry Pi Beginner's Guide, Updated for Raspberry Pi 400, 1st Edition, Raspberry Pi Trading Ltd, Cambridge, 2020.