In: Progress in Education. Volume 37
Editor: Roberta V. Nata
ISBN: 978-1-63483-337-0

Chapter 7

TEACHING CONTROL SYSTEMS IN ELECTRICAL ENGINEERING EDUCATION PROGRAMS

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ABSTRACT

The Control Systems is a course taught in Engineering Education programs all over the world. The knowledge transmitted to engineering students is important for their future understanding of other topics as well as for their practical and research activities as graduates.

In Control Systems courses, many authors analyze different kind of systems: electrical, mechanical, chemical, etc. Many of these concepts are drawn from very complex systems that most of the students are not likely to encounter in their daily activities. For instance, very few of them are going to have to design the trajectory of a spacecraft that flies in the cosmos. Nor do they need to design the controller to correct the trajectory of a boat in the middle of the ocean. The majority of them will end up working on industry applications. They need to understand how these installations work, how to diagnose and control them. For this reason, undergraduate students need to encounter in the universities' laboratories "hands-on" experimental applications to be capable of measuring different characteristics, to see "with their own eyes" the effect of changing one variable of the system and to design a controller for that system. Furthermore, they need to measure the effect of certain parameter variation in influencing the stability state of the system and what does it mean that a system is unstable.

This chapter presents a "hands-on" approach of the Control System course. This is focused on practical implementations of systems and controllers. The described method brings to the readers' attention a method to design applicable systems and mathematical representations in order to have a better understanding of the concepts.

This reader of this chapter needs previous knowledge of Operational Amplifiers and Electric Circuits. The author also assumes the readers understand basic concepts of Control System theory: transfer function, system stability, root locus graphs, etc.

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ABBREVIATIONS

OA – operational amplifier
DC – direct current
AC – alternative current
DIY – do it yourself

1. INTRODUCTION

The Control System course develops necessary competencies for present day engineers.

In order to analyze one system, a specialist needs to know and understand how it is represented. This means the use of the mathematical apparatus that describes its behavior, the block schematic representation and analysis, stability and the required means necessary to change the systems' response to different input signals. In order to be able to analyze and design an autonomous controlled system, students need to have had previous similar experience and practice in a safe environment. Once basic principles are mastered, one can move on to a higher level of competences.

This chapter introduces such a safe environment where students can learn and "make mistakes" without the fear of spoiling expensive equipment. The cost of this method is in the reach of anyone. Thus, this method can be implemented as "do it yourself"[1] experiments.

2. THE ACTUAL AND PROPOSED METHOD

Most of the present-day manuals and practices are based on mathematical representation (in different methods), block schematic representations and usually MATLAB[1] (or equivalent software) simulations.

Computer simulation is a very powerful tool available to educators, scientists, teachers, researchers, engineers, etc. It allows making analysis and studies before a system is released into production. Thus, many behaviors can be checked, analyzed and corrected in the prototype stage of system development. However, for students, is crucial to be able to make connections between theoretical concepts and "real life" experiments. The current practice of studying engineering fields is to do experiments in educational laboratories. There is the perfect environment to see the link between theory and practice.

Many textbooks contain quite complicate examples of applications like:

- Spacecraft
- Ocean boat
- Nuclear reactor

[1] MATLAB is a registered trademark of The Mathworks, Inc., 3 Apple Hill Drive, Natick MA 01760-2098.

- Satellite
- Etc.

These are very good to understand the importance of the course. It is obvious that any of the mentioned examples relay on automated behavior control and correction. However, these applications cannot be replicated in laboratory conditions in the vast majority of Universities. This leads to “simulation only” laboratory practices.

This chapter presents a different approach to “simulation only” Control System laboratory. The use of cheap electronic implementations for the mathematical and symbolical representations for systems, complex notion (stability, controller design, etc.) is brought into the reach of many laboratories or even as “do it yourself” practice.

Recently, hobbyists around the world have access to cheap and easy to use solutions for programmable devices, which can provide facile ways to generate signals of various waveforms. Furthermore, these systems can be easily used for data acquisition. The method covered in this chapter combined with programmable devices leads to integrate and complete solutions for system analysis.

3. The Necessary Tools

Covering the proposed applications in this chapter requires the use of several software and hardware tools:

- *System simulators.* MATLAB is widely used both in research, education and engineering communities. However, there are free equivalent tools that can be used without the concern of a commercial license, like SCILAB, Octave, etc. [16].
- *Electronic simulators.* Many companies and groups offer electronic simulators. In this chapter, simulations were performed using TinaTi from Texas Instruments [2].
- *Electronic boards.* The applications in this chapter are based on a Texas Instruments’ electronic board displayed in Figure 1.

4. Electronic Implementation of Mathematical Operations

The block schematic is a symbolic representation of mathematical equations that describe a systems’ behavior. A block schematic indicates the signal flow between the systems’ elements. The electronic implementation of block schematic contains schematics that are able to process their input signal similar to corresponding mathematical operation. This can be done using Operational Amplifiers (OA) networks. The following figures displays few basic structures used in this chapter:

FoK theory describes how teachers can draw upon their minoritized students' strengths, knowledge and skills from their life experience, to support academic learning. Making connections to students' life experience has powerful potential to enhance school-based learning, through making academic concepts more accessible, enhancing the relevance of academic learning, and validating the experience, skills, and values of diverse students and their families.

This chapter provides a literature review of pedagogical applications of FoK theory, building on Gloria Rodriguez's in-depth analysis of pedagogical applications of FoK theory. Rodriguez sorted teachers' professional practice into three categories, depending on the rationale for the instructional strategies utilized. Applications in different categories differed in frequency and depth of connections made to students' and their families' FoK, and whether the learning was conducted in, or related to, real community settings. Rodriguez's themes are further elaborated and linked to various pedagogical applications in this chapter.

Unlike Rodriguez's review of teachers' pedagogical reasoning, this review focuses on what teachers have done – what pedagogical decisions and actions they have taken to deliberately apply the FoK concept in their professional practice. For the purposes of this review, the guiding research question was: How do different pedagogical applications in schools connect to FoK? In this examination of classroom applications of FoK theory, findings reveal that teachers' pedagogical applications of FoK theory can be sorted to reveal further themes which can advance knowledge in the field, illuminating possible approaches to the work that teachers could take. Themes relate to whether the pedagogical approach draws out or draws on FoK, and whose FoK is central.

This analysis of pedagogical applications of FoK theory may support teachers and teacher educators, in their efforts to identify ethical approaches to schooling for minoritized students, to work towards social justice aims.

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This chapter presents a "hands-on" approach of the Control System course. This is focused on practical implementations of systems and controllers. The described method brings to the readers' attention a method to design applicable systems and mathematical representations in order to have a better understanding of the concepts.

Figure 1. Electronic board.

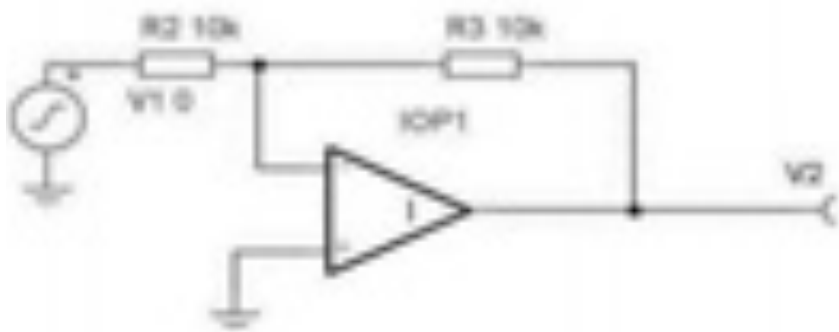

Figure 2. Inverting structure.

- Inverting structure

$$V_2 = -\frac{R_3}{R_2} V_1 \tag{1}$$

- Non-inverting structure

$$V_2 = \left(1 + \frac{R_3}{R_2}\right) V_1 \tag{2}$$

- Voltage follower structure

$$V_2 = V_1 \tag{3}$$

- Summation structure

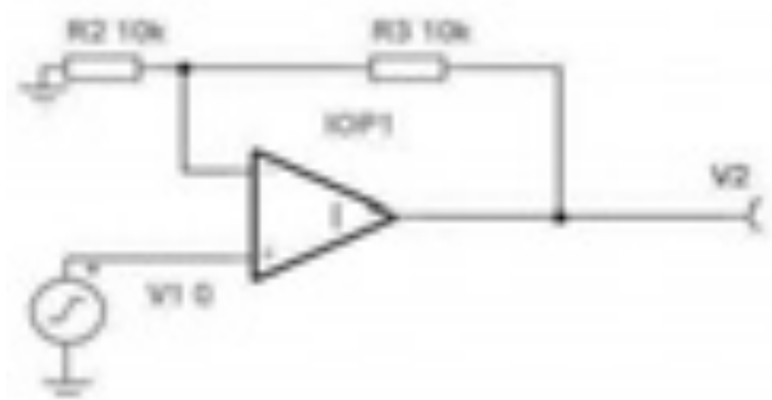

Figure 3. Non-inverting structure.

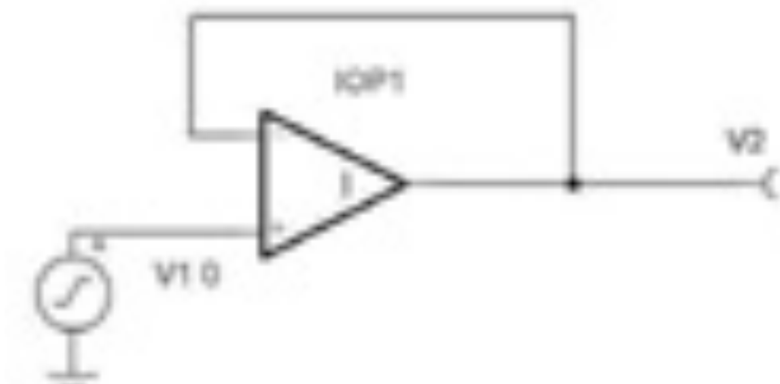

Figure 4. Voltage follower.

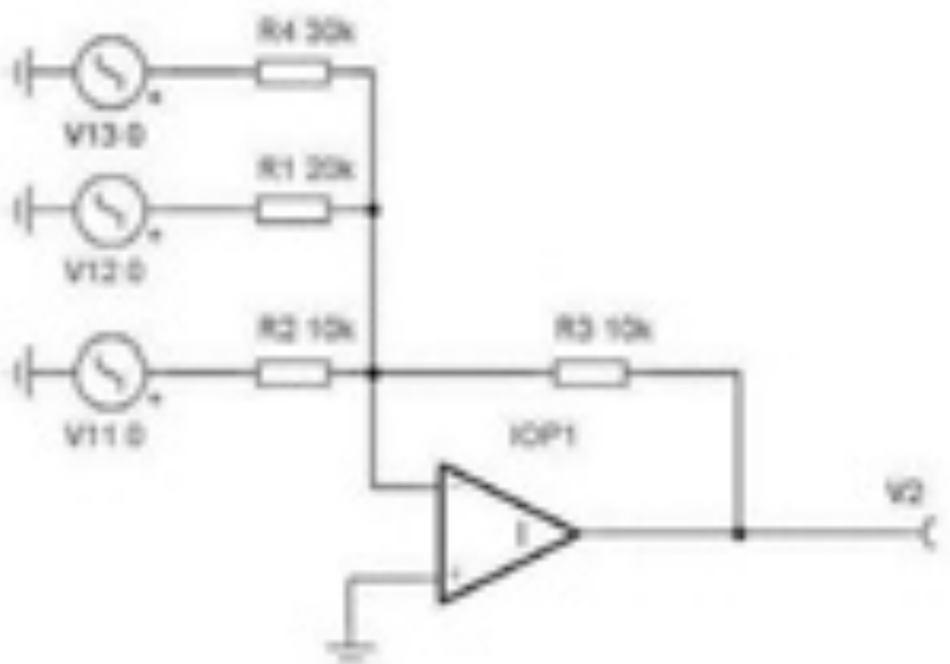

Figure 5. Summator.

$$V_2 = -\left(\frac{R_3}{R_2}V_{11} + \frac{R_3}{R_1}V_{12} + \frac{R_3}{R_4}V_{13}\right) \tag{4}$$

- Difference structure

$$V_2 = \frac{R_4}{R_2}\left(\frac{R_2+R_3}{R_1+R_4}\right)V_1 - \frac{R_3}{R_2}V_2 \tag{5}$$

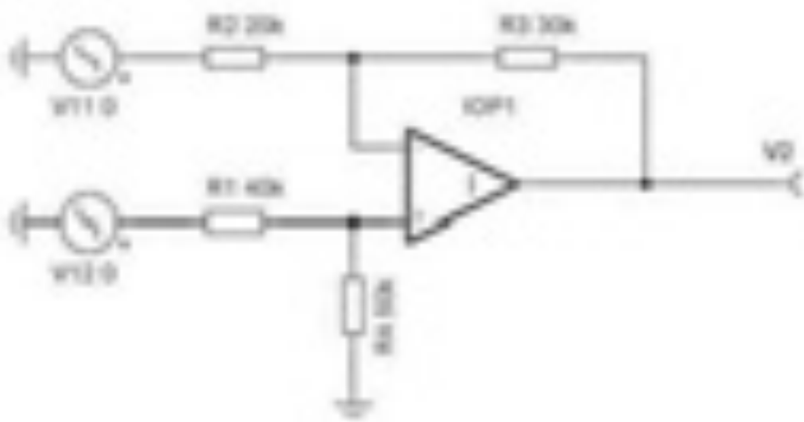

Figure 6. Differentiator.

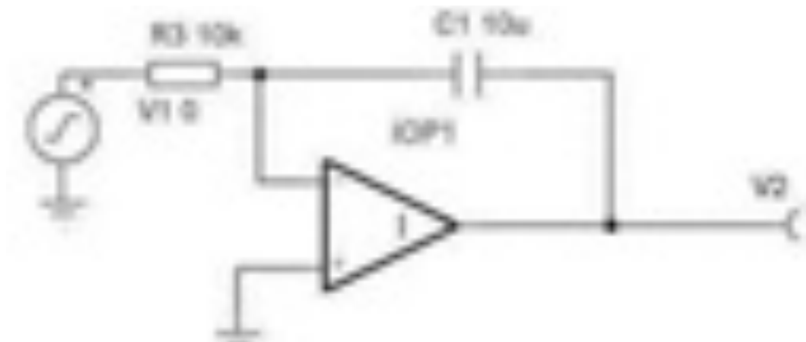

Figure 7. Integrator.

- Integration structure

$$V_2 = -\frac{1}{sC_1R_3}V_1 \tag{6}$$

$$V_2 = -\frac{R_1}{R_3}\frac{1}{sC_1R_1+1}V_1 \tag{7}$$

- Derivation structure

$$V_2 = -sC_1R_3V_1 \tag{8}$$

There are certain standard signals used in system analysis. They can be generated either by electronic hardware or by programmable systems.

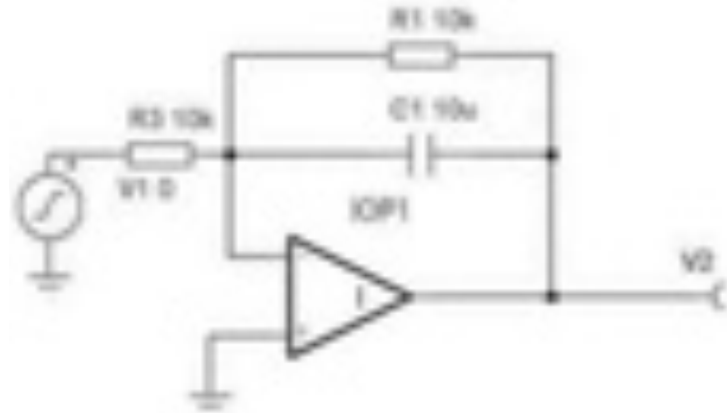

Figure 8. Integrator with resistance feed-back.

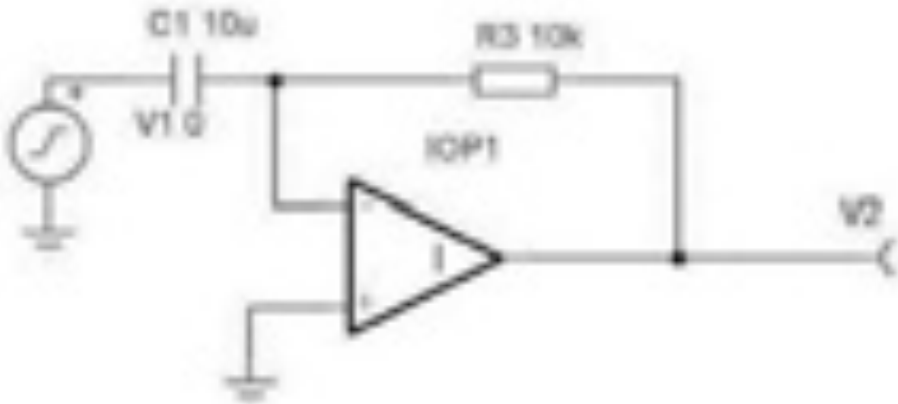

Figure 9. Derivator.

5. Hands-on Examples

"Hands-on" refers to experiments that can be done with available real components following certain instructions [3]. Combining this method with signal generation and data acquisition it can be observed the behavior of the analyzed system.

5.1. First-Order Systems

A first-order system's general transfer function is indicated in equation (9):

$$G_1(s) = \frac{1}{sT+1} \tag{9}$$

As an example, it is considered a random first-order system, whose transfer function is displayed in Figure 10 and is indicated in equation (10):

$$G_1(s) = \frac{1}{s+1.5} \tag{10}$$

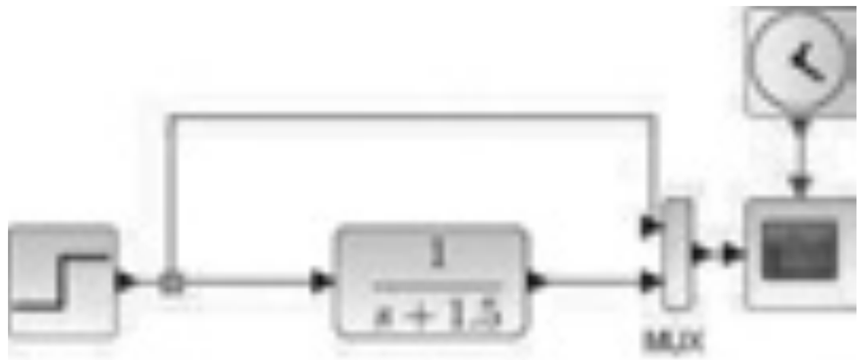

Figure 10. First-order system.

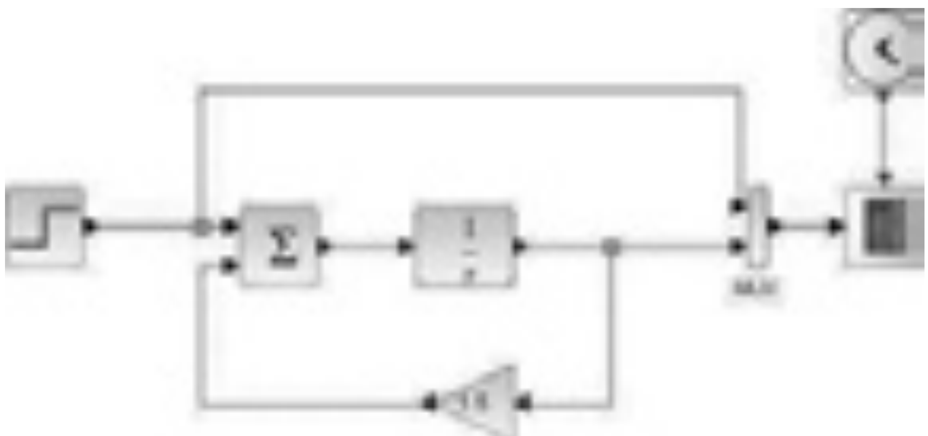

Figure 11. First-order system with feedback path.

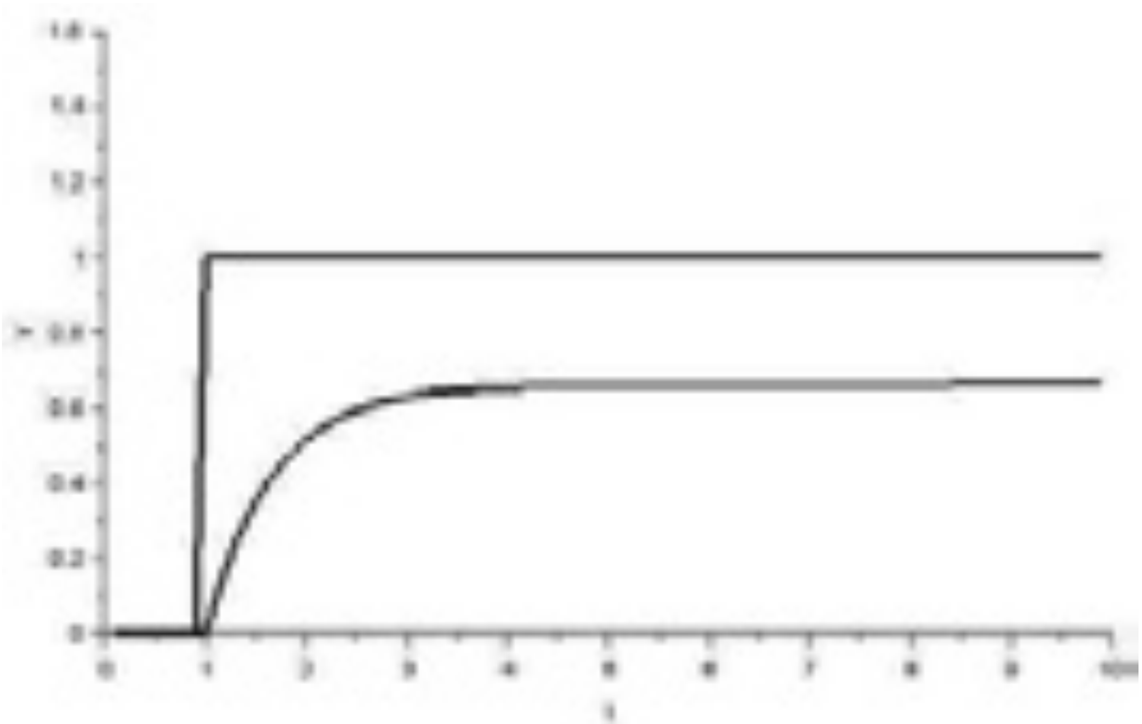

Figure 12. Step response of the first-order system.

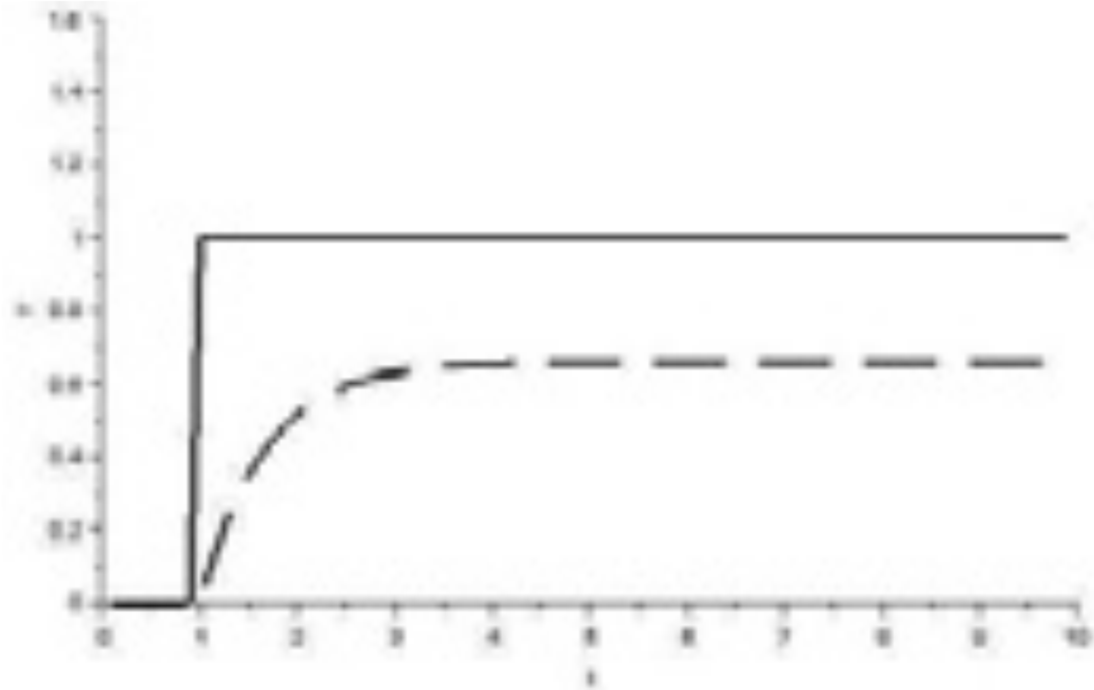

Figure 13. Step response of the first-order system with feedback path.

The block schematic representation of the system is implemented using SCILAB[2] software and is displayed in Figure 10. The transitory response of the considered system is indicated in Figure 11. Direct and inverse Laplace's transformation applied to equation (10) leads to the time variable function that expresses the systems' transient and steady-state behavior. This demonstration is not included in this chapter. The references indicate detailed information about this mathematical demonstration.

In order to implement the considered system with OA networks, its' transfer function has to be expanded as in equation (11):

$$G_1(s) = \frac{1}{s+1.5} = \frac{\frac{1}{s}}{1+\frac{1}{s}1.5} \tag{11}$$

The expression (11) indicates an implementation of the system in which it is included a feedback loop, whose transfer function is the constant 1.5. This form of the system block diagram, displayed in Figure 11, makes easier its electronic implementation. In this representation, the integration operation becomes the transfer function of the feed-forward path.

Figure 12 and Figure 13 displays the time response of the same system with a step impulse as the input signal.

Both representations of the first-order system are displayed in Figure 10 and Figure 11 are presented together in Figure 14. The analysis of Figure 15 leads to the conclusion that both representations are equivalent as far as their behavior for the same input signal, which in this case is a step signal.

[2] http://www.scilab.org/scilab/about.

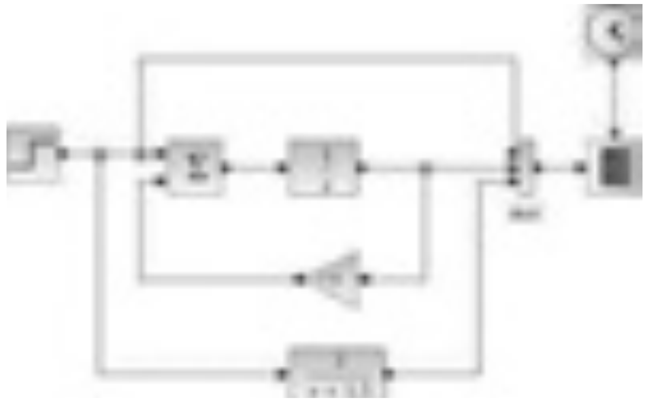

Figure 14. First-order system with and without feedback path.

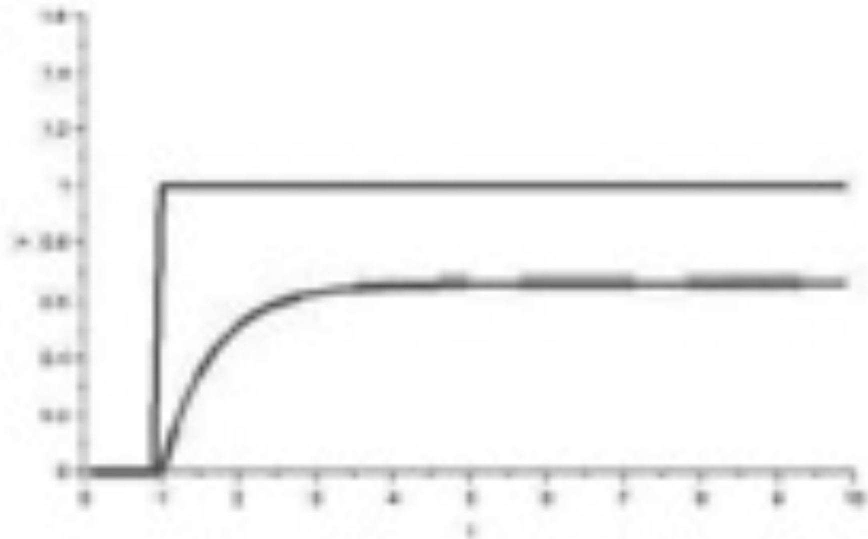

Figure 15. Step response of first-order system.

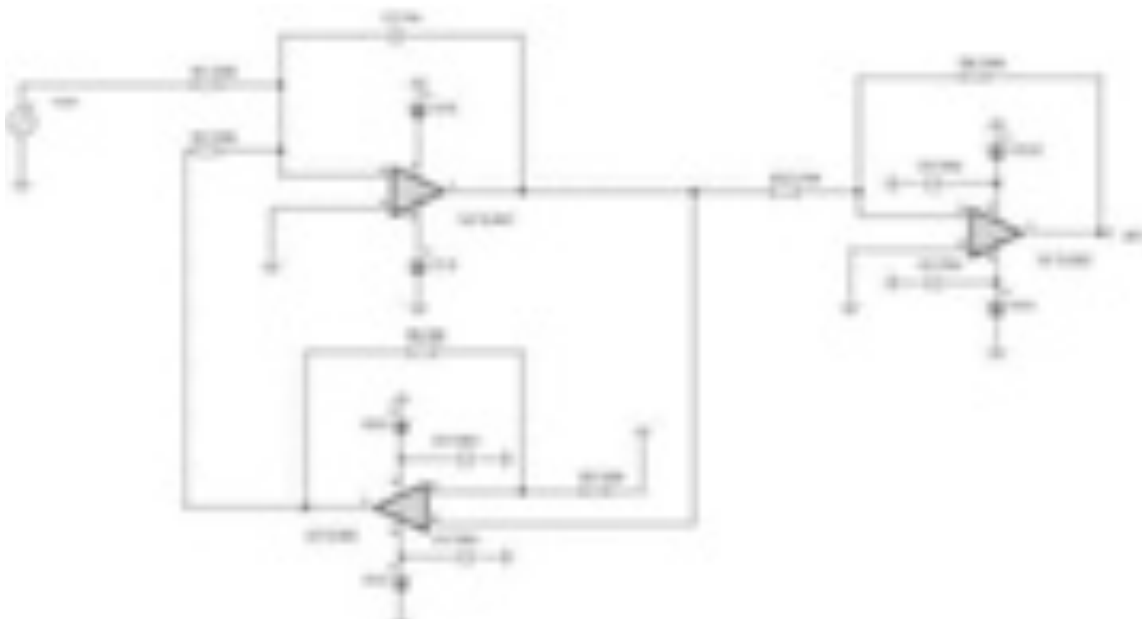

Figure 16. OA implementation of the first-order system.

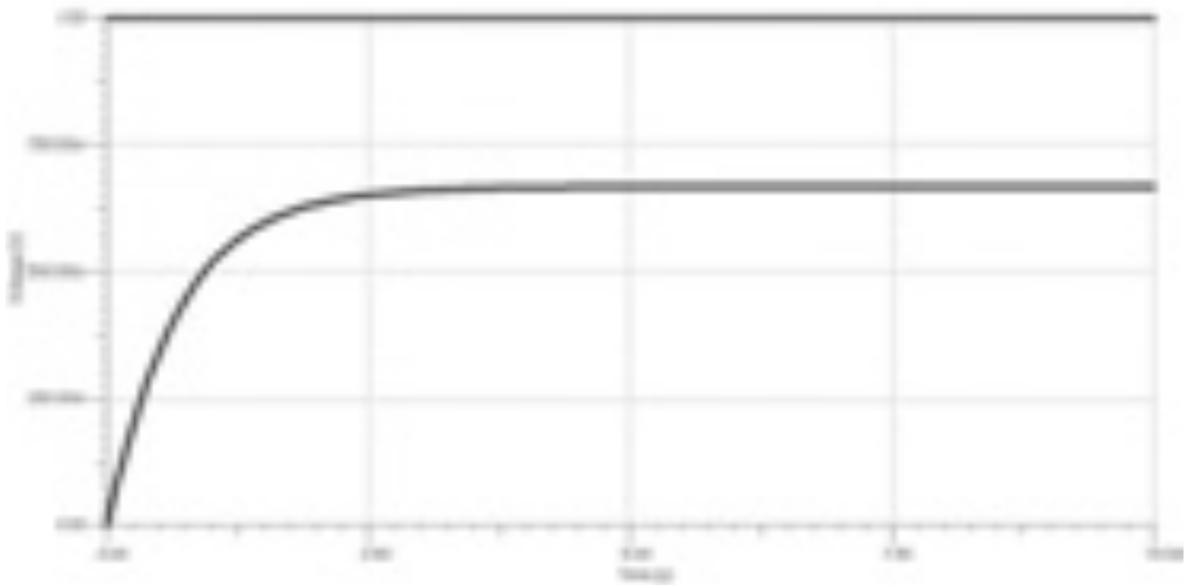

Figure 17. Step response of the OA implementation of the first-order system.

Once the first-order system displayed in Figure 10 is implemented with the equivalent representation of Figure 14, it can be developed its' implementation using OA configurations.

Figure 16 displays the implementation of the first-order system with OA. The U2 circuit implements both the integration (Figure 7) and the summation (Figure 5) operations. The capacitor connected to the feedback loop of the U2, ensures the implementation of the integration operations. The transfer function that this configuration implements is indicated equation (12):

$$G_{U2\_integration}(s) = \frac{\frac{1}{sC_3}}{R_1} = \frac{1}{sC_3R_1} = \frac{1}{s\cdot 10\cdot 10^{-6}\cdot 100\cdot 10^{3}} = \frac{1}{s} \tag{12}$$

The U3 circuit is connected as a non-inverting structure (Figure 3) because it needs to ensure the multiplication by 1.5. As this value is greater than 1, it can be implemented easier with this configuration then with others. In order to obtain the same sign for the output as for the excitation signal, it is necessary to use the inverting (Figure 2) structure built with U1. The graph displayed in Figure 17 indicates the fact that the evolution of the first-order system is similar regardless the implementation solution (Figure 10, Figure 11 and Figure 16).

In conclusion, the configuration displayed in Figure 16 behaves as a first-order system described by the transfer function of the equation (10).

5.2. Second-Order Systems

Second-order systems are defined by transfer functions expressed in equation (13):

$$G(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} = \frac{\omega_n^2}{s\cdot(s+2\zeta\omega_n)+\omega_n^2} \tag{13}$$

Where:

ω_n – natural pulsation
ζ – amortization factor

In order to obtain an electronic implementation, it is considered the second-order system displayed in Figure 18. In this example $\omega_n = 3$and $\zeta = 0.3$. The numeric values of the natural pulsation and the amortization factor leads to the transient response of the system for a step excitation impulse displayed in Figure 20.

Figure 18. Second-order system.

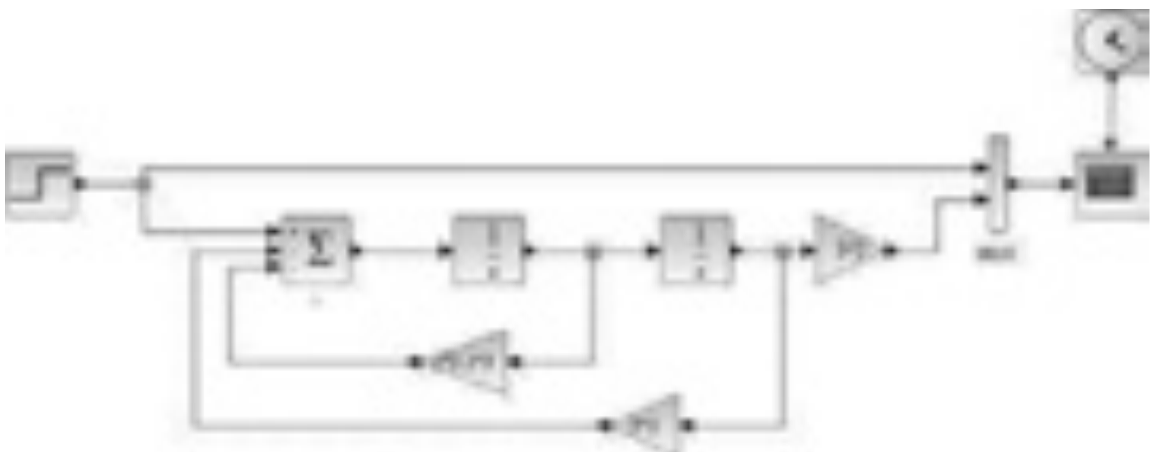

Figure 19. Second-order system with nested loops.

Figure 19 displays an equivalent representation of the system arranged so that the feed-forward path includes the integration and constant multiplication operations. The simulation of this representation indicated in Figure 21 is similar to Figure 20. Both representations indicate the presence of an overshoot and a period of amortization.

Figure 22 displays both representations of the second order system. The transient behavior is indicated in Figure 23.

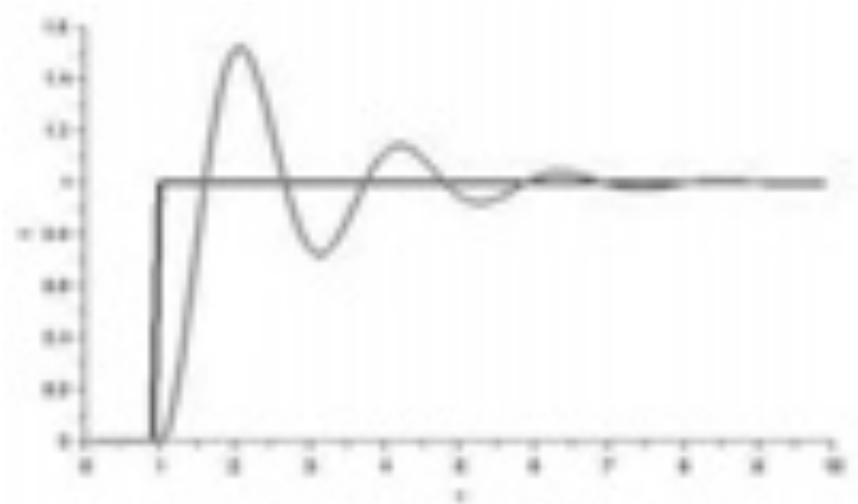

Figure 20. Transitory response of the second-order system.

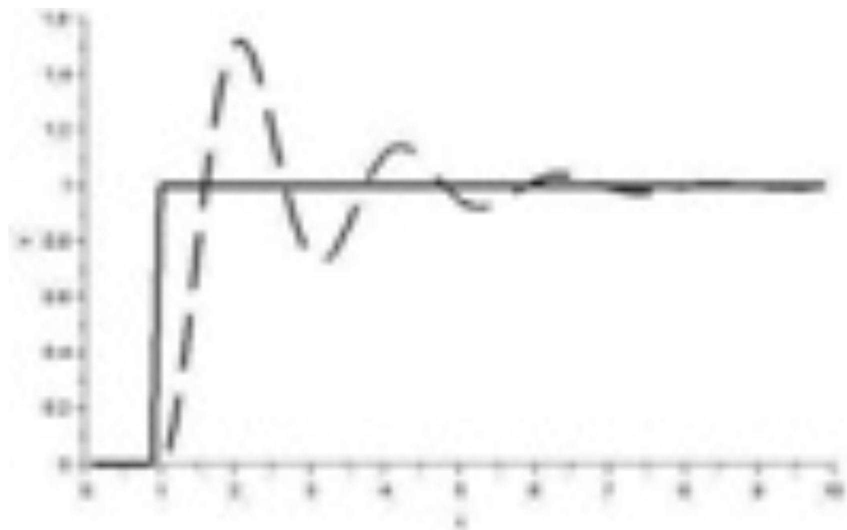

Figure 21. Transitory response of the second-order system with nested loops.

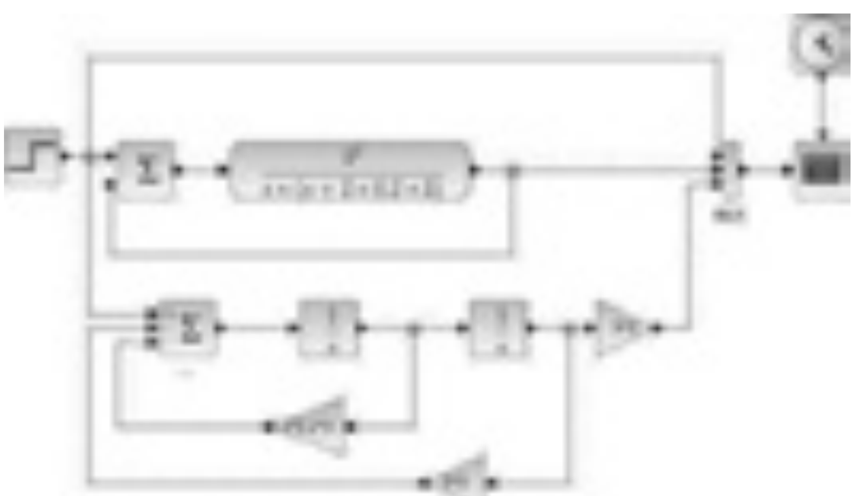

Figure 22. Second-order system with and without nested loops.

This reader of this chapter needs previous knowledge of Operational Amplifiers and Electric Circuits. The author also assumes the readers understand basic concepts of Control System theory: transfer function, system stability, root locus graphs, etc.

Chapter 8 - In this empirical investigation, the authors analyzed the relationship between school district wealth and instructional expenditures over a 5-year period for Texas school districts. School districts were divided into 4 quartiles of school wealth, with quartile 1 being the poorest school districts with respect to school wealth and with quartile 4 being the richest school districts, again with respect to school wealth. Statistically significant differences were revealed for all 5 school years, with the quartile having the lowest average instructional expenditures ratio being the upper quartile. Also present in the results was a consistent trend for the instructional expenditures ratio to decrease from the second through fourth quartiles. Districts in the largest wealth quartile consistently had lower instructional expenditures ratios than districts in the other 3 quartiles. Effect sizes were moderate for 4 of the 5 years, and small for the most recent year. With the exception of the wealthy school districts, it is possible that the overall total amount of instructional expenditure, rather than a ratio of the total amount, may make a bigger difference in student achievement. Implications of the author's findings and suggestions for future research are provided.

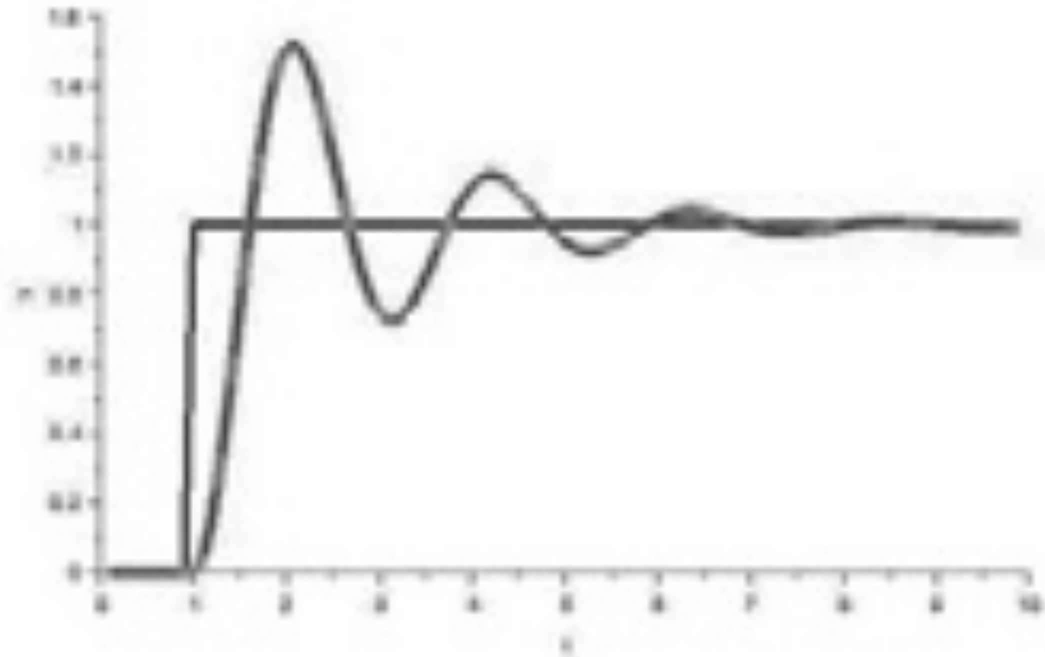

Figure 23. Transient response of the second-order system.

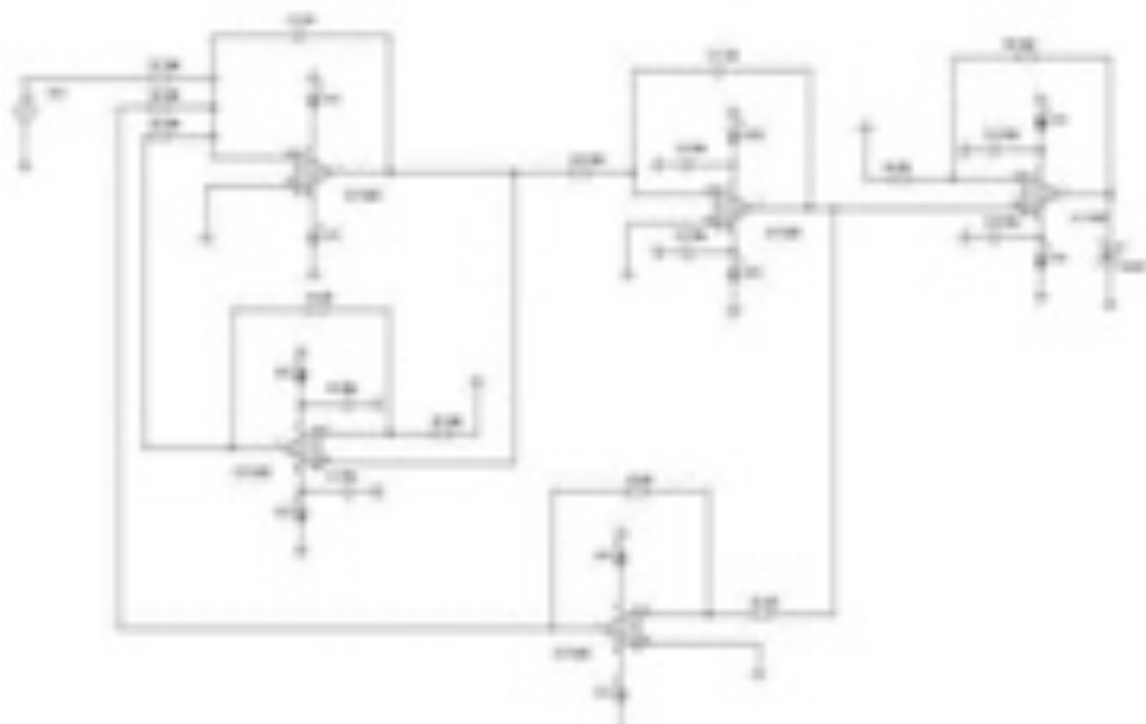

Figure 24. Second-order system OA implementation.

Using the same procedure as for the 1st order system, Figure 24 displays the electronic implementation of the 2nd order system. The nested loops are constructed with different OA configurations. Thus, the inner loop contains a non-inverting structure (U3) (Figure 3) while the outer loop contains an inverting structure (U4) (Figure 2). This is due to the different signal sign they need to return at the summing point implemented by U2 circuit. The response of this configuration, displayed in Figure 25 proves the equivalence between block representation of the 2nd order system (Figure 18, Figure 19 and Figure 22) and the OA network (Figure 24).

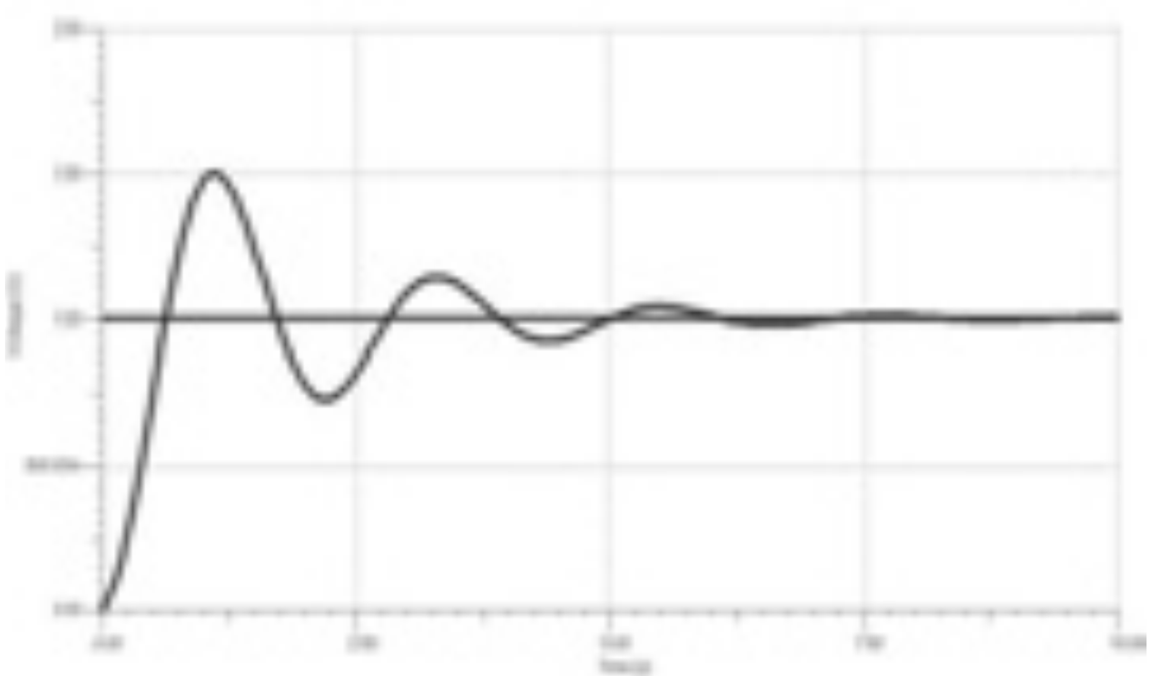

Figure 25. Second-order system transient response.

5.3. Higher-Order Systems

The same procedure applies for higher-order systems. For these systems, there is no general expression of its transfer function as is the case of 1st and 2nd order systems.

For the electronic implementation, similar steps are used with 3rd order systems as displayed in Figure 26 and Figure 27. The transient responses of this system are indicated in Figure 28 and Figure 29.

Figure 26. Third-order system.

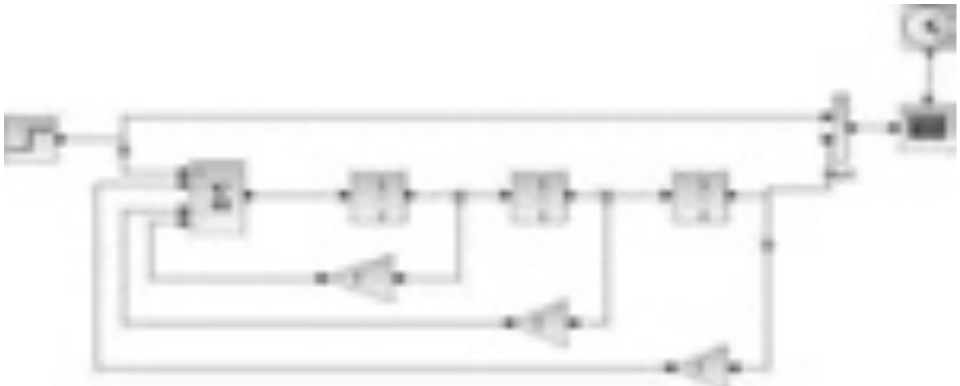

Figure 27. Third-order system with nested loops.

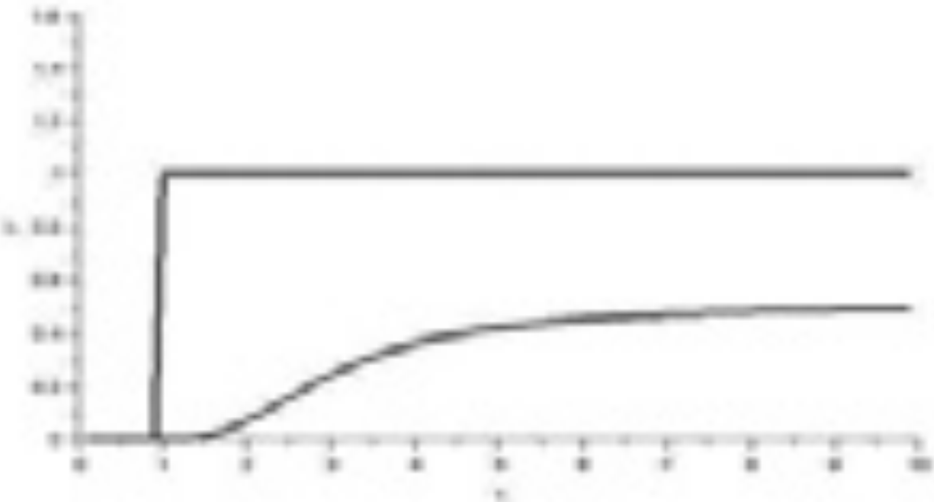

Figure 28. Transient response of third-order system.

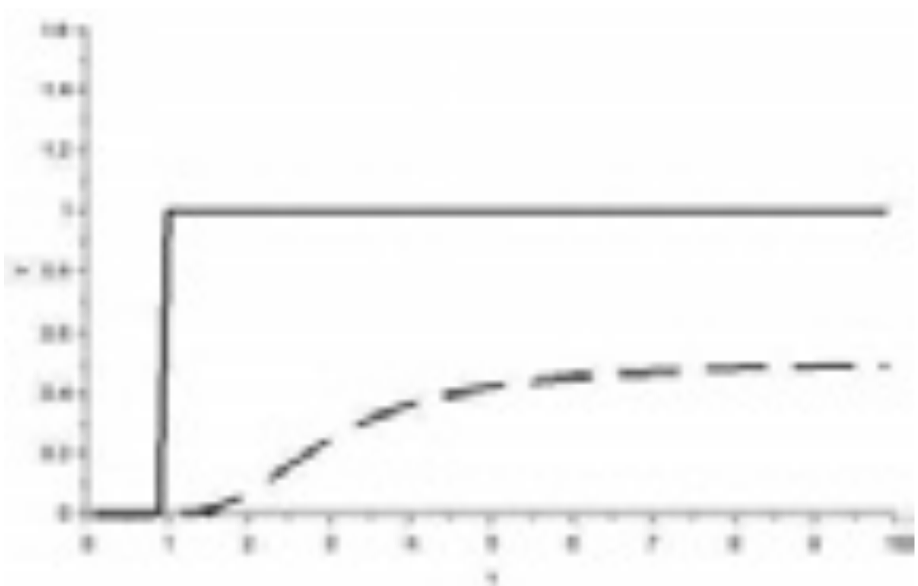

Figure 29. Transient response of third-order system with nested loops.

Figure 30 and Figure 31 demonstrate the equivalence between the two-block representations of the 3rd order system.

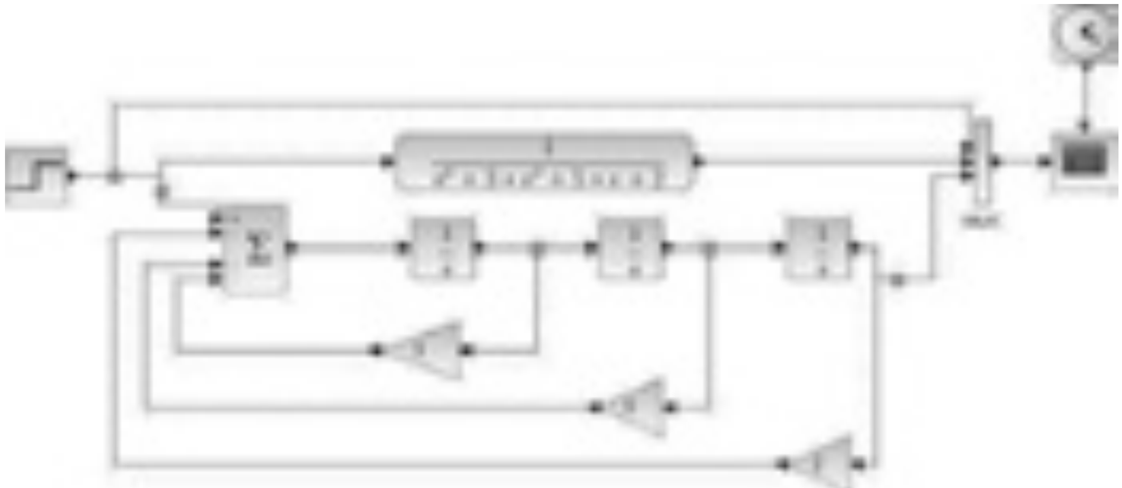

Figure 30. Third-order system with and without nested loops.

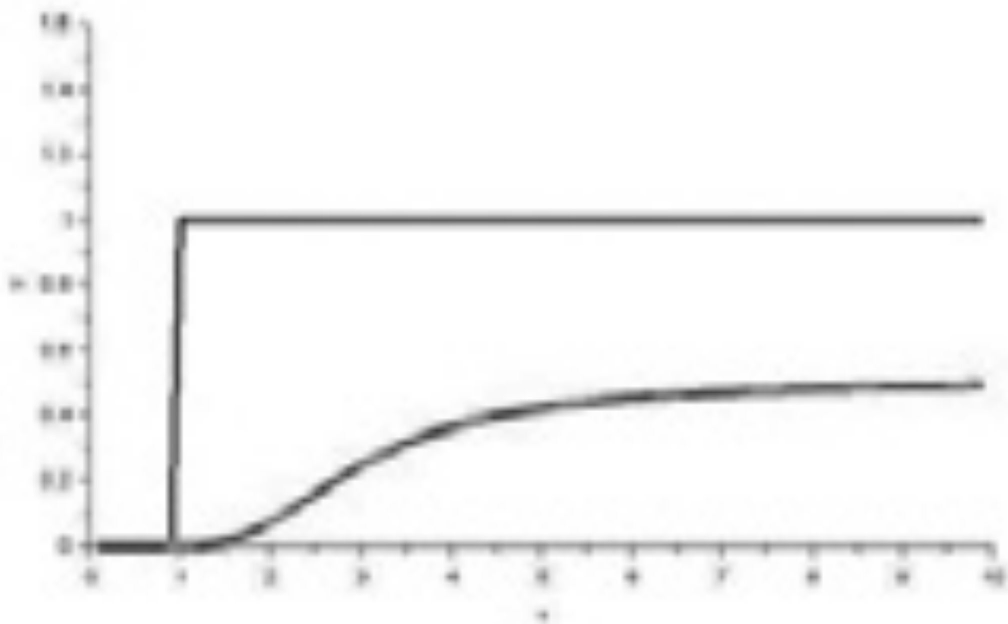

Figure 31. Transient response of third-order system.

Figure 32 displays the electronic implementation of the 3rd order system using OA networks. The U2, U4 and U6 circuits implement the nested loops. The mathematical operations required for the 3rd order system displayed in Figure 27, determines the inverting or non-inverting configurations. Figure 33 proves a similar behavior of the presented implementations of the 3rd order system.

For a superior-order system applies the same decomposing algorithms of the transfer function. Thus the integrative mathematical operations are separated in the transfer function expression. Following this algorithm, for the electronic implementation applies the same rules as for the 1st, 2nd and 3rd order systems previously presented. Analyzing the signal sign after each integration operation determines the nested loops' configurations with inverting and non-inverting structures.

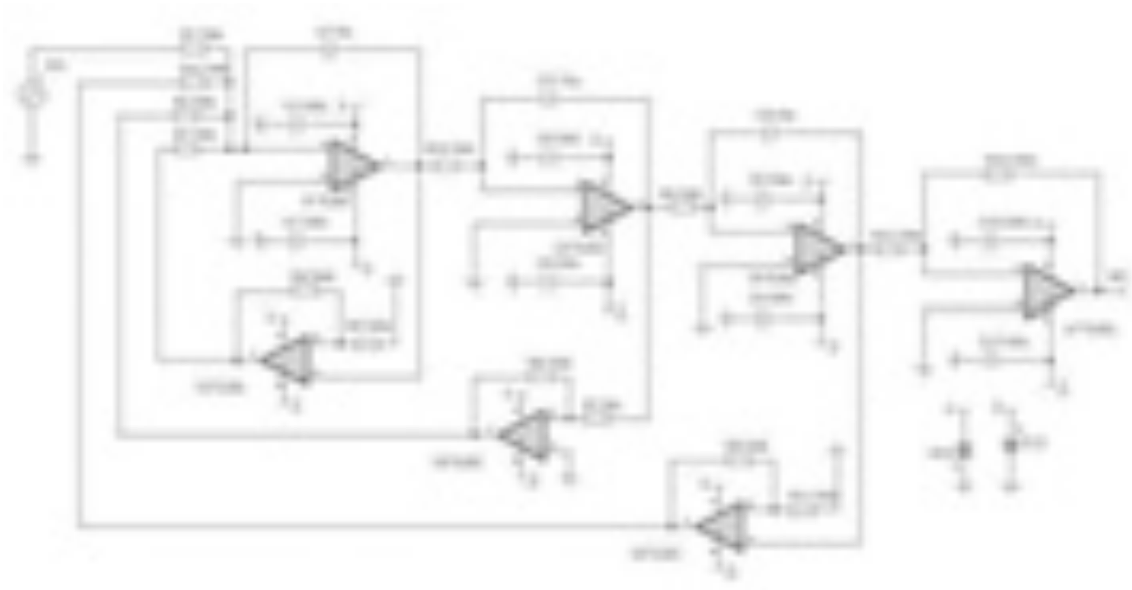

Figure 32. Electronic implementation of 3rd order system.

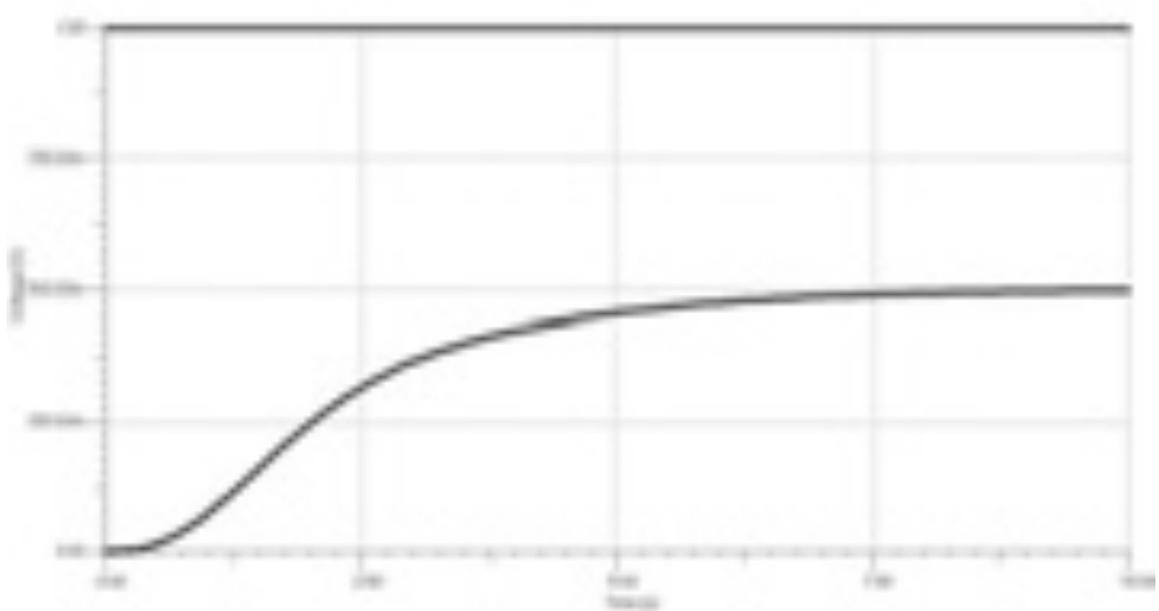

Figure 33. Transient response of 3rd order system.

5.4. Systems' Stability

A linear, time-invariant system is defined as:

- Stable, if the error of the natural response tends to zero when the time approaches to infinity.

- Unstable, if the error of the natural response grows when the time approaches to infinity.
- Critical stable, if the error of the natural response is constant or oscillates with the same amplitude when the time approaches to infinity.

There are various methods to determine the stability for a system. In this chapter is applied the Routh stability determination criteria described in all referenced manuals [4].

For the discussion throughout this chapter, it is considered the transfer function of a 3rd order system displayed in equation (14). In this example, there is a variable parameter *K*, which determines the stability of the system.

$$G(s) = \frac{K}{s^3+3s^2+5s+K} \tag{14}$$

For stability determination based on the Routh criteria, it is used a SCILAB [5] program:

```
clc;
s=%s;
num=1;
den=s^3+3*s^2+5*s;
R=routh_t(num/den,poly(0,'K'))
H=syslin('c',num,den);
clf();evans(H,100);sgrid();
```

Table 1. Routh table

R =	
1 - 1	5 - 1
3 - 1	K - 1
15 - K ------ 3	0 - 1
K - 1	0 - 1

Table 1 indicates the expressions of the Routh table. The analysis of the Routh coefficients is indicated in Table 2.

Table 2. System stability analysis

<table>
<tr><td>Routh expression</td><td colspan="5">Sign variation for Routh variables</td></tr>
<tr><td>K</td><td>-∞</td><td>0</td><td></td><td>15</td><td>+∞</td></tr>
<tr><td>$\frac{15-K}{3}$</td><td colspan="3">++</td><td>+++++ 0 --------</td><td>--------------------</td></tr>
<tr><td>$\frac{K}{1}$</td><td>--------------------------------------</td><td>0</td><td colspan="3">+++ +++</td></tr>
<tr><td>Stability domain</td><td>-</td><td>-</td><td>stable</td><td>critical stable</td><td>unstable</td></tr>
</table>

Depending on the values of K, the system can be:

- For $K \in (0 \div 15)$ the system is stable.
- For $K > 15$ the system is unstable.
- For $K = 15$ the system is critical stable.

The root locus design, displayed in Figure 34 confirms the presence of the three stability domains of the system: stability, instability and critical stability. The root locus displayed in Figure 34 is drawn when parameter K varies.

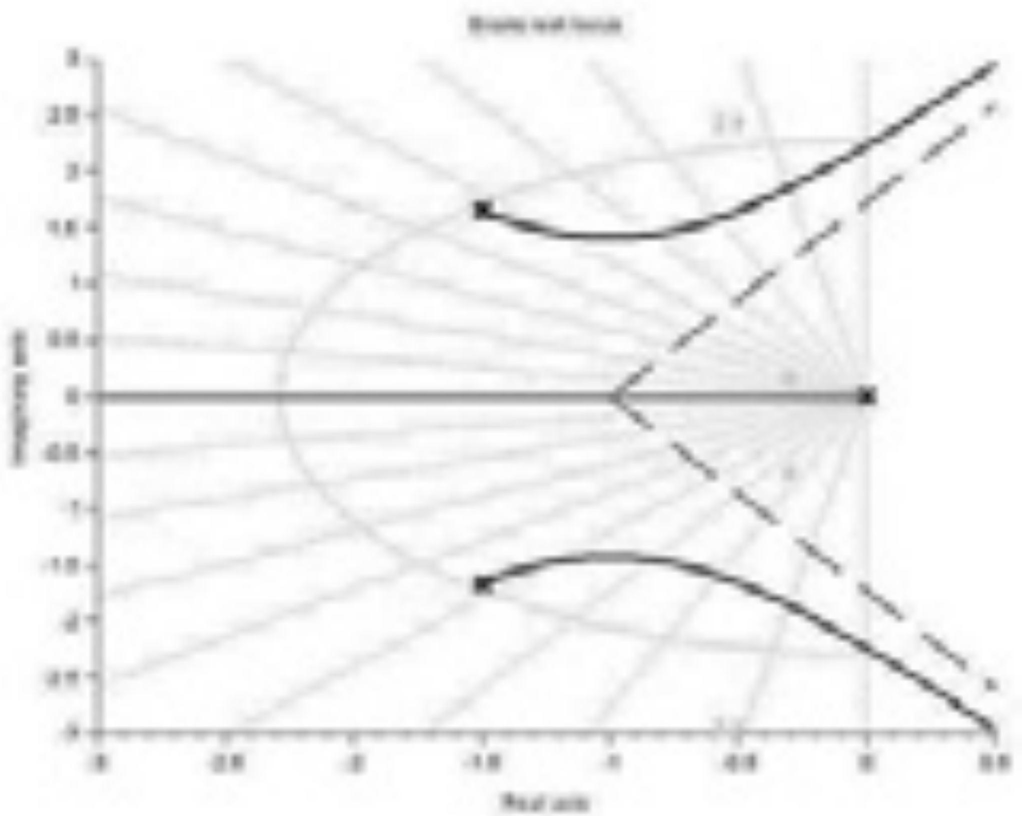

Figure 34. Root-locus representation.

Applying the same procedures discussed for the 1st, 2nd and 3rd order system analysis, the electronic implementation of the system is displayed in Figure 35, Figure 37 and Figure 39. In these figures, the parameter K gets various values: 7, 15 and 20. The K variation is obtained from the values of resistor networks of circuits U7 and U6.

U7 structure is an inverting configuration (Figure 2), whose amplification factor is:

$$V_2 = -\frac{R_{14}}{R_{13}} V_1 \tag{15}$$

U6 structure is an inverting configuration (Figure 2), whose amplification factor is:

$$\mathrm{V_2} = \left(1 + \frac{\mathrm{R_9}}{\mathrm{R_{11}}}\right) \mathrm{V_1} \tag{16}$$

Choosing different resistor combinations, according to (15) and (16) results the three analyzed situations:

- For the stable configuration $K = 7$:
    - $R_{14} = 700k\Omega$, $R_{13} = 100k\Omega$, $R_9 = 600k\Omega$, $R_{11} = 100k\Omega$
- For the critical stable configuration $K = 15$:
    - $R_{14} = 150k\Omega$, $R_{13} = 10k\Omega$, $R_9 = 140k\Omega$, $R_{11} = 10k\Omega$
- For the unstable configuration $K = 20$:
    - $R_{14} = 200k\Omega$, $R_{13} = 10k\Omega$, $R_9 = 190k\Omega$, $R_{11} = 10k\Omega$

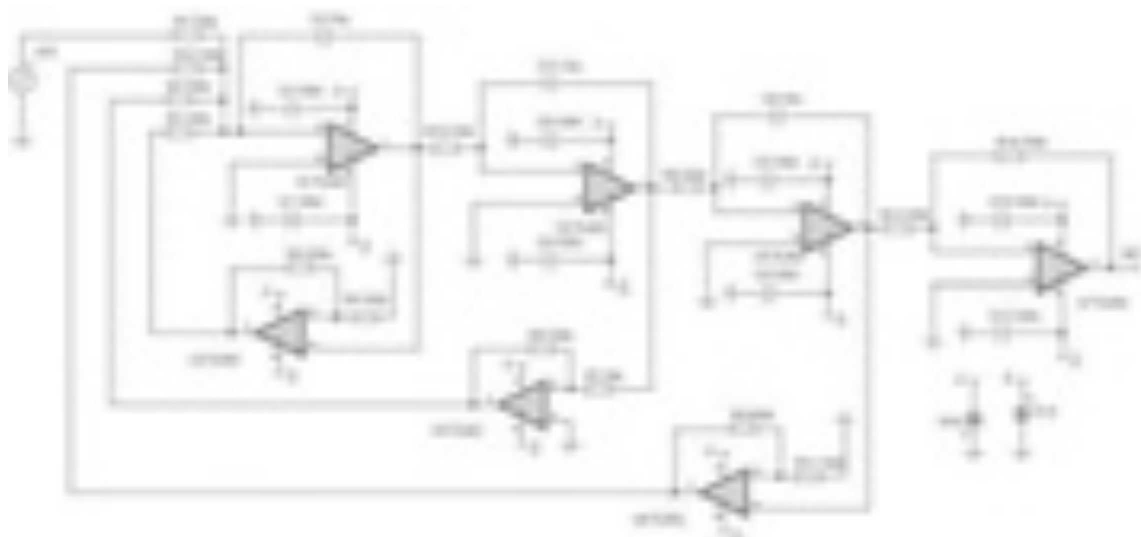

Figure 35. OA implementation of the system – $K = 7$.

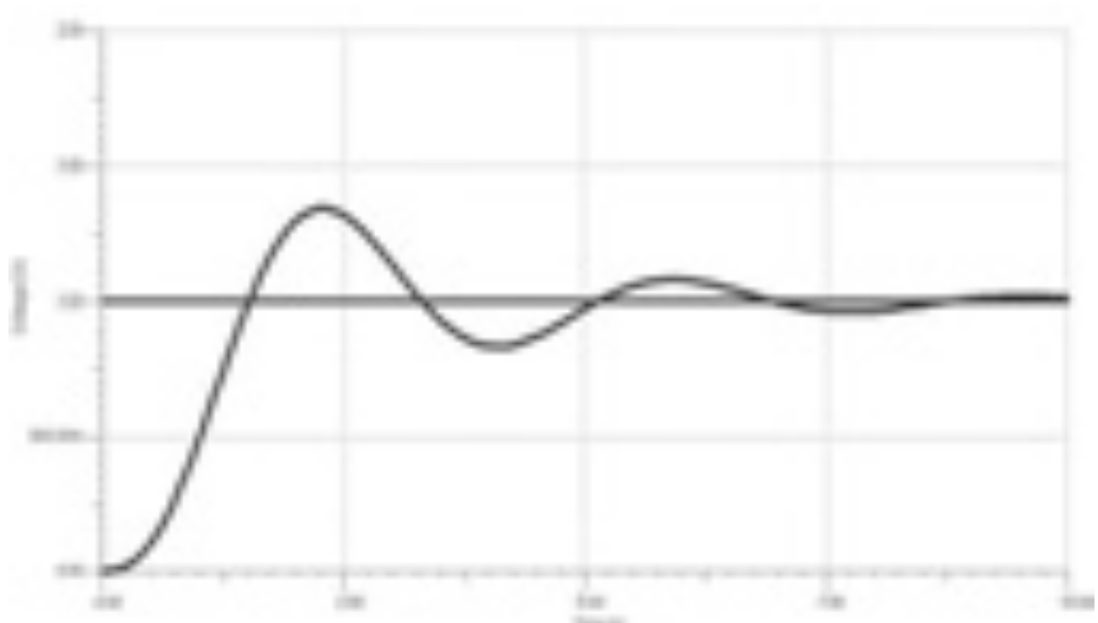

Figure 36. Transient response of the OA implementation of the system - $K = 7$.

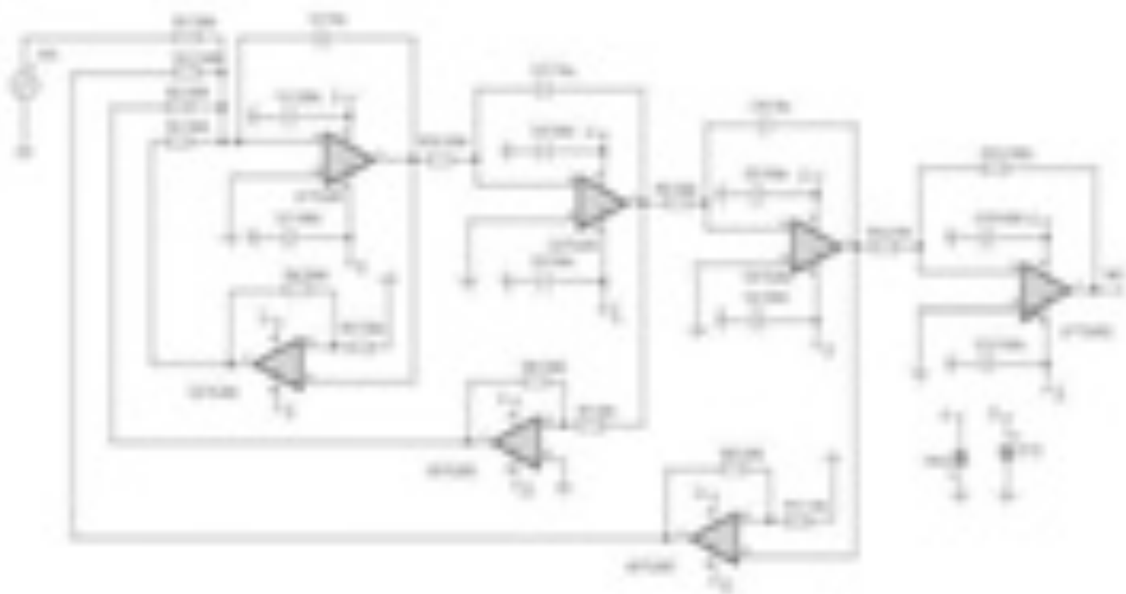

Figure 37. OA implementation of the system – $K = 15$.

Figure 38. Transient response of the OA implementation of the system - $K = 15$.

Figure 40 displays the step response of the unstable configuration (Figure 39). The amplitude in this situation is growing while the acquisition time arises. In the Control Theory textbooks, it is stated that in these situations if no measure is taken, the output signals' amplitude can rise to the point to self-destroying the system. In the OA implementation, the amplitude of the output signal is limited when the circuits saturate. In the presented implementations, it was used the TL082 OA produced by Texas Instruments. In the data sheet, Texas Instruments indicates that the saturation voltage [6] has a typical value of ± 13.5 V.

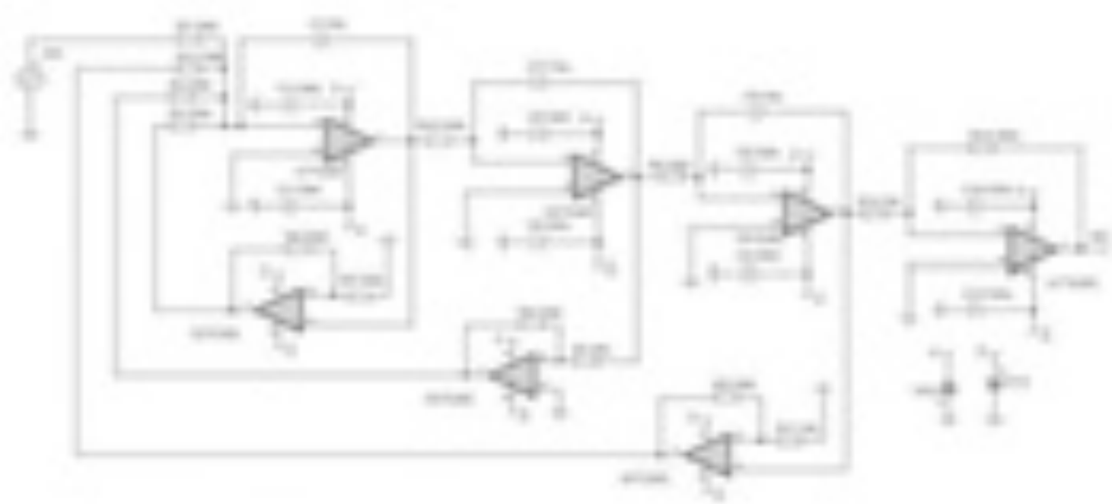

Figure 39. OA implementation of the system – $K = 20$.

Figure 40. Transient response of the OA implementation of the system - $K = 20$.

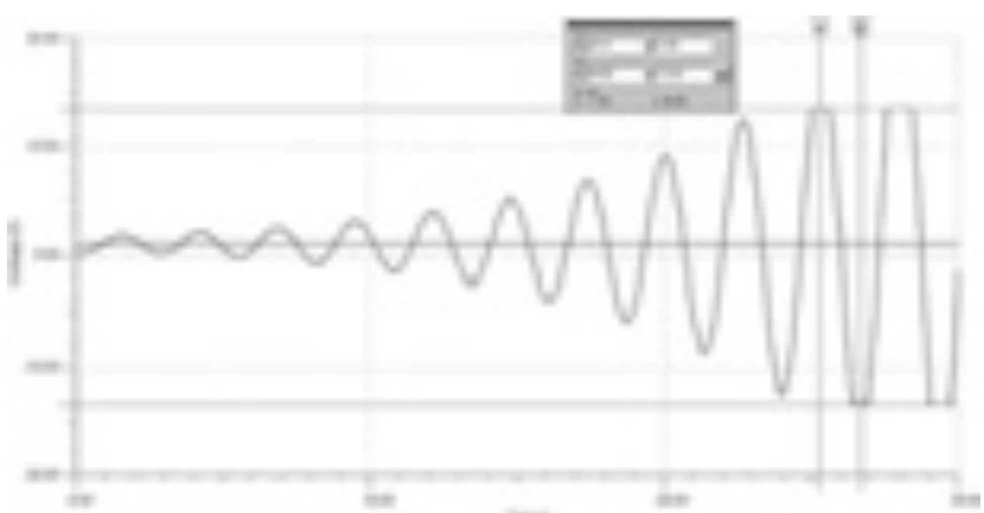

Figure 41. Unstable saturated system.

Figure 41 displays the unstable saturation situation. The values indicated are + 13.45 V and –13.44 V. These values are in accordance with the data indicated by Texas Instruments.

5.5. Controller Design

The purpose for the Control Systems course is to learn to design compensating structures in order to change the undesired behavior of a certain system. There are many situations when systems need to have a different behavior than their natural one.

In Figure 42 is displayed an electronic system whose transitory response is indicated in Figure 43. Table 3 indicates the natural parameters of the transitory response of the system. These parameters can be directly measured using specific instruments or can be calculated from the mathematical expression of the transfer function of the system.

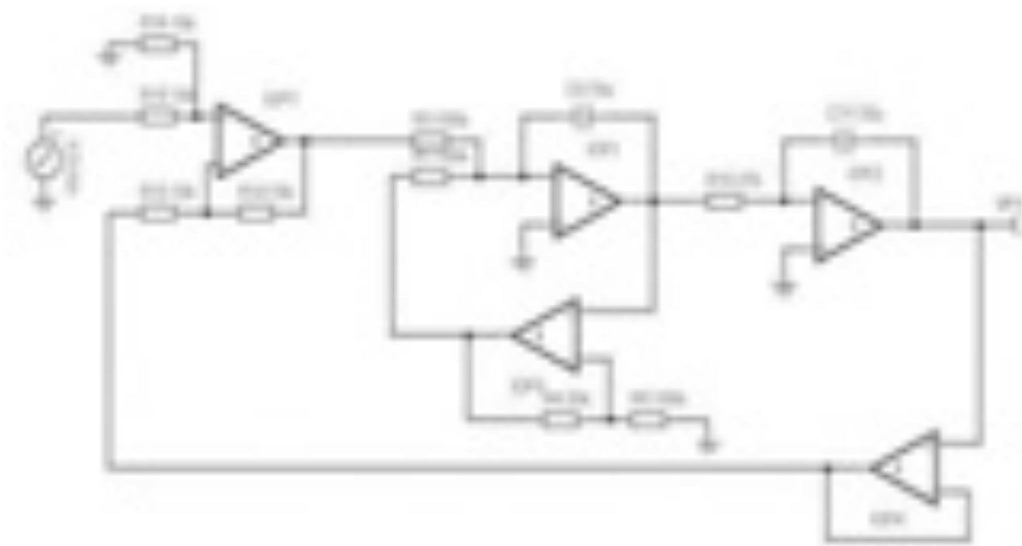

Figure 42. Original system.

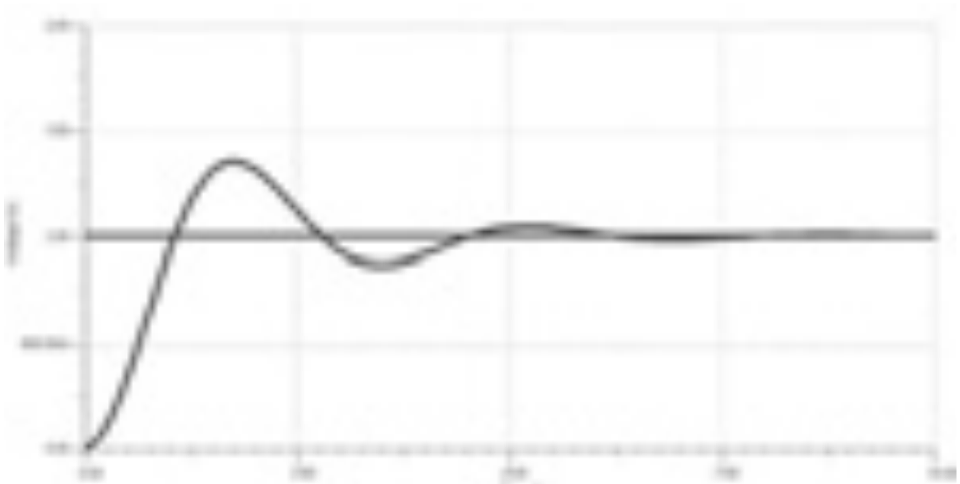

Figure 43. Transient response of the original system.

Table 3. Initial values of the transient response

Rising time	1.09 [s]
Overshooting time.	1.79 [s]
Overshooting value	35.00 [%]
Settling time for ± 2% error	6.47 [s]
Settling time for ± 5% error	4.85 [s]

The normal function of the system requires a change of the overshooting as indicated in Table 4:

- Overshooting value needs to decrease at 85% from the initial value.
- Overshooting time needs to decrease at 50% of the original value.

Table 4. Desired values of the overshooting

Overshooting time	0.90 [s]
Overshooting value	29.75 [%]

The imposed conditions indicated in Table 4 leads to the desired transient response from Table 5. The algorithm that provides these values is classic and is described in the bibliographic references. It is not the purpose of this chapter to go over the mathematical support of this calculation.

Table 5. Desired values of the transient response

Rising time	0.56 [s]
Overshooting time	0.90 [s]
Overshooting value.	29.75 [%]
Settling time for ± 2% error	2.75 [s]
Settling time for ± 5% error	2.07 [s]

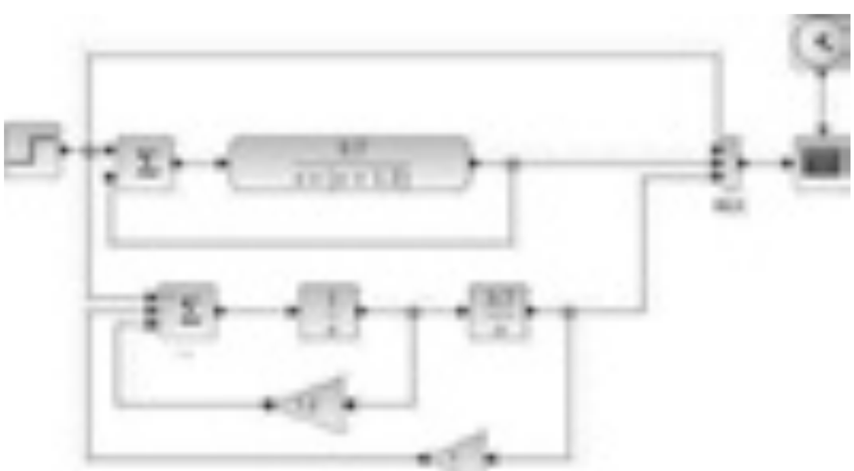

Figure 44. Block schematic of the original system with and without nested loops.

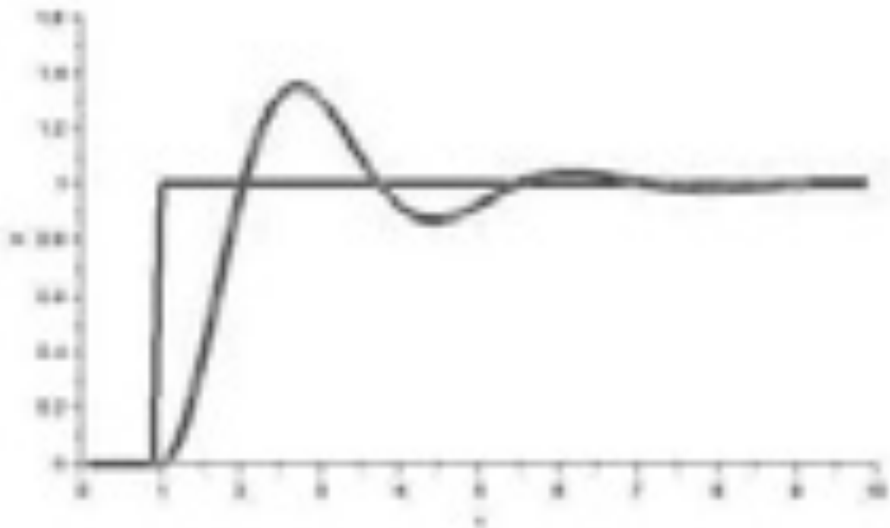

Figure 45. Transient behavior of the original system.

The process of controller design consists in:

- determination of the transfer function of the original system
- determination of the controller structure
- determination of the controllers' parameters.

In the analyzed situation, it is the desire to change the transient behavior only. Therefore, a lead compensator is used.

The electronic structure of the original system leads to the block schematic and transfer function displayed in Figure 44. Both representations have a similar transient behavior as it was demonstrated in previous paragraphs and is displayed in Figure 45. This behavior corresponds to the original parameters of the system mentioned in Figure 43 and Table 3. The times in Figure 45 are delayed by 1 regarding the values of Table 3 because the input signal has the same delay from the time origin.

The transfer function of the feed forward path for the system is expressed by the equation (17):

$$G(s) = \frac{3.7}{s\cdot(s+1.2)} \tag{17}$$

The design algorithms presented in Control System Theory manuals lead to the calculation of the transfer function of the controller expressed by equation (18) and displayed in Figure 46. This is a series connected lead compensator [7] that modifies the transitory behavior of the output signal. The parameters of the output signal are indicated in Table 5. Once these parameters are calculated, the following operation is to choose the available components for the RC networks that used in OA network implements as close as possible the desired transfer function. Resistor and capacitor values have to be chosen from standardized values found in electronic devices catalogs.

$$G(s) = \frac{3.7\cdot(s+2.1)}{s+4.25} \tag{18}$$

The electronic schematic of the lead compensator is implemented by the circuits IOP5 and IOP6 displayed in Figure 49. Choosing the resistors and capacitors for obtaining a transfer function of the compensator as close as possible in the expression in equation (18) results the expression in the equation (19):

$$G(s) = \frac{3.6\cdot(s+1.96)}{s+4.17} \tag{19}$$

The normal design procedure is to check the behavior error that results from the comparison between the calculated transfer function and the transfer function of the values of the chosen elements. This error is displayed in Figure 48. The analysis of the error indicates a very slight difference between the two situations and the design procedure stops. In case that the difference would be unacceptable, the design procedure continues until the error lowers to an acceptable level.

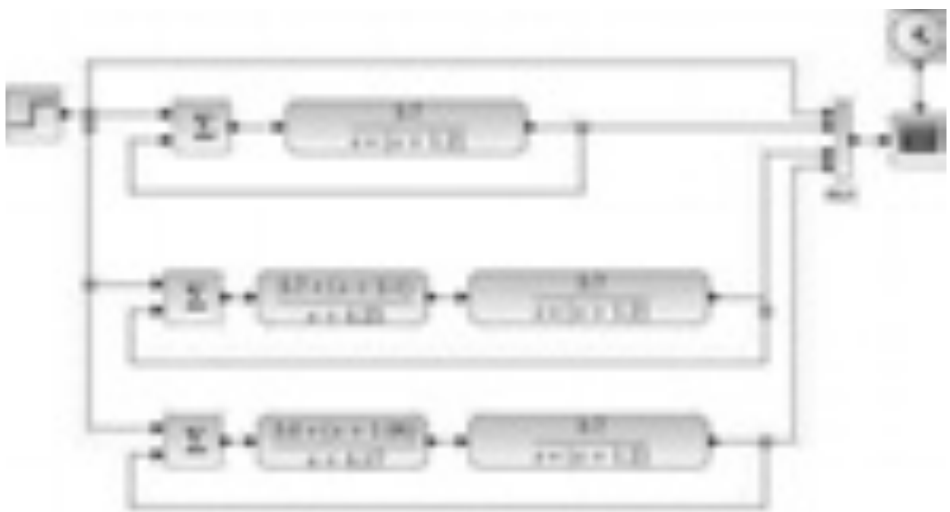

Figure 46. Block schematic of the original system without and with the controller.

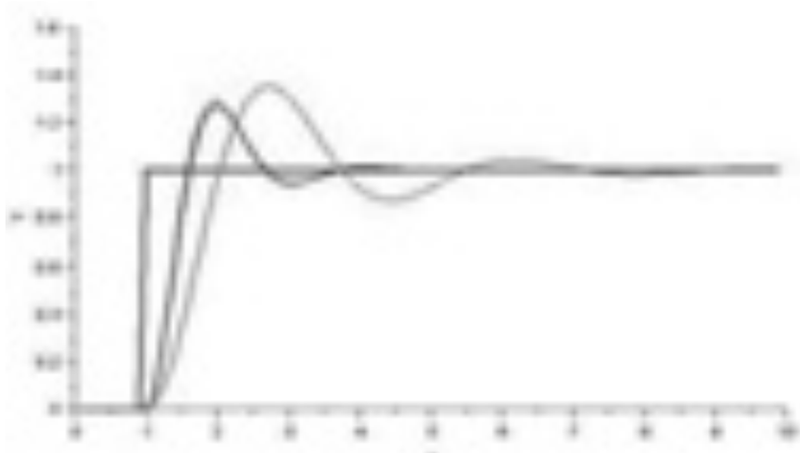

Figure 47. Desired transient behavior.

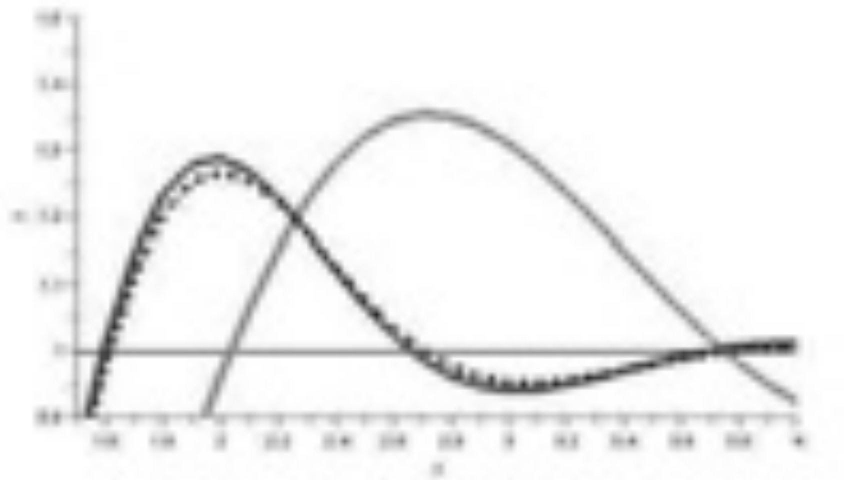

Figure 48. Details of desired transient behavior.

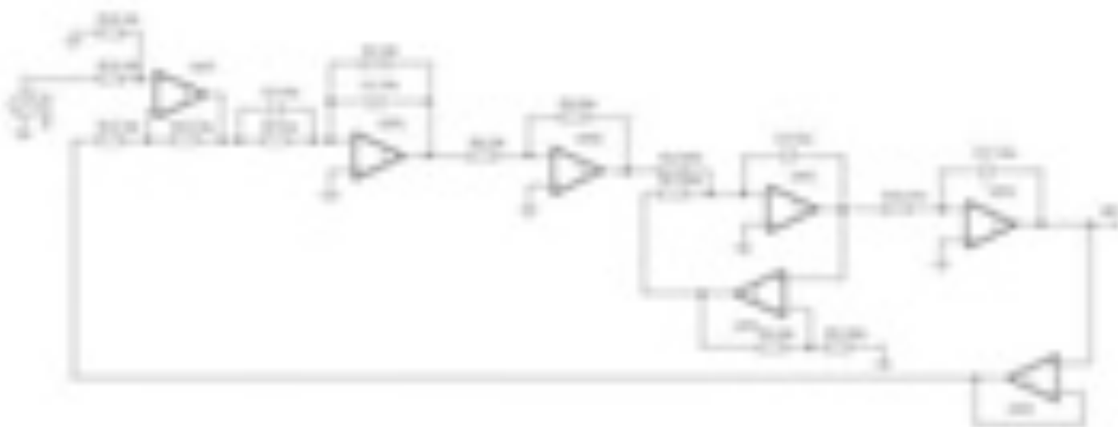

Figure 49. Compensated system.

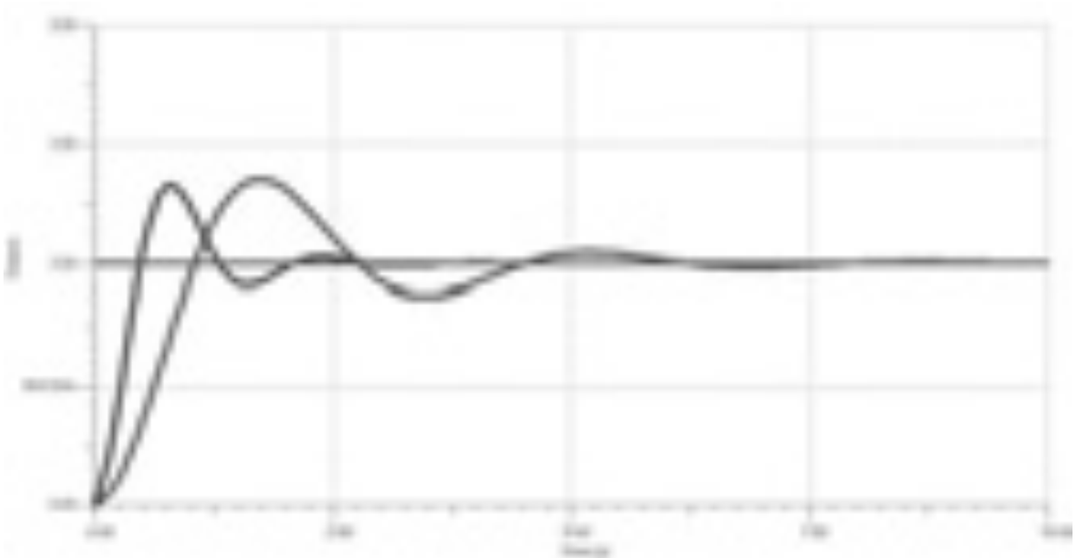

Figure 50. Transient behavior of the original and compesated system.

Figure 49 displays:

- The original system composed by IOP1 – IOP4 and the summer IOP7.
- The compensator composed by IOP5 and IOP6.

5.6. Practical Implementation

In this paragraph, we are going to exemplify some technical systems that can be simulated with OA network based electronic schematics.

5.6.1. DC Motor

The DC motor is used in a wide type of applications: industrial, automotive, education, home appliances, etc. [8].

The schematic of a DC separated field excitation (permanent magnet) is displayed in Figure 51. This representation indicates the electrical input voltage supply U_A[V], armature current I_A[A], as well as the output mechanical shaft speed Ω[rad/s].

The transient behavior of the motor is mathematically described by the equation (20):

$$U_A = R_A i_A(t) + L_A \frac{di_A(t)}{dt} + K\Phi\Omega(t)$$
$$J\frac{d\Omega(t)}{dt} = m - m_f - m_s \quad (20)$$

Where:

U_A – voltage applied to motor's terminals.
I_A – armature current
R_A, L_A – electric parameters of the motor: armature resistance and inductance
J, f – mechanical dynamic parameters:
J – total inertial torque;
f – viscous friction coefficient
m – electromagnetic torque
$m_f = f \cdot \Omega$ – viscous friction torque
m_s – kinetic friction torque

Figure 51. DC motor schematic (permanent magnet excitation).

The Laplace transform applied to (20) under null initial conditions leads to the motors' transfer function expressed by equations (21) and (22):

$$\begin{aligned} U_A &= R_A I_A(s) + L_A s I_A(s) + K\Phi\Omega(s) \\ Js\Omega(s) &= K\Phi I_A(s) - f\Omega(s) - m_s \end{aligned} \tag{21}$$

$$\begin{aligned} I_A(s) &= [U_A - K\Phi\Omega(s)]\frac{1}{R_A + L_A s} \\ \Omega(s) &= [K\Phi I_A(s) - m_s]\frac{1}{sJ+f} \end{aligned} \tag{22}$$

Figure 52 and Figure 53 displays the block implementation of equations (21) and (22):

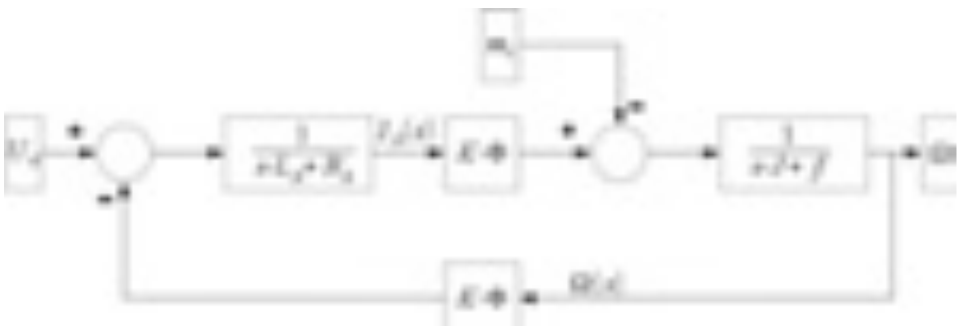

Figure 52. Block schematic of the DC motor.

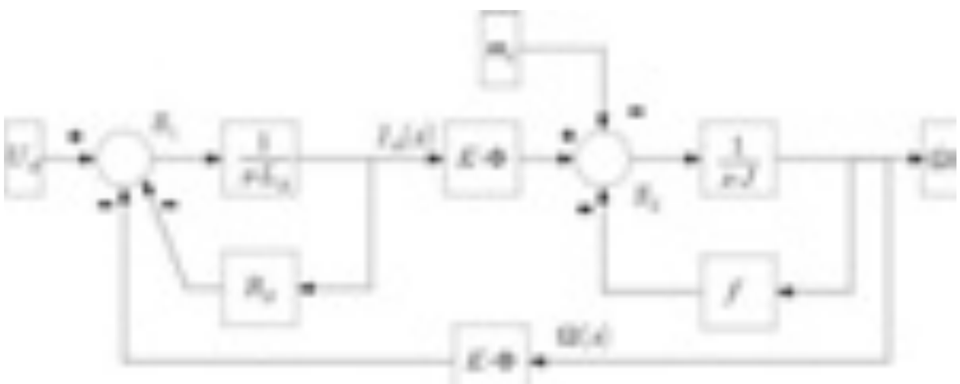

Figure 53. Expanded block schematic of the DC motor.

The expanded block schematic of the DC motor (Figure 53) is a re-arranged form of the regular schematic (Figure 52). Its' analysis indicates what are the numerical values of the feed-forward and feed-back paths of the electrical and mechanical implementations of the transfer function of the DC motor [8]. Combining both transfer functions leads to the equivalent electronic implementation of this motor displayed in Figure 54.

The model presented in Figure 54 is validated through experimental tests. Table 6 contains the nominal values indicated on the nameplate of the motor. The values of R_A and L_A are obtained either by direct or by experimental measurements of voltage and current through the inductor coil with DC and AC voltage supply. The mathematical model of the DC motor depends of the mechanical values' J and f. There are various methods described throughout the literature for the laboratory determination of these parameters [9]. Table 7 and Table 8 displays the experimental determined values for the considered DC motor.

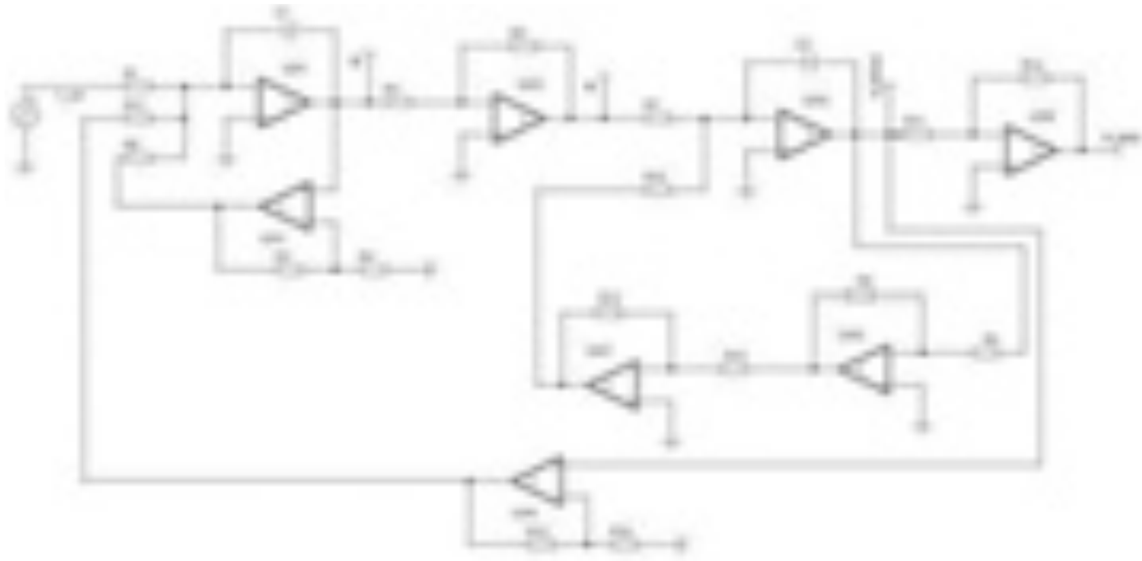

Figure 54. Electronic implementation of the DC motor model.

Table 6. Nominal Data for the DC Motor

	Nominal data		
	Data	Value	Unit
1	U_A	200	V
2	I_A	2,0	A
3	n_n	1500	rot/min

Table 7. Direct Data for the DC motor measurement

	Measured data		
	Data	Value	Unit
1	R_A	15,8	Ω
2	L_A	0,41	H

Table 8. Determined Data for the DC Motor

	Measured data		
	Data	Value	Unit
1	J	0,29·10-3	kg·m2
2	f	1,48·10-3	Nm/rad/s

Figure 55 displays the dynamic behavior for the real and simulated motor. The electronic model of the DC motor has a very little error compared with the real motor. The experimental and mathematical analysis proves that the electronic implementation of the motor is following the real behavior with an acceptable error.

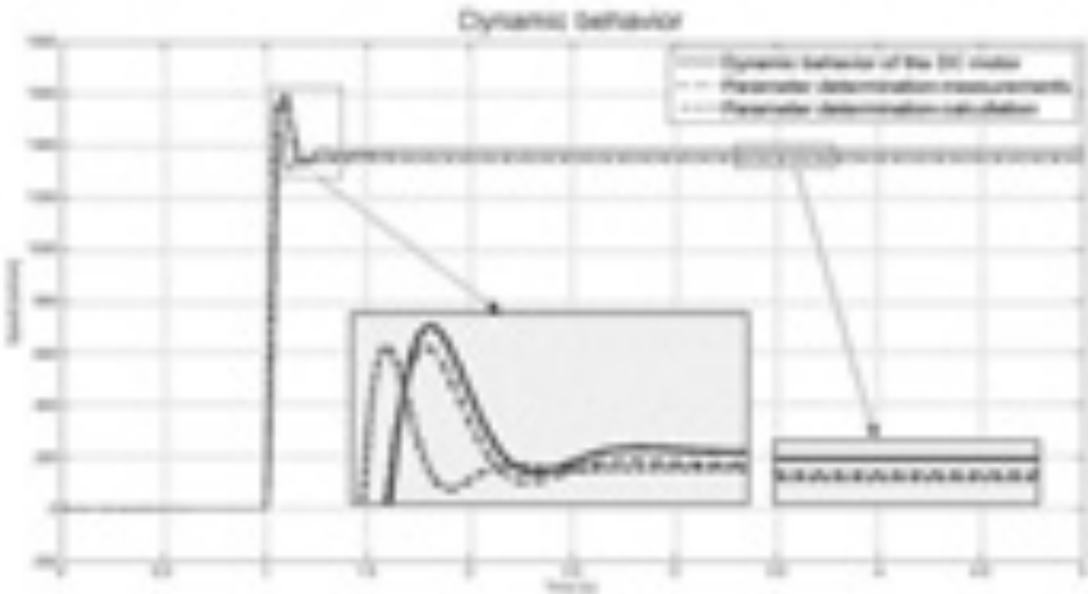

Figure 55. Dynamic behavior of the DC motor.

5.6.2. Satellite Tracking Antenna

The Control Systems literature contains various examples of systems that are modeled by transfer functions and block schematic. One of such examples is the model of a satellite tracking antenna [10, 11].

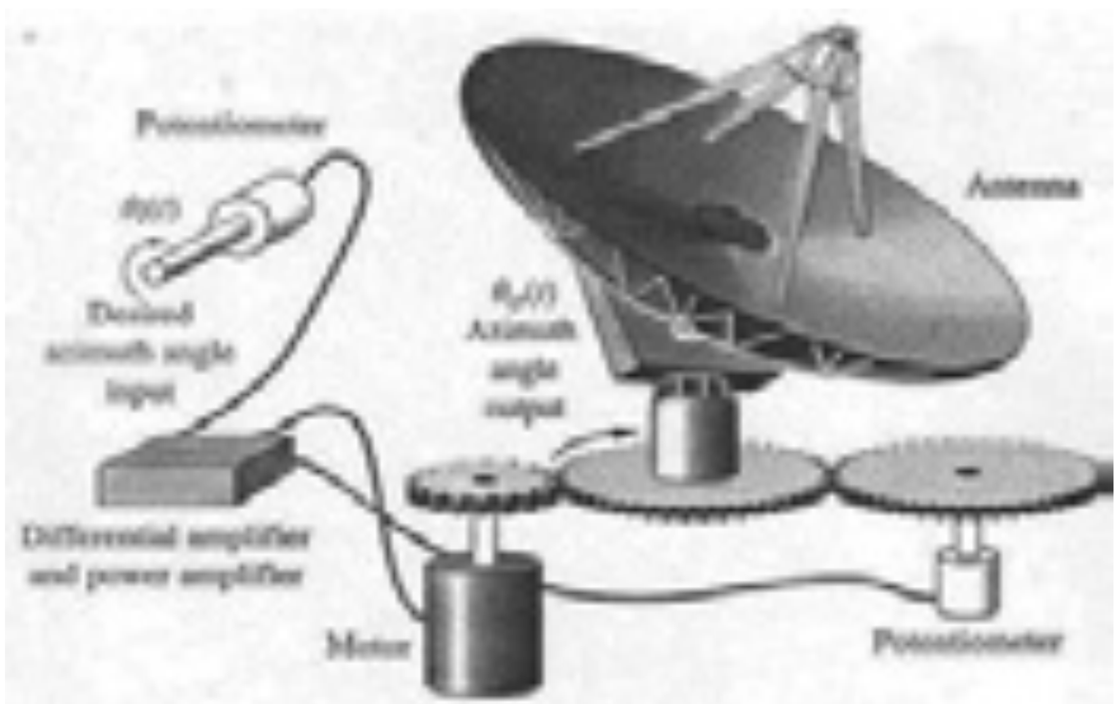

Figure 56. Satellite tracking antena.

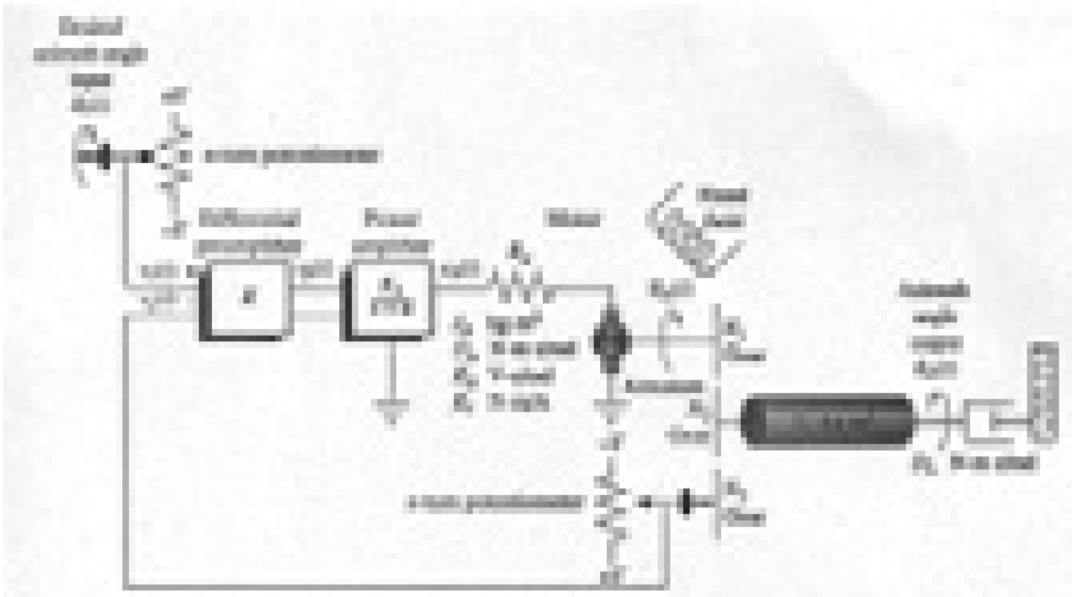

Figure 57. Electric schematic of the satellite traking antenna.

Equation (23) expresses the feed-forward path of the transfer function of the satellite tracking antenna [11]. The transfer function indicates a 2^{nd} order system that can be implemented as a block schematic both with and without nested loops.

$$G(s) = \frac{20.83}{s^2+101.71s+171} \quad (23)$$

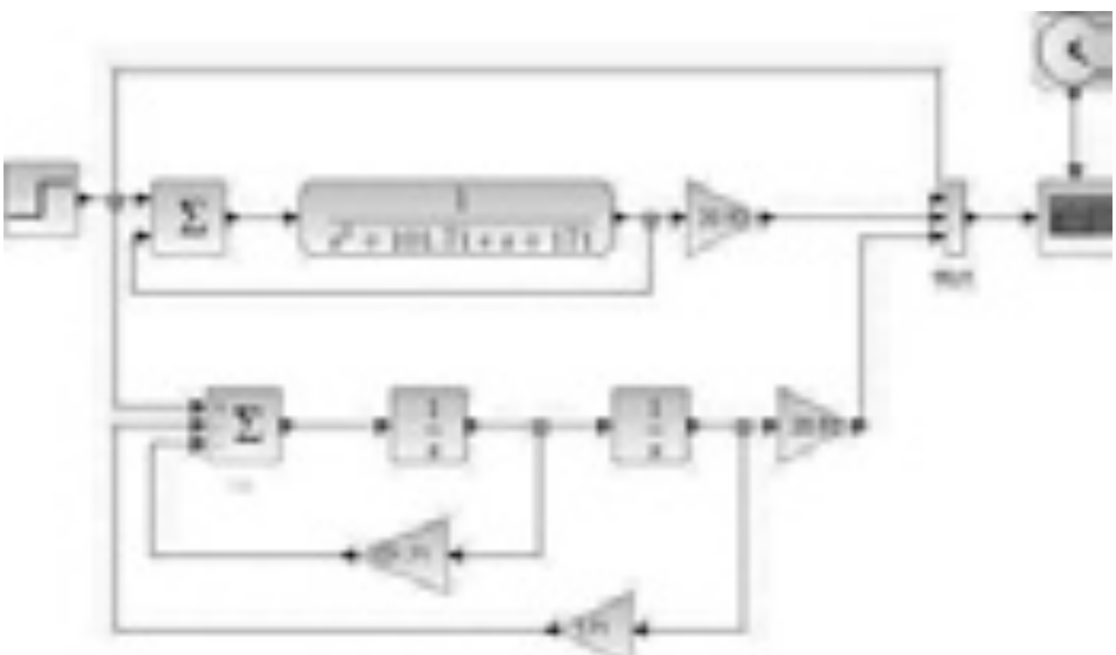

Figure 58. Block schematic representation of the satellite tracking antenna.

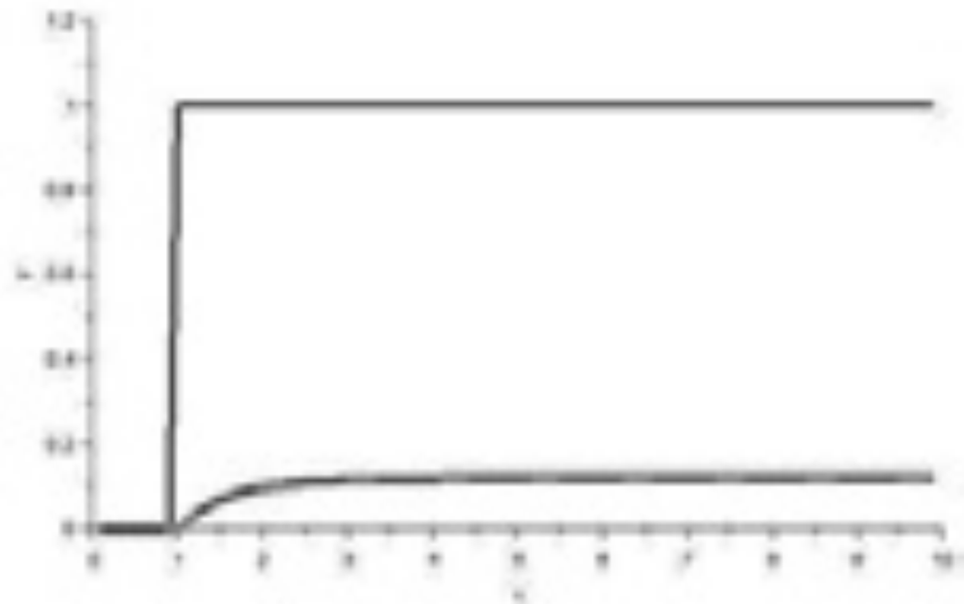

Figure 59. Dynamic response of the satellite tracking antenna.

As in this case direct measurements are not an accessible option for regular laboratories, the verification of correctness is checked by comparing the mathematical time dependent equation of the output signal (24) of the system with the electronic implementation. The function representation is displayed in Figure 60.

$$\omega_0(t) = 0.122 + 2.12 \cdot 10^{-3} \cdot e^{-100 \cdot t} - \\ -0.124 \cdot e^{-1.71 \cdot t} \tag{24}$$

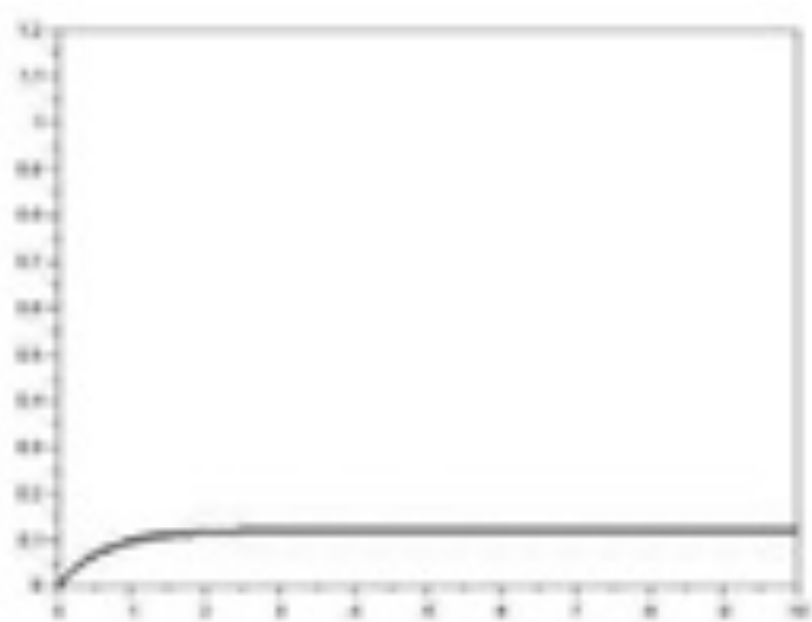

Figure 60. Graphical representation of the time dependant output signal of the satellite tracking system.

The circuit in Figure 61 displays how the transfer function and block schematic simulation models of the satellite tracking system are implemented using the presented method of this chapter. The output signal of the electronic model (Figure 62) matches exactly the block schematic simulation for a step input signal. The error between the electronic model and the graphical representation of the time variant expression of the system is minimal.

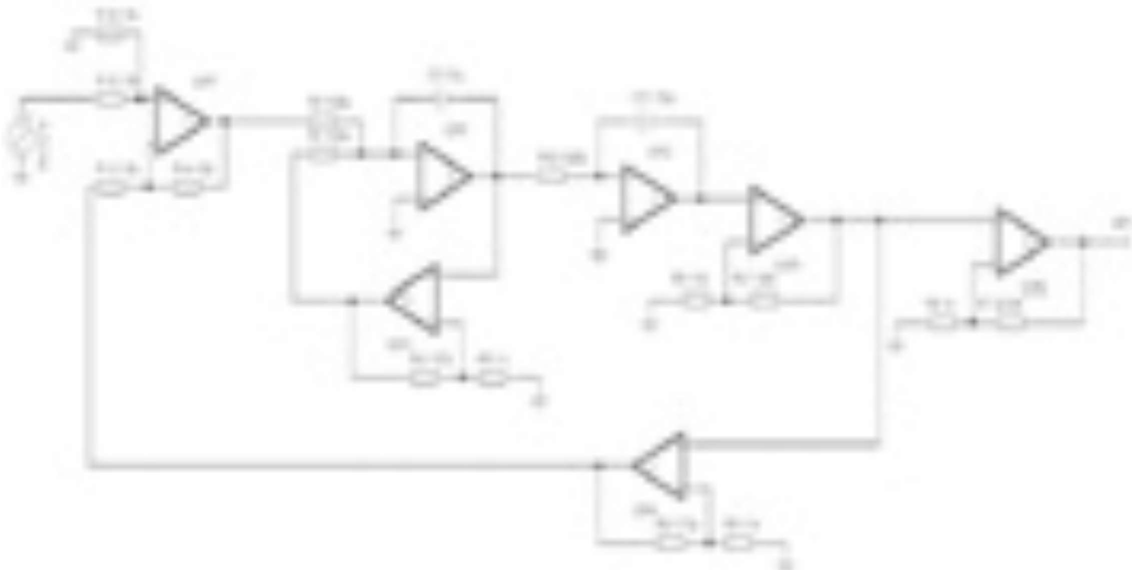

Figure 61. Electronic model of the satellite tracking system.

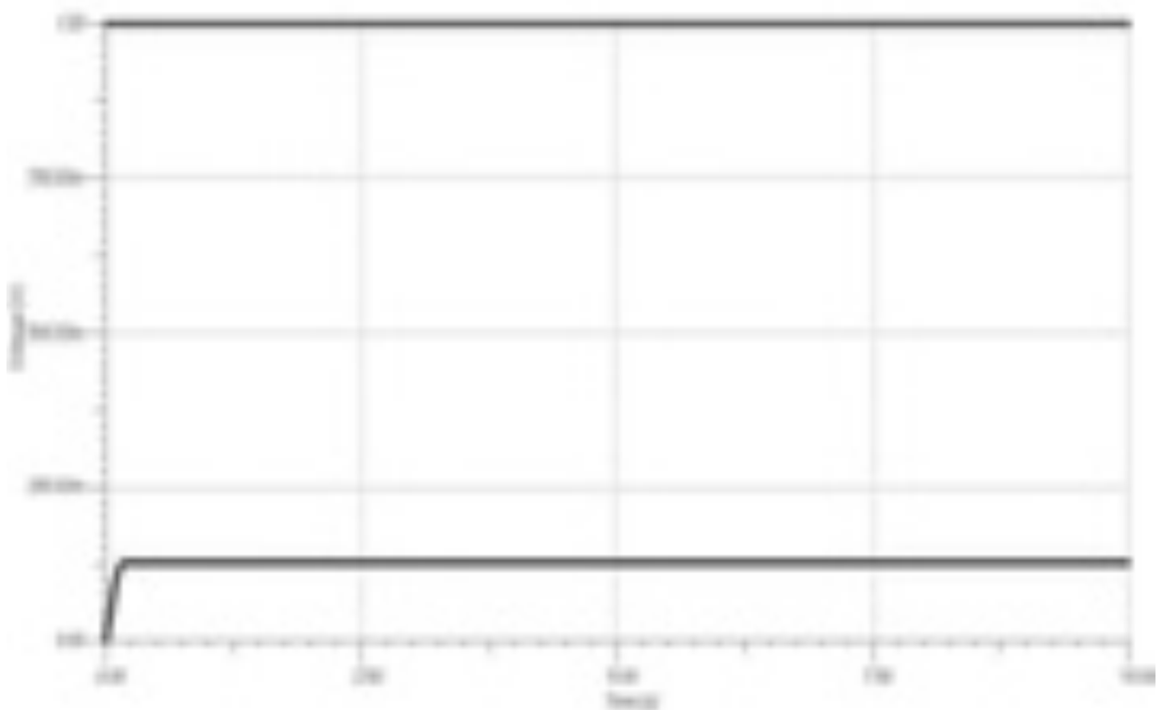

Figure 62. Dynamic response of the electronic model of the satellite tracking system.

CONCLUSION

In this chapter was presented a different approach to the classical method of teaching the Control Systems course.

The simulation of a system supposes that the systems' equations can be expressed by mathematical relations. Transfer function is a very basic and key concept used in teaching this course. Based on the transfer function representation it is developed the block schematic of a system. Once a system is expressed by its transfer function and the block schematic, it can be simulated and studied using available dedicated software tools.

One problem of the classic teaching methods is the difficulty that appears sometimes, to link mathematical concepts and representations to "hands-on" experiments. In addition, concepts as stability, instability and critical stability are not easy to 'see' and measure in regular laboratories. This is because analyzed systems are not always available or in the reach of Universities.

Recently, the Open Source projects like Arduino [12] are welcomed all over the world at various educational levels. The Arduino community publishes a very wide spectrum of open-source applications free available on the Internet. Furthermore, there are important multinational companies that produce accessible programmable devices. They have educational programs that encourage Universities to apply for donations and competitions. Due to their easy access, the user community developed 'Arduino-like' programming environment [13].

There are some particular applications that are very useful for the proposed approach:

- Signal generation [14]
- Data-Acquisition [15]

The possibility of easy access to signal generation and data acquisition for general "DIY" projects combined with the presented methodology, makes the Control System course available for study inside, but most interesting outside University laboratory. The implementation of block schematics and transfer function leads to the possibility of studying control theory concepts outside the Universities' walls.

The impact of this approach is that just as open-source electronic and software tools captured many hobbyists, the possibility of cheap experiments could lead to better understanding of complicate concepts of control theory.

A different benefit from this approach is that stands could be brought on the educators' experimental table with distinct possibilities of changes. The DC model presented in paragraph 0 can implement diverse motor models by changing only cheap elements (resistors and capacitors). This allows the teachers to design various applications at a very low price. In a practical laboratory course, a group of students can be split and work on the same application at the same time, compare the results and share similar experiences. Furthermore, the teacher might choose to split a group of students and have them work in smaller teams on different applications.

OA network simulation of complex systems can be also interesting for industrial applications. There are times when very complicate systems need to be studied before mass production. In this situation different internal signals of the system might have a complicate waveform that is difficult to be expressed by mathematical relations. If the control of such a system supposes analyzing of an unusual signal, and the decision needs to be based on certain characteristics, such a signal can be measured and acquired from the electronic model of that system covered throughout this chapter.

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