ISSN: 2594 - 2905

DESIGN OF A FEEDFORWARD COMPENSATOR FOR AN UNDERDAMPED RLC CIRCUIT THROUGH LGR ANALYSIS FOR THE MODIFICATION OF ITS CHARACTERISTIC TIMES

DESIGN OF A FEEDFORWARD COMPENSATOR FOR AN UNDERDAMPED RLC CIRCUIT THROUGH LGR ANALYSIS FOR THE MODIFICATION OF ITS CHARACTERISTIC TIMES

Hernández Sánchez César[1], González Playas Fidel[2], Lastre Domínguez Carlos Mauricio[3], Cruz Gómez Milton[4], Sosa Cruz Pablo Moisés[5]

https://doi.org/10.61117/ipsumtec.v7i2.302

[1]Master of Science, Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca, Departamento de Ingeniería Electrónica,cesar.hernandez@itoaxaca.edu.mx, 9511959974, CP 68000. https://orcid.org/0009-0002-2890-8099
[2]Master of Science, Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca, Departamento de Ciencias Básicas, fidel.playas@itoaxaca.edu.mx, 9511959974, CP 68000. https://orcid.org/0009-0007-9817-6897
[3]PhD in Engineering, Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca, Departamento de Ingeniería Electrónica,Carlos.lastre@itoaxaca.edu.mx, 9511959974, CP 68000. https://orcid.org/0000-0003-2737-7644
[4]Sixth Semester, Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca, Department of Electronic Engineering 21160352@itoaxaca.edu.mx, 9717166873, CP 71220. https://orcid.org/0009-0004-1919-7891
[5]Sixth Semester, Tecnológico Nacional de México/Instituto Tecnológico de Oaxaca, Department of Electronic Engineering 21160406@itoaxaca.edu.mx, 9511473390, CP 68264. https://orcid.org/0009-0007-3907-7020

Abstract -- In this paper, a feedforward compensator for an underdamped RLC circuit was designed and developed with the objective of improving its stability and transient response. The process included obtaining the transfer function of the circuit using the node method and Kirchhoff's Law, confirming its underdamped condition. Python was used to automatically calculate the values of the circuit components, as well as the step response parameters.

The design of the compensator was performed using the Locus Geometric Root Geometry (LGR) method to determine the values of the compensator that would improve the response of the system. Subsequently, the compensator was implemented first on a breadboard and then on a PCB, verifying its behavior with simulations in Proteus and Matlab, and with practical measurements.

As a result, greater stability, faster and more controlled transient response, significant reduction of overshoot and overall optimization of system performance were achieved.

Keywords: RLC circuit, Compensator, System.

Abstract -- In this document, a lead compensator was designed and implemented for an underdamped RLC circuit aiming to enhance its stability and transient response. The process involved deriving the circuit's transfer function using nodal analysis and Kirchhoff's Law, confirming its underdamped condition. Python was employed to automatically compute component values and step response parameters.

The compensator design utilized the Root Locus Method (RLM) to determine compensator values that would improve system response. Subsequently, the compensator was prototyped on a breadboard and then on a PCB, validating its behavior through simulations in Proteus and Matlab, as well as practical measurements.

As a result, increased stability, faster and controlled transient response, significant reduction in overshoot, and overall system performance optimization were achieved.

Key words -. RLC circuit, Compensator, System.

INTRODUCTION

In this report, the application of a feedforward compensator in an underdamped RLC circuit is addressed with the objective of improving stability and transient response of the system. The context of study focuses on the challenges associated with the presence of underdamping in RLC circuits, which can lead to undesired oscillatory responses. To address this issue, the implementation of a feedforward compensator is explored, highlighting its ability to introduce positive phase at the crossover frequency. This approach results in tangible benefits, such as increasing the gain margin and minimizing over oscillation, thus improving the overall system stability. This report provides a detailed overview of the theory, design and results associated with the application of a feedforward compensator in a specific underdamped RLC circuit context.

DEVELOPMENT

Materials:

- Voltage regulator LM7805
- 4 LM741 operational amplifiers
- 3 Resistors of 10kΩ

EDUCACIÓN
TECNOLÓGICO NACIONAL DE MÉXICO
IPSUMTEC
ISSN: 2594 - 2905

- 2 Resistors of 100kΩ
- 2 Resistors of 1MΩ
- 1 120Ω resistor
- 1 Resistor of 150kΩ
- 1 Resistors of 270Ω
- 1 Resistors of 5100Ω

- 2 Electrolytic capacitors of 1uF
- 2 x 100nF ceramic capacitors
- 2 x 10nF ceramic capacitors
- 1 1nF ceramic capacitor
- 1 10mH inductor

- 1 NE555
- 1 oscilloscope

CREATION FROM CIRCUIT RLC SUB-AMOTIGUATED

.

The realized circuit consists of 3 resistors, a capacitance y a inductance, was chosen was .this configuration in order to obtain a function of second transfer. The circuit is that of the

Figure 1, and as can be seen the output voltage o also called V_o is taken at the capacitor.

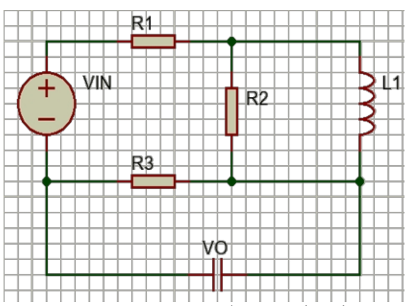


Figure 1. Proposed RLC circuit.

OBTAINING THE TRANSFER FUNCTION OF THE RLC CIRCUIT.

To obtain the transfer function, the analysis of the difference of the output with respect to the input was made using the node method, according to Kirchhoff's current law. Subsequently, this analysis was performed in the circuit to find the equations, as shown in Figure 2.

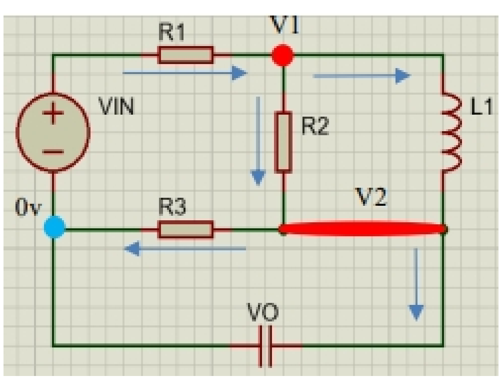


Figure 2. Analysis by nodes.

The following is the algebraic process obtaining the equations by the method of nodes, with which the transfer function of the circuit was obtained.

$$\frac{v_{in}-v_1}{R_1} = (v_1 - v_2)\left(\frac{1}{R_2} + \frac{1}{Ls}\right) \quad \text{Eq. (1)}$$

$$(v_1 - v_2)\left(\frac{1}{R_2} + \frac{1}{Ls}\right) = v_2\left(\frac{1}{R_3} + Cs\right) \quad \text{Eq. (2)}$$

$$v_2 = v_{out} \quad \text{Eq. (3)}$$

$$(v_{(1)} - v_{out}) = \frac{v_{out}(R_{(2)}Ls)(1+CsR_{(3)})}{R_3(Ls+R_{(2)})} \quad \text{Eq. (4)}$$

$$v_1 = v_{out}\left[\frac{R_2Ls + CLR_3R_2s^2}{R_3Ls + R_3R_2} + 1\right] \quad \text{Eq. (5)}$$

$$\frac{v_{in}}{R_1} = \left(v_{out}\left[\frac{R_2Ls+CLR_3R_{(2)}2s}{R_3Ls+R_3R_2} + 1\right] - v_{out}\right)\left(\frac{1}{R_2} + \frac{1}{Ls}\right) + \frac{v_{out}}{R_1}\left[\frac{R_2Ls+CLR_3R_{(2)}2s}{R_3Ls+R_3R_2} + 1\right] \quad \text{Eq. (6)}$$

$$v_{in} = R_1v_{out}\left[\frac{1+CR_3s}{R_3}\right] + v_{out}\left[\frac{R_2Ls+CLR_3R_2s^2}{R_3Ls+R_3R_2} + 1\right] \quad \text{Eq. (7)}$$

$$v_{in} = v_{out}\left[\frac{R_1+CR_1R_3s}{R_3} + \frac{R_2Ls+CLR_3R_{(2)}2s}{R_3Ls+R_3R_2} + 1\right] \quad \text{Eq. (8)}$$

$$\frac{v_{out}}{v_{in}} = \frac{1}{\left[\frac{R_1+CR_1R_3s}{R_3} + \frac{R_2Ls+CLR_3R_{(2)}2s}{R_3Ls+R_3R_2} + 1\right]} \quad \text{Eq. (9)}$$

Simplifying this equation we obtain the following result which corresponds to the transfer function.

$$\frac{v_{out}}{v_{in}} = \frac{R_3Ls + R_3R_2}{CLR_{(3)}(R_{(1)}+R_2)s^2 + (R_{(1)}L + R_{(1)}R_2R_3C + R_2L + R_{(3)}L)s + R_{(2)}(R_{(1)}+R_3)} \quad \text{Eq. (10)}$$

To verify that the circuit is under-damped, the discriminant of the second order equation in the denominator must be negative, since this indicates whether the roots are complex. To facilitate the task of obtaining the resistance, inductance and capacitance values, Python was used to perform the calculations in an automated manner.

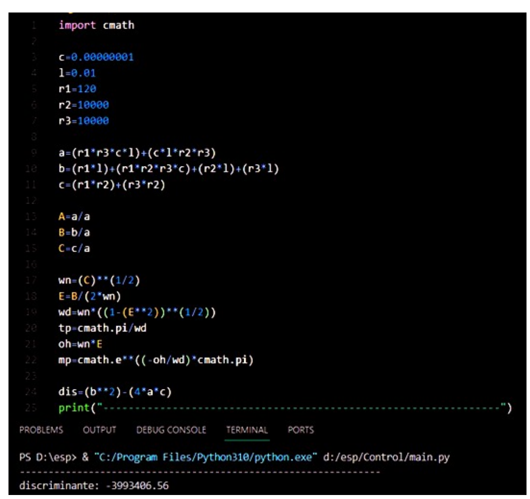


Figure 3. Calculation of the discriminant in Python.

For resistance values of 10kΩ, 120Ω, capacitance of 10nF and inductance of 10mH, the discriminant is

ISSN: 2594 - 2905

negative, this indicates an under-damped behavior.
Subsequently, with the help of Python, the different parameters describing the step response of the system were calculated, of which the most interesting ones are the peak time, maximum over-elongation and the settling time, the latter was calculated for a 2% error criterion as shown in Figure 4.

```
wn=(C)**(1/2)
E=B/(2*wn)
wd=wn*((1-(E**2))**(1/2))
tp=cmath.pi/wd
oh=wn*E
mp=cmath.e**((-oh/wd)*cmath.pi)
```

Figure 4. Parameters.

STEP RESPONSE
In the simulation and physical tests, a peak time of approximately 31µs, a settling time of 252µs and an over elongation of 60% were expected.

➢ Simulation in Proteus 8.

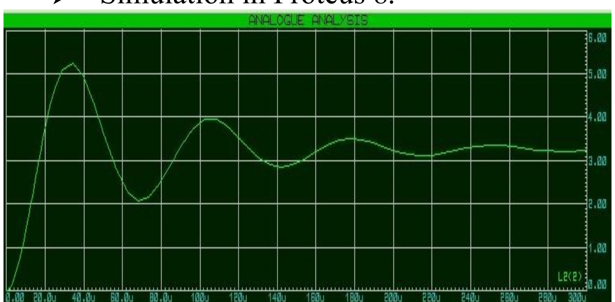


Figure 5. Simulation with step response.

➢ Simulation in Matlab

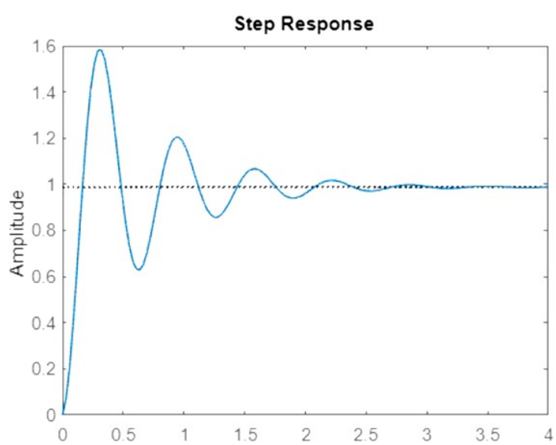


Figure 6. Matlab simulation with step response.

After the successful completion of the simulation, we proceeded the laboratory tests, in which the following results were obtained on the oscilloscope for the different response parameters.

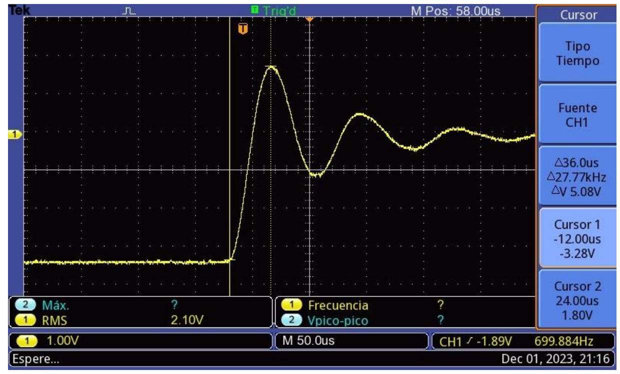


Figure 7. RLC Peak time.

➢ RLC circuit settling time.

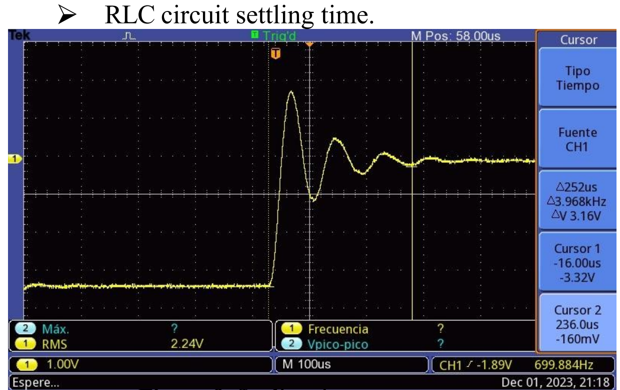


Figure 8. Settling time.

➢ Maximum overshoot of the RLC circuit.

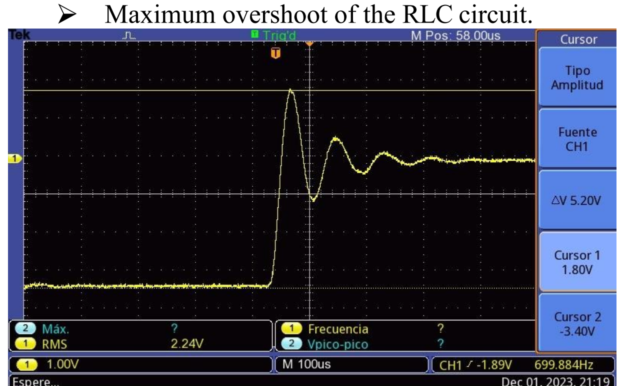


Figure 9. Maximum over impulse.

➢ Settling value of the RLC circuit.

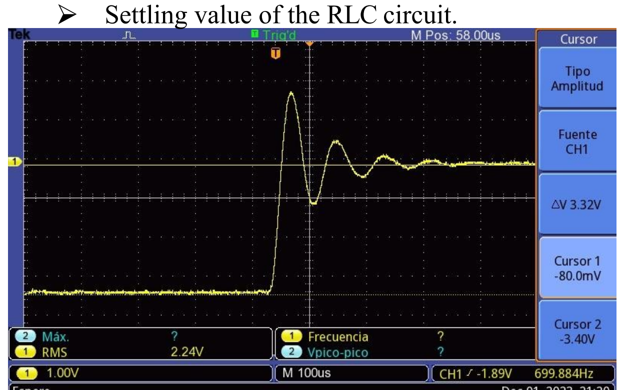


Figure 10. Settlement value.

ISSN: 2594 - 2905

Table 1. Comparative table of times obtained without compensator.

COMPARISON OF TIMES OBTAINED			
Weather	Proteus 8	Matlab	physical
tp	32 µs	31.9 µs	36 µs
mp	60%	58%	58%
t_s	250 µs	252 µs	252 µs
Vs	3.33 v	3.43 v	3.32 v
t_d	10 µs	10.16 µs	10.24 µs
t_r	15 µs	15.95 µs	16.17 µs

DESIGN OF AN ADVANCE COMPENSATOR.

For the design of the compensator it is necessary to make the analysis with the closed-loop transfer function, and as the function obtained from the RLC circuit is open-loop, the following clearance of the formula corresponding to the unitary feedback is made.

$$T(s)=\frac{G(s)}{1+G(s)} \therefore G(s)=\frac{T(s)}{1-T(s)} \qquad \text{Eq. (11)}$$

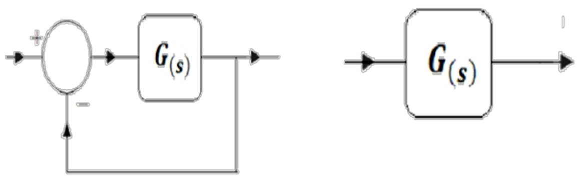


Figure 11. Closed loop and open loop.

The operation is performed to obtain G(s).

$$T(s)=\frac{R_3LS+R_3R_2}{CLR_3(R_1+R_2)^2 S^2+(R_1L+R_1R_2R_3C+R_2L+R_3L)S+(R_1R_2+R_3R_2)} \qquad \text{Eq. (12)}$$

$$G(s)=\frac{R_3LS+R_3R_2}{CLR_3(R_1+R_2)^2 S^2+(R_1L+R_1R_2R_3C+R_2)LS+R_1R_2} \qquad \text{Eq. (13)}$$

$$G(s)=\frac{9881.42S+9881422924.9}{S^2+21857.7S+11857707.09} \qquad \text{Eq. (14)}$$

For this closed-loop transfer function, the corresponding poles and zeros are as follows.

Poles**:**

S = -10000

S = -11857

Zero**:**

S= 1000000

With respect to the open loop function the corresponding poles, zeros and natural frequency are as follows:

$$T(s)=\frac{9881.42S+9881422924.9}{S^2+31739.13S+10000000000} \qquad \text{Eq. (15)}$$

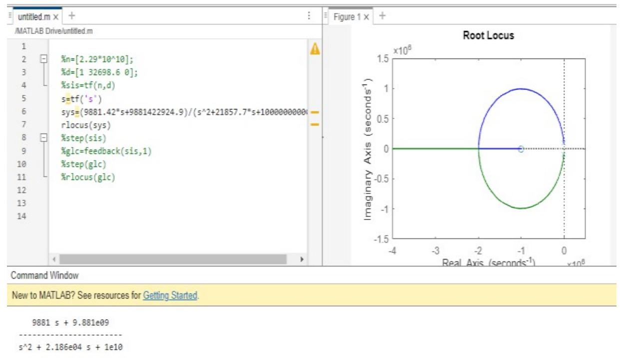


Figure 12. LGR in open loop.

Poles:

S= -15869± 98732j

Zero:

S= 1000000

Damping factor Ξ = 0.158

Natural frequency

Wn =100000

For the compensator, values are proposed for ε=0.5 and ωn = 50000, since the aim is to reduce the settling . With these we obtain a new equation

$$S^2+50000S+2500000000 \qquad \text{Eq. (16)}$$

Equalizing to zero and clearing S, we obtain the poles of this new equation

$$s= -25000\pm 25000\sqrt{3}j \qquad \text{Eq. (17)}$$

Once these values are available, the Angle deficiency between the poles and zeros of the closed loop system and the desired pole is calculated.

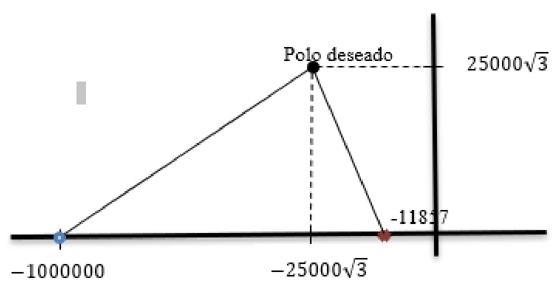


Figure 13. Angle deficiency.

$$P1\ \varnothing=180°-\tan^{-1}(25000\sqrt{3}/13143) \qquad \text{Eq. (18)}$$

$$P2\ \varnothing=180°-\tan^{-1}(25000\sqrt{3}/15000) \qquad \text{Eq. (19)}$$

$$C\varnothing=180°-\tan^{-1}(25000\sqrt{3}/975000) \qquad \text{Eq. (20)}$$

Table 2. Poles and zeros.

POLO	ANGLE
S =− 10000	109.11°
S =− 11857.65	106.88°
ZERO	ANGLE
S =− 1000000	2.54°

$$+C\varnothing - P1\varnothing - P2\varnothing \quad \text{Eq. (21)}$$

$$\text{Deficiency}= 180° + 2.54° - 109.11° - 106.88° \quad \text{Eq. (22)}$$

$$\text{Deficiency}= -33.45° \quad \text{Eq. (23)}$$

Having the deficiency angular is a is performed procedure to find the poles and zeros of the compensator, first draw a horizontal line at the desired pole, then a line from the origin to the desired pole, then draw a line in the middle, from which 2 more lines will be drawn cutting the real axis and these values correspond to the compensator.

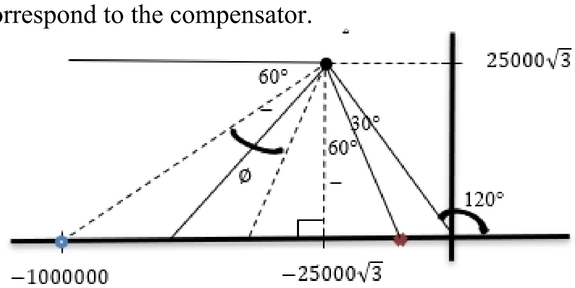
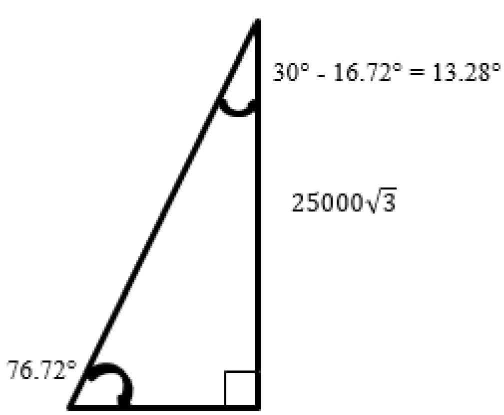


Figure 14. Determination of the pole and zero of a feedforward network.

Obtaining zero.



$$\tan(76.72°)=\frac{25000\sqrt{3}}{CA} \quad \text{Eq. (24)}$$

$$CA=\frac{25000\sqrt{3}}{\tan(76.72°)} \quad \text{Eq. (25)}$$

$$CA= 10220.02 \quad \text{Eq. (26)}$$

$$C= -25000 - 10220.02 \quad \text{Eq. (27)}$$

$$C= -35220.02 \quad \text{Eq. (28)}$$

Obtaining the pole.

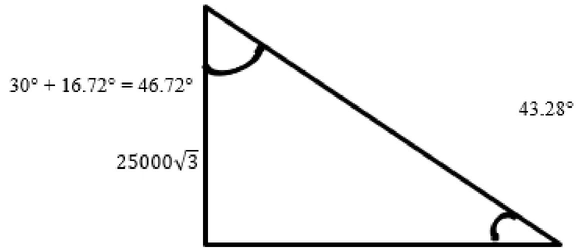


Figure 16. Method of obtaining the pole.

$$\tan(43.28°)=\frac{25000\sqrt{3}}{CA} \quad \text{Eq. (29)}$$

$$CA=\frac{25000\sqrt{3}}{\tan(43.28°)} \quad \text{Eq. (30)}$$

$$CA= 45982.33 \quad \text{Eq. (31)}$$

$$P= -25000 - 45982.33 \quad \text{Eq. (32)}$$

$$P= -70982.33 \quad \text{Eq. (33)}$$

With the pole and zero obtained, the equation of the compensator is written.

$$G(S)= Kc\frac{S+35220.03}{S+70982.33} \quad \text{Eq. (34)}$$

$$T= (35220)^{-1} \quad \text{Eq. (35)}$$

$$T= 28.3929\times 10^{-6} \quad \text{Eq. (36)}$$

$$\alpha T= (70982.33)^{-1} \quad \text{Eq. (37)}$$

$$\alpha= 0.4961 \quad \text{Eq. (38)}$$

$$Kc= 0.305 \quad \text{Eq. (39)}$$

$$G(S)= 0.305\frac{S+35220.03}{S+70982.33} \quad \text{Eq. (40)}$$

Determination of Kc from the condition of magnitude.

$$\left|Kc\cdot\frac{S+35220.02}{S+70982.33}\cdot\frac{9881.42S+9881422924.9}{S^2+21857.7S+11857707.09}\right| \quad \text{Eq. (41)}$$

$$Kc= \left|\frac{(S+70982.33)(S^2+21857.7S+11857707.09)}{(S+35220.02)(9881.42S+9881422924.9)}\right| \quad \text{Eq. (42)}$$

The open-loop transfer function of the designed system is:

$$F(s)= \left[0.305\frac{S+35220.03}{S+70982.33}\right]\left[\frac{9881.42S+9881422924.9}{S^2+21857.7S+11857707.09}\right] \quad \text{Eq. (43)}$$

The resulting closed-loop transfer function is:

$$\frac{3013.833s^2+3119981254.15316s+1.06147x10^{14}}{s^3+95853.8631s^2+4790068803.68416s+1.14564x10^{14}} \quad \text{Eq. (44)}$$

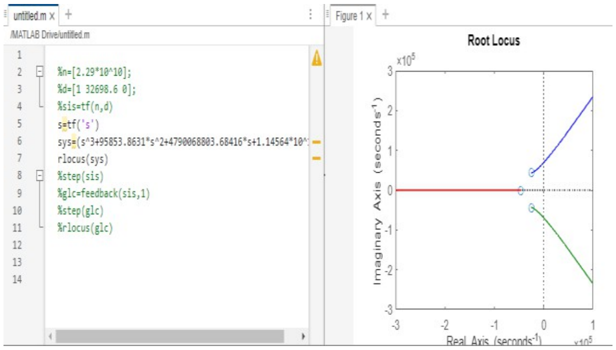


Figure 17. LGR with compensator and feedback.

The values of the components to be used for the compensator are determined.

$$0.305=\frac{R4R4C1}{R3C2} \quad \text{Eq. (45)}$$
$$0.4961=\frac{R2C2}{R1C1} \quad \text{Eq. (46)}$$
$$28.3929\times 10^{-6}= R1C1 \quad \text{Eq. (47)}$$
$$1.43\times 10^{-3}= R2C2 \quad \text{Eq. (48)}$$
$$R1= 283.92 \quad \text{Eq. (49)}$$
$$R2= 1435.3 \quad \text{Eq. (50)}$$
$$R3= 5100 \quad \text{Eq. (51)}$$
$$R4= 155.5 \quad \text{Eq. (52)}$$
$$C1= 100nF \quad \text{Eq. (53)}$$
$$C2= 10nF \quad \text{Eq. (54)}$$

After obtaining F(s), the procedure is performed to visualize the peak and maximum times on impulse of the RLC circuit with the compensator and feedback, the verification of these times is performed with the oscilloscope.

```
>> test

ans =

  -2.4989e+04 + 4.3276e+04i
  -2.4989e+04 - 4.3276e+04i
  -4.5875e+04 +          0i

ans =

  -1.0000e+06
  -3.5220e+04
```

Figure 18. Poles and zeros.

For the calculation of the times, Matlab was used to obtain the poles of the transfer function of the already compensated system, where the imaginary part of dominant poles corresponds to Wd, with these the other parameters are calculated.

$$w_d= 4.3276\times 10^4 \quad \text{Eq. (55)}$$

$$\frac{3013.833s^2+3119981254.15316s+1.06147x10^{14}}{(s^2+50000s+2490000000)(s+4.5875\times 10^4)} \quad \text{Eq. (56)}$$

$$wn= 50000 \quad \text{Eq. (57)}$$
$$\zeta= 0.5 \quad \text{Eq. (58)}$$
$$tp= 72us \quad \text{Eq. (59)}$$
$$\partial= 25000 \quad \text{Eq. (60)}$$
$$mp= 0.16 \quad \text{Eq. (61)}$$
$$t_s= 160us \quad \text{Eq. (62)}$$

- Weather peak with compensator and feedback.

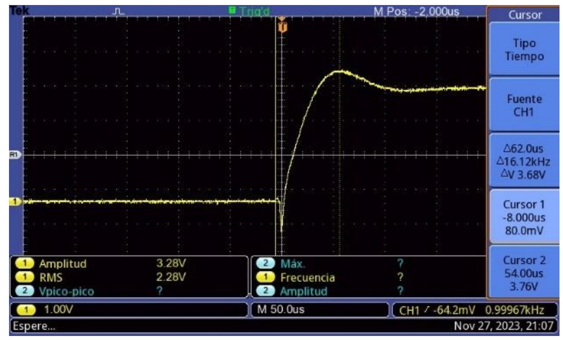


Figure 19. Peak time with compensator and feedback.

- Maximum overdrive with compensator and feedback.

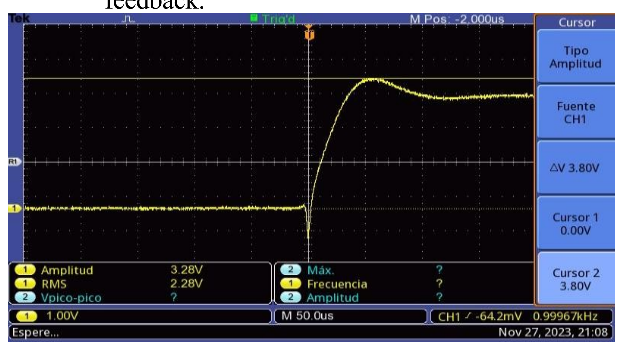


Figure 20. Maximum overshoot with compensator and feedback.

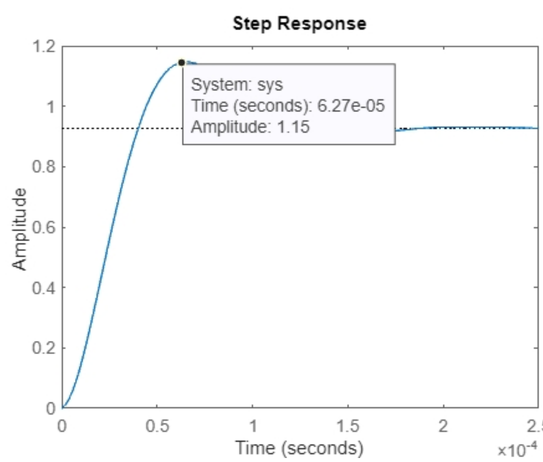


Figure 21. Underdamped signal with compensator and fed back in Matlab.

Comparative table of times obtained with compensator.

COMPARISON OF TIMES OBTAINED			
Weather	Proteus 8	Matlab	physical
tp	64 µs	62.7 µs	62 µs
mp	16%	15%	16%
t_s	168 µs	168 µs	168 µs
Vs	3.33 v	3.36 v	3.32 v
t_d	25.8 µs	23.1 µs	23.6 µs
t_r	44 µs	38.7 µs	39.3 µs

DISCUSSION AND ANALYSIS OF RESULTS

To contextualize the results obtained in this study, it is relevant to compare our findings with previous research in the field of control engineering and electrical systems.

The work of Quintero et al. (2020) used the same method of developing a compensator as the one shown in this study, so that the results in both studies were to improve the behavior of underdamped signals, in terms of stability and transient response of the system. Although naturally, the data, values and elements of the RLC circuits did not have similarities, it is notable that the techniques employed were the same and the overall expected results were the same.

Similarly, the results can be obtained but with a different approach, which seeks to improve the control and stability of the system, highlighting the relevance of different methods in the optimization of control systems such as the analysis by the bode stability criterion [1].

An additional study implemented a Proportional Integral Derivative (PID) control, tuning its parameters using the Ziegler-Nichols method[2]. This method is different from the one used in our study and the others mentioned above, since Ziegler-Nichols is based on an empirical approach to tune the PID controller parameters with the objective of improving the system response.

Although the Ziegler-Nichols method and the design of feedforward compensators have different theoretical foundations and implementation procedures, both aim to improve the stability and transient response of the controlled system.

In comparison, the results of our study show that the use of the LGR-designed feedforward compensator can provide an accurate and controlled improvement in transient response and system stability, similar to the results obtained with a Ziegler-Nichols tuned PID controller. However, the process of design and parameter tuning in our approach can be more direct and based on the mathematical analysis of the poles of the system, in contrast to the more empirical approach of the Ziegler-Nichols method.

After designing the compensator, we proceeded to simulate it with the help of the Proteus software, where the Op-Amp was used to apply the compensator, shown in Figure 22.

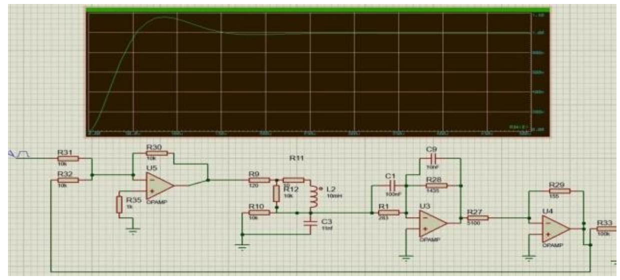


Figure 22. Circuit with simulated compensator.

The next step, naturally, is the implementation of the circuit once the times and values of the compensator have been checked, as these must be equal to calculated, for the implementation of the circuit Op-Amps of the UA741CN model were used, which, despite having 8 terminals, only include one Op-Amp each, so 4 in total were used (Figure 23.).

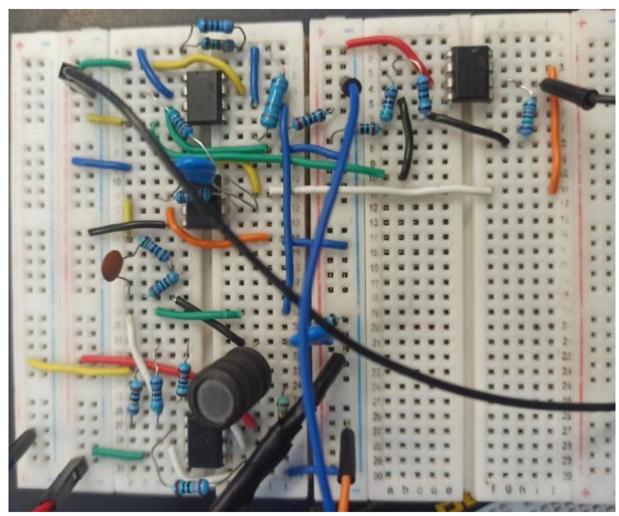


Figure 23. RLC circuit with compensator implemented.

After several tests where the results were often not convincing, finally the problems were solved, such as bad connections on the "breadboard" or even deficient or unreliable material due to its large margin of error such as some voltage sources and oscilloscope probes. However, when the times and values were equal or very close to those obtained in the simulation, we continued to the next step, the implementation of the circuit on PCB.

The circuit design was made in EasyDEA, a software that facilitates the creation of a circuit design.

PCB (Fig 24) and also where it is possible to request the creation of the same with the ease of home delivery.

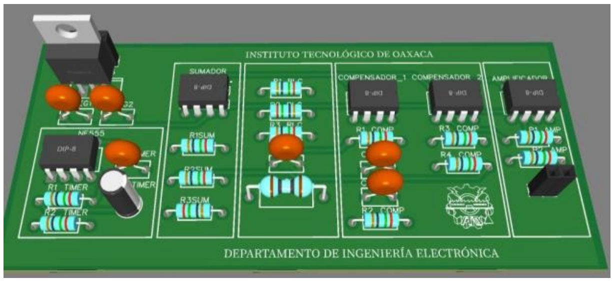


Figure 24. PCB layout.

Finally, the PCB was soldered together with the respective components and final tests were performed to monitor that all results will remain the same.

Figure 25. Finished PCB.

CONCLUSIONS

Summarizing, in this report, an RLC circuit was analyzed to obtain its transfer function and the times and values associated with an underdamped response were evaluated. Subsequently, a compensator specifically designed to modulate this signal was implemented, seeking to improve the transient response and the stability of the system.

The compensator was designed with the objective of adjusting the dynamics of the underdamped RLC circuit, optimizing the response in terms of settling time, overshoot and unwanted oscillations. This approach is based on the use of additional components or control techniques to selectively influence the system response.

In terms of practical applications, this type of compensator is important in industrial and technological contexts. For example, in process control systems, the implementation of compensators can significantly improve the stability of industrial processes, reducing undesired response times and minimizing unwanted oscillations.

Also, in the field of power electronics, the application of compensators in underdamped RLC circuits contributes to optimize the response of the power electronics. transient of switch-mode power supplies, improving the efficiency and quality of the power supplied.

Thus, this project not only addresses the theory and analysis of an underdamped RLC circuit, but also demonstrates the practical utility of compensators in modifying and improving the dynamic response of such a system, with potential applications in various areas of engineering and technology.

In future studies, the application of other types of compensators, within the same LGR analysis, such as the lag compensator and also the leading-lag compensator, will be explored to further improve the performance of underdamped RLC circuits.

Another step would be to consider the use of frequency analysis techniques for the design and optimization of compensators. This approach will allow us to evaluate the response in different frequency bands, thus optimizing system performance in terms of stability, transient response and noise suppression.

ACKNOWLEDGMENTS

We thank the Instituto Tecnológico de Oaxaca and the Department of Electronic Engineering for the loan of the laboratory and equipment for this project.

BIBLIOGRAPHY .

[1] Orlando, S. V., & Rosario, L. O. M. (2019). Design of a forward compensator by means of the bode stability criterion to control the displacement of a dc motor, International congress of electronic engineering electro memo, (41), 224-229. https://itchihuahua.mx/revista_electro/2019/CON-2_C.pdf

[2] Thomas, N., & Poongodi, P. (2009, July 1-3). Position Control of DC Motor Using Genetic Algorithm Based PID Controller. World Congress on Engineering 2009, 1, 1618-1622. http://iaeng.org/publication/WCE2009/WCE2009_pp1618-1622.pdf

[3] The Operational Amplifier - Practical Applied Electronics (2023, December 2). diarioelectronicohoy since 2002 professional electronics technical newspaper. professional . https://www.diarioelectronicohoy.com/blog/el-amplifier-operational

[4] The response of an RC circuit to a step voltage (article)| Khan Academy. (2023, December 2). Khan Academy. https://es.khanacademy.org/science/electrical-engineering/ee-circuit-analysis-topic/ee-natural-and-forced-response/a/ee-rc-step-

response#:~:text=Si%20el%20cambio%20es%20un,es%20una%20respuesta%20al%20escalón
[5] Alexander, C. K. (2008). Fundamentals of electric circuits (4th ed.). McGraw-Hill.
[6] Boylestad, R. L., & Nashelsky, L. (2003). Electronics: theory of circuits and electronic devices. Pearson education.
[7] Floyd, T. L., Salas, R. N., González, L. M. O., & López, G. P. (2007). Principles of electrical circuits. Pearson Educación.
[8] Sadiku, M. (1999). Elements of Electromagnetism. Compaia Ed. Cont.
[9] Floyd, T. L. (2002). Electronic Devices. Ed. Limusa S.A. C.V.
[10] Introduction to control systems: concepts, applications, and simulation with MATLAB (1st ed.) (2010). Pearson Education, S.A. http://lcr.uns.edu.ar/fcr/images/Introduccion%20a%20The%20Control%20Systems%20of%20Control%20.pdf
[11] Bernardoni, R., & R D. Novodvoretz, O. (n. d.). Guide to study 8: Circuits RLC series. https://www.inet.edu.ar/wp-content/uploads/2020/07/ELECTRONICS_Gu-- a08-RLC--circuits.pdf
[12] Santos, C. o. V., & Echavarría, J. L. R. (2012). Fundamentals of electrical circuits. Metropolitan Institute of Technology.
[13] Ornelas, F. (n. d.). Analog control II Design and compensation of systems in the frequency domain. Umich. https://dep.fie.umich.mx/~fornelas/data/uploads/pres_03_dc.pdf
[14] Ogata, K. (2010). Modern control engineering 5th ed.). Pearson Educación, S. A. https://ingenierovizcacom/material/libros/sd/ingino.enieria-de-control-moderna-ogata-5ed.pdf.
[15] Quintero-Rojas, J., C. B., & Coronel, M. (2020). Design and construction of an analog control module type forward-retarder as a learning tool in control theory. Technical Journal of the Faculty of Engineering, University of Zulia, 43(3), 150-158. https://www.redalyc.org/articulo.oa?id=605766264006

CONTRIBUTION ROLES

Role	Author(s)
Conceptualization	Milton Cruz Gómez (collaborator) Pablo Moisés Sosa Cruz (Contributor)
Data Curation	Milton Cruz Gomez Pablo Moises Sosa Cruz
Administration from project	Fidel González Playas (Contributor)
Resources	Milton Cruz Gómez (collaborator) Pablo Moises Sosa Cruz (collaborator)
Software	Milton Cruz Gómez (collaborator) Pablo Moisés Sosa Cruz (Contributor)
Supervision	Cesar Hernández Sánchez (principal)
Validation	Carlos Mauricio Lastre Domínguez (collaborator)
Visualization	Carlos Mauricio Lastre Domínguez (collaborator)
Redaction (original draft)	Milton Cruz Gómez (collaborator) Pablo Moisés Sosa Cruz (collaborator) Cesar Hernández Sánchez (principal)
Editorial staff (proofreading and editing)	Fidel González Playas (collaborator)