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Assessment of IAE and ITAE-based objective functions for PID controller tuning in buck converters within space systems

Avaliação de funções objetivo baseadas em IAE e ITAE para ajuste de controlador PID em conversores buck em sistemas espaciais

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Abstract

Precise tuning of PID controller gains is essential for effective system regulation achieving desired stability criteria and minimizing errors. Various PID tuning techniques have been explored in literature, but some may yield suboptimal results. In this context, the use of genetic algorithms emerges as a promising approach to enhance PID controller tuning. This study presents the application of this algorithm for tuning the PID parameters of a buck converter, considering different objective functions in the optimization problem description. The results were satisfactory highlighting the superiority of the optimized PID compared to the PID tuned using the relay method. The most significant finding was that the optimization using the IAE objective function proved to be substantially more effective showing about a 46% improvement compared to the relay method. This underscores the effectiveness of genetic algorithms in optimizing PID controllers for space systems.

Keywords:
Genetic Algorithm. PID tuning. Buck Converter.

Abstract

O ajuste preciso dos ganhos do controlador PID é fundamental para garantir uma regulação eficaz do sistema, atingindo os critérios de estabilidade desejados e minimizando erros. Diversas técnicas de ajuste de PID foram testadas na literatura, mas algumas podem resultar em desempenhos subótimos. Neste contexto, o uso de algoritmos genéticos mostra-se promissor para aprimorar o ajuste do controlador PID. Este estudo aborda a aplicação desse algoritmo para ajustar os parâmetros PID de um conversor buck, considerando diferentes funções objetivos na descrição do problema de otimização. Os resultados obtidos foram satisfatórios, destacando a superioridade do PID otimizado em comparação ao PID ajustado pelo método de relé. O resultado mais relevante foi que o ajuste otimizado utilizando a função objetivo IAE demonstrou ser significativamente mais eficaz, apresentando cerca de 46% de melhoria em comparação ao método de relé, enfatizando a eficácia dos algoritmos genéticos na otimização de controladores PID em sistemas espaciais.

Palavras-chave:
Algoritmo Genético. Ajuste PID. Conversor Buck.

1 INTRODUCTION

The control of industrial processes can be accomplished through various methods including PI (Proportional and Integral) control and PID (Proportional, Integral, and Derivative) control, which remain prevalent in the industrial domain (ÅSTRÖM; HÅGGLUND, 2001). This is primarily attributed to their favorable performance when appropriately calibrated and their widespread adoption by a majority of manufacturers despite variations in implementation (ISERMANN, 1989).

In order to ensure exhibit proper performance of the PID controller precise tuning of its gains - namely, the proportional, integral, and derivative constants - is imperative. This meticulous calibration enables the controller's actions to effectively regulate the system facilitating its stabilization in accordance with specified criteria, such as minimizing steady state error, achieving desired settling time and mitigating overshoot (ISERMANN, 1989). Although PID control demonstrates high applicability, its tuning, i.e., the adjustment of its gains can pose a significant challenge. This is due to the fact that the tuning process depends on the specific plant being controlled. Such plants can encompass diverse domains including steel production (CALVO-ROLLE et al., 2013), automotive industries (COPANI et al., 2022), and aerospace systems (XU; ZHANG, 2018).

Recent advancements in space technology have seen a significant increase in the deployment of automated systems. According to Borin et al. (2019), Chang et al. (2022), Chen et al. (2023) the use of PID-based control in space systems has improved operational efficiency underscoring the importance of precise control mechanisms.

The main objective of this study is to explore the application of Genetic Algorithms for precise tuning of PID controller parameters specifically designed for a buck converter aiming to optimize system response and minimize absolute error. Due to the potential variation in results based on the construction of the objective function the paper evaluates some objective functions to assess how the choice of function can influence the tuning outcome.

As a case study, a Buck converter will be used, which is employed to regulate the voltage level supplied to various components of the satellite operating at different voltage levels (MAGALHÃES; MOREIRA, 2020; IBRAHIM et al., 2019; CHIU; KIM, 2023). The present study builds upon the findings of Mattos et al. (2021). As proposed by Mattos et al. (2021), tuning the PID controller of a Buck converter presents significant challenges due to parametric variations in input voltage or load that may occur during operations. This research extends the original findings by incorporating the application of genetic algorithms for the tuning process.

2 PROBLEM STATEMENT

According to Somefun, Akingbade and Dahunsi (2021), there are multiple approaches to perform the tuning of the PID controller and these methods can be classified into three categories: plant-model based, hybrid methods, and plant-model free methods. Each method requires a different configuration and may also necessitate fine adjustments that do not ensure that the controlled plant will meet the specifications. In order to overcome the difficulties encountered in each method, it is possible to resort to optimization algorithms (hybrid methods) to perform the search for the PID controller parameters (JOSEPH et al., 2022; BORIN et al., 2019).

One of the most commonly used optimization algorithms for PID controller tuning is the Genetic Algorithm (GA), which seeks individuals (solutions) that best meet the problem requirements (KALAVANI et al., 2019).

Although the GA is efficient the objective function needs to be well-designed in order that the algorithm optimizes the problem. However, establishing the objective function is not always an easy task. Each author devises an objective function, and among the most common ones are (JOSEPH et al., 2022):

a. Integral Absolute Error (IAE)

$$IAE = \int_0^{\tau} |e(t)| \quad (1)$$

b. Integral Time Absolute Error (ITAE)

$$ITAE = \int_0^{\tau} t|e(t)| \quad (2)$$

In this study, we aim to individually assess the efficacy of Equations (1) to (2), which are treated as distinct objective functions, to determine which yields the most favorable outcome for PID tuning in the context of the Buck converter.

3 METHODOLOGY

3.1 Buck Converter Modeling

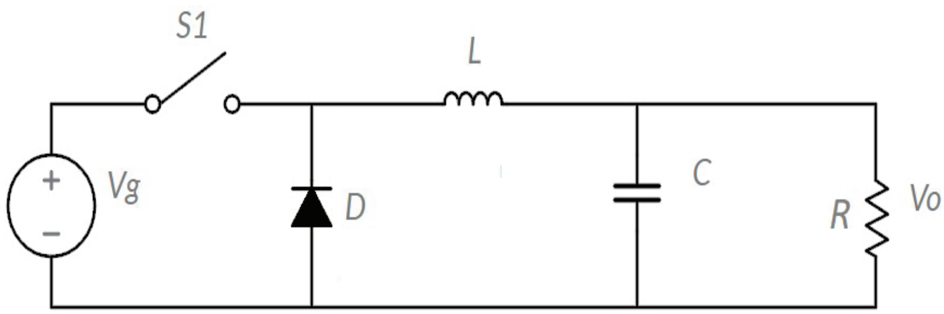
The characterization of the Buck converter, illustrated in Figure 1, was conducted using state-space modeling. This method is encapsulated in Equations 3 and 4.

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (3)$$

$$y(t) = Ex(t) + Fu(t) \quad (4)$$

In addressing the operation of the Buck converter, depicted in Figure 1, it is imperative to clarify that the study considers the average model of the converter. This model encapsulates the average effects of the Pulse Width Modulation (PWM) switching behavior over time, rather than a static ‘switch-closed’ condition. When the switch is closed, the diode (D) is reverse-biased preventing current flow. Conversely, when the switch is open, the inductor (L) releases energy to the load (R) and capacitor (C). The average model, therefore, represents the continuous-time behavior of the converter with the duty cycle of the switch dictating the average output voltage (Vo). The state-space representation for this average model is described by Equations 5 and 6, which account for the dynamics of the PWM switching and provide a more accurate depiction of the converter’s operation.

Figure 1 – Buck Converter.



Source: SEVERNS and BLOOM (1985).

$$\begin{bmatrix} \left(\frac{dI_L}{dt}\right) \\ \left(\frac{dv_C}{dt}\right) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{CR} \end{bmatrix} * \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} * V_g \quad (5)$$

$$V_O = \begin{bmatrix} 0 & 1 \end{bmatrix} * \begin{bmatrix} i_L \\ v_C \end{bmatrix} + [0] * V_g \quad (6)$$

Table 1 – Buck Converter Parameters.

Parameters	Description	Case			
		1	2	3	4
V_g $[V]$	Input Voltage	25	25	30	30
V_o $[V]$	Output Voltage	15			
C [μF]	Filter Capacitance	100			
L [μH]	Filter Inductance	100			
f_s $[MHz]$	Switching frequency	30			
R [Ω]	Load	0.5	1	0.5	1

Source: MATTOS et al. (2021)

Based on the presented Equations, the state-space model of the Buck converter can be derived as presented by Mattos et al. (2021). To accomplish this, it is essential to determine the variable values, as indicated in Table 1, where Case 1 represents the ideal system condition without any parameter variations, Case 2 and Case 3 represent intermediate scenarios, and Case 4 represents the worst-case scenario, as it shows the highest resonance peak.

3.2 Reference PID

According to Mattos et al. (2021), the parametric variations in and are due to fluctuations in the input bus voltage or changes in load during the operation of the system where the Buck converter is employed. In this work, the values of the worst-case scenario will be considered, i.e., and , for the establishment of the PID gains, as shown in Table 1.

However, in order to restrict the search space of the genetic algorithm a reference PID was defined using the relay method. This method aims to introduce controlled and limited oscillations into the system as proposed by Åström and Hågglund (1984). The parameters found are:

$K_{pREF} = 0.3518$;

$T_{iREF} = 1.5684 * 10^{-4}$; and

$T_{dREF} = 3.9211 * 10 - 5$.

The Equation 7 is modified by substituting the PID values.

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right) \tag{7}$$

where (OGATA, 2010):

- K_p - proportional gain - adjusts the controller output based on the magnitude of the error.
- T_i - integral gain - involves accumulating the past error information to eliminate any steady-state offset.
- T_d - derivative gain - anticipates the future trend by utilizing the predicted future values of the control error. This helps accelerate the response time of the system.

3.3 Controller Performance

The Equations 1 to 2 describe the objective function (J) that will be used in the optimization problem, which will be described as follows: Minimize:

$$F(x) = J \tag{8}$$

where,

$$x = \{K_p, T_i, T_d\} \tag{9}$$

Subject to:

$$\frac{K_{pREF}}{100} \leq K_p \leq K_{pREF} * 100 \tag{10}$$

$$\frac{T_{iREF}}{100} \leq T_i \leq T_{iREF} * 100 \tag{11}$$

$$\frac{T_{dREF}}{100} \leq T_d \leq T_{dREF} * 100 \tag{12}$$

The Genetic Algorithm (GA) comprises three main operators that simulate natural selection: selection, crossover, and mutation (GOLDBERG, 1989).

The initial population within our GA is selected based on a criterion of randomness within a stipulated range defined by Equation 10 to 12. This approach ensures a diverse yet representative sample of potential solutions, which is crucial for enhancing the convergence speed and accuracy of the optimization process.

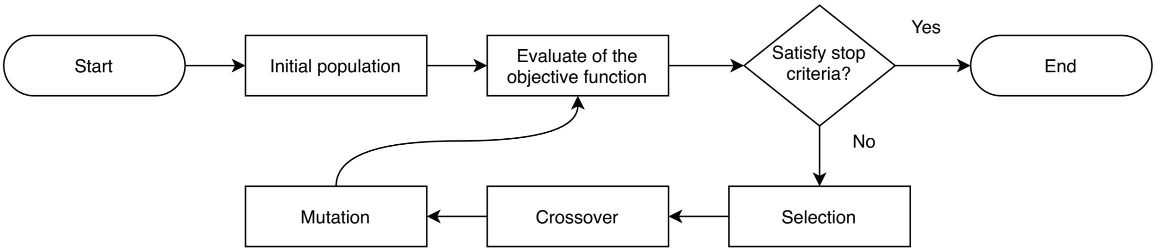
The Genetic Algorithm (GA) was configured ad-hoc utilizing the parameterization detailed in Table 2. Two stopping criteria were adopted for the Genetic Algorithm: the first relates to the number of evaluations of the objective function, specifically after 100,000 evaluations. The second criterion pertains to the maximum number of stall generations with a tolerance of . Consequently, if there are no improvements in the objective function, i.e., a difference within the tolerance, after 50 generations the algorithm will terminate the search for the optimal PID parameters.

Table 2 – GA hyperparameters setup.

Parameter	Value
Initial population	Random
Number of evaluations	100000
Population size	50
Selection	Roulette
Crossover	One point
Crossover rate	0.8
Mutation	0.01

The GA algorithm continues to run until the termination criteria are met. For a comprehensive description of the GA algorithm, refer to Goldberg (1989). A simple representation of the GA algorithm is depicted in Figure 2.

Figure 2 – Genetic Algorithm.



Source: Rodrigues et al. (2021)

To ensure a consistent basis for comparison among different objective functions the Root-Mean-Square Error (RMSE) was used to calculate the system response after optimization, as Equation 13.

$$E_{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[(y_i - \hat{y}_i)^2]} \quad (7)$$

4 RESULTS AND DISCUSSIONS

Table 3 presents the PID controller settings for the cases analyzed in this paper.

Table 3 – PID Gains.

Parameter	Relay	IAE	ITAE
K_p	0.3518	27.0657	26.6581
T_i	$1.5684*10^{-4}$	0.0146	0.0146
T_d	$3.9211*10^{-5}$	$1.8562*10^{-5}$	$1.8562*10^{-5}$
RMSE	2.4177	1.2833	1.2840

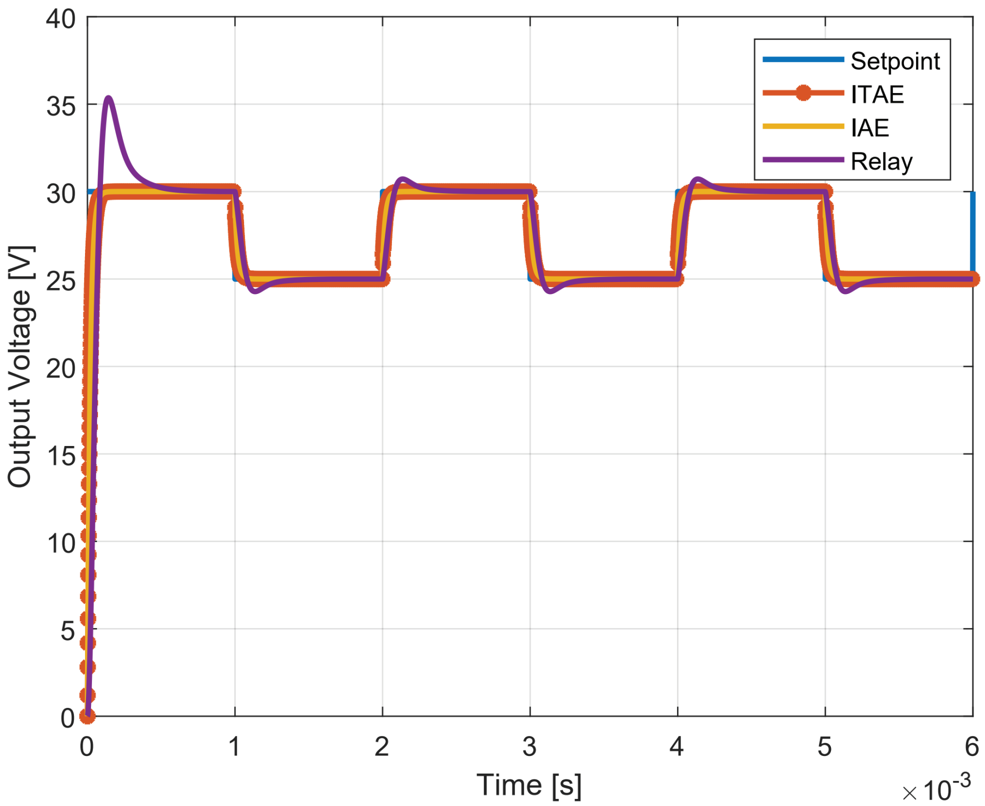
Source: The Authors (2023).

Figure 3 shows a comparison of the PID tuning approaches discussed in this article considering the output voltage variation from 25 to 30 V under the worst-case load scenario. With the relay method tuning some oscillations are observed suggesting room for improvement although the overall response meets the basic criteria for satisfaction. The responses with the optimized tunings were similar with the curves being almost completely superimposed.

In terms of the RMSE error, the relay method tuning resulted in a value of 2.4177, the ITAE objective function tuning yielded 1.2840, and the IAE objective function tuning achieved 1.2833. Therefore, the IAE objective function produced the best tuning set, that is, with the lowest IAE error. In relation to the relay method, the optimization obtained by the IAE objective function was approximately 46% better.

The Integral of Absolute Error (IAE) objective function outperformed others due to its direct measure of the magnitude of the error, which is particularly advantageous in space systems where consistent accuracy is critical for maintaining operational stability and avoiding cumulative errors. This finding is critical for system design and operation as it underscores the importance of minimizing error magnitude, which can have significant cumulative effects over the duration of a space mission, potentially affecting both mission success and the longevity of the spacecraft.

Figure 3 – Comparisons between the PID gain adjustments.



Source: The Authors (2023).

5 CONCLUSIONS

This study has demonstrated the effectiveness of using a Genetic Algorithm (GA) for the tuning of PID controller parameters in a Buck converter, which is critical for space systems. The results have shown that the IAE objective function provided the best tuning results among the tested functions yielding the lowest error and thus the most favorable system response under the worst-case load scenario. The optimized PID parameters tuned via the GA significantly outperformed those obtained through the relay method with approximately 46% better optimization in terms of the IAE objective function.

The implications of these findings are substantial for the design and operation of space systems, where precision and reliability are paramount. By ensuring more accurate control the longevity and success of space missions can be greatly enhanced. Moreover, the reduction in error magnitude achieved through the optimized PID tuning contributes to the overall stability and efficiency of the system, which is essential in the challenging environment of space.

For future work, it would be beneficial to explore the application of other objective functions in the PID tuning process. While the IAE objective function has proven effective in this context there may be alternative functions that could offer improvements in specific scenarios or for particular system dynamics. Testing different objective functions could provide a more comprehensive understanding of their impact on system performance and lead to the development of more advanced tuning methodologies. Additionally, further research could investigate the scalability of the proposed method and its applicability to other types of converters and control systems used in space technology.

In conclusion, the application of GA for PID tuning in space system components like the Buck converter shows promising improvements in system performance. The exploration of various objective functions remains an open field for enhancing the robustness and adaptability of control systems in the demanding realm of space exploration. For future studies, it might be beneficial to explore other objective functions for PID tuning to potentially improve the system dynamics and performance. Investigating the scalability of this method and its applicability to other types of converters and control systems in space technology could lead to more advanced tuning methodologies. This research paves the way for stronger and more adaptable control systems in the challenging and demanding realm of space exploration.

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