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Control and Monitoring System Design for Industrial Ovens: Identification and Tuning Methods

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Abstract: *This study investigates the identification and tuning of controllers for a resistive electric furnace using first-order system approximation methods. Three methods were compared: Ziegler-Nichols, Smith, and Hägglund. The results revealed that the Ziegler-Nichols method led to a significantly higher time constant, making it less suitable for systems with high dead time. The Smith and Hägglund methods yielded similar results, but Hägglund demonstrated greater robustness with a higher controllability factor. Using the Hägglund method as a basis, PI and PID controller parameters were determined using the Ziegler-Nichols, Tyreus-Luyben, and Cohen-Coon methods. PI controllers performed poorly, particularly in systems with high delays. The Ziegler-Nichols method showed the best performance, meeting control objectives with acceptable overshoot and settling time. These findings highlight the importance of selecting the appropriate identification and tuning methods to ensure effective and robust control of resistive electric furnace systems*

Keywords: *Process Automation, PID Controller, Temperature Control, Industrial Ovens, Control System Design*

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I. INTRODUCTION

The analysis and control of systems, as outlined by Lage (2018), form a fundamental area of engineering, focused on the mathematical modeling of systems and the implementation of strategies to optimize production processes. This optimization is crucial to minimizing time and resource wastage while improving efficiency and cost-effectiveness. Automatic control plays a critical role in a variety of industrial applications, including temperature, pressure, level, and flow control, in addition to more complex systems in industrial automation (Ogata, 2010; Odloak & Kwong, 2019).

Historically, the pursuit of effective control over physical systems has been driven by the dual goals of process optimization and operational safety. Manual control, the simplest form of intervention, has been sufficient in many domains where precision and flexibility are essential. However, as technology advanced and industrial operations became increasingly complex, it became clear that manual control could no longer meet the demands of modern applications (Prata, 2013; Lage, 2018).

This growing complexity in industrial systems has led to a pressing need for automation. Classical control methods, while effective for simpler systems, have proven inadequate in addressing the challenges posed by more dynamic and complex processes. The need for advanced control and tuning methods has thus become essential to meet the increasing demand for precision, stability, and responsiveness in modern industries (Bega, 2012; Ogata, 2010).

In light of these challenges, the objective of this study is to design and develop an advanced temperature control and monitoring system for industrial furnaces. These systems are integral to numerous industrial processes, where precise temperature regulation is critical to maintaining quality and efficiency. To achieve this, mathematical models are employed to identify the transfer function of first-order systems, and the performance of different PID controller tuning methods is evaluated. Specifically, the study compares the Ziegler-Nichols, Tyreus-Luyben, and Cohen-Coon methods to determine which approach offers the most effective solution for optimizing the furnace system (Ziegler & Nichols, 1942; Åström & Hägglund, 2004).

The insights gained from this research aim to contribute to the advancement of industrial automation by improving the design and implementation of robust, efficient, and effective temperature control systems.

II. DEVELOPMENT

2.1 Control Systems and Temperature Control.

A control system is an arrangement of components connected or related in such a way as to command, direct, or regulate itself or other systems. Temperature control plays a crucial role across diverse areas of industry and science, with applications ranging from research laboratories to industrial furnaces (Dantas, 2013).

Historically, temperature control dates back to antiquity, when rudimentary furnaces were used for metal smelting and ceramic production. However, significant advancements were only achieved in the late 18th century. James Watt, the inventor of the steam engine, developed a centrifugal governor to regulate boiler temperature, marking an important milestone in the evolution of temperature control (Prata, 2003; Phillips and Harbor, 1997; Guimarães, 2013, Domingues, 2007)

Aligned with the scope of this study, it is noteworthy that advances in sensor technology, such as thermocouples and resistance temperature detectors (RTDs), have enabled more precise measurements, thereby improving control efficiency. Several types of temperature measurement sensors exist, with emphasis on PT-100 thermocouples and MAX-6675 (type K) sensors, which will be utilized in the development of this study (Bega, 2012).

2.2 Methods for Determining PID Controller Parameters.

Modified PID structures are currently used in the industry, with various practical methods for smooth switching between manual and automatic operation, as well as programmed gain, being commercially available. However, as these controllers are often developed without an accurate model of the plant, adjustments can be challenging (Ogata, 2010).

Several methods exist for tuning PID controller parameters. In this study, the Ziegler-Nichols, Tyreus-Luyben, and Cohen-Coon methods were selected. Tuning involves determining parameter values for controllers such that the associated processes exhibit desired properties. For this reason, most PID controllers tend to be tuned in the field, contributing to precision enhancements.

Precision improvements in PID controllers are essential for enhancing the performance and response of the controlled system. By applying these methods, it is possible to significantly improve the accuracy and efficiency of PID controllers, ensuring that the operated system maintains optimized and stable performance.

2.2.1 **Ziegler-Nichols Methods.**

Among the proposed methods, the so-called "First Ziegler-Nichols Method" assumes the identification of the actual plant using a proposed algorithm, enabling the determination of delay (L), gain (K), and system time constant (τ) parameters, with a=KL/τ, which represents the value at which the tangent line intersects the ordinate axis to determine τ.

The PID controller parameters can be directly determined using the equations presented in Table 1. This method applies exclusively to first-order systems with delay and no finite zeros, whose unit step response curve assumes an "S" shape, as illustrated in Figure 1.

Table 1. Tuning Parameters for the First Ziegler-Nichols Method

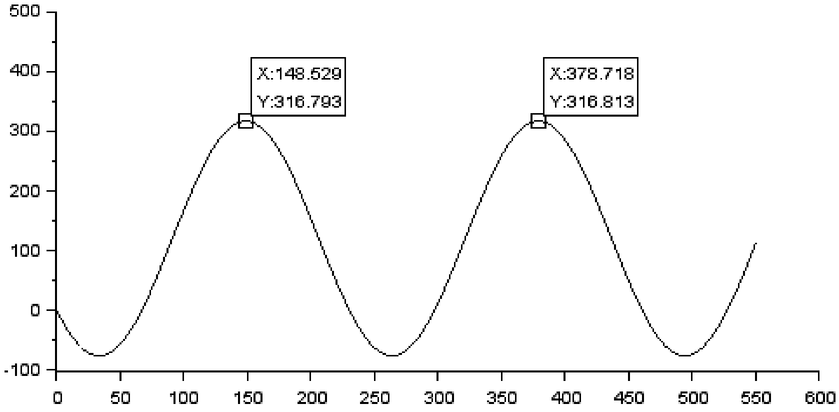
Controller	K_p	T_i	T_d
P	$\frac{\tau}{L}$	∞	0
PI	$0{,}9\frac{\tau}{L}$	$\frac{L}{0{,}3}$	0
PID	$1{,}2\frac{\tau}{L}$	$2L$	$0{,}5L$

Source: Ogata (2010)

For the "Second Ziegler-Nichols Method," it is considered that if the system response curve, under a unit step input, does not exhibit the "S" shape and the studied process includes input signal integrators, the first tuning method is not applicable. In this case, the application of the second method is initiated. The integrative (Ti = ∞) and derivative (Td = 0) parameter values are then adjusted (Ogata, 2010).

With these values entered into the controller and using only proportional gain action (Kp), Kp is varied from zero to a critical gain value (Kcr). Beyond this point, process control enters the instability zone, where the output response exhibits sustained oscillations in the form of a sinusoidal wave characterized by a critical period (Pcr). The PID controller parameters can be obtained using the equations described in Table 2 (Ogata, 2010).

Figure 1. Sustained Oscillation at the Critical Period



Source: Authors (2024)

Table 2. Tuning Parameters for the Second Ziegler-Nichols Method

Controller	K_p	T_i	T_d
P	$0{,}5K_{cr}$	∞	0
PI	$0{,}45K_{cr}$	$\frac{1}{2}P_{cr}$	0
PID	$0{,}6K_{cr}$	$0{,}5P_{cr}$	$0{,}125P_{cr}$

Source: Ogata (2010)

2.2.2 **Tyreus-Luyben Method.**

Analogous to the second Ziegler-Nichols method, the Tyreus-Luyben method seeks to identify the critical gain (Kcr), at which point the process control enters the instability zone, and the output response exhibits sustained oscillations with a critical period (Pcr) Ziegler-Nichols parameters are generally more aggressive, whereas the Tyreus-Luyben method offers a more conservative tuning approach (Ibrahim, 2016).

The Tyreus-Luyben method follows the same procedure as the closed-loop Ziegler-Nichols method. This method, however, is restricted to calculating parameters for PI and PID controllers. Similar to the closed-loop Ziegler-Nichols methods, the integral and derivative modes are initially disabled, effectively functioning as a proportional controller, to determine the values as outlined in Table 3.

Table 3. Tuning Parameters for the Tyreus-Luyben Method

Controller	K_p	T_i	T_d
PI	$0{,}31K_{cr}$	$0{,}31p_{cr}$	–
PID	$0{,}45K_{cr}$	$2{,}2P_{cr}$	$P_{cr}/0{,}63$

Source: Ibrahim (2016)

2.2.3 **Cohen-Coon Method.**

Similarly to the Ziegler-Nichols method, the Cohen-Coon method uses the real plant identification by approximating the first-order transfer function with delay. This method is also based on the quarter-decay criterion in response to a process disturbance. It was specifically developed for processes with higher dead times.

The key difference lies in its application to processes with significant dead times, i.e., where there is an uncontrollable factor within the range 0,4<L/τ<4,5. However, its robustness is relatively reduced for values L/τ<2 (Ibrahim, 2016). The PID controller parameters can be directly determined, as indicated in Table 4 (the value of aaa is obtained through calculations).

Table 4. Tuning Parameters for the Cohen-Coon Method

Controller	K_p	T_i	T_d
P	$\frac{1}{a}\left(1+\frac{L}{3\tau}\right)$	–	–
PI	$\frac{1}{a}\left(0{,}9+\frac{L}{12\tau}\right)$	$\frac{L(30\tau+3L}{9\tau+20L}$	–

PID	$\frac{1}{a}\left(\frac{4}{3}+\frac{L}{4\tau}\right)$	$\frac{L(32\tau+6L}{13\tau+8L}$	$\frac{4\tau L}{11\tau+2L}$

Source: Vasconcellos (2017)

2.3 **Performance Criteria of the Controller.**

In general, the performance evaluation of PID controller tuning is carried out using techniques that involve performance criteria, such as overshoot, rise time, settling time, and steady-state error, all of which will be considered in this study. Other techniques, such as variability analysis, can also be employed. Variability reflects the proximity of the process variable (PV) to its setpoint (SP), regardless of random disturbances (Filho, 2014). The primary criterion for process control tuning, which must always be pursued, is system stability.

According to Ogata (2010), some commonly used criteria include: Dead time – the delay between when a change or variation in the process variable occurs and when this change is observed; Rise time – the time it takes for the system to go from 10% to 90% of the steady-state value (setpoint); Overshoot Percentage – the extent to which the process variable exceeds the steady-state value, expressed as a percentage of the final value (values equal to or less than 25% are considered good or satisfactory); Settling time – the time required for the process variable to reach and stay within a certain percentage (commonly 5%) of the final value; Steady-state error – the final difference between the process variable and the setpoint under steady-state conditions.

Another significant aspect of the system, besides absolute stability, is the transient regime, which requires special attention. Since a physical control system contains stored energy, the system's output does not immediately follow the input when subjected to a signal, instead exhibiting a transient response before reaching steady-state conditions. Therefore, analyzing the behavior of the response during the transient regime is essential. These criteria can be calculated by monitoring the trajectory of the controlled variable relative to its desired reference value (setpoint) over an evaluation window.

III. EXPERIMENTAL PROCEDURE

3.1 **Company Overview.**

The study was conducted in a bakery industry located in the city of Beira, in the Ponta-Gêa neighborhood, Mozambique, Africa. The establishment focuses on production and commercialization. Its production capacity is approximately 800 units per hour, which equates to about 7,500 units per day. The products are distributed to direct customers (B2C), resellers (B2B), and neighboring communities..

3.2. **Matherials.**

3.2.1 **Oven Specifications and Measurement System**:

The oven studied in this work has the following technical specifications: Power Supply Voltage: 110 or 220 V; Nominal Current: 85 A; Operating Frequency: 60 Hz; Power: 18.70 Kw; Maximum Temperature: 240°C; Height: 2070 mm; Width: 3046 mm; Length: 2485 mm; Net Weight: 410 kg; Capacity: 12 trays of 60x800 cm.

Table 5 presents the relationship between the firing angle, temperature, and voltage variation in the oven's resistance.

Table 5. Relationship Between Angle, Temperature, and Voltage for the Oven

Angle	Voltage V_r	Temperature
34°	27	30 ℃
67°	55	60 ℃
135°	110	120 ℃
270°	220	240 ℃

Source: Authors (2024)

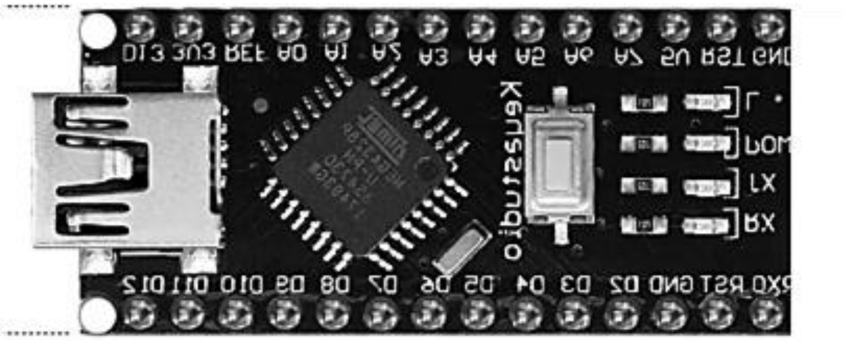
The oven consists of a step-down transformer/regulator that converts the power from 110/220 V to 30 V. The primary side (110/220 V) is connected to the power grid, while the secondary side is connected to the oven's resistance. For temperature measurement inside the oven, a K-type thermocouple (MAX-6675) was used. This thermocouple sends a 4 to 20 mA signal through its transmitter, proportional to the temperature, to an analog input on the controller. The controller then converts this value into Engineering Units, using it as the process variable (PV). The thermocouple used is illustrated in Figure 2.

To establish the interface between the computer and the oven/thermocouple setup, a data acquisition board was used. The board employed in this work was the Arduino Nano CH340 (Figure 3), manufactured by the same company. Among the relevant characteristics of this board are: Microcontroller: ATmega328P-AU; 16 analog input/output channels; Analog input range: ±5 V; Maximum input voltage: 12 V; Maximum input/output current: 40 mA.

Figure 2. K-type thermocouple kit (Max – 6675)

Source: Authors (2024)

Figure 3. Arduíno Nano



Source: Authors (2024)

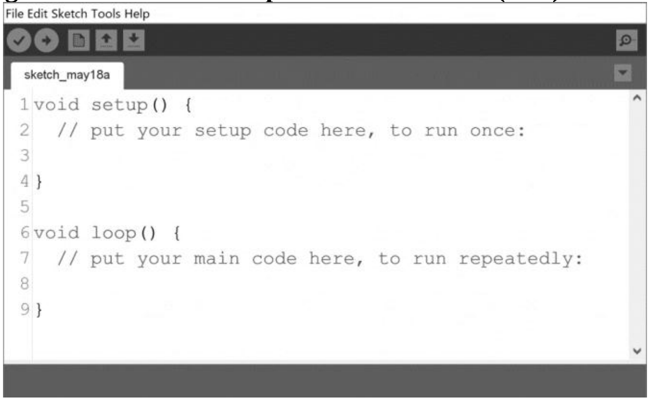
3.2.2 **Programming and Simulation Tools**

For programming the source code, the Arduino Integrated Development Environment (IDE) was used, as illustrated in Figure 4.

To carry out the necessary tests and adjustments for controller tuning, the software Scilab version 2023.1.0 (x64 binary) was employed. Scilab is a free, open-source tool that offers a wide range of mathematical functions, in addition to the ability to incorporate programs written in various programming languages. Within Scilab, we utilized the Xcos utility for simulation, which allows the graphical construction of mathematical models through block diagrams. The Xcos interface is shown in Figure 5.

The simulations were conducted on a computer with the following technical specifications: Processor: Intel Core i5-2400, 3.10 GHz CPU; RAM: 4.00 GB installed; Operating System: Windows 10 Pro (Version 21H2, 64-bit).

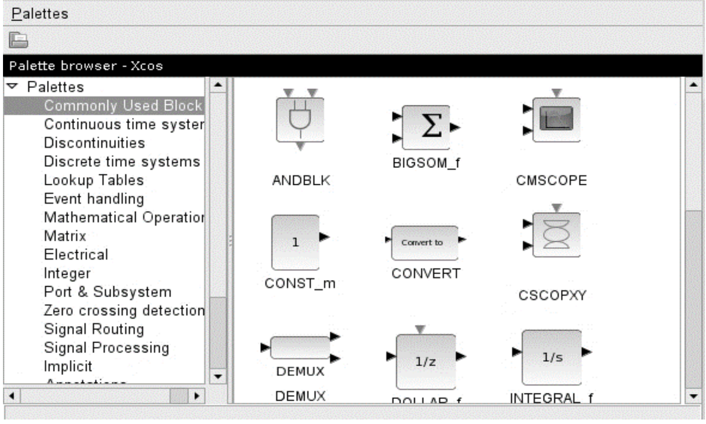
Figure 4. Arduino development environment (IDE) interface



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Source: Authors (2024)

Figure 5. Xcos Interface



Source: Authors (2024)

IV. RESULTS AND DISCUSSIONS

One of the most objective ways to identify a system is through its step response. To induce a change in the output, the control loop was set to manual mode, and a step input was applied. By recording the temperature variation, the goal was to determine the gain, time constant, and dead time, resulting in the step response model. Initially, the microcontroller was programmed to read the analog input from the thermocouple and display the results through serial communication, allowing data recording via software. It is noteworthy that, after the initiation of the tests, the oven's temperature increased by 31.5°C until it reached 180°C (the standard operating temperature). The behavior of the system was observed as a first-order system with delay.

The transfer function for the first-order system with delay, using the Hägglund method, is given by Equation 1, resulting in Equation 2.

Equation 1: The transfer function for the first-order system with delay (Hägglund method).

$$G(s) = \frac{U(s)}{E(s)} = \frac{Ke^{-Ls}}{\tau s + 1} = \frac{0{,}932e^{-94s}}{146s + 1}$$

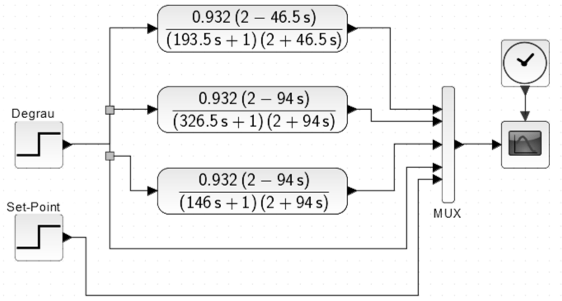
Equation 2: Mathematical rationalization of Equation 1, in terms of s

$$G(s) = \frac{U(s)}{E(s)} = \frac{0{,}932}{(146s + 1)} \frac{(2 - 94s)}{(2 + 94s)}$$

After calculating the values of the transfer function parameters for first-order systems with delay using each method, we proceeded to simulate the system's response to a change in the set-point. The block diagram simulated in Xcos is shown in Figure 6. Figure 7 shows the response of the three methods used, compared to the response of the actual plant.

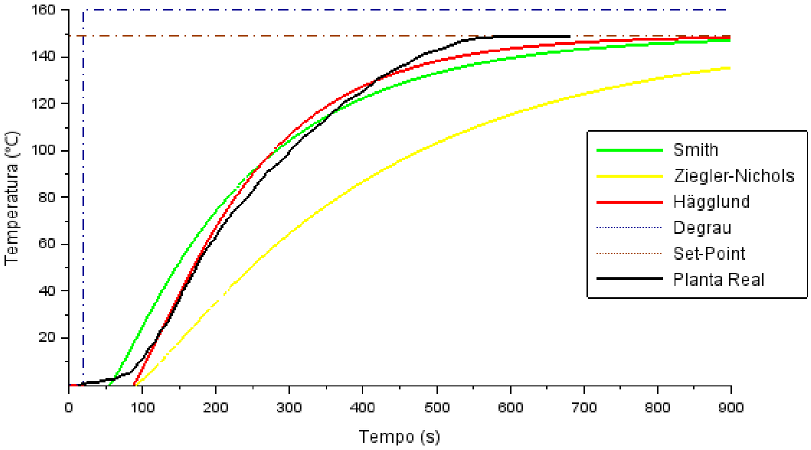
When comparing the curves, it can be observed that the transfer functions obtained by the Hägglund and Smith methods were in closer agreement with the plant's response. On the other hand, the Ziegler-Nichols method showed the least satisfactory performance among the three proposed methods. This result is directly related to the significantly higher value of the time constant obtained, compared to the other two methods.

Figure 6. Block diagram for the different methods



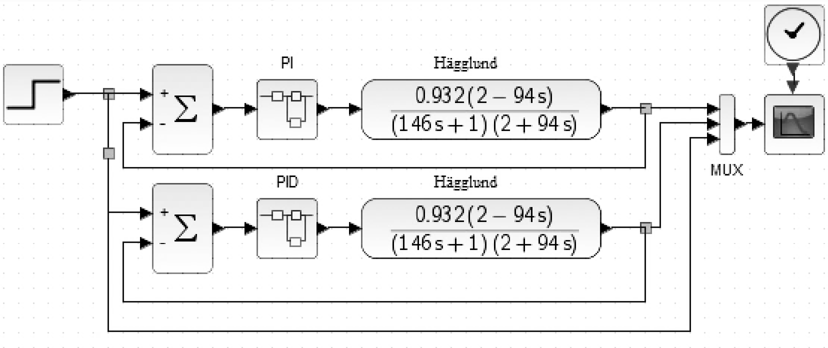
Source: Authors (2024)

Figure 7. Comparison of identification methods with Actual Curve.



Source: Authors (2024)

Figure 8. Block diagram of the controllers applied to the systems



Source: Authors (2024)

The determination of the controller parameters is performed for the Hägglund plant approximation, as its approximation shows behavior closer to the actual plant. The designed controllers were tested by adjusting the T_i value according to the value that ensures better performance. The block diagram simulated for the implementation of the controllers is in the shown Figure 8

4.1 **Ziegler-Nichols Method.**

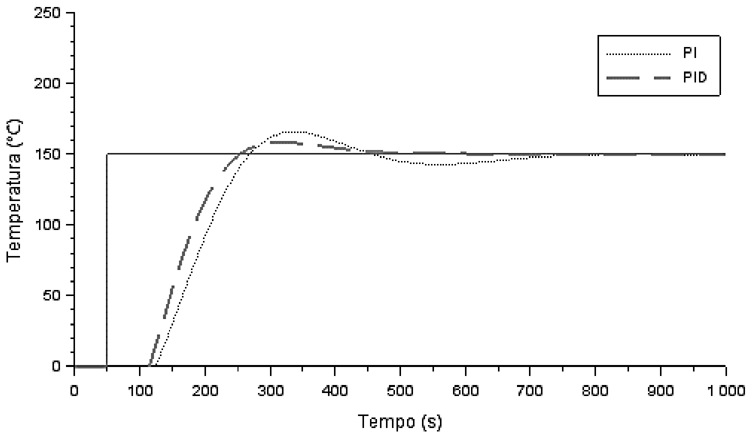
The controller parameters for the Ziegler-Nichols method are presented in Table 6. The results of the controller implementation on the system are illustrated in Figure 9. The PID controller demonstrated better performance for all criteria, compared to the PI controller. The performance criteria are presented in Table 7.

Table 6. Tuning for the first Ziegler-Nichols method

System	Controller	PI	PID
Hägglund	K_p	1,398	1,864
	T_i	0,0075	0,009
	T_d	–	47,00

Source: Authors (2024)

Figure 9. Results of the controller action on the system (Ziegler-Nichols)



Source: Authors (2024)

The results of the controller implementation on the system are illustrated in Figure 9. The PID controller demonstrated better performance for all criteria, compared to the PI controller. The performance criteria are presented in Table 7.

Table 7. Performance criteria for each controller (Ziegler-Nichols)

Criterion	PI	PID
Sobressinal (%)	10,59	5,65
Tempo de subida (s)	219,10	204,14
Tempo de acomodação (s)	676,99	393,51

Source: Authors (2024)

4.2 **Tyreus-Luyben Method.**

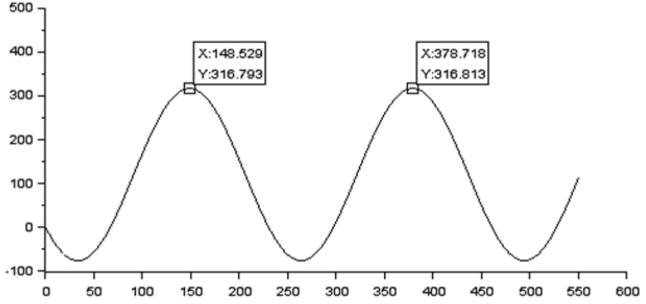
By adjusting the integral and derivative parameters to zero and using only the proportional action (Kp), the critical gain value (Kcr) — at which the process control enters the instability zone and the output response exhibits sustained oscillations — was 4.40841. The critical period (Pcr) was 230.189. The controller parameters for the Tyreus-Luyben method are presented in Table 8.

Table 8. Tuning for the Tyreus-Luyben method

System	Controller	PI	PID
Hägglund	K_p	1,98379	2,64505
	T_i	0,0100	0,0110
	T_d	−	28,7736

Source: Authors (2024)

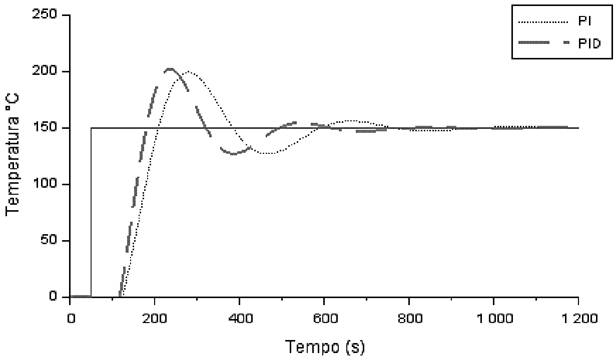
Figure 10. System response in sinusoidal form.



Source: Authors (2024)

The system response in sinusoidal form can be observed in Figure 10, while the results of the controller implementation on the system are illustrated in Figure 11.

Figure 11. Results of the controller action on the system (Tyreus-Luyben)



Source: Authors (2024)

Both controllers exhibit performance that can be interpreted as unsatisfactory. Although the controllers show a reduced rise time, they have a high overshoot percentage and a long settling time. The performance criteria for the controllers are presented in Table 9.

Table 9. Performance criteria for each controller (Tyreus-Luyben).

Criterion	PI	PID
Overshoot (%)	32,7	34,7
Rise time (s)	156,31	128,80
Settling time (s)	864,34	698,32

Source: Authors (2024)

4.3 **Cohen-Coon Method.**

The controller parameters for the Cohen-Coon method are presented in Table 10. The PID controller showed more satisfactory performance, with a slightly higher overshoot percentage than the PI controller, but with shorter rise and settling times. The performance criteria are presented in Table 11. The results of the controller implementation on the system are illustrated in Figure 12.

Table 10. Tuning for the Cohen-Coon method

System	Controller	PI	PID
Hägglund	K_p	1,3110	2,0540
	T_i	0,0090	0,0120
	T_d	–	30,600

Source: Authors (2024)

Table 11. Performance criteria for each controller (Cohen-Coon)

Criterion	PI	PID
Overshoot (%)	20,11	25,92
Rise time (s)	211,89	155,65
Settling time (s)	689,30	507,26

Source: Authors (2024)

Figure 12. Results of the controller's action on the system (Cohen-Coon)

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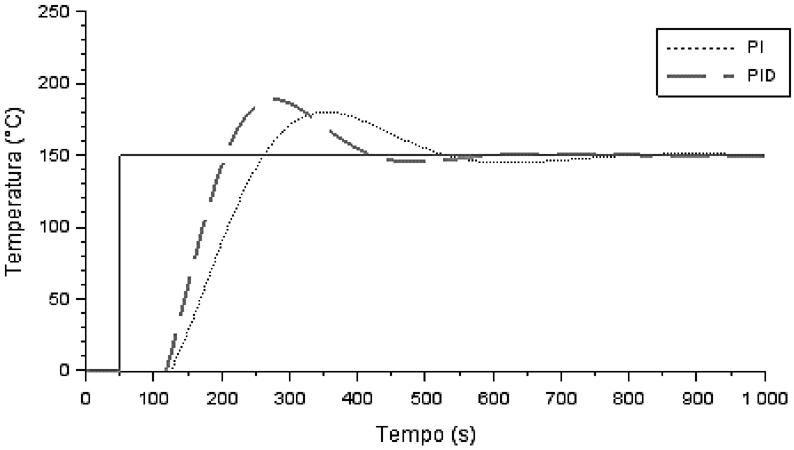
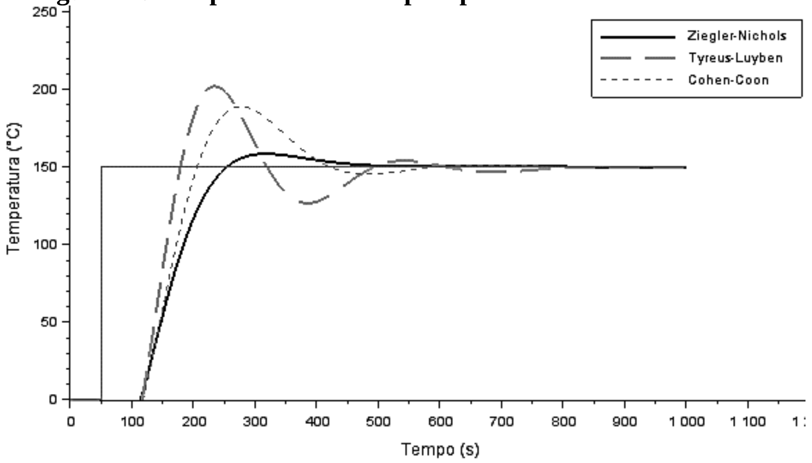


Source: Authors (2024

4.4 **Comparisson of results**

In order to analyze which of the proposed methods provides the best performance regarding step reference tracking, we compared the results of the three methods considering only the PID controller parameters that showed the best results across all methods: Ziegler-Nichols, Tyreus-Luyben, and Cohen-Coon. The result is shown in Figure 13. Comparisons of the performance criteria for the three methods are presented in Table 12.

Figure 13. Comparison of the step response for the three methods



Source: Authors (2024)

Table 12. Performance Comparison Between Tuning Methods

Critério	Ziegler-Nichols	Tyreus-Luyben	Cohen-Coon
Overshoot (%)	5,65	34,7	25,92
Rise Time (s)	204,14	128,80	155,65
Settling Time (s)	393,51	698,32	507,26

Source: Authors (2024)

The control system obtained using the Cohen-Coon method presents an acceptable rise time (155.65 s) but a significantly high overshoot percentage (25.92%). In contrast, the Ziegler-Nichols method offers a slightly higher rise time (204.14 s) but with a much lower overshoot percentage (5.65%) and the shortest settling time among the three methods (393.51 s).

As for the Tyreus-Luyben method, although it offers a reduced rise time (128.8 s), it presents a considerably long settling time (692.32 s) and the highest overshoot percentage (34.7%) among the three methods. For the control objectives of this project, the parameters obtained by the Ziegler-Nichols method seem to meet the requirements more effectively.

When comparing the PID controller parameters obtained by the Ziegler-Nichols method with those presented in the study by Vasconcellos (2017), some differences are observed. In Vasconcellos' study, the parameters were Kp = 0.24; Ti = 0.0065; and Td = 18.45, while in this study, we obtained Kp = 1.864; Ti = 0.009; and Td = 47. This discrepancy in the constant values can be explained by the distinct characteristics of the plants identified in each study. Although the temperature variation considered in both studies was similar (185 ℃ in this study), the plant identified by Vasconcellos had a delay of 42 s and a time constant of 86.5 s, while the plant in this study had a delay of 94 s and a time constant of 146 s. These differences are crucial for the controller design.

This comparison supports the study by Prata (2013), which suggests that in systems with higher delays and time constants, controllers with higher parameters are generally required due to the dynamic characteristics of these systems. A large time delay indicates a slower system response to changes in control or disturbances, requiring a more aggressive controller to compensate for this delay. If the time constant is large, it means the system is slow to reach its final state. Controllers with higher parameters help speed up the system's response, making it faster and more responsive.

V. CONCLUSION

The models obtained through first-order system approximation for identifying the transfer function of the furnace proved effective, except for the Ziegler-Nichols method, which is not recommended for systems with significantly high dead time. The time constant obtained using this method was considerably larger compared to the other two methods evaluated.

The Smith and Hägglund methods yielded similar results, with a notable advantage for the Hägglund method, which produced a system with a higher controllability factor ($L/\tau \cong 0.644$) compared to the Smith method ($L/\tau \cong 0.24$). This provided greater robustness to the system obtained by the Hägglund method. Based on the Hägglund method's approximation, it was possible to determine the parameters for the PI and PID controllers using the Ziegler-Nichols, Tyreus-Luyben, and Cohen-Coon methods. The PI controllers consistently underperformed across all scenarios, especially in systems with high dead time. When comparing the three tuning methods, the Ziegler-Nichols method demonstrated the best performance parameters for control objectives, with 5.65% overshoot and 393.51 s settling time. Despite a slightly higher rise time, the overall performance was superior. On the other hand, the high overshoot percentage in the Tyreus-Luyben and Cohen-Coon methods (34.7% and 25.92%, respectively) makes them impractical for systems requiring high-performance standards. These conclusions emphasize the importance of carefully choosing the identification and controller tuning method based on the specific characteristics of the system. The proper selection ensures more effective, robust control adapted to the process conditions, optimizing the performance of the controlled system

Conflict of interest

There is no conflict to disclose.

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