UNIVERSIDAD SAN FRANCISCO DE QUITO

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Design of control schemes for systems with difficult dynamics: An application in the TCLAB.

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DE TRABAJO DE FIN DE CARRERA

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José Andrés Feijóo Muñoz

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PRÓLOGO

Esta tesis investiga estrategias de control avanzadas para gestionar dinámicas complejas en sistemas de control, centrándose en sistemas con retrasos prolongados, respuesta inversa y comportamiento integrador. El estudio utiliza el Laboratorio de control de temperatura (TCLab) como banco de pruebas para analizar y comparar la efectividad del control integral proporcional (PI) y el control de modo deslizante basado en Smith Predictor (PS SMC) para abordar dinámicas de sistemas desafiantes. Al explorar los fundamentos teóricos de estas metodologías de control y evaluar su desempeño utilizando métricas como la integral de salida de control al cuadrado (ISCO) y la integral de error al cuadrado (ISE), la investigación tiene como objetivo proporcionar información sobre las estrategias de control óptimas para sistemas con comportamientos complejos. . Los hallazgos subrayan la importancia de un modelado preciso de sistemas y el potencial de las técnicas de control avanzadas en la gestión de dinámicas complejas, lo que ofrece valiosas implicaciones para el campo de la ingeniería de sistemas de control.

***Palabras Clave*:** estrategias de control avanzadas, dinámicas complejas, retrasos prolongados, respuesta inversa, comportamiento integrador, dinámica de sistemas, evaluación del desempeño, técnicas de control.

RESUMEN

Este estudio profundiza en el desafío de gestionar dinámicas intrincadas dentro de los sistemas de control, específicamente aquellos caracterizados por retrasos prolongados, respuesta inversa y comportamiento integrador. La investigación aprovecha el Laboratorio de Control de Temperatura (TCLab) como un proceso para analizar y desarrollar estrategias de control diseñadas para abordar estas dinámicas exigentes. La investigación se centra en dos metodologías de control principales: control integral proporcional (PI) y control de modo deslizante basado en Smith Predictor (PS-SMC), que ofrece parámetros de ajuste específicos para que TCLab administre de manera efectiva su curva de respuesta única y su tiempo de retardo. El estudio subraya la importancia de modelar con precisión sistemas físicos para diseñar estrategias de control impactantes, enfatizando el potencial de técnicas de control avanzadas en sistemas que exhiben respuesta inversa y tiempo muerto prolongado. Las evaluaciones de desempeño de los esquemas de control se llevan a cabo utilizando métricas de integral de salida de control al cuadrado (ISCO) e integral de error al cuadrado (ISE), lo que brinda información integral sobre los comportamientos de cada controlador derivados de modelos dinámicos desafiantes. Los hallazgos resaltan la importancia de comprender el comportamiento del sistema para un análisis preciso y una evaluación del desempeño, lo que ofrece valiosas implicaciones para el campo de la ingeniería de sistemas de control.

Palabras Clave**:** latencia, procesos dinámicos, error de seguimiento, no lineal, respuesta inversa, tiempo muerto prolongado, integración de sistemas.

SUMMARY

This study delves into the challenge of managing intricate dynamics within control systems, specifically those characterized by long delays, reverse response, and integrative behavior. The research leverages the Temperature Control Laboratory (TCLab) as a process to analyze and develop control strategies designed to address these demanding dynamics. The research focuses on two main control methodologies: proportional integral control (PI) and Smith Predictor-based sliding mode control (PS-SMC), which offers specific tuning parameters for TCLab to effectively manage its unique response curve and its delay time. The study underscores the importance of accurately modeling physical systems to design impactful control strategies, emphasizing the potential of advanced control techniques in systems that exhibit reverse response and prolonged downtime. Performance evaluations of the control schemes are carried out using control output integral squared (ISCO) and error integral squared (ISE) metrics, providing comprehensive information on the behaviors of each controller derived from models. challenging dynamics. The findings highlight the importance of understanding system behavior for accurate analysis and performance evaluation, offering valuable implications for the field of control systems engineering.

***Keywords*:** latency, dynamic processes, tracking error, nonlinear, inverse response, long dead time, systems integration.

DEDICATION

To my beloved family, whose unwavering support and encouragement have been my pillars throughout this academic journey. Your love has been my motivation, and I am endlessly grateful for the sacrifices you’ve made to see me succeed.

To the beauty of life itself, for the challenges that shaped my resilience and the moments that fueled my inspiration. Each hurdle was a lesson, and each triumph a celebration.

This thesis is a testament to the strength found in familial bonds and the endless possibilities that life presents. Thank you for being my constant source of love and inspiration.

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To all the professors, thank you for your tireless efforts, your commitment to student success, and for creating an environment that fosters learning and growth. Your collective impact has been immeasurable, and I am truly grateful for the wisdom and inspiration you have shared with me throughout my academic journey.

1 Introduction

This study focuses on addressing the complexities of managing challenging dynamics within control systems, particularly those characterized by prolonged delays, inverse response, and integrative behavior. Utilizing the Temperature Control Laboratory (TCLab) as a testbed, the research explores the efficacy of two primary control methodologies:Proportional-Integral (PI) control (Ogunnaike, 1994) and Smith Predictor based Sliding Mode Control (Camacho and De la Cruz, 2004) in a portable Plant/Lab such as TCLab By providing specific tuning parameters for TCLab, the study aims to develop effective control strategies tailored to handle the unique response curve and latency of the system . The research underscores the importance of accurately modeling physical systems to devise impactful control strategies, highlighting the potential of advanced control techniques in systems with complex dynamics (Herrera et al., 2020).

Performance evaluations of the control schemes are conducted using metrics such as integral of squared control output (ISCO) and integral of squared error (ISE), offering valuable insights into the behaviors of each controller derived from challenging dynamic models. This study contributes to the field of control systems engineering by emphasizing the significance of understanding system behavior for precise analysis and performance evaluation, with implications for real-world applications .

In the following sections, on the fundamental aspects of the TCLab system, including response patterns and inherent difficulties in temperature control. It examines two main control methodologies in detail: Proportional-Integral (PI) control and Smith Predictor based Sliding Mode Control (PD-SMC). Specific tuning parameters are provided for each methodology. The study compares these control schemes based on their effectiveness in managing errors and controlling the system. Accurately modeling physical systems is highlighted as crucial for developing effective control strategies. The study emphasizes the potential of advanced control techniques in systems with inverse response and long dead time. This approach aims to enhance the performance and efficiency of control systems in managing complex dynamics within industrial processes.

2 Fundamentals

2.1 Description of the TCLab Module

TCLab is a system used for feedback control sutudy using Arduino, which includes components such two transistors working as heaters and two thermistors used as temperature sensors. The main goal of this device is to carefully control the temperature of the transistors by precisely regulating the current flowing through them (Hedengren, 2020). This arrangement is illustrated in Figure 1.

Each sensor and actuator pair is connected to a heat sink, maintaining direct and constant contact through a bonded thermochromic material. In this system, the transfer of thermal energy from the heaters to the sensors occurs through processes such as conduction, convection and radiation, in addition to heat transfer from the device to the surrounding environment. This interaction between the elements of the TCLab, both with each other and with the environment, makes it an excellent system to observe and study the interactivity and coupling of the different variables involved in temperature control (Hedengren, 2020).

For the development of this work, the TCLab was used in Single Heater configuration, that is, only one heating element and one temperature sensor were used.

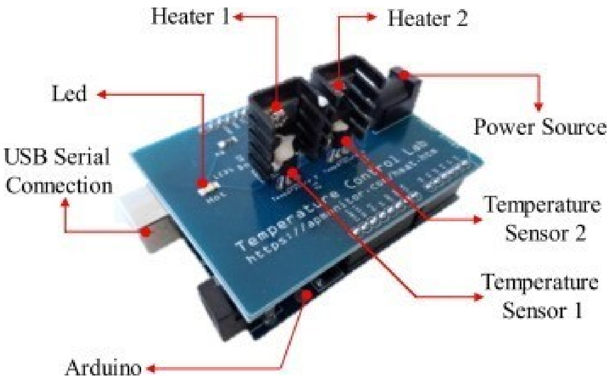

Figure 1: Temperature Laboratory Scheme [1]

2.2 Processes under study

First order plus time delay

The most straightforward manner to represent a plant is through the First-Order Plus Dead Time (FOPDT) model, which involves a system featuring a lone pole ($\frac{1}{\tau}$), a dead time (t_0), and system gain (K).

$$G_p = \frac{K}{\tau s + 1} e^{-t_0 s} \tag{1}$$

Inverse response

Systems with inverse response reflect an initial reversal in the system's transient response, thus showing an initial slope opposite to its final steady-state value. Mathematically, this phenomenon is represented by the location of one or more zeros in the Laplacian right half-plane (Camacho et al., 2020).

$$G_p = \frac{K(-\eta s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{2}$$

Long-Dead time

Systems with long dead time are considered those in which the dead time is greater than the time constant ($\tau < t_0$).

Integrating systems

Integrating systems are those that have a pole at the origin, so these plants, in the presence of a non-zero input, never present a steady state since the time response does not converge (Visioli and Zhong, 2011).

$$G_p = \frac{1}{s}\frac{K}{\tau s+1}e^{-t_0 s} \tag{3}$$

2.3 PI - PID Controller

A PID controller (proportional-integral-derivative) is a control technique that employs feedback and is used in industrial and engineering processes; being the most used. Its name comes because the control action is calculated based on proportional, integral and derivative correction of the tracking error value $e(t)$ (Camacho et al., 2020). The tracking error is the difference between a desired value R(t) or reference and the process value, in this case the value of Temperature $T(t)$. A PI controller, as its name indicates, is a type of controller that only uses the proportional and integral part as presented in 4.

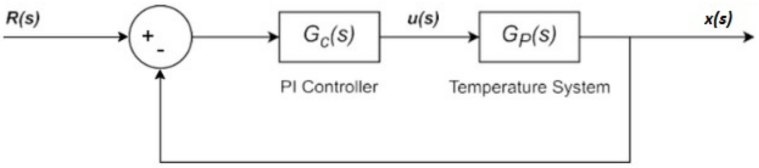

Figure 2: PI Controller: Block Diagram

$$u(t) = Kp\left(e(t) + \frac{1}{T_i}\int e(t)\,dt\right) \tag{4}$$

where $u(t)$ is the control signal, Ti and Kp are tunning values.

There are several methods for tuning PI/PID controllers (Smith and Corripio, 2005), the most common being tuning using an open loop model. Table 1 presents the Dahlin tuning parameters (Smith and Corripio, 2005).

Table 1: Parameter values

Method	K_p	T_i
Dhalin	$\frac{\tau}{2Kt_m}$	τ

2.4 Sliding mode controller

A sliding mode controller (SMC) is an advanced control technique used primarily in nonlinear dynamic systems to achieve robust and accurate performance. Its main objective is to maintain the system in a sliding mode, a specific set of dynamic conditions, despite disturbances or uncertainties present in the system.

The heart of this technique is an sliding surface ($S(t)$), a set of conditions that defines the ideal behavior of the system. The state constraints are represented by this surface, where each point satisfies all performance conditions simultaneously. The surface is an integral-differential equation acting on the tracking error as proposed on (Camacho et al., 2020).

$$S(t) = f\left(e(t), \int e(t)dt, \dot{e}(t), \lambda, n\right) \tag{5}$$

λ is the tuning parameters and n is the order of the equation. To ensure that the system follows the surface the reference value, the error must be near or at zero; for that to be true $\dot{S}(t) = 0$. Once the sliding surface is decided, the control signal must be determined U_t, which is composed of two parts: a continuous part, function of the controlled variable and its reference; and a discontinuous, nonlinear part that represents the switching element of the control signal and is responsible for bringing the states of the system to the surface (see expression 6).

$$U_t = U_C(t) + U_D(t) \tag{6}$$

(Camacho et al., 2020) proposes to use a sigmoid function as the discontinuous part.

$$U_D(t) = K_D \frac{S(t)}{|S(t)| + \delta} \tag{7}$$

where K_D and δ are tunning values.

Smith Predictor based sliding mode controller

The Smith predictor (PS), emerged as a dead time compensator. This control structure emerged with the idea of improving the performance of PID controllers in the control of plants with dominant time delay. Its main advantage is that it eliminates the nonlinearity of the characteristic equation of the closed-loop control system, when its internal model perfectly describes the dynamic behavior of the plant. Since the design of the sliding mode controller (SMC) is based on the assumption that acts over a FOPDT plant, for the present work an SMC controllers based on internal model were used. In particular a Smith predictor (PS-SMC) as proposed by (Camacho and De la Cruz, 2004) and (Camacho et al., 2007), which scheme is shown in 3.

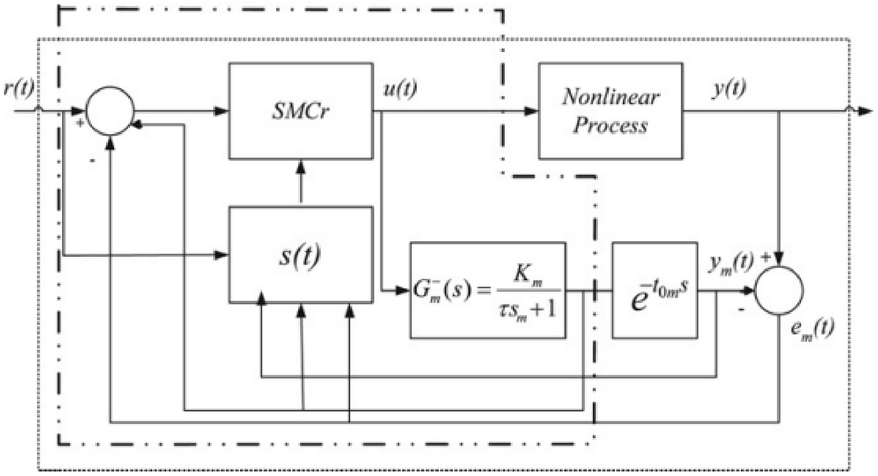

Figure 3: PS-SMC scheme (Camacho and De la Cruz, 2004).

Where G_m is the internal model FOPDT from which the sliding surface is calculated. The control scheme shown in the figure 3 is not intended for integrating systems, so we use a variant of the control scheme proposed by (Camacho et al., 2007).

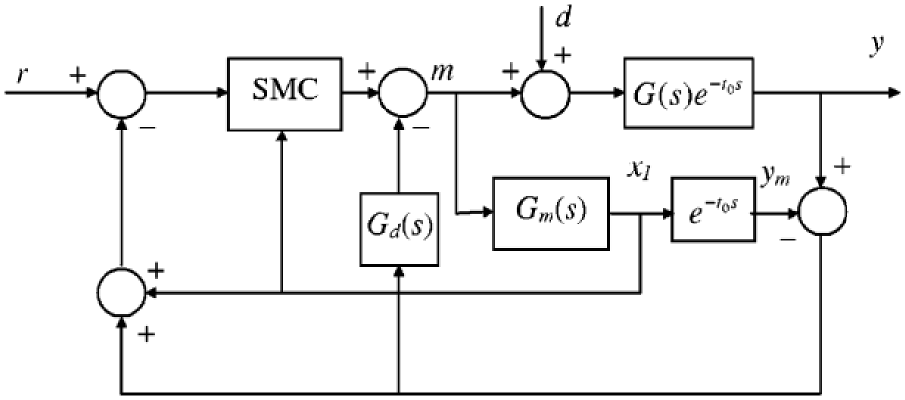

Figure 4: PS-SMC scheme for integrating systems. (Camacho et al., 2007).

For this case, the itnernal model G_m is representad as IFOPDT. And the function $Gd(s)$ is added to reject the load disturbances.

3 Identification Methods

In this section we are showing different proceding..... From the open-loop response of the TCLab laboratory, a FOPDT model was identified from which three difficult dynamics models were established for study: Long-Dead time, integrating, inverse response.

3.1 FOPDT - Model identification

The TCLab has its response as a FOPDT system, so in order to obtain the first-order model plus delay time, the Smith two-point empirical identification method was used, which determines that the two time instants selected are when the response reaches 28.3% and 63.2% of the settling value (Smith, 1972). The gain (K), the time constant (τ) and the apparent dead time (tm) of the system are calculated from .

$$\begin{cases} \tau = 1.5(t_{63} - t_{28}) \\ tm = t_{63} - \tau \\ K = \frac{\Delta y}{\Delta u} \end{cases} \tag{8}$$

The step response from which the points are obtained is shown in Figure 5, and is obtained from a step change of $\Delta u = 20$, from 40 to 60.

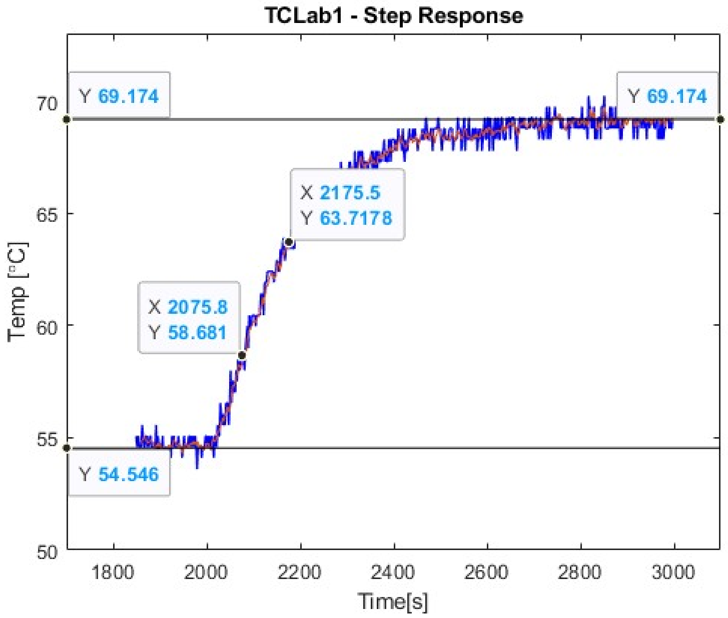

Figure 5: Step Response

The obtained transfer function is presented in (9).

$$G_p = \frac{0.7314}{149.55s + 1} e^{-25.95s} \tag{9}$$

3.2 Difficult dynamics systems

Based on the previous system, the three difficult dynamics models are proposed, for this purpose, it is necessary to introduce modifier blocks, via software (Matlab), prior to the TCLab control signals, as shown in Figure 6.

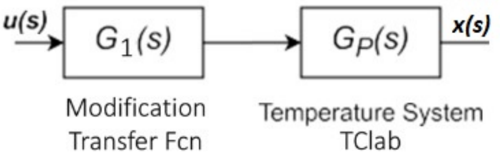

Figure 6: Block diagram for system modification in TCLab

In this way the following complex dynamics systems are proposed. These proposed models are variations of the original TCLab model (Refer to Figure 6):

Inverse response

$$G_{p(inv)} = \left(\frac{-73.275s+1}{25.65s+1}\right)\left(\frac{0.7314e^{-25.95s}}{149.55s+1}\right) \tag{10}$$

To obtain the new FOPDT approximation for the proposed modified TCLab, for inverse behavior, the laboratory response curve to a $\Delta u = 20$ step change (at $t = 2000$ is obtained:

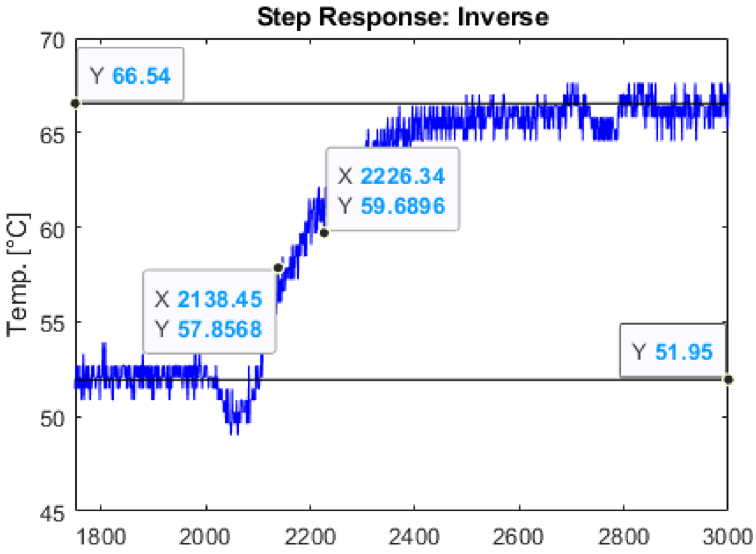

Figure 7: Step Response for inverse system

As before the Smith identification method is used, obtaining the following FOPDT transfer function.

$$G_{FOPDT(inv)} = \frac{0.7295e^{-94.583s}}{131.75s+1} \tag{11}$$

Long-Dead time

$$G_{p(LDT)} = \left(\frac{0.7314e^{-25.95s}}{149.55s + 1} \right) e^{-129.7s} \tag{12}$$

Applying the same procedure as in the previous case, it is obtained:

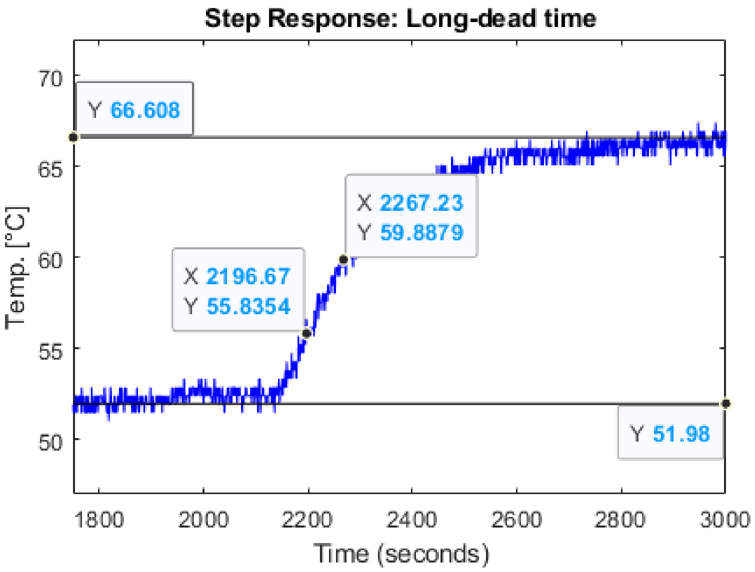

Figure 8: Step Response for Long-dead time (LDT) system

$$G_{FOPDT(LDT)} = \frac{0.7314e^{-161.3s}}{105.9s + 1} \tag{13}$$

Integrating systems

$$G_{p(int)} = \frac{1}{s} \left(\frac{0.7314e^{-25.95s}}{149.55s + 1} \right) \tag{14}$$

To obtain the integrating FOPDT model, an impulse input must be applied to the plant, as opposed to the previous cases in which a step input is applied.

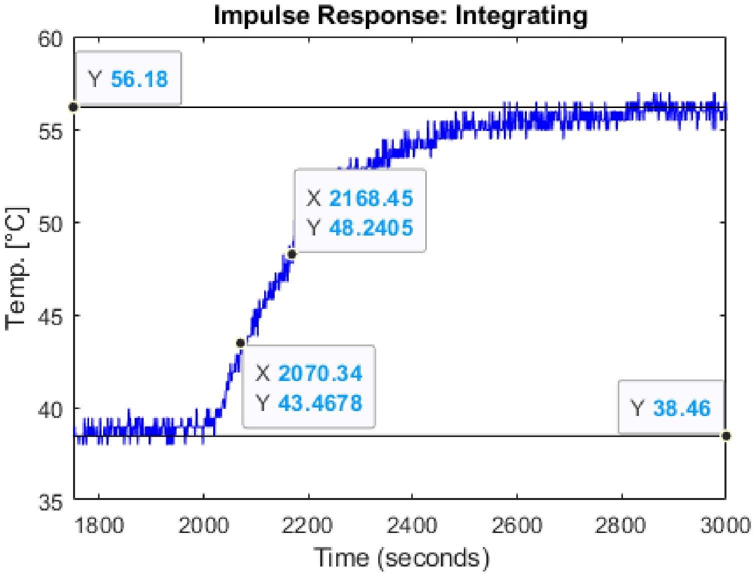

Figure 9: Step Response for Long-dead time (LDT) system

The obtained integrating first-order plus deadtime (IFOPDT) model is:

$$G_{IFOPDT(int)} = \frac{0.886e^{-21.5s}}{s(146.55s+1)} \tag{15}$$

Finally, the validation of the models obtained is presented in 10.

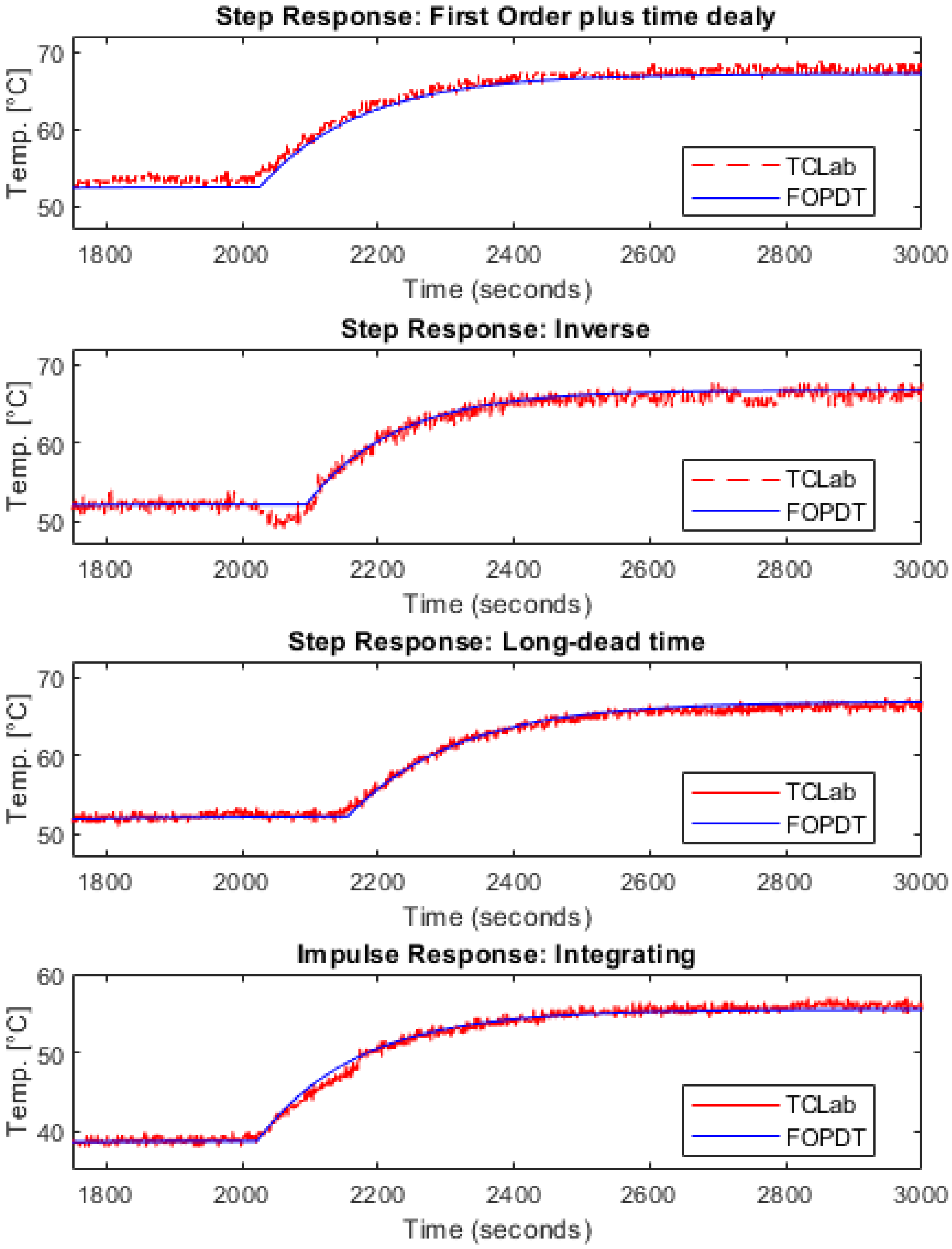

Figure 10: TCLab Response vs FOPDT Identification

4 Controller design

4.1 PI Controllers

Using the parameters presented in last chapter (see table 1), the proportional and integral constants of the controller are obtained by the Ziegler-Nichols (ZN), Dahlin, IMC and Cohen-Coon (CC) methods. The constants are presented in Table 2.

Table 2: PI Constant Values

Method	**Dahlin**	
	K_p	τ_i
First Order	3.906	146.55
Inverse	0.9547	131.75
Long-dead time	0.4489	105.9

4.2 Sliding Mode Controller

To design the controller, the FOPDT model of the plant is considered approximating the delay as a pole (via Taylor expansion):

$$G(s) = \frac{K}{\tau s + 1} e^{-t_0 s} \approx \frac{K}{(\tau s + 1)(t_0 s + 1)}$$

The FOPDT is is transformed to its differential equation:

$$\frac{d^2x}{dt^2} + \frac{t_0 + \tau}{t_0 \tau}\frac{dx}{dt} + \frac{1}{t_0 \tau} x = \frac{K}{t_0 \tau} u \tag{16}$$

The following Sliding surface equation is taken:

$$S(t) = \frac{de(t)}{dt} + \lambda_1 e(t) + \lambda_2 \int e(t)\, dt$$

The first derivative of the surface is calculated and equals zero.

$$\dot{S} = \frac{d^2e}{dt^2} + \lambda_1 \frac{de}{dt} + \lambda_2 e = 0$$

The defitition of the tracking error is applied $e(t) = r(t) - x(t)$. So,

$$\frac{d^2R}{dt^2} - \frac{d^2x}{dt^2} + \lambda_1\frac{dR}{dt} - \lambda_1\frac{dx}{dt} + \lambda_2 R - \lambda_2 x = 0 \tag{17}$$

Adding equations 16 and 17

$$u_C = \frac{t_0\tau}{K}\left[\left(\frac{t_0+\tau}{t_0\tau} - \lambda_1\right)\frac{dx}{dt} + \frac{x}{t_0\tau} + \lambda_2 e + \frac{d^2R}{dt^2} + \lambda_1\frac{dR}{dt}\right]$$

Since the references are step-type, we neglect the reference derivatives:

$$u_C = \frac{t_0\tau}{K}\left[\left(\frac{t_0+\tau}{t_0\tau} - \lambda_1\right)\frac{dx}{dt} + \frac{x}{t_0\tau} + \lambda_2 e\right]$$

To simplify the control action, let $\frac{t_0+\tau}{t_0\tau} = \lambda_1$, so the control signal equation is obtained:

$$u_C = \frac{t_0\tau}{K}\left[\frac{x}{t_0\tau} + \lambda_2 e\right] \tag{18}$$

As presented in chapter 2.4, the discontinuous part of the controller is a sigmoid function. (Camacho and De la Cruz, 2004) explains that $\lambda_2 \leq \frac{\lambda_1^2}{4}$.

PS-SMC variant for integrating system

For the integrating system, its necessary to use an integrating first-order plus deadtime (IFOPDT) model. So, the control signal for this particular system, calculated as above, is:

$$u_C = \frac{1}{K}\left[(1-\tau\lambda_1)\frac{dx(t)}{dt} + \tau\lambda_2 e(t)\right] \tag{19}$$

(Camacho and De la Cruz, 2004) determines that $\lambda_1 = \frac{1.5}{\tau}$ for systems whose $CR = t_o/\tau < 4$ In the same way, the sigmoid function is used for the other half of the control acid.

Table 3: Tuning values for PS-SMC controllers

System	λ_1	λ_2	K_D	δ
First Order	4.522e-2	4.6e-4	263.94	69.047
Inverse	1.816e-2	7.84e-5	11.25	68.019
Long-Dead time	1.311e-2	4.08e-5	67.642	68.077
Integrating	1e-2	1.26e-5	388.15	68.341

Table 3 shows the tuning constants obtained for each of the systems.

5 Results

In this section, the PI-Dahlin and PS-SMC controllers are tested for the TCLab plants presented above. The controllers will be analyzed in terms of their performance. For each plant/controller the same test was performed: 3 reference changes every 1250 seconds, the first two changes are +20 degrees, starting at 35 degrees and a last change of -10 degrees.

5.1 PI Controller

PI Controller for TCLab inherent response - FOPDT

Figure 11 shows the results obtained for the PI control applied to a plant whose response resembles a first order plus delay time (FOPDT). It can be seen that the response of the controller is fast, with a settling time of about 350 seconds, but that because of this fast action it is observed in consequence that the panel presents over-peaks of about 3 degrees.

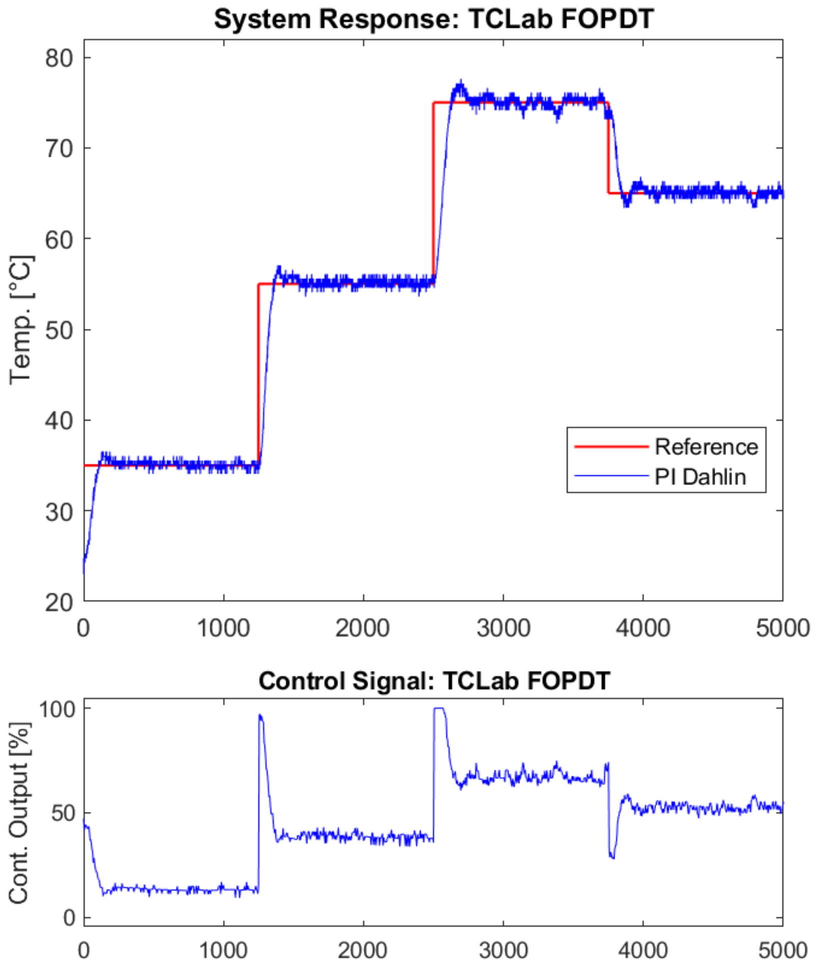

Figure 11: PI Response: FOPDT.

PI Controller for Inverse Response

The plant has over-peaks of about 3 degrees, equivalent to 15% of the reference change, and a settling time of about 1000 seconds. The control signal does not present abrupt changes, nor does it reach saturation conditions (given by the physical conditions of the plant).

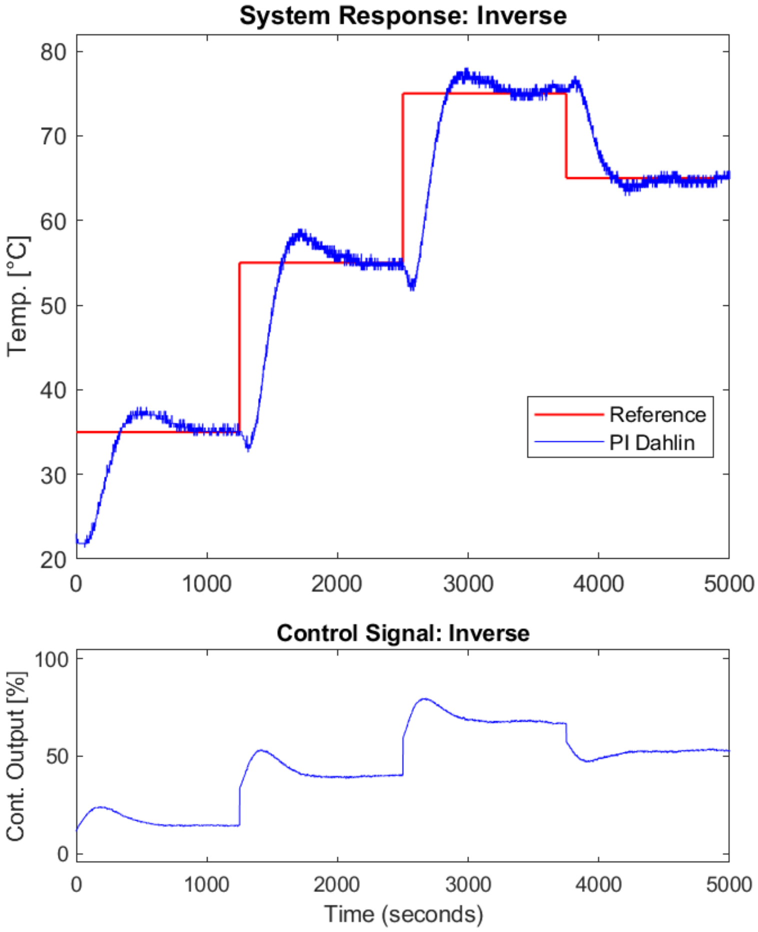

Figure 12: PI Response: Inverse.

PI controller for Long-dead time Response

It is noticeable, in Figure 13, that the system presents the same percentage of over-peak as for the previous plants (3 degrees). The settling time for this case is close to 1200 seconds, very close to the reference change intervals.

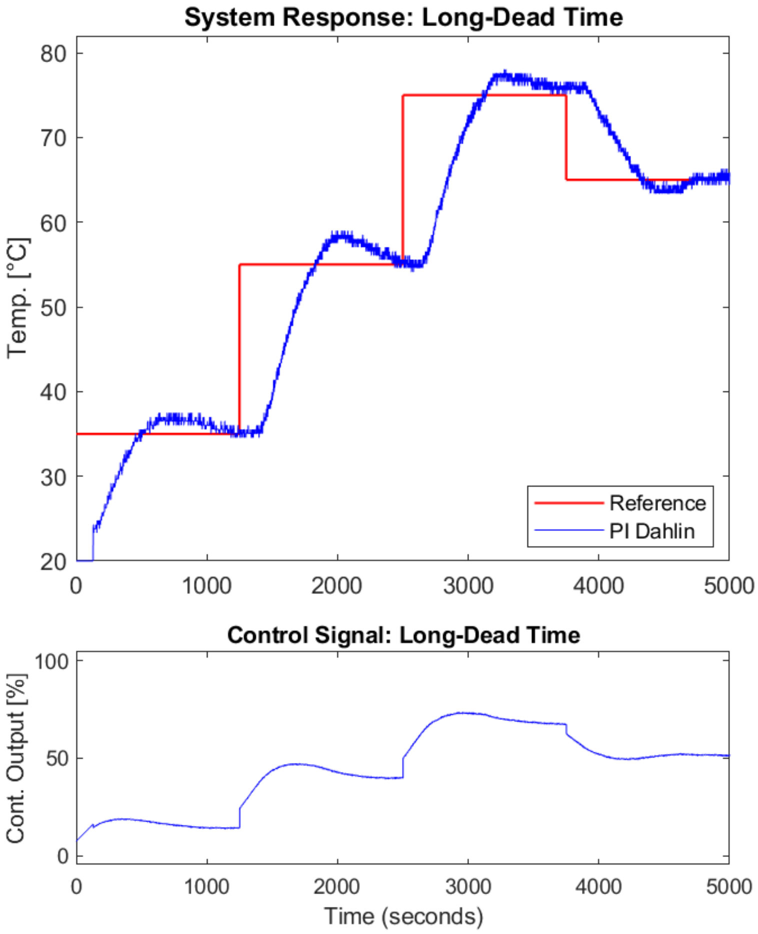

Figure 13: PI Response: Long-dead time.

5.2 PS-SMC Controller

PS-SMC Controller for TCLab inherent response - FOPDT

Figure 14 shows the results obtained for the PS-SMC controller applied to the inherent response of TCLab, a plant whose response resembles a FOPDT. The system response is not over-peaked and has a fast response time of less than 250 seconds.

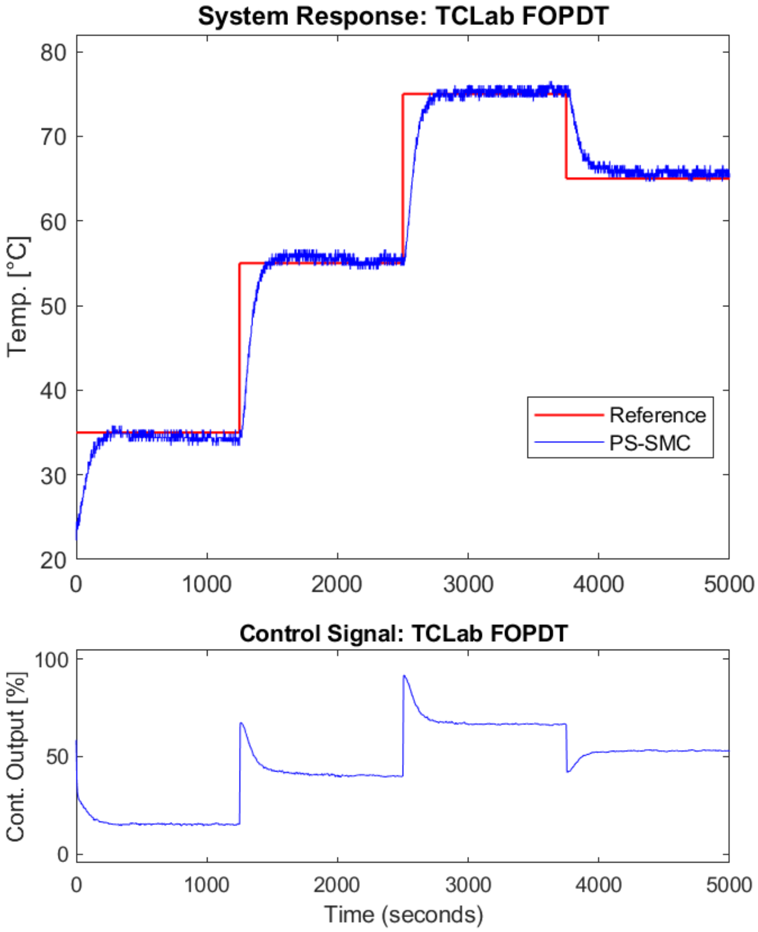

Figure 14: PS-SMC Response: FOPDT.

PS-SMC Controller for Inverse Response

Figure 15 presents the results. The plant has no over-peak and a settlig time of around 400 seconds.

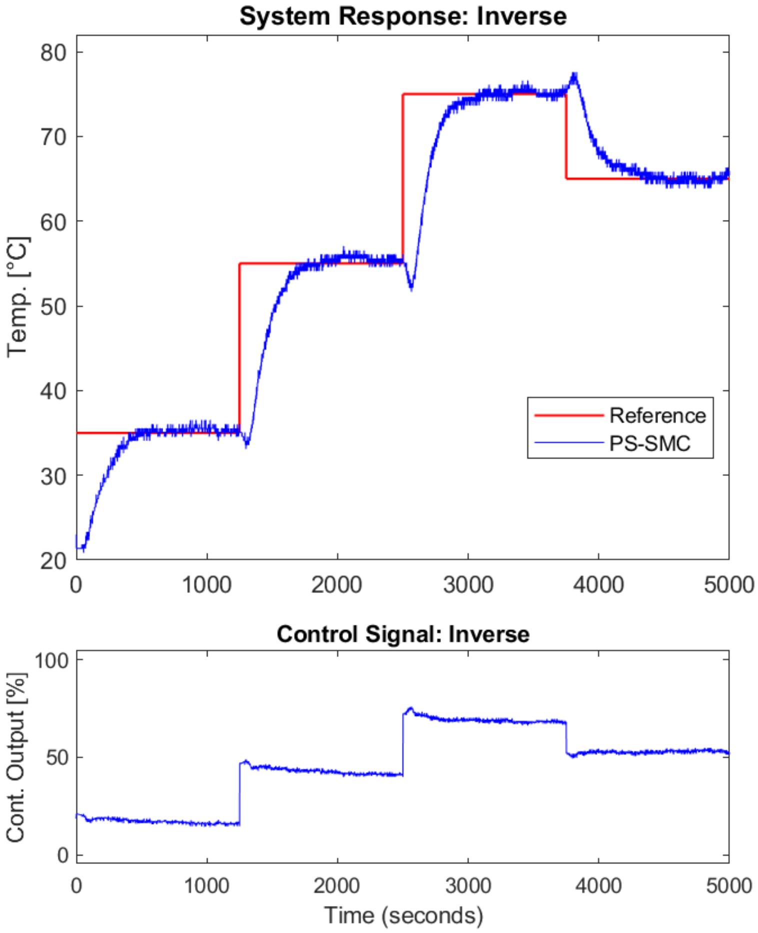

Figure 15: PS-SMC Response: Inverse.

PS-SMC Controller for Long-dead time Response

Results are shown in In Figure 16. As before plant-response has no over-peak and in this system the settling time is around 725 seconds. Control action is smooth.

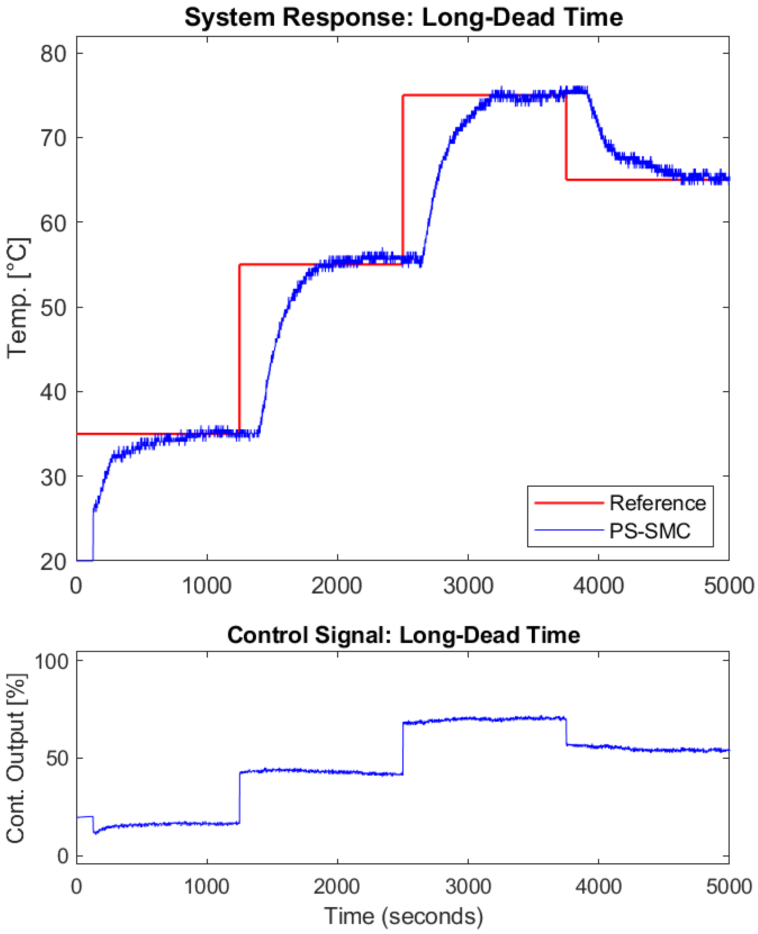

Figure 16: PS-SMC Response: Inverse.

PS-SMC Controller for Integrating Response

For a plant with an integrating model, only the PS-SMC controller was tested and is shown in Figure 17.

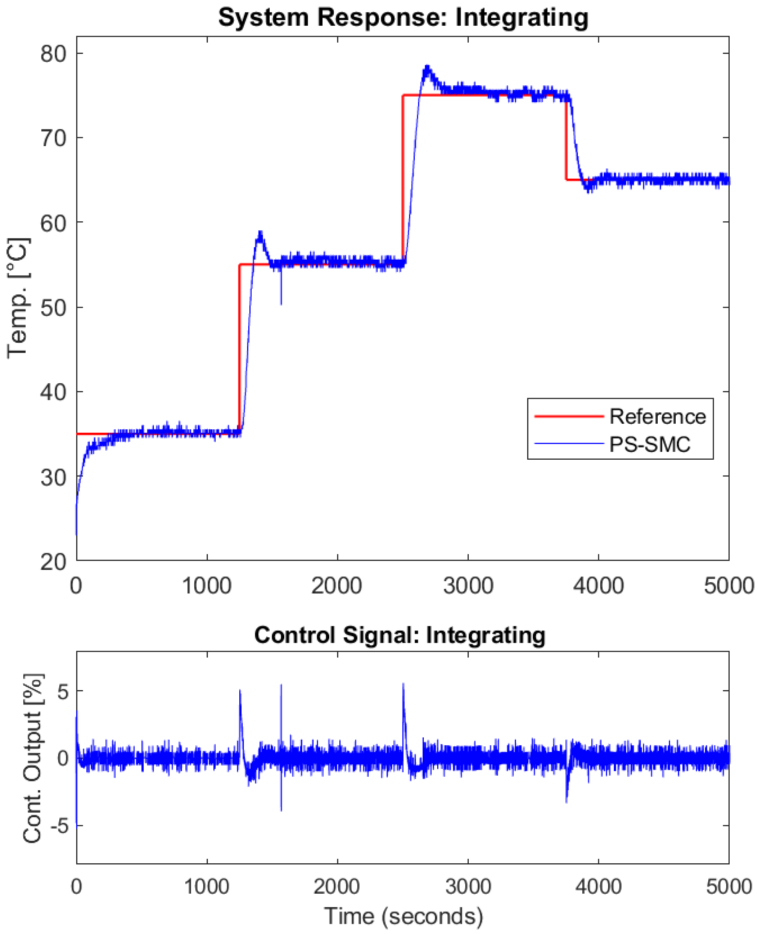

Figure 17: PS-SMC Response: Integrating.

The sliding mode controller based on PS, for this type of plant, did present an over-peak, which was 17% of the reference change, which is to be expected due to the behavior of a plant of this type. Likewise, due to the type of system, the control action is not smooth and presents large and rapid changes. However, since the output, as presented in 6 the integrator block is emulated before the TCLab, and it was found that the signal perceived by the TCLab was similar to that of the previous systems.

5.3 Controllers' comparison

Since all the controllers implemented in the systems were subjected to the same reference changes, it is possible to perform a 1-to-1 comparison between PI-Dahlin and PS-SMC. For this purpose, two performance metrics were used, the integral of squared error - ISE and the integral of squared control output - ISCO.

Analyzing figure 18, it can be observed that: for the original TCLab system, FOPDT, the PI controller is the one with the best performance, mainly if we analyze the ISE index. However, for the systems with difficult dynamics, the PS-SMC controller is the best performer, being the fastest one to establish the system in its set point.

On the other hand, reviewing the behavior of the ISCO index over time, it can be deduced that the control signal has a similar effect on the actuator in terms of its demand in both types of control (PI-Dahlin and PS-SMC).

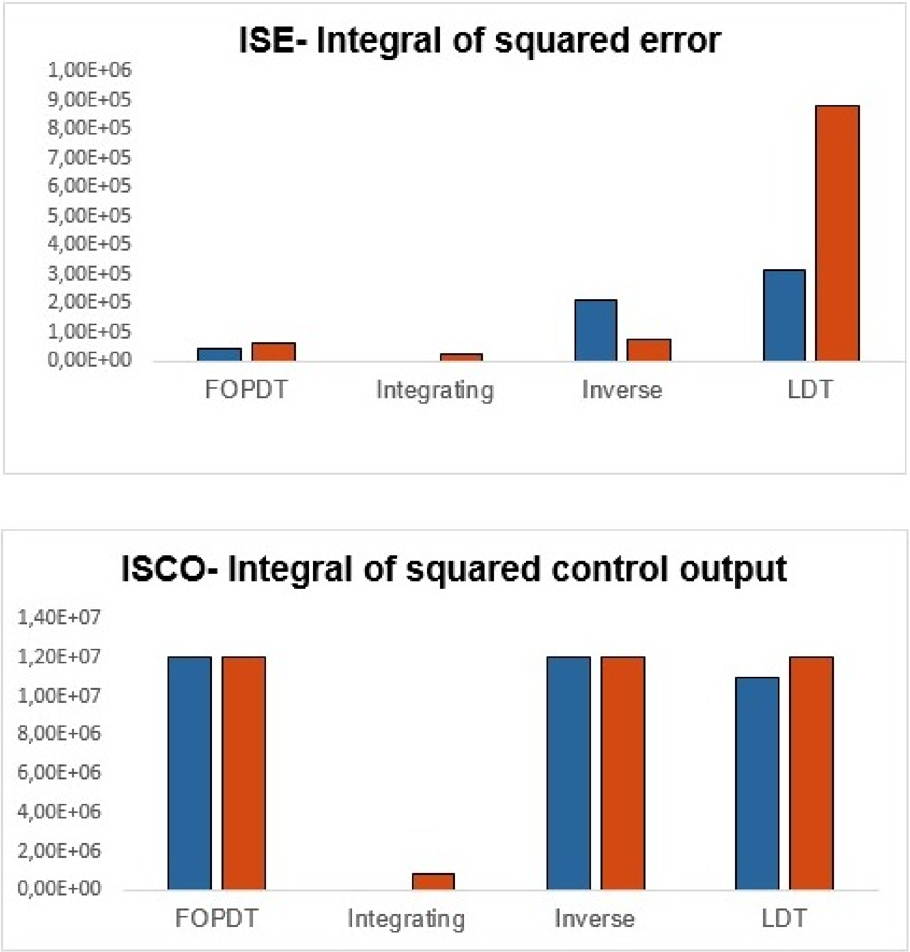

Figure 18: Final value of ISCO and ISE for all systems

Table 4: ISE and ISCO final values

Parameters	**First Order**	**Inverse**	**Long-dead time**	**Integrating**
ISE				
PI-Dahlin	4.56E+04	2.14E+05	3.13E+05	-
PS-SMC	6.66E+04	7.73E+04	8.58E+04	2.60E+04
ISCO				
PI-Dahlin	1.20E+07	1.21E+07	1.17E+07	-
PS-SMC	1.20E+07	1.21E+07	1.24E+07	8.86E+05

6 Conclusions

A plant, such as TCLab, facilitates the study and analysis of different control strategies due to its portability, versatility and mutability. Allowing the researcher to easily modify its behavior through Matlab.

In this paper, TCLab is used to approach control schemes for systems with difficult dynamics. As a result, it highlights the need for a thorough understanding of the behavior for accurate modeling to facilitate the correct implementation of various control techniques. For this particular study: a PI controller and a Sliding Mode Controled based on Smith Predictor.

In this context, the effectiveness of the PS-SMC control in handling complex systems such as those proposed throughout this paper is underline. It is concluded that the PS-SMC, compared to the Dahlin PI controller, shows superior performance when analyzing various factors such as settling time, over-peak and ISCO/ISE performance indexes. This comparison highlights the advantages of advanced control techniques in systems with inverse response, long-dead time and especially in integrating systems, where a classical control technique such as PI cannot guarantee the controllability of the system. Nevertheless, due to its simplicity it is worth emphasizing the PI control scheme for plants/systems that present a simple, first order-like behavior with short delay times.

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