Tunable PID Controller from the WinCC Unified Interface via OPC UA

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***Abstract*—In this study, it was sought to implement a Proportional-Integral-Derivative (PID) controller in SIMATIC S7-1500 Programmer Logic Controller (PLC) with Open Platform Communications United Architecture (OPC UA) communication and tunable control from WinCC unified, in order to reduce the settling time of the temperature variable in the plant SO 3536-8T. Using the Ziegler-Nichols PID rule, adjustments were made to the K_p, T_i and T_d coefficients of the PID controller. Initially set with values of $K_p = 1.0$, $T_i = 20.00$ s, $T_d = 0.1$ s, and $e_{ss} \leq 2\%$. Without tuning, a maximum settling time of 193 s was achieved for a setpoint of 50 °C. After tuning from the WinCC unified interface, improved parameters ($K_p = 6.05$, $T_i = 0.75$ s, $T_d = 0.15$ s) were obtained for $e_{ss} \leq 2\%$, presenting an underdamped response and a maximum settling time of 54 s. The tests present a reduction of the settling time of the variable higher than 60.25%, evidencing the effectiveness of the tunable PID controller in improving the system performance. Overall, the successful implementation of this tunable PID controller not only optimized the efficiency of the control system, but also provided a considerable reduction in the settling time of the temperature variable in the plant, representing a significant advance for the operation and overall efficiency of the process.**

***Index Terms*—embedded controller, Proportional-Integral-Derivative (PID) control, transient response time, under damped control, Ziegler-Nichols PID**

NOMENCLATURE

DCS: Distributed control system
e_{ss}: Steady state error
I/O: Input/output
K_p: Proportional gain
OPC UA: Open platform communications Unified Architecture
PID: Proportional-Integral-Derivative
PLC: Programmer Logic Controller
PN: Profinet
SCADA: Supervisory Control and Data Acquisition
T_i: Integral time
T_d: Derivative time
WinCC: Windows Control Center
ZN: Ziegler-Nichol

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I. INTRODUCTION

In recent years, significant progress in process automation has led to the continuous emergence of innovative technologies and improved devices. This progress implies the need for the field of process control and automation to adapt to the changing technological environment. The use of PID controller tuning techniques, in combination with PLCs incorporating efficient technological resources with OPC UA communication, has led to the development of new technologies and improved devices [1–3], which are a promising alternative to developing tunable controllers that can be integrated into industrial processes through client-server interfaces.

PID controllers have survived many changes in technology; starting with pneumatic control, using DCS [4]. Today, the PID controller is very different from 50 years ago [5]. Usually logic, block function, selector and sequence are combined with the PID controller [6]. Thus, many sophisticated regulatory control strategies, multivariable control, start-up and shutdown strategies can be designed around classical PID control [7]. This provides the basis for good regulation, safe operation, smooth transition and fast start-up to stop processes. In this scenario, PLCs provide special features for tuning, gain scheduling (Kp, Ti and Td), and control algorithms for PID controllers [8].

The SIMATIC S7-1500 PLC is a modular automation system for medium and higher performance ranges [9]. The different controller versions allow the performance to be dependent on the application. Depending on the requirements, the PLC can be extended with I/O modules for digital signals and analog signals; it is also expandable for technology modules and communication modules [10].

OPC UA communication was developed to overcome the limitations presented by its predecessor the classic OPC, having as one of the advantages the interoperability in Industry 4.0 [11]. It was designed to work only with Windows operating systems. OPC UA is currently a platform independent for manufacturers and therefore open as it ensures a flow of information between components from different suppliers, being the OPC

Foundation is the association responsible for the development of this standard OPC UA and has two innovations or features to highlight the classic OPC protocol [12].

The first innovation of OPC UA replaces the COM and DCOM protocol, specific to Windows, with open and independent protocols so that they can work under other operating systems. With an important implementation not only at the level of computer equipment such as Windows, Linux, Mac, etc.; but, also at the level of cell phone devices such as Android and different types of controls and monitoring devices, sensors, controllers, etc. They interact with the real world by incorporating additional security mechanisms and are capable of interacting with PLCs [13]. The second feature is that OPC UA incorporates the object-oriented system information model that incorporates traditional OPC functionalities and other new and innovative ones oriented to data types and methods [14].

WinCC Unified is a new software used in TIA Portal as of version 16, released in 2019. The most significant difference to the previous WinCC software; Unified is browser-based in nature [15]. It is based on Internet technologies such as HTML5, SVG and JavaScript. JavaScript acts as a scripting language on all devices, both panels and control room computers. Scripting can be used for all functions, such as data processing, object creation, etc. Internet technologies allow open interfaces [12]. Users can access the system through various devices, such as computers, tablets and smartphones, and no separate downloads are required. The unified system is scalable, which means that programs scale from panels to complete SCADA systems [16].

The research proposed in this paper aims to implement a tunable PID controller from WinCC Unified integrated into an S7 1500 PLC with OPC UA communication. It will significantly improve the PID controller tuning process by integrating it with the WinCC Unified interface using OPC UA as the communication protocol. This integration enables remote and centralized configuration of PID controller parameters, simplifying the fine-tuning of the control system, which represents the gap in automatic control. Eliminating the need for manual adjustments on site reduces the settling time of the controlled variable and the resources required to optimize the system control, ensuring secure and reliable communication between the interface and the controller, thus improving the efficiency and stability of the industrial automation system.

II. Related Work

Several works have been done with PID controllers embedded in PLC, this type of controllers can be tunable manually or semi-automatically. Manual tuning controllers require an expert to set the gains K_p, T_i, and T_d according to his experience in the process, using the trial and error method [17]; while semi-automatic tuning controllers require an operator to enter the tuning block or platform; in the case of SIMATIC S7 1500 PLCs it is tuned in TIA Portal by accessing the "configuration" tab of the PID_Compact in the Technology Objects folder. This process is performed during the development of the application program, which is difficult when this same controller must be adapted to a new process or process with different requirements.

Tong, Wang, and Shen [18] designed and implemented a system to control the temperature at the industrial level, this study focused on the creation of a temperature control system for heating water in a furnace, the acquisition of data and control parameters of the furnace was performed by the PLC SIMATIC S7-1500 which also kept controlled the temperature variable, its programming was developed in Ladder on the TIA Portal platform. For the operator control and visualization of the temperature variable data, an HMI screen was implemented.

On the other hand, S. S. Wibowo, I. N. Syamsiana, and B. I. Kurniawan [19] developed a work for automatic metal plate production and proposed a model for the thickness control system in the rolling mill; for which they employed the Ziegler-Nichol (ZN) response curve method, in conjunction with other optimization methods, to tune the PID controller parameters of the system. In addition, they used OPC UA communication to perform the online semi-physical simulation using the SIMATIC S7-1500 PLC. The comparative study revealed that by applying the same displacement step signal between rollers, the over-response of the system when tuned, is reduced, which significantly contributes to improving the accuracy and speed of the system. These results make practical applications in control engineering feasible.

Likewise, other combined methods seek to improve the efficiency of PID controllers; among them are cascaded PID controller configurations [20] and Fuzzy PID controllers [21]. The use of additional devices makes the controller more expensive. As in the case of all optimization problems, tuning the parameters of the PID algorithm to achieve accurate and stable closed-loop control is a major challenge. This situation is a dilemma for both users and designers, especially in practical applications [22]. Tuning these PID controllers in a reliable and user-friendly way from some interface is considered one of the technical gaps; that is faced with this work, where the PID controller tuning is executed online from the HMI interface developed in WinCC Unified.

III. Materials and Methods

A. Requirements

For the implementation of the PID controller tunable from WinCC Unified via OPC UA, in principle the SIMATIC S7 1500 PLC with CPU 1516-3 supporting Profinet and Profibus communication (PN/DP) and PID_Compact instruction was required: CPU with display; working memory 1 MB for code and 5 MB for data; operation time with bits of 10 ns; TCP/IP transport protocol [23]. Built-in OPC UA server and client with firmware V2.6.

For the reading of the analog sensor installed in the thermal plant, the 16-bit AI 8xU/I/RTD/TC analog input module AI 8xU/I/RTD/TC was used [24] in groups of 8; 4 channels with RTD measurement; the voltage input was parameterized from 0 to 10 V.

The high-speed DQ 32x24VDC/0.5A digital output module was used to activate the heater in the plant. Fig. 1 shows the components of the control and communication station: (a) CPU S7 1500, (b) 32-channel digital input module, (c) 32-channel digital output module, (d) analog input module AI8 x U/I/RTD/TC, (e) analog output module AQ4 x U/I and (f) Profinet communication switch (PN), which was used from the control and automation laboratory of the Faculty of Electronic Engineering-Systems.

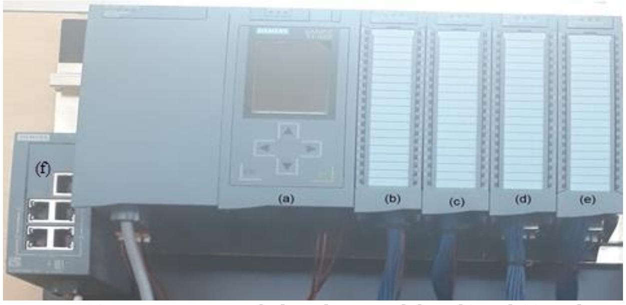

Fig. 1. (a) S7 1500 PLC with digital I/O modules, (b) and (c) analog I/O, (d), (e) and (f) PN communication switch.

The plant used for thermal tuning consists of the SO 3536-8T module shown in Fig. 2, with operating range from 0 ℃ to 100 ℃, the maximum process temperature being approximately 96 ℃. The output voltage of the temperature sensor is linear and proportional to the temperature (0–100 ℃/0–10 V).

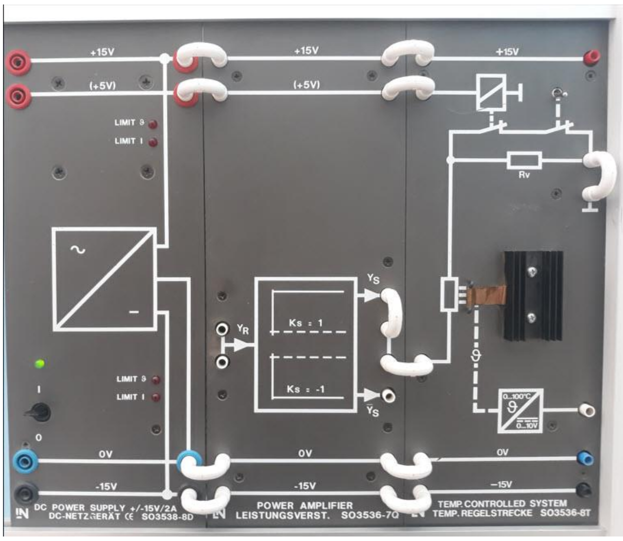

Fig. 2. Thermal plant with an operating range of 0-100 ℃.

In the thermal plant module, the sensor is in series with the plant, and for an ambient temperature of 25 ℃ it gives a transfer function represented by Eq. (1) [25].

$$G(s) = \frac{4.76e^{-7s}}{24s+1} \tag{1}$$

The PID controller represented in the block diagram in Fig. 3 needs to be tuned for a specific application; for which the classical methods of trial and error and process reaction curve are used [7]. The process reaction curve methods include the step response method and the Ziegler-Nichols frequency response method [26]. The relay tuning method [27] and the Cohen-Coon method addressed the efficiency and robustness of PID formulas for processes with dead time-to-time constant ratios between 0.1 and 1 [28].

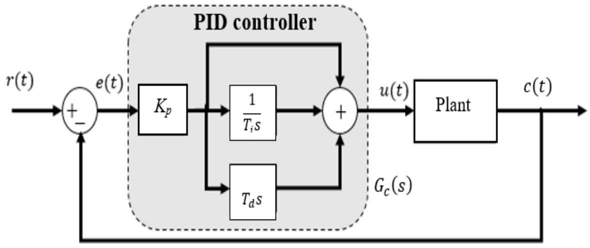

Fig. 3. PID controller diagram.

Tuning was carried out using the Ziegler-Nichols frequency response method. For the tuning of the PID controller from WinCC Unified, $T_i = \infty$ and $T_d = 0$. With setpoint at 50% ($r(t)$ = 50℃) and using only the proportional control action (K_p) presented in Fig. 4, where $e(t)$ is the error representing the difference $c(t) - r(t)$, and controller output $u(t)$ activating the heater (actuator) of the plant. K_p is increased from 0 to a critical value of K_{cr}; where the variation of the temperature in the plant $c(t)$ measured in ℃ presents sustained oscillations.

Thus, the critical gain K_{cr} allows us to obtain the critical period (P_{cr}) experimentally of the oscillation [29], as shown in Fig. 5.

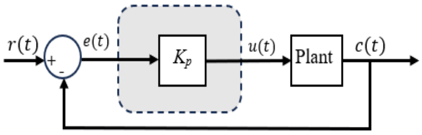

Fig. 4. Closed loop system with only the parameter Kp of proportional control action to obtain K_{cr} experimentally.

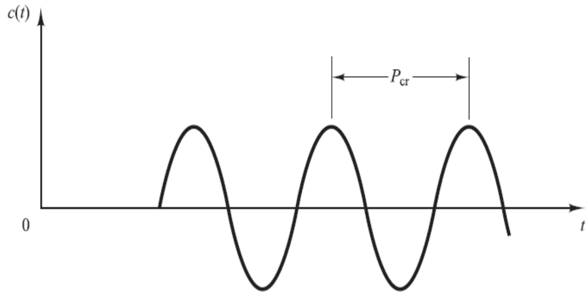

Fig. 5. Sustained oscillation with period P_{cr}.

Ziegler and Nichols based on P_{cr} suggested setting the parameter values K_p, T_i, and T_d according to Eqs. (2) to (4), which represents the PID controller:

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{2}$$

$$G_c(s) = 0.6K_{cr}\left(1 + \frac{1}{0.5P_{cr}s} + 0.125P_{cr}s\right) \tag{3}$$

$$G_c(s) = 0.075K_{cr}P_{cr}\,\frac{(s+\frac{4}{P_{cr}})^2}{s} \tag{4}$$

The experimental values are summarized in Table I, being used in this work PID type controller.

TABLE I: ZIEGLER-NICHOLS TUNIZNG RULE BASED ON CRITICAL GAIN K_{CR} AND CRITICAL PERIOD P_{CR}

Controller type	K_p	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\frac{1}{1.2}P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.25P_{cr}$

The controller was implemented in PID_Compact which has Anti-Windup and allows the weighting of P, I, and D actions. It has the following operating modes: idle, initial optimization, fine optimization, automatic mode, and manual mode [30]. The PID algorithm of the PID_Compact block integrated into the S7 1500 PLC operates according to Eq. (5).

$$y = K_p[(bw - x) + \frac{1}{T_i s}(w - x) + \frac{T_d s}{aT_d s+1}(cw - x)] \quad (5)$$

where y is the output value of the PID algorithm, K_p proportional gain, s Laplace operator, b proportional action weighting, w setpoint, x process value, T_i integration time, T_d derivative action time, a derivative delay coefficient (derivative delay $T_1 = aT_d$), and c derivative action weighting.

B. System Model

The tunable PID controller server was implemented in the SIMATIC S7 1500 PLC, using the PID_Compact instruction block and the Ziegler-Nichols PID rule. The plant temperature data were obtained through the analog input module, the process results were sent to the digital output module, sending modulated signal to the actuator constituted by a heater. All PLC values are transparent to OPC UA communication [31].

From the server diagram presented in Fig. 6, the "Temperature" variable is in the process, the values of this variable are obtained by the analog sensor in ranges of 0–10 V equivalent to values of 0–100 ℃. The temperature is obtained by the analog input module sampled every 100 ms. These values are sent to the PID controller; where the normalization and scaling of the variable values is performed.

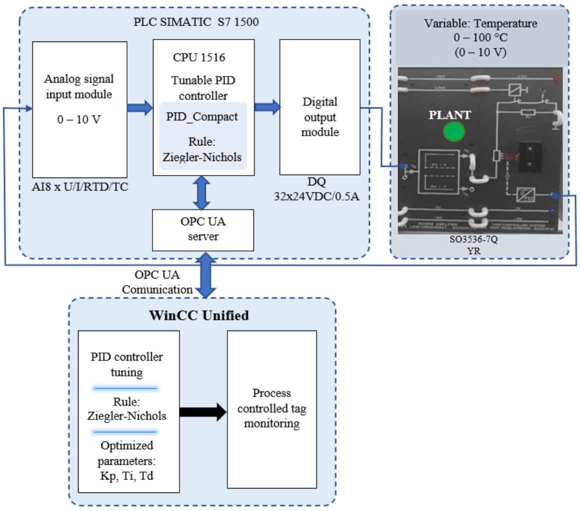

Fig. 6. Diagram of the server of the tunable PID controller implemented in PLC S7 1500 with PID_Compact and communication with WinCC Unified via OPC UA.

The PID_Compact block shown in Fig. 7 was inserted into the CyclicInterrupt organization block, which is fast response (OB30) [32], with input/output data storage in the DB1130 block. PID_Compact has defined inputs and outputs: the Setpoint input, allows the client interface to set the desired value of the variable to be controlled; Input allows the input of variable values in the range of 0–100 %; Input_PER allows the input of analog data in the range of 0–27648. Output gives percentage values (0–100 %) of the manipulated or control signal going to the actuators; Output_PER gives values for analog output (0–27648) for actuator control; Output_PWM gives pulse width modulated signal, which was connected to the YR terminal of the heater power amplifier SO3536-7Q via the address of the digital output module % Q4.0.

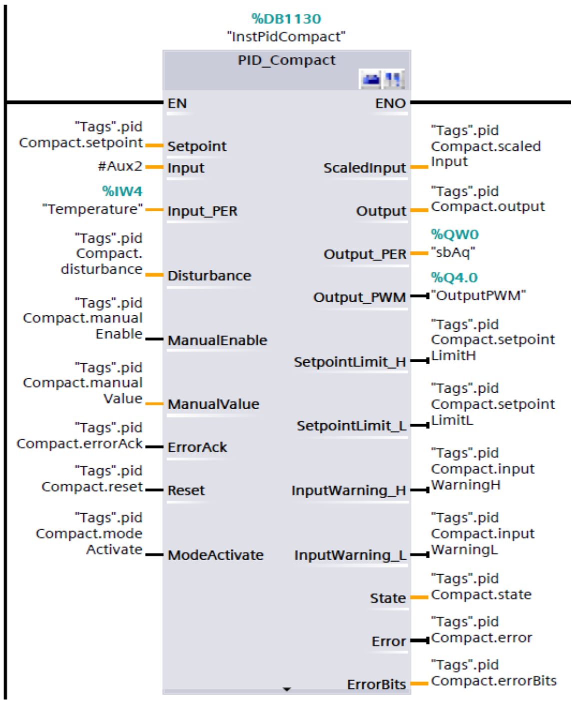

Fig. 7. 1PID_Compact instruction block with inputs and outputs prior to configuration.

The PID_Compact block was configured for temperature regulation in ℃ in automatic CPU restart mode, with parameter input by Input_PER which is of analog type (0–27648), and Output_PWM output, these settings are presented in Fig. 8.

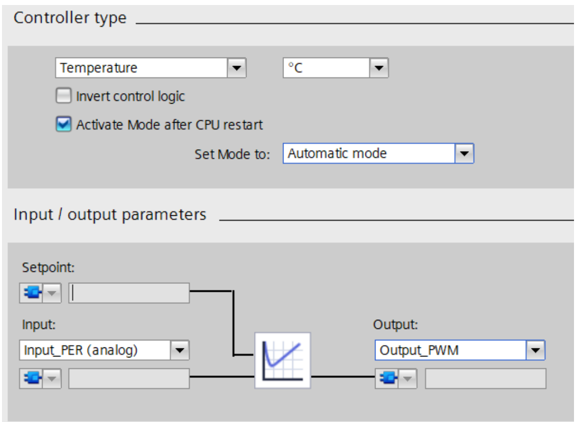

Fig. 8. Basic setting of the PID_compact instruction block.

In Fig. 9, shows the setting of the limits for the variable "Temperature" from 0–100 ℃, the analog input for the actual value scale has a numerical value ranging from 0–27648, which corresponds directly to the limits of the variable.

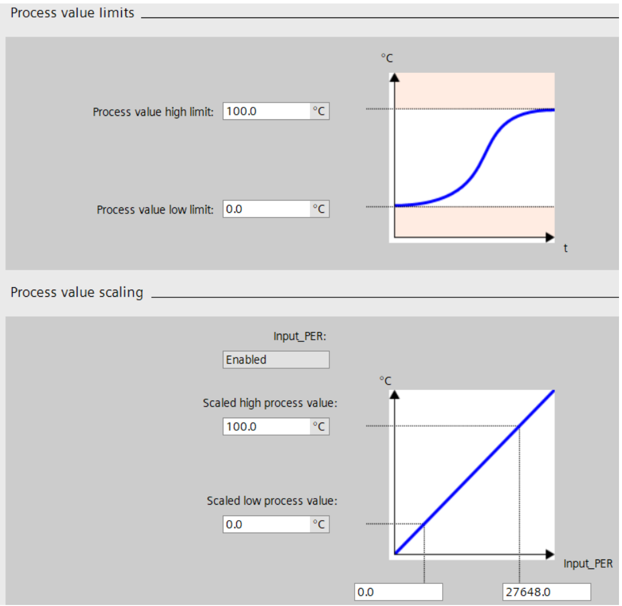

Fig. 9. Limit settings and scaling of the actual value in the PID_compact instruction block.

In advanced settings, manual input was activated (see Fig. 10), which allowed tuning to be performed from the client interface of the PID controller developed in WinCC Unified. The PID parameter data did not need to be modified (K_p = 1.0, T_i = 20.00 s, T_d = 0.1 s), this served as a reference to determine the improvements obtained with the tuning; in addition, the PID controller structure was selected.

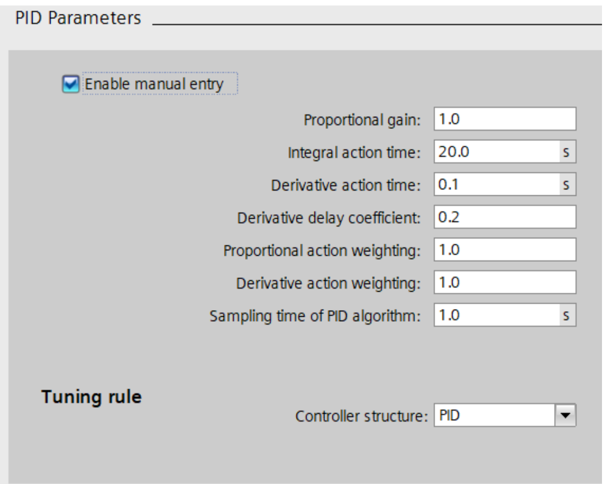

Fig. 10. Parameter settings of the controller with PID structure in manual mode.

In the TuneRule variable of PIDSelfTune-TIR-TuneRule the "Ziegler-Nichols PID" tuning rule is selected, having "Automatic PID" as default input. This configuration was performed from the client interface of the tunable PID controller, selecting for the study option 1 of Text_List_TuneRuleTIR presented in Fig. 11. To select the tuning mode from WinCC Unified, Pretuning and Fine tuning were configured in TuningMode.

To facilitate the OPC UA connection of the different tags and variables between the server and client of the tunable PID controller, the interface function block "Hmi" (FB3) of Fig. 12 was generated.

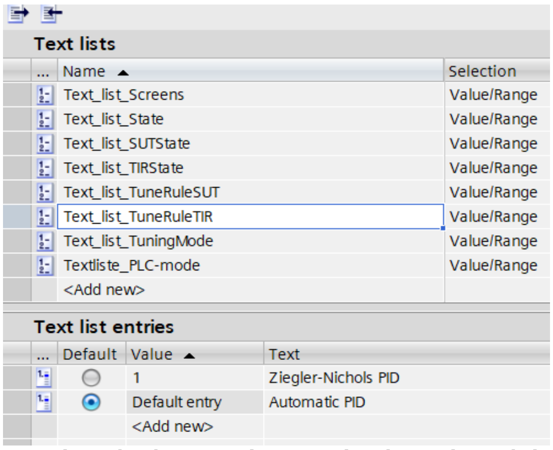

Fig. 11. Values taken by TuneRuleTIR to select the Ziegler-Nichols PID tuning rule.

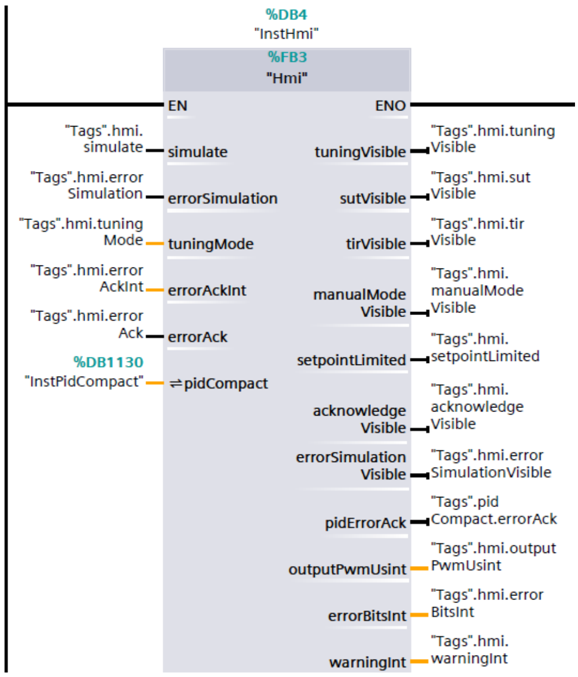

Fig. 12. 2 Tags and input and output variables of the "Hmi" function block.

The OPC UA server communication was configured in the PLC S7 1500, being the server address generated automatically based on the ethernet address assigned to the PLC. Fig. 13 shows that when selecting "Activate OPC UA server" the server addresses are generated, being these opc.tcp://192.168.0.1:4840 and opc.tcp://192.168.1.1:4840, where the communication is through port 4840, with up to 15 simultaneous sessions and 10000 registered nodes.

Then, in the TIA Portal, we proceeded to compile the entire structure of the configured hardware and the program corresponding to the tunable PID server and proceeded to load it into the SIMATIC S7 1500 PLC.

On the other hand, the client of the tunable PID controller was implemented in WinCC Unified V19; which maintains communication via OPC UA protocol with the server. From this interface, it was possible to select the Ziegler-Nichols PID rule, activate the tuning process, and visualize the optimized K_p, T_i, and T_d parameters.

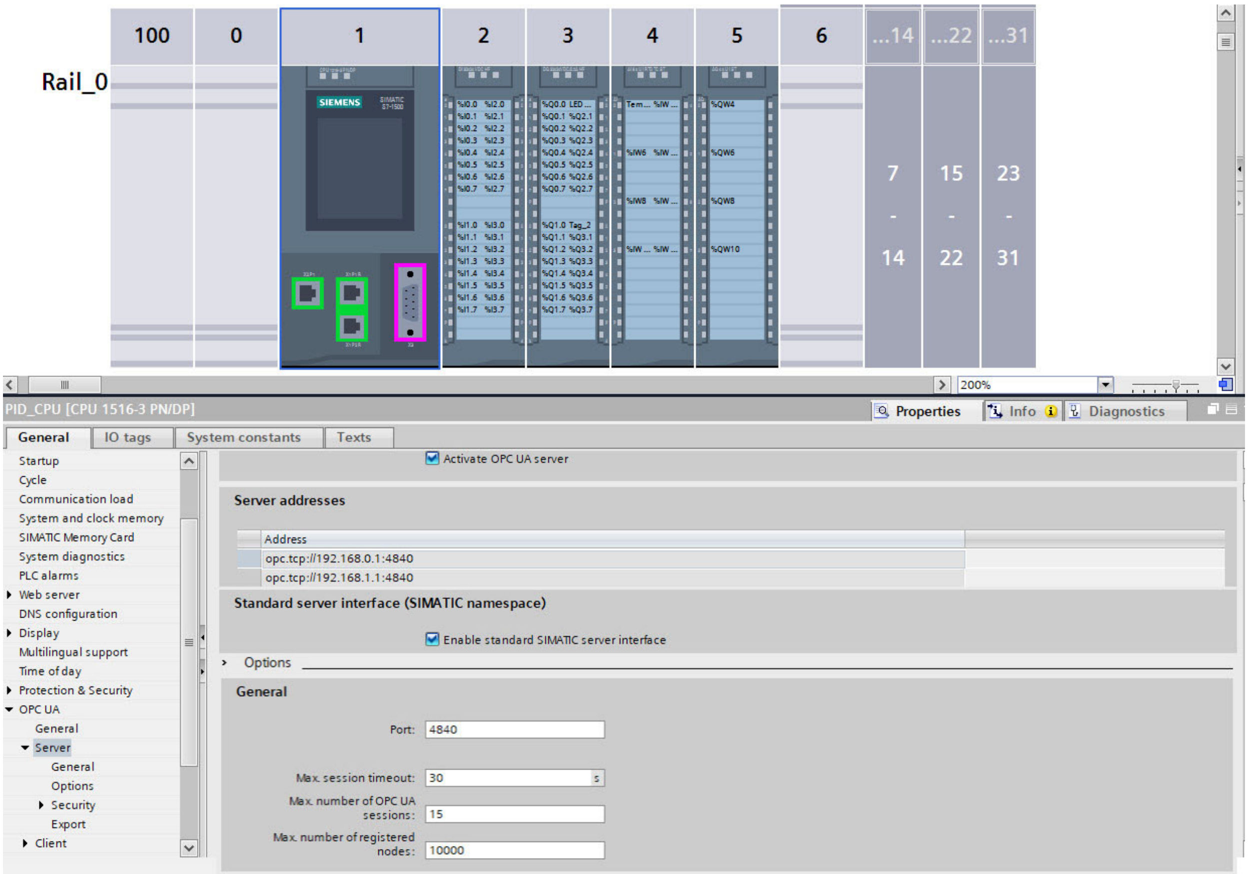

Fig. 13. Server configuration for OPC UA communication.

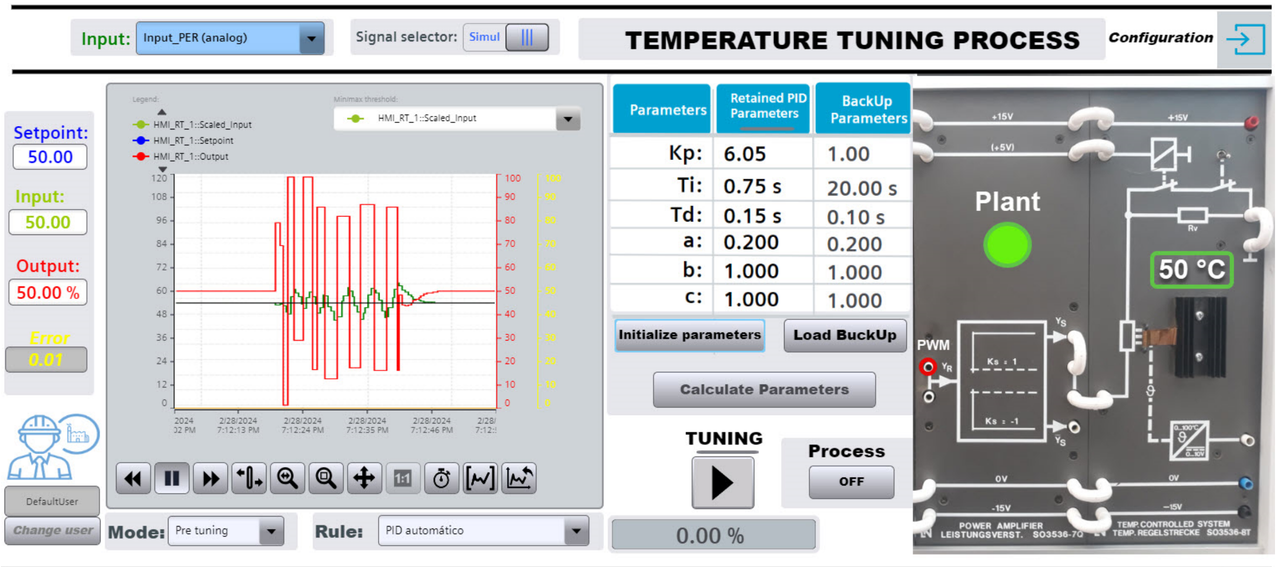

Fig. 14. Components of the image “Temperature_Tuning” based on the Ziegler-Nichols PID method.

One of the most important images is Temperature_Tuning shown in Fig. 14; it allows finding the appropriate values for the parameters K_p, T_i, and T_d of the PID controller, the temperature variable in the thermal plant being in the range of 0–100 ℃, after selection of the fine-tuning mode with the Ziegler-Nichols method with critical gain K_{cr} and critical period P_{cr}.

Also, it was possible to monitor the controlled variable of the process. In the folder Images located within the HMI_RT_1 interface, the different images were created in WinCC Unified, whose overall operation follows the flow diagram in Fig. 15.

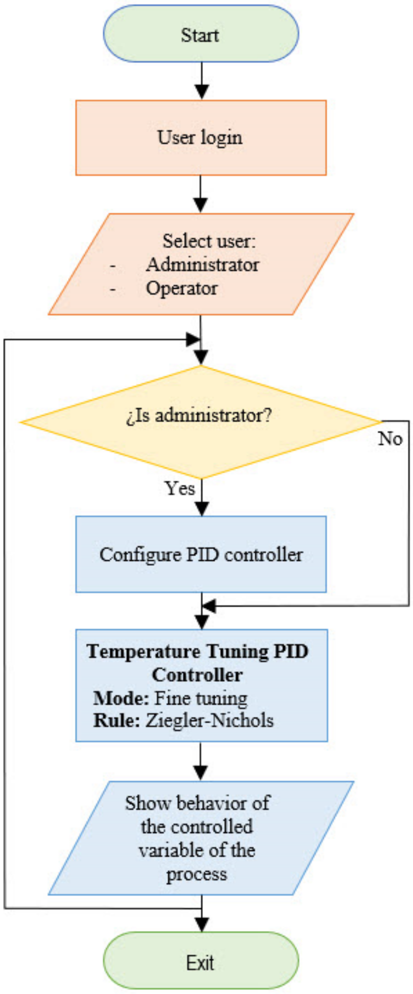

Fig. 15. Image execution flowchart of the client image execution of the tunable PID controller implemented in WinCC Unified.

IV. Results and Discussions

A. Results

The result of the response of the untuned PID controller to 10 inputs that varied in step from ambient temperature (at ≈ 12°C) to setpoint (see Table II) with preset parameters: K_p = 1.0, T_i = 20.00 s, T_d = 0.1 s considering $e_{ss} \leq 2\%$, for the temperature variable in the thermal plant, was of the over damped type; obtaining negative maximum overshoot values (%) amounting up to –1.99 % and a maximum settling time of 192 s.

Table II. Results of Experiments with Untuned PID Controller for the Temperature of the Thermal Plant

Run	Setpoint (°C)	Settling time (s)	Normalized settling time 1(%)
1	at 25	109	56.48
2	at 30	146	75.65
3	at 35	166	86.01
4	at 40	169	87.56
5	at 50	173	89.64
6	at 60	176	91.19
7	at 70	177	91.71
8	at 80	179	92.75
9	at 90	184	95.34
10	at 95	192	100.00

When tuning the PID controller, from the WinCC Unified interface by OPC UA, using the Ziegler-Nichols PID rule, based on the critical gain K_{cr} and critical period P_{cr}, for a setpoint of 50% of the Temperature variable, in the process, resulted in the parameters K_p = 6.05 s, T_i = 0.75 s and T_d = 0.15, with which the settling time was determined for different setpoint values of this controlled variable, being the result presented in Table III.

Table III. Results of Experiments with Tuned PID Controller for the Temperature of the Thermal Plant

Run	Setpoint (°C)	Settling time (s)	Normalized settling time 2(%)
1	at 25	24	12.44
2	at 30	27	13.99
3	at 35	29	15.03
4	at 40	31	16.06
5	at 50	34	17.62
6	at 60	37	19.17
7	at 70	39	20.21
8	at 80	42	21.76
9	at 90	49	25.39
10	at 95	54	27.98

When performing the comparison of means with Student's t-statistic for the normalized settling time variable of the untuned and tuned PID controller presented in Table II and Table III respectively, having significance alpha = 0.05 for a 60% improvement of the settling time of the temperature variable for an $e_{ss} \leq 2\%$; a p-value of 0.047 is obtained (see Fig. 16), when tuning the PID controller using the Ziegler-Nichols rule from WinCC Unified by OPC UA.

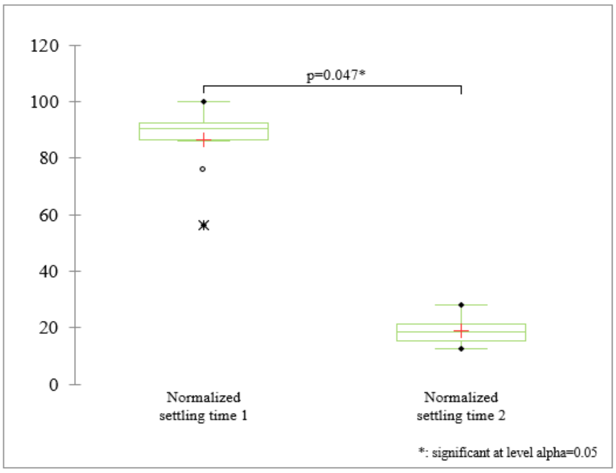

Fig. 16. Comparison of "Normalized settling time" averages of the untuned and tuned PID controller.

B. Discussions

From the results, a tunable PID controller was obtained; constituted by a server configured in PLC S7 1500 that has as a fundamental element the PID_Compact module configurable with the Ziegler-Nichols rule, with OPC UA communication that allowed the interaction with the client implemented in WinCC unified, from whose interface the controller was tuned. The operation was tested by determining the reduction of the settling time of the controlled variables. This verification was carried out with respect to pre-established PID parameters before tuning, and after tuning, different PID parameters were obtained for the process; which shows that the PID controller must be uniquely tuned for each type of process, on which depends the performance of the PID controller in a real system against setpoint changes and external disturbances.

On the other hand, the control of the temperature variable in the thermal plant when tuned presents high efficiency (greater than 60%) with the optimal parameters found being $K_p = 6.05$, $T_i = 0.75$ s, $T_d = 0.15$ s for $e_{ss} \leq 2\%$, with a controlled temperature signal of the under-damped type, allowing adequate stabilization against different values of the step setpoint.

V. Conclusions

The server of a tunable PID controller was implemented on an S7 1500 PLC using the PID_Compact technology module, which is configurable with the Ziegler-Nichols rule, communicating data via the OPC UA industrial protocol with the client developed in WinCC Unified.

It was possible to reduce the settling time of the controlled variable "Temperature" of the thermal plant (SO3536-8T) by more than 60 % for steady state error $e_{ss} \leq 2\%$ within the nominal process range of 0–100 °C, allowing proper stabilization of the variable.

Future research should delve deeper into PID controller tuning through the WinCC and OPC UA interface, investigating the incorporation of predictive models and machine learning techniques, and determining how these models can anticipate system changes and adjust PID parameters proactively.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

H. Carbajal-Morán, C. A. Galván-Maldonado and E. M. Ramos-Lapa conducted the research implementing the tunable PID controller from WinCC Unified by OPC UA; they also contributed with data acquisition and analysis, and validation of the results. J. F. Márquez-Camarena contributed to the editing of the article/figures. All authors approved the final version.

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