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Design of a Cascaded PID Controller for Temperature Control of Heating Furnaces

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Abstract: The effectiveness of cascaded PID controller systems for industrial heating furnace temperature control is assessed in this research. It is evident from the literature on control theory that the ideal PID controller is no longer suitable for controlling non-linear phenomena, such as temperature. For managing these nonlinear processes, a PID controller in a cascaded design is preferable to a traditional single loop control system. It is limited in its ability to select the optimal PID improvements, though. In order to determine the optimal PID gain values in cascaded form, this study evaluates the performance using standard tuning methods. Finding the system's dynamic performance characteristics in each scenario allowed for the performance examination of several algorithms. MATLAB/Simulink is used to model the complete system, According to the simulation results, the suggested cascaded PID design may lead to robust dynamic performance and rapid reaction.

Keywords - System of Cascaded Control, PID (Proportional plus Integral plus Derivative) controller, dynamic performance analysis, Matlab/Simulink, temperature process control, and tuning ideas.

INTRODUCTION

- I. Using two PIDs in tandem to obtain higher dynamic performance than a single PID is one of the most flexible ways to use PID controllers. The term "cascaded PID controller" refers to this. The two PIDs in this controller are positioned so that one PID's set point is managed by another PID. Using the output of another PID as a set point, one PID controller functions as an inner loop controller. Another PID functions as an outer loop controller, regulating the system's physical characteristics including flow, pressure, and temperature. As a result, the cascaded PID controller raises the controller operating frequency while decreasing the system's time constant.
- II. The cascade control system is unique in a few ways. They are Quality control, Anti-interference, ability, flexibility and quickness. Thus, it is typically utilized in the following situations:
 - A longer control channel delay.
 - Nonlinearly controlled objects with significant load variations
 - A sudden shift in the systemA cascade control system primarily consists of interconnected sets of control loops. There are two types of loops: primary and secondary. The primary loop keeps an eye on the control variable and provides an output to the secondary loop based on deviations from its set point. The primary loop provides the secondary loop with its set point, which it uses to adjust the reference variable. The furnace is the most crucial piece of thermal equipment utilized in the metallurgical industry. As a result, certain fundamental techniques for automatically regulating furnace temperature have been identified. For example, constant control of furnace process variables, cascade control of

temperature in the furnace and flow of the fuel, the control of fuel and combustion air mixture ratio, and also control of oxygen content in flue gas. So far, the control focus has moved to performance optimization. The furnace temperature is mostly controlled by the gas flow regulation. Cascaded PID controller is well suited because the control of gas flow in the furnace is a typical process and larger capacity lag in the furnace temperature control system.

Pre-regulating the interference that affects the intermediate variables will enhance the dynamic quality of the entire system. Compared to a single loop control system, the cascade control system is more effective. Additionally, it is faster, more flexible, and offers better quality control than a single loop. The advantages of a cascaded control system include the ability to efficiently account for external disturbances, decreasing variable response dead time. compatible with feed-forward and feed-back control designs, among other control systems. However, cascade control has certain disadvantages, such as the need for multiple control loops, the complexity of the physical and computational architecture, and the potential expense of extra controllers and sensors.

III. FURNACE CASCADE CONTROL SYSTEM

- IV. The figure depicts the components of a furnace temperature control system. 1. T1T stands for measuring temperature for raw material exports, while T1C is the primary controller and T2C is the secondary controller.
- V. materials, and T2T stands for furnace hearth temperature measurement. The furnace temperature control system functions in the following basic ways.

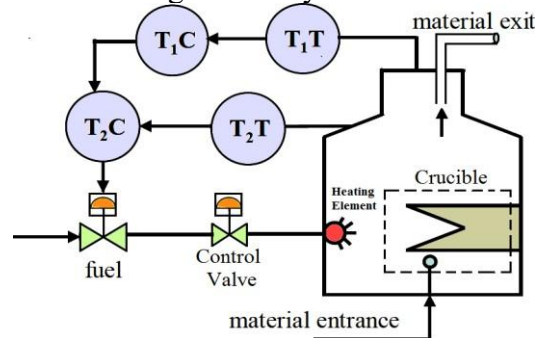


Figure.1 Cascaded control of furnace temperature system

The secondary controller (T2C) receives the output of the primary controller (T1C) as a set point. The fuel flow is managed by T2C. From the crucible's entrance to its exit, the material is heated to a predetermined temperature during the heating process. There are three capacity components in the system temperature, ranging from the fuel combustion chamber to the raw material export. They are the heated raw materials, the hearth, and the furnace. One side of the system is affected by load and raw material side disturbances, while the other side is affected by burning side disturbances like fuel, pressure, and air flow.

The raw material is the main object in the furnace temperature control system, and the furnace hearth is the secondary object. The temperature of the furnace's hearth is a subcontrolled variable, whereas the temperature of the raw materials in the export is the primary controlled variable. The raw material flow and material temperature at the input are the main sources of disruption. The fuel pressure before to the valve, the heat value of the fuel-air mixture fed to the furnace hearth, etc. are examples of secondary disturbances.

One of the most crucial safety measures for cascaded PID control systems is to make sure that the main and sub loop time constants match when choosing design parameters. This will allow for safe operation without resonance.

VI. CASCADED PID CONTROL SYSTEM DESIGN

The figure.2 shows the furnace cascade PID control system. The equations 1 and 2 are the transfer functions for Primary and secondary objects.

$$G_1(s) =$$

$$G_2(s) = \frac{1}{(s + 1/30)(s + 1/3)1/10(1)} \frac{1}{(s + 1/10)(s + 1)^2(2)}$$

Figure.3 [1] illustrates how this system is built in MATLAB/Simulink. The PID controller and table are represented mathematically in equation 3.3. 1 illustrates the impact of raising KP, KI, and KD gains on dynamic characteristics.

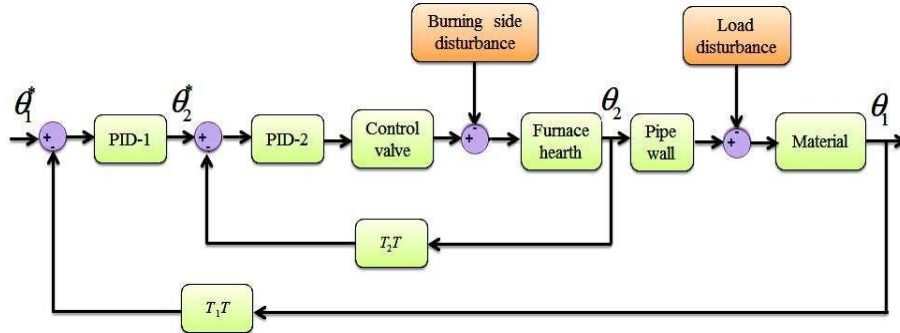


Figure.2 Furnace cascade PID control system model

$$P(t) = K_p e_p(t) + K_I \int e_p(t) dt + K_D \dot{e}_p(t) \quad (3)$$

Where; $P(t)$ = Control signal applied to the plant.

K_p = Proportional gain constant

$K_I = \frac{K_p}{T_I}$ = Integral gain constant

$K_D = K_p \times T_D$ = Derivative gain constant.

Parameter	Rise time (Tr)	Overshoot (Mp)	Settling time (Ts)	Error (Ess)
K_p	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Decrease Significantly
K_D	Minor Decrease	Decrease	Decrease	No effect

Table.1 Effect of increasing P, I, and D gains on dynamic characteristics

Hence, the PD controller is used to have fast settling; PI controller is used to have less steady state error. And PID controller is used to have all individual control actions. Hence, different combinations of controllers should be selected properly to get the desired characteristics. This paper uses ultimate gain/ultimate cycle methods for PID parameter tuning.

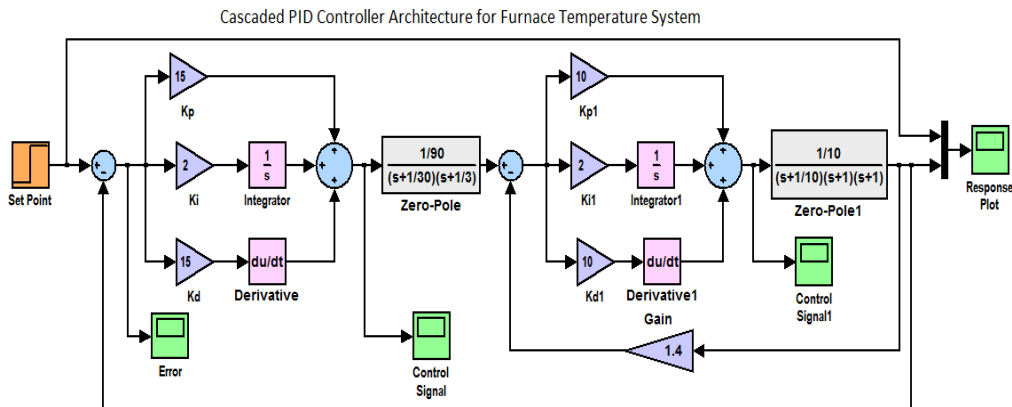


Figure.3 MATLAB/Simulink model of cascaded PID controller design for furnace temperature control

VII. ULTIMATE CYCLE METHOD FOR TUNING OF PID CONTROLLER GAINS

VIII. The simplest and most efficient approaches for configuring the PID controller gains are the ultimate cycle/ultimate gain/cyclic oscillations methods. These techniques can be broadly divided into three categories, which are listed below [2].

The Ziegler-Nichols (ZN) PID controller tuning technique.

The Ziegler-Nichols PID controller tuning method is modified.

The tuning procedure for Tyreus-Luyben (TL) PID controllers.

In industrial manufacturing, the furnace temperature exhibits non-linear, time-varying, and delay characteristics. Therefore, we are unable to develop a mathematical model that is absolute. The process of choosing the right values for KP, KI, and KD gains is always unpleasant and difficult. The outer loop PID is adjusted utilizing tuning techniques to lessen the aforementioned issues and enhance transient response parameters. The optimal choice of values for proportional (KP), integral (KI), and derivative (KD) gains is necessary for PID controller tuning.

The procedures for determining critical gain (Kc) and critical time period (Tc) values are as follows [3], [4],

IX. [5] as well as [6]. The PID controller gain settings process flow is depicted in Figure 4. [7].

Step 1: Minimize the impact of integral and derivative actions by designing the system with a proportional controller with unity feedback.

Step 2: Increase the proportional gain value gradually until the system starts to show persistent oscillations.

Step 3: The critical gain (Kc) is the gain at which the system shows continuous oscillations or constant cycling around the set point. The crucial time period (Tc) is the time interval that corresponds to these oscillations.

Step 4: Take note of these Kc and Tc values.

Step 5: Determine the Kp, Ki, and Kd gain values from these values using the approach indicated in Table 2.

Parameter	Ziegler- Nichols PID controller Tuning Formula	Modified Ziegler- Nichols PID controller Tuning Formula	Tyreus-Luyben PID controller Tuning Formula
T_i	$T_i = \frac{T_c}{2}$	$T_i = T_c$	$T_i = 2.2 \times T_c$
T_D	$T_D = \frac{T_c}{8}$	$T_D = \frac{T_c}{3}$	$T_D = \frac{T_c}{6.3}$
K_p	$K_p = 0.6 \times K_c$	$K_p = 0.2 \times K_c$	$K_p = 0.45 \times K_c$
K_i	$K_i = \frac{K_p}{T_i}$	$K_i = \frac{K_p}{T_i}$	$K_i = \frac{K_p}{T_i}$
K_D	$K_D = K_p \times T_D$	$K_D = K_p \times T_D$	$K_D = K_p \times T_D$

Table.2 Tuning formulas for PID controller design in different methods

Figure.5 shows, the overall MATLAB/Simulink model for PID controller design with different tuning methods. The parameter gain values obtained for different PID controllers are listed in Table.3. Figure.6 shows the elaborated design of the furnace system with Ziegler-Nichols PID controller.

S.NO	METHOD NAME	Kp	Ti	KI	TD	KD
1	Ziegler-Nichols(ZN) tuning formula	24.24	5.238	4.627	1.3095	31.742
2	Tyreus-Luyben tuning formula	18.18	23.047	0.788	1.662	30.215
3	ModifiedZiegler-NicholsTuning formula	8.08	10.476	0.771	3.492	28.215

Table.3 P, I, D parameters obtained for different tuning formulas

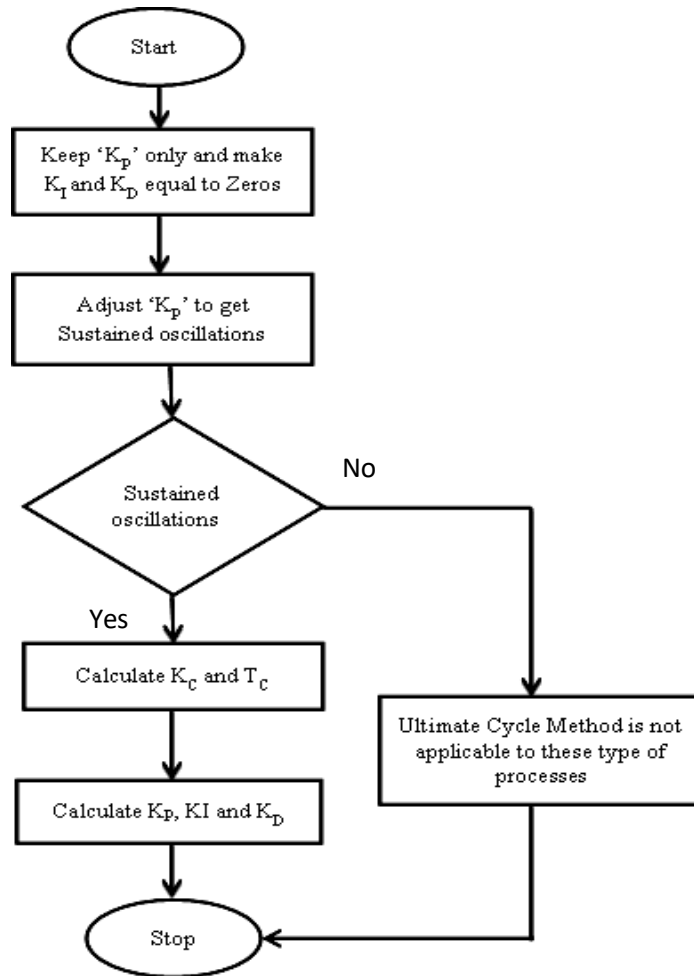


Figure.4 Flow chart for PID tuning procedure

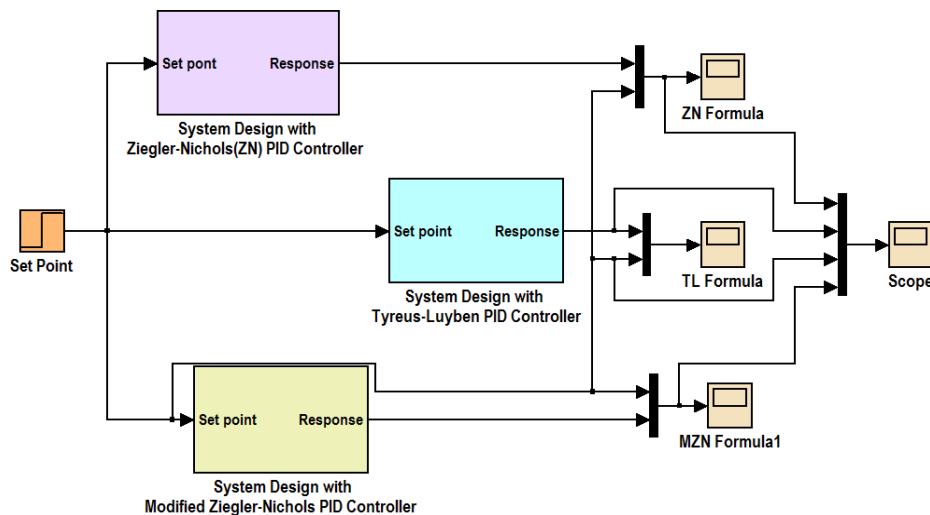


Figure.5 Comparison model for all the methods.

X. DYNAMIC PERFORMANCE CHARACTERISTICS

XI. Dynamic response is the term used to describe how a closed loop system's reaction changes over time [8].

The following parameters can be computed in order to examine this time response.

Rise time (T_r): The time needed for the system's response to go from a low value to a high

value is known as the "rise time." These values are typically 90% and 10% of the steady-state value, respectively.

The delay time (T_d) is the amount of time needed for the system's response to first go from zero to fifty percent of the steady-state value.

The settling time (T_S) is the amount of time it takes for the answer to enter and stay within a given error band. Typically, the acceptable error range is between 2 and 5 percent of the steady-state value.

When the system enters a steady state, the discrepancy between the desired and actual responses is known as the steady-state error (ESS).

The ratio of the first peak value measured from the steady-state value to the steady-state value is known as the peak overshoot (MP).

The time it takes for the response to reach the initial peak overshoot is known as the peak time.

Stability: When a system generates bounded output for a bounded input, it is considered stable.

Quick rising, minimal delay time, zero steady-state error, rapid settling, minimal overshoot, and stability are all characteristics of the optimal system response.

XII. Simulation Results

Figure.7 shows the formation of sustained oscillations about the set point. Figures 8-11 shows the response of the system with PID controller designed with various tuning formulas. Figure 12 shows the comparative result for all the responses. The transient response/dynamic performance characteristics are calculated and tabulated as shown in the table.4.

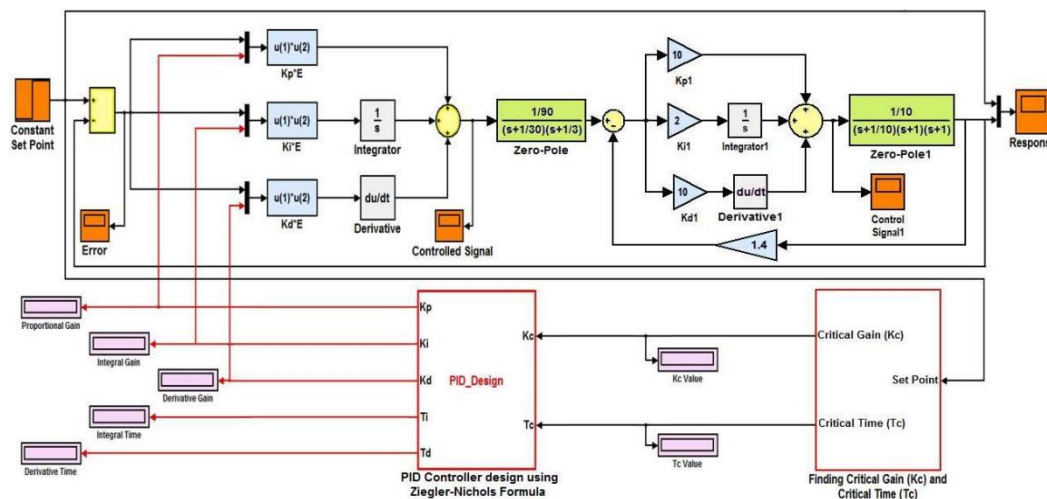


Figure.6 MATLAB/Simulink model of the furnace system with Ziegler-Nichols cascaded PID controller

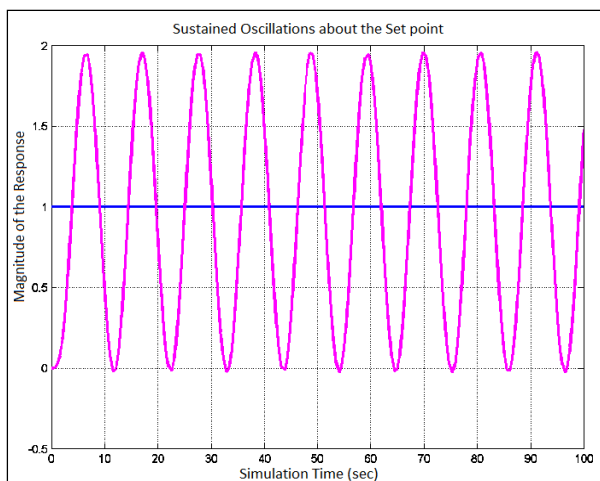


Figure.7 Sustained oscillations about set point

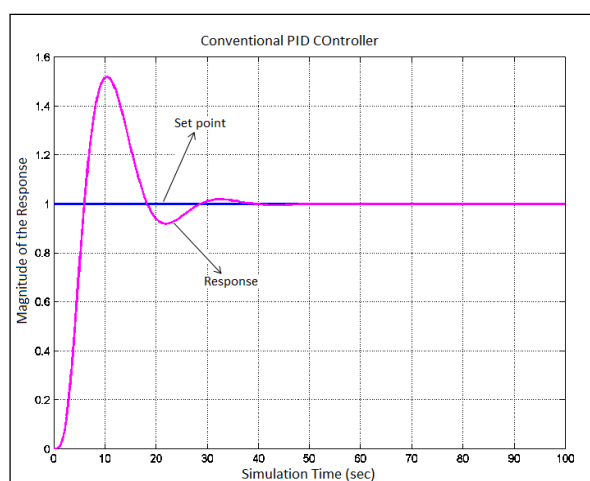


Figure.8 System response with generic PID controller

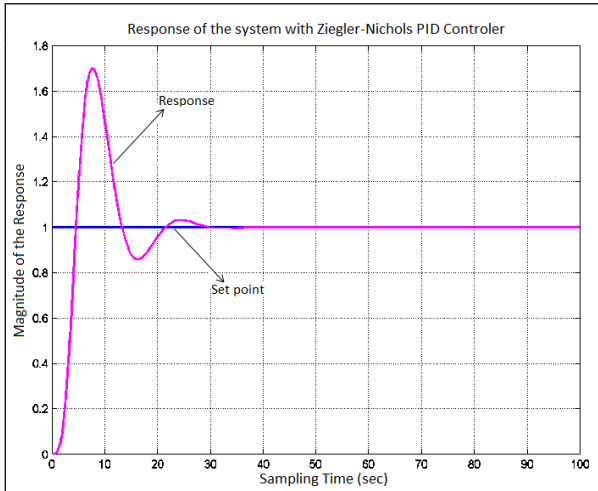


Figure.9 System response with cascaded ZN PID

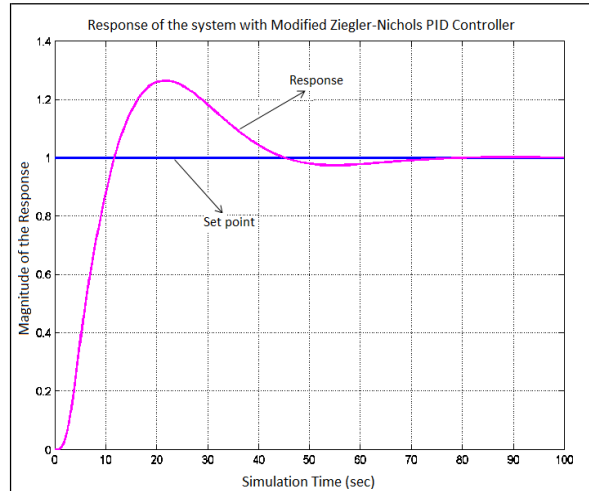


Figure.10 Response with cascaded Modified ZN PID

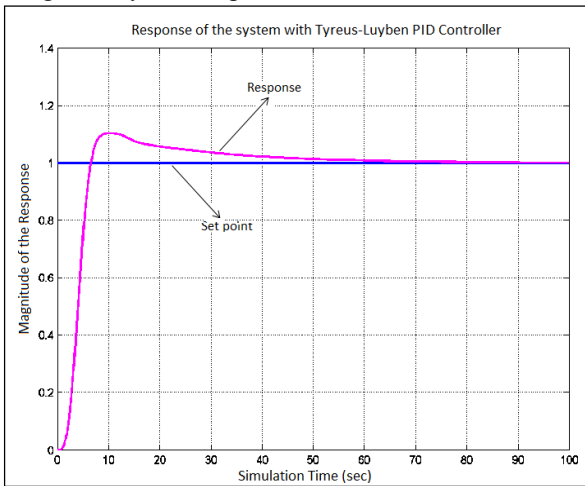


Figure.11 System response with cascaded TL PID

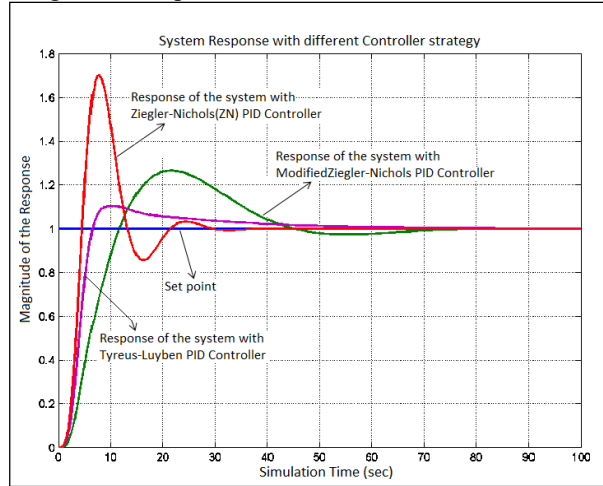


Figure.12 Comparison of all responses

S. No.	Controller Used	Time Domain Performance Parameters					
		Delay Time (T_d) in Sec	Rise Time (T_r) in Sec	Settling Time (T_s) in Sec	Peak Overshoot (M_p) in %	Transient Behavior	%Steady state Error (E_{ss})
1.	Ziegler-Nichols PID Controller	2.763	2.456	38.40	58.20%	Oscillatory	0
2.	Modified Ziegler-Nichols PID Controller	5.296	7.644	78.285	31.52%	Oscillatory	0
3.	Tyreus-Luyben PID Controller	3.377	3.531	67.175	11.02%	Smooth	0

Table.4 Comparison of different time domain specifications

XIII. Conclusion

XIV. First, the temperature process controller for an industrial heating furnace in the paper uses a traditional PID controller. The cascaded PID controller gain settings are then adjusted using a variety of tuning procedures. Everyone's performance is compared to one other and tallied in Table 4. The following points are evident from the table.

The Ziegler-Nichols PID controller features severe oscillations with a very high peak overshoot of 58.20%, despite producing a response with shorter delay time, rising time, and settling time. The system's performance is harmed as a result.

The Tyreus-Luyben PID Controller's delay time, rise time, and settling time values are nearly identical to the Ziegler-Nichols method and better than the Modified Ziegler-Nichols approach. Additionally, it has a significant advantage in terms of decreased overshoot and smooth transient behavior.

In order to regulate non-linear processes like temperature, it is determined that the Tyreus-Luyben tuning procedure is most appropriate for configuring the settings of cascaded PID controller gains.

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