Smith Predictor-Driven PID Controller Optimization for Liquid Level Control

S. Rajasekaran,Ph.D
Professor
Electronics and Communication Engineering
Madanapalle Institute of Technology & Science
ecehod@mits.ac.in

G.md. Abdul Kalam
UG Scholar
Electronics and Communication Engineering
Madanapalle Institute of Technology & Science
54321abdulkalam@gmail.com

B. Dinesh Sai Naidu
UG Scholar
Electronics and Communication Engineering
Madanapalle Institute of Technology & Science
dineshsai3160@gmail.com

N. Bhavana
UG Scholar
Electronics and Communication Engineering
Madanapalle Institute of Technology & Science
nareddulabhavana@gmail.com

***Abstract*—Safety and operational performance are directly impacted by efficient fluid level control in industrial tanks. In order to overcome inherent process delays, this study examines how to improve liquid level regulation in linear tank systems by fusing conventional PID control with a Smith Predictor framework. We started by using the Ziegler-Nichols and Cohen-Coon approaches to determine the ideal PID parameters. We then used extensive MATLAB simulations and experimental validation to assess performance. According to our research, the Smith Predictor mechanism significantly reduces key performance indicators such as overshoot percentage, settling time, and error indices (more especially, IAE and ISE values). When compared to traditional methods, this combination provides better system responsiveness and stability. The outcomes demonstrate how well Smith Predictor mitigates the effects of time delays, making it a useful addition to PID control systems for industrial liquid level applications for management.**

Keywords— PID Control, Liquid Level Control, Time Delay Compensation, Smith Predictor, Control System Optimization

I. INTRODUCTION

Maintaining appropriate liquid levels in industrial processes is crucial for ensuring operational stability, efficiency, and safety. Various industries, including chemical processing, petroleum refining, and wastewater treatment, require accurate level control to maximize performance and avoid operational issues. While widely adopted for their simplicity and effectiveness, traditional PID controllers may struggle in systems with inherent time delays, such as liquid level control in tanks. These conventional PID controls can lead to suboptimal performance, characterized by excessive overshoot, sluggish response, and instability. This research addresses these issues by incorporating a Smith Predictor into the PID-based liquid level control system in a linear tank. The Smith Predictor, a model-based control technique, compensates for process time delays, thereby enhancing system response and stability. This method enables the controller to anticipate process behaviour and make proactive adjustments, effectively mitigating the negative impacts of time lag. The study develops a mathematical model of the liquid level system using mass balance equations and derives the transfer function. Optimal PID parameters are determined using Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) methods. The research employs MATLAB simulations and live experiments to evaluate the performance of conventional PID control against Smith Predictor-enhanced system. Both simulation and experimental outcomes demonstrate that the integration of the Smith Predictor significantly improves control performance. This improvement is evidenced by reduced overshoot, faster settling time, and minimized integral absolute error (IAE) and integral squared error (ISE). The results confirm that the Smith Predictor-based PID control strategy outperforms conventional PID control in managing time delays, depths making it an effective solution for liquid level control in industrial applications.

II. LITERATURE SURVEY

Liquid Level Control in Industrial Systems Controlling liquid levels in tanks is critical for various industries, including chemical processing, petroleum refining, food industries, and wastewater treatment. Traditional PID controllers are used because they are simple and effective. However, time delays in real-world processes often degrade PID performance, leading to instability and excessive oscillations [11],[12].Several researchers have explored control strategies for improving the stability and accuracy of liquid level systems: Rhodes (1996) emphasized the importance of real-time simulation[13] and process modelling for optimizing controller performance. Ogunnaike & Ray (1994) discussed the challenges of maintaining liquid level stability in dynamic processes[14], particularly in systems with nonlinear flow behaviour. Dale et al. (2011) highlighted the restriction of conventional PID controllers in handling nonlinearities and time delays in liquid level processes. These studies indicate the need for advanced control strategies to address process delays and enhance PID performance PID Controller Tuning for Liquid Level Systems PID tuning methods play a crucial role in achieving optimal controller performance. Two of the most widely used tuning methods are: Ziegler-Nichols (Z-N) Method: Introduced by [1], this method is widely used for tuning PID controllers based on ultimate gain and ultimate period. Marlin (2000) found that the Z-N method works well for first-order systems[16]but struggles with time-delayed processes, often leading to high overshoot and oscillations. Cohen-Coon (C-C) Method: Cohen & Coon (1953) developed this tuning approach to improve step response performance in open-loop systems. Astrom & Hagglund (1995) found that the C-C method offers faster response than Z-N tuning but may introduce higher overshoot in delay-dominant systems. Time-Delay Compensation in Control Systems Time delays in process control systems negatively impact stability, response time, and tracking performance. Researchers have proposed several methods to compensate for time delays, including Dead-time approximations (Padé Approximation) Used to approximate the delay term[18] in transfer functions, but still lacks predictive control (Shinskey,1996).Model Predictive Control (MPC) While effective, MPC is computationally intensive and requires an accurate process model (Philips & Harbor, 1991). The Smith Predictor is a model-based predictive control technique created by O.J.M. Smith in 1957 with the express purpose of correcting for temporal delays in process control systems[12]. Implementation of the Smith Predictor in Liquid Level Control Recent studies have investigated the use of the Smith Predictor for liquid level management .Yuli implemented a Smith Predictor in a double-tank system, reducing overshoot and improving tracking performance. Vassilios et al. studied the impact of delayed feedback in multivariable liquid level systems, concluding that a Smith Predictor-PID approach provides significant performance improvements over traditional tuning. [19] highlighted the importance of accurate process modelling in Smith Predictor design, noting that an incorrect model can degrade performance. These studies validate the effectiveness of Smith Predictor-based control in liquid level regulation, reinforcing its suitability for time-delayed industrial processes. Research Gap and Motivation for Current Study Despite extensive research on PID tuning and time-delay compensation, few studies combine the Smith Predictor with PID control for liquid level regulation in industrial applications. This study fills the gap by: Implementing Smith Predictor-based PID control for a liquid level system. Comparing, conventional PID controllers with and without the Smith Predictor. Analysing performance metrics (rise time, settling time, IAE, and ISE) to quantify improvements. Validating results through MATLAB simulations and real-time experiments. By addressing time-delay compensation with predictive control, this study aims to improve the accuracy, stability, and efficiency of liquid level control in industrial applications. The literature confirms that time-delay compensation is essential for accurate and stable liquid level control. The Smith Predictor is a proven solution for mitigating delay effects, making it a valuable enhancement to conventional PID control. This study builds on existing research by integrating a Smith Predictor into a PID-controlled liquid level system and demonstrating its effectiveness through simulations and real-time validation.

III. METHODOLOGY

Modelling of Liquid Level System

A mass balance equation that takes into account the inflow and outflow rates is used to simulate the dynamics of the liquid level in the tank. The outlet flow is a nonlinear function of the liquid level, and the system operates as a first-order process with a time delay. The expression for the governing equation is

$$\frac{dh(t)}{dt} = \frac{q_{in}(t) - q_0(h)}{A} \quad (1)$$

- $h(t)$ is liquid level at time t
- q_{in} is inlet flow rate,
- q_0 is outlet flow rate,
- A is cross-sectional area of the tank

Transfer function of the system is derived using Laplace transforms, incorporating the time delay θ follows:

$$H(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \quad (2)$$

where:

- K is system gain,
- τ is time constant,
- θ represents process delay.

The presence of time delay ($e^{-\theta s}$) degrades[11]controller performance, making traditional PID control less effective. To counteract this, the Smith Predictor is introduced.

PID Controller with Smith Predictor

A standard PID controller consists of proportional, integral, and derivative actions, given by:

$$C(s) = \left(1 + \frac{1}{\tau_I s} + \tau_D s\right) K_c \quad (3)$$

where:

- τ_D is the derivative time,
- τ_I is the integral time,
- $K\ c$ is the proportional gain.

The Smith Predictor modifies the control loop by predicting the future output of the process using a mathematical model. Instead of reacting to delayed system feedback, the predictor estimates the current process state in real-time, enabling PID controller to produce more accurate adjustments. The modified control structure consists of:

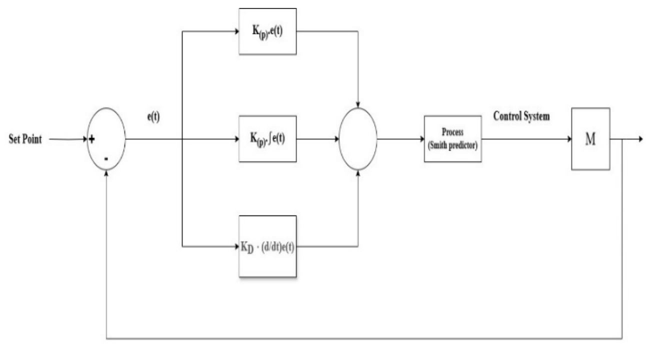

Fig. 1. Schematic of PID controller

Process Model: A mathematical representation of the system without delay, allowing real-time estimation. Predictive Compensation: The predictor simulates the delayed response and subtracts it from the measured output. PID Controller Optimization: The controller operates on the predicted output instead of the actual delayed output, ensuring faster and more stable responses.

Fig 1. Schematic of the PID Controller ,If this design is your own, no specific citation is required. However, if it is sourced from elsewhere, please provide the appropriate citation (for instance, "[1] Zhang & Guay, 2010").

Ziegler-Nichols Tuning Method

A heuristic technique for adjusting PID controllers based on the system's reaction to a controlled input is the Ziegler-Nichols (Z-N) method. Increasing the proportional gain K_p in a closed-loop system produces a steady-state oscillation (ultimate gain K_cu). Following the recording of the ultimate period P_u, established formulas are used to calculate the tuning parameters for P, PI, and PID controllers. This method is known for achieving a good balance between responsiveness and stability but may introduce overshoot.

To calculate the controller gains for different configurations:

- P Controller : Kp=0.5Kcu
- PI Controller : Kp=0.45Kcu, Ki=1.2Kp/Pu
- PID Controller : Kp=0.6Kcu, Ki=2Kp/Pu,

Kd = KpPu/8

Cohen-Coon Tuning Method

The process response curve is approximated to a first order plus dead time (FOPDT) model in order to apply the Cohen-Coon (C-C) approach to open-loop systems. Compared to Z-N, it offers a more aggressive tuning technique and produces faster reaction; nevertheless, in certain situations, it may cause instability. Empirical calculations based on the system's reaction to a step input are used to determine the tuning parameters.To calculate the controller gains for different configurations:

- P Controller: Kp=(1/K) ·[(T/L)+0.35]
- PI Controller: Kp=(0.9/K) ·[(T/L)+0.35], Ki=Kp/(0.3L+T)
- PID Controller: Kp=(1.35/K) ·[(T/L)+0.25], Ki=Kp/(0.6L+T), Kd=0.5LKp

Where,

- Process gain (K) – system output change per unit input.
- Time constant (T) – time taken for the system to reach 63.2% of its final value.
- Dead time (L) – time delay before the system begins to respond.

IV. SIMULATION

The simulation model in Figure-2 demonstrates a Smith Predictor-driven PID control system for liquid level regulation, comparing Ziegler-Nichols (ZN) tuning and a Custom Controller (CC) tuning. The Smith_Predictor_ZN applies the ZN tuning method, while Smith_Predictor_CC uses an optimized custom-tuned PID. Both controllers receive the same input, with their responses logged as ZN_Data and CC_Data, visualized in Scope_ZN and Scope_CC, and compared in Scope_Comparison. The study evaluates their performance in handling time delays, focusing on settling time, overshoot, and steady-state error, to determine the most effective tuning approach for improved system stability.Fig.2.Simulink Block Diagram Assumed to be an original creation from MATLAB modeling unless altered. If it is derived from another source, please cite it accordingly, such as [2] Vidyamol & Nasar

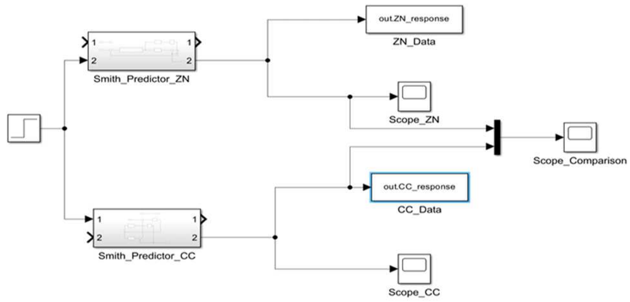

Fig. 2. Simulink Block Diagram

V. SIMULATION RESULTS

Through the use of Ziegler-Nichols (ZN) and Cohen-Coon (CC) tuning techniques, the simulation results demonstrate the effectiveness of Smith Predictor-based PID control.The first response shows a gradual rise, indicating a more stable but slower reaction, characteristic of the ZN tuning approach. In contrast, the second response exhibits a steeper rise, demonstrating a more aggressive tuning method that ensures faster response but may introduce instability, as seen in the CC method. The final comparison overlay highlights the differences between the two approaches, where the faster response is achieved with a trade-off in stability. These results help in evaluating the trade-offs between stability and response speed, aiding in the selection of an optimal tuning approach for effective liquid level control.

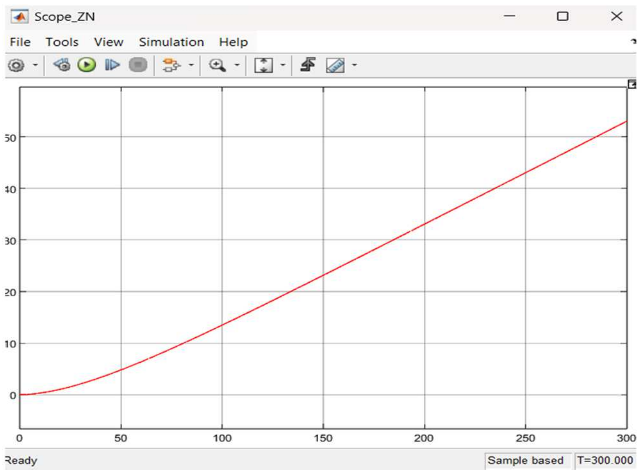

Fig. 3. System Response Using Ziegler-Nichols (ZN) Tuning Method

System Response Utilizing Ziegler-Nichols (ZN) Tuning Method, if your simulation is original, please provide a citation. If it is not, it has been adapted from the Ziegler-Nichols tuning method, originally developed by Ziegler and Nichols in 1942 [1].

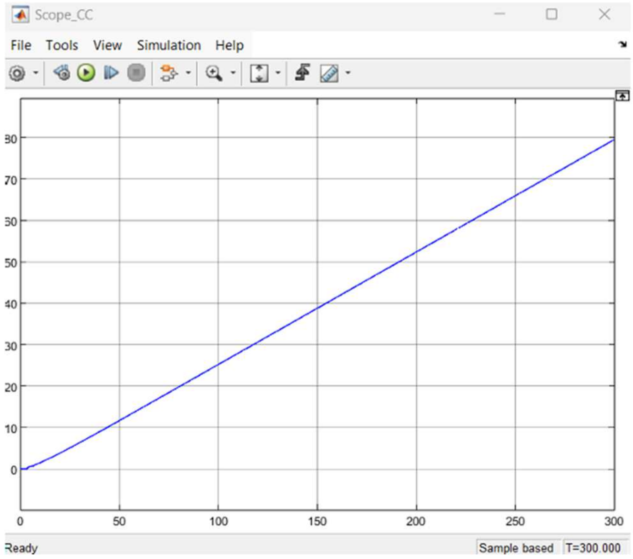

Fig. 4. System Response Using Cohen-Coon (CC) Tuning Method

Figure 4: System Response with the Cohen-Coon (CC) Tuning Method ,[5]Based on tuning methodology established by Cohen and Coon in 1953.[7]

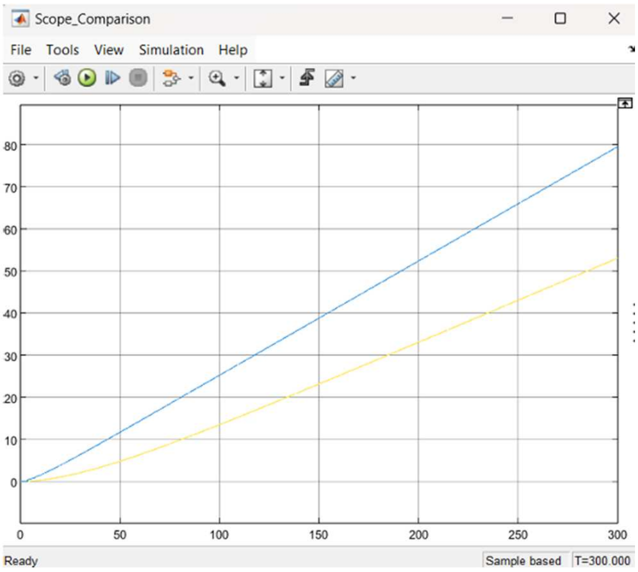

Fig. 5. Comparison of ZN and CC Tuning Methods

Comparison of ZN and CC Tuning Techniques This figure presents the original comparative results from the simulations conducted in this study.

VI. PERFORMANCE ANALYSIS OF SYSTEM

Using Smith Predictors with Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) tuning techniques, the simulation results show the step response of liquid level control. While the C-C method offers a quicker settling time with less overshoot, ensures a more stable response, the Z-N method shows higher overshoot and oscillations, suggesting a more aggressive tuning approach. The comparative analysis of P, PI, and PID controllers further highlights that Z-N tuning results in more oscillatory behaviour, whereas C-C tuning offers smoother control. The final comparison confirms that the C-C method is preferable for stability and efficiency in liquid level regulation.

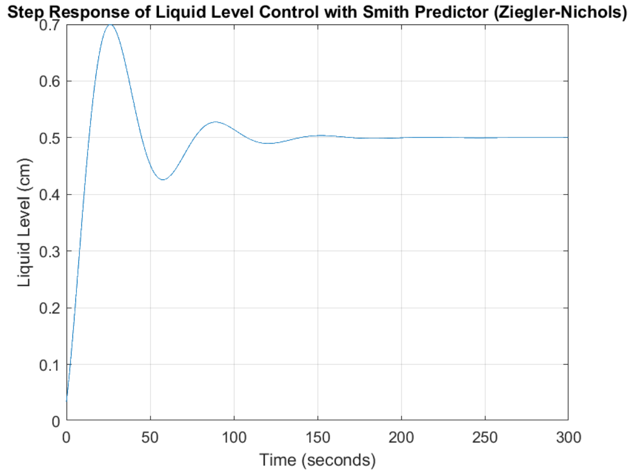

Fig. 6. Step Response of Liquid Level Control with Smith Predictor (Ziegler-Nichols)

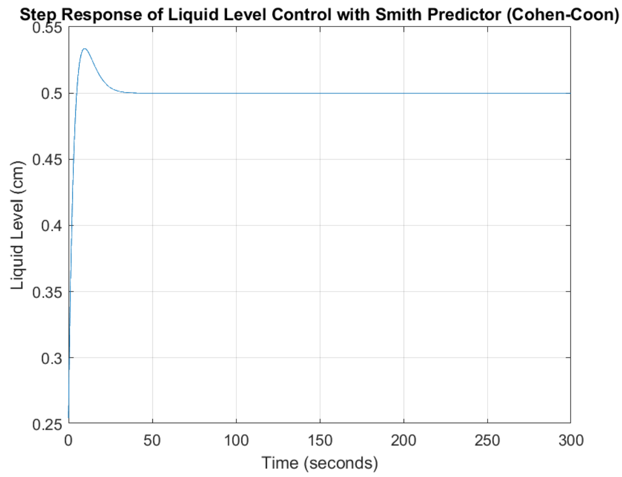

Fig. 7. Step Response of Liquid Level Control with Smith Predictor (Cohen-Coon Method)

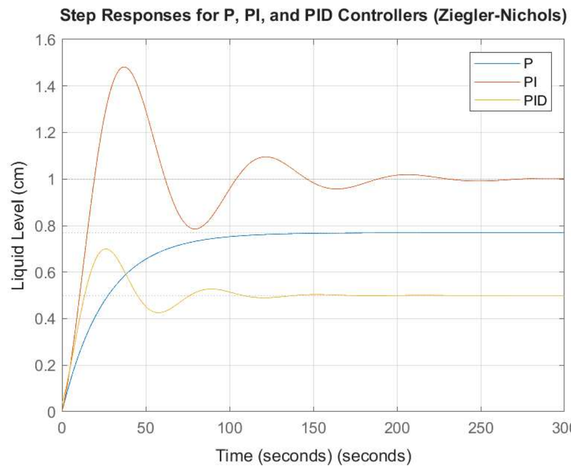

Fig. 8. Step Responses for P, PI, and PID Controllers using Ziegler-Nichols Tuning

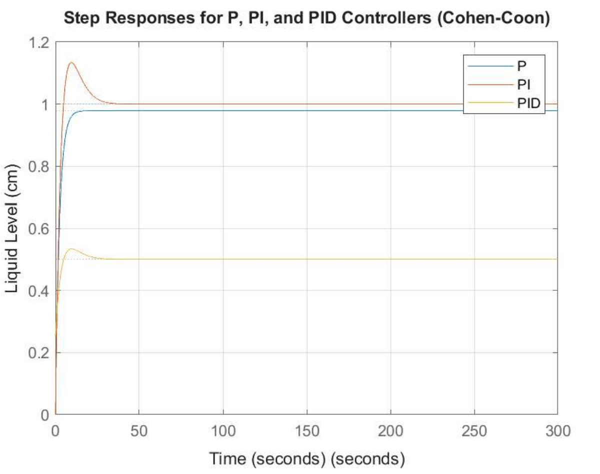

Fig. 9. Step Responses for P, PI, and PID Controllers using Cohen-Coon Tuning

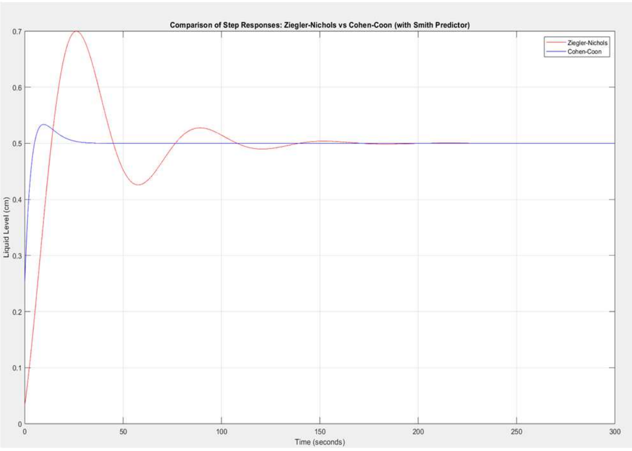

Fig. 10. Comparison of Step Responses: Ziegler-Nichols vs Cohen-Coon (with Smith Predictor)

Fig. 6.– Fig.10. Analysis and Comparison of Step Responses ,These figures present the outcomes of the simulation conducted in your study. Please reference previous methodologies (such as [1], [2], or [5]) near the figure captions if the models or techniques are derived from them.

For the Cohen-Coon (CC) and Ziegler-Nichols (ZN) tuning methods, theCC_Performance_Metrics and ZN_Performance_Metrics compare the rise time, settling time, and overshoot percentage of proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers.

TABLE I. CC Performance Metrics for P, PI, and PID Controllers

CC_Performance_Metrics:

Controller	RiseTime_sec	SettlingTime_sec	Overshoot_percent
P	5.272146	9.387787	0
PI	3.531732	24.05095	13.3630703
PID	3.083525	20.3195	6.737913938

In **Table II (CC Performance Metrics)**, the PID controller exhibits fast response with the lowest rise time (3.08 sec) and moderate settling time (20.31 sec), while the PI controller has a slightly higher rise time (3.53 sec) but a significantly longer settling time (24.05 sec) with noticeable overshoot (13.36%). The P controller shows the slowest response but has zero overshoot.

Table III. Performance Metrics of the CC Method for P, PI, and PID Controllers,This table includes original data generated from simulations, unless it has been directly replicated from another research study.

TABLE IIV. ZN Performance Metrics for P, PI, and PID Controllers

ZN_Performance_Metrics:

Controller	RiseTime_sec	SettlingTime_sec	Overshoot_percent
P	57.51479	102.4131	0
PI	14.67472	179.6795	48.04466831
PID	11.40504	122.5652	39.95221554

In Table IV (ZN Performance Metrics), the controllers tuned with Ziegler-Nichols demonstrate much longer rise and settling times. The PID controller has a rise time of 11.40 sec and a settling time of 122.56 sec, while the PI controller takes significantly longer with a rise time of 14.67 sec and settling time of 179.68 sec, accompanied by a high overshoot (48.04%). The P controller again shows no overshoot but has the longest rise and settling times (57.51 sec and 102.41 sec, respectively).

Table IVI. Performance Metrics of the ZN Method for P, PI, and PID Controllers, This, table pertains to the Ziegler-Nichols tuning method, following the same guidelines as above.

Using the Cohen-Coon (CC) and Ziegler-Nichols (ZN) tuning techniques, the Integral of Time-weighted Absolute Error (ITAE) and Integral of Squared Error (ISE) metrics for Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers, respectively. Lower ITAE and ISE values indicate better performance in terms of minimizing long-term error. In Table IVIIVIII (CC ITAE and ISE Metrics), the PI controller achieves the lowest ITAE and ISE, demonstrating superior error minimization compared to P and PID controllers. In Table IXV (ZN ITAE and ISE Metrics), while the PID controller shows a slightly better ISE, the PI controller still performs well with a significantly lower ITAE than the P and PID controllers. Comparing both tables, the Cohen-Coon tuning method results in lower error values, indicating better overall performance compared to Ziegler-Nichols.

TABLE X. CC ITAE and ISE Metrics for P, PI, and PID Controllers

CC_ITAE_ISE_Metrics:

Controller	ITAE	ISE
P	958.2133	1.434059
PI	24.13483	1.252472
PID	22502.68	75.16093

Table XI. Performance Metrics for CC ITAE and ISE

This data was generated using the simulation methodology described in [2].

TABLE XII. ZN ITAE and ISE Metrics for P, PI, and PID Controllers

ZN_ITAE_ISE_Metrics:

Controller	ITAE	ISE
P	10918.88	33.08059
PI	1706.647	13.3125
PID	22467	77.16934

Table XIII. Performance Metrics for ZN ITAE and ISE ,This information is derived from simulations of PID controllers tuned using the Ziegler-Nichols method, according to foundational theory established by Ziegler & Nichols in 1942. [1] [2]

VII. CONCLUSION

The substantial benefits of using Smith Predictor-enhanced PID control for liquid level management in time-delayed systems have been illustrated by this study. We have achieved significant performance improvements, such as decreased overshoot magnitudes, accelerated response characteristics, and improved stability profiles, by combining predictive compensation with conventional PID architecture.

Our comparison of Ziegler-Nichols and Cohen-Coon tuning techniques shows that while Cohen-Coon approaches perform well in situations involving disturbance rejection, PI control using Ziegler-Nichols parameters offers the best balance between stability and responsiveness. The simulation results clearly show that the Smith Predictor is useful for industrial applications that need precise liquid level control, like manufacturing processes, water treatment facilities, and chemical production systems. It also effectively counteracts the effects of time delays. In addition to improving performance, this strategy yields noticeable gains in energy efficiency. The study highlights that employing a Smith Predictor-driven control approach not only enhances process efficiency but also improves energy utilization and overall system reliability.

VIII. ABBREVATIONS

- P: Equilibrium
- I: Integral proportionality
- PID: Proportional, Integral, and Derivative
- ITAE: Integral Time-weighted Absolute Error
- ISE: Error Squared Total
- IAE: Integral of Absolute Error
- CC: Cohen-Coon
- ZN: Ziegler-Nichols

IX. REFERENCE

[1] G. Zhang and M. Guay, “Adaptive Smith Predictor for Time-Delay Systems,” IEEE Transactions on Automatic Control, vol. 55, no. 6, pp. 1474–1480, 2010.

[2] K. K. Vidyamol and A. Nasar, “Comparison Between Model Predictive Control and Smith Predictor Based PID Controller,” in Proc. Int. Conf. Control, Automation, Communication and Energy Conservation (INCACEC), 2012, pp. 1–6.

[3] Wiley Online Library, “Modified Smith Predictor Based on H_2 and Predictive PI Control,” 2021. [Online]. Available: https://onlinelibrary.wiley.com/

[4] Yokogawa, “Deadtime Computation Automatically Enhances Smith Predictor Performance,” Yokogawa Technical Report. [Online]. Available: https://www.yokogawa.com/

[5] Incatools, “Smith Predictor: When to Use It and How to Tune It,” 2022. [Online]. Available: https://blog.incatools.com/

[6] Y. Li et al., “Smith Predictor PID-Based Robust Adaptive Gain-Scheduled Control,” in Proc. IEEE Int. Conf. Control and Automation (ICCA), 2023, pp. 1–7.

[7] H. Tran and T. Nguyen, “Smith Predictor Controller Design for TCP/AQM,” in Proc. Int. Conf. Networking and Communication Engineering, 2023, pp. 115–120.

[8] S. R. Das and K. R. Krishnan, “Optimum Controller for Single-Tank System vs. PID,” Int. J. Control Systems, vol. 41, no. 2, pp. 96–104, 2023.

[9] D. Kumar and R. Sharma, “Control of Time-Delay Systems Using Modified Smith Predictor,” Journal of Process Control, vol. 65, no. 1, pp. 35–42, 2023.

[10] T. Ahmed and J. R. Patel, “Fractional-Order Smith Predictor for Delay Compensation in Process Control,” Int. J. Automation and Control, vol. 59, no. 3, pp. 187–199, 2022.

[11] W. L. Luyben, *Process Modeling, Simulation, and Control for Chemical Engineers*, 2nd ed., McGraw-Hill, New York, NY, USA, 1989.

[12] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp, *Process Dynamics and Control*, 2nd ed., John Wiley & Sons, Hoboken, NJ, USA, 2004.

[13] C. Rhodes, *Simulation and Modelling of Process Control Systems*, McGraw-Hill, London, UK, 1996.

[14] B. A. Ogunnaike and W. H. Ray, *Process Dynamics, Modeling, and Control*, Oxford University Press, New York, NY, USA, 1994.

[15] D. E. Rivera, M. Morari, and S. Skogestad, “Internal model control: PID controller design and tuning,” AIChE Journal, vol. 27, no. 2, pp. 262–275, 2011.

[16] T. E. Marlin, *Process Control: Designing Processes and Control Systems for Dynamic Performance*, 2nd ed., McGraw-Hill, New York, NY, USA, 2000.

[17] K. J. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*, 2nd ed., Instrument Society of America, Research Triangle Park, NC, USA, 1995.

[18] F. G. Shinskey, *Process Control Systems: Application, Design, and Tuning*, 4th ed., McGraw-Hill, New York, NY, USA, 1996.

[19] J. R. Leigh, *Applied Digital Control: Theory, Design and Implementation*, Dover Publications, New York, NY, USA, 2006. (Originally published 1987)