Cascade PID Controllers Applied on Level and Flow Systems in a SMAR Didactic Plant

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***Abstract*—The practical application of knowledge acquired during undergraduate studies is crucial for students to address real-world problems and seek solutions. The SMAR PD3 didactic plant provides a conducive environment for experiments in systems such as level and flow, common in various industrial sectors. Cascade control, an approach that sequentially uses two or more controllers, stands out as a promising strategy to enhance precision and stability in industrial processes. This work proposes a study on cascade control in flow and level systems, demonstrating its application in the didactic plant. The process involved system identification, tuning of conventional and cascade PI and PID controllers, followed by the implementation of the Successive Loop Closure technique. Results, in line with specialized literature, indicate that the implementation of cascade controllers in the industry can improve specific processes affected by disturbances or changes in variables, directly impacting the overall functioning of the process.**

***Index Terms*—Cascade Control, Successive Loop Closure, PI and PID Controllers, SMAR Didactic Plant.**

I. INTRODUCTION

Automatic control is present in various industrial sectors, playing an essential role in numerous engineering and scientific applications, ranging from simple manufacturing processes to the construction of rockets, encompassing a wide array of processes involving physical variables such as pressure, temperature, flow, level, humidity, viscosity, etc. [1], [2].

In industrial settings, level control is widely employed, serving as a crucial component for the regulation of reagents, preparation of mixtures, liquid storage, and various other applications. The control of substance levels becomes indispensable, even critical for mitigating risks to human life.

As a result, fine-tuned control becomes a reality, necessitating the application of more advanced techniques. Cascade control is one such example, considered by some authors as an advanced technique that enables better regulation and elimination of steady-state errors [3]. Its more agile response capability, owing to the dynamics of internal loops, facilitates the compensation of disturbances associated with manipulated variables and the elimination of nonlinearities [4].

The work by [5] provides a comprehensive analysis of cascade control strategies for stable, unstable, and integrating processes. The study explores both conventional and modified implementation models, highlighting advantages and disadvantages, especially concerning system delay time. The conclusion underscores that an increase in the number of internal loops results in more adjustable parameters and the use of filters, emphasizing the need to employ this strategy judiciously to minimize parameters and reduce internal loops.

A successful implementation of cascade control topology has been observed in automatic pilot systems, such as drones and Autonomous Surface Vehicles (ASVs), based on Successive Loop Closure (SLC). For instance, the work of [6] demonstrates the application of SLC and optimal control, incorporating Proportional, Integral and Derivative (PID) controllers. The study's results showcase the robustness, reliability, and applicability of the new technique.

The primary objective of this study is to implement the Cascade Control strategy with SLC, analyze the performance results in stabilizing the water column in the tank, and compare it with conventional closed-loop control. This approach will be specifically directed towards level and flow control systems. The addressed theme involves aspects related to instrumentation and control, system identification through linear methods, and the implementation of a multi-level cascade control system for flow and level, using PID and Proportional and Integral (PI) controllers.

The structure of this work is divided into the following topics: Section II details some descriptions of the SMAR PD3 didactic plant; Section III addresses the identification for level and flow systems; Section IV presents the tuning methods used and their characteristics; Section V shows the development and some previous results for the cascade control; Section VI presents the experimental tests obtained in the didactic plant; and finally, Section VII concludes this work.

II. SMAR PD3 DIDACTIC PLANT

A SMAR PD3, a didactic plant used for the study (Fig. 1), was manufactured by SMAR Equipamentos Industriais, a Brazilian multinational company operating in the industrial automation sector. The SMAR PD3 allows students to interact with industrial equipment found in the field and to use communication protocols and software developed for large-scale applications [7], [8].

Figure 1: Illustration of the SMAR PD3 didactic plant

The plant incorporates several industrial process loops involving physical variables such as flow, level, and temperature, where its instrumentation devices enable the manipulation and monitoring of these variables. Furthermore, it provides the flexibility to create additional control loops beyond those provided by the manufacturer without the need for physical changes to the equipment and devices.

The majority of devices and instruments in the plant are developed by SMAR, including pressure and temperature sensors, as well as valve positioners. The instruments are identified following the S 5.1 standard of the International Society of Automation (ISA) using tags. Fig. 2 illustrates the water cycle and the arrangement of instruments used in the level control loops of the heating tank:
where Flow Indicator and Transmitter (FIT), Level Indicator and Transmiter (LIT), and Flow Positioner (FY).

III. SYSTEM IDENTIFICATION

The identification of the flow and level systems was conducted through an experimental method, involving the setup of the plant with the configuration of the level and flow transmitters. The valve was opened to simulate consumption at approximately 35 degrees, allowing the water column to stabilize at around 72% of the level. With the configured settings and parameterization completed, the tank filling process was initiated remotely using commands generated in Simulink® by applying a step input for the 100% opening of the pneumatic valve.

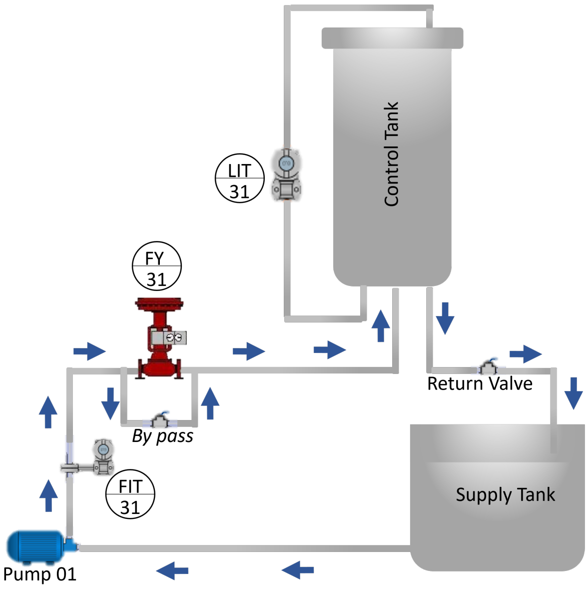

Figure 2: System flowchart

Several methods mentioned in the work of [9] were employed. The Tangent Method was applied for the flow system, while the General Two-Point Method was used for the level system. Through these methods, the parameters of the approximate first-order plus dead time equation representing the real system were determined, as Equation 1:

$$G(s) = \frac{K}{\tau s + 1} e^{-\theta s}, \tag{1}$$

where $G(s)$ is the transfer function, K is the static gain, τ is the time constant and θ is the transport delay time.

Fig. 3 depicts the response of the flow system, represented by the red curve:

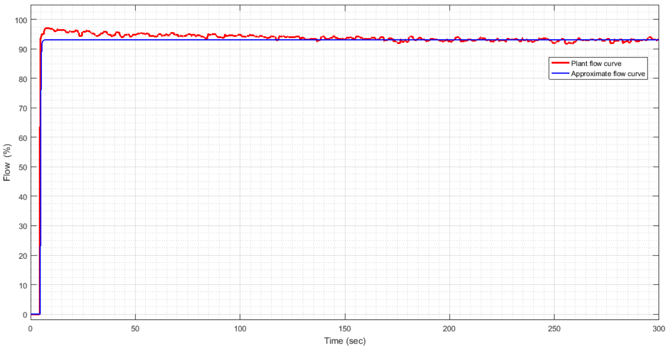

Figure 3: Flow open-loop response and its identified transfer function

It is evident that it does not correspond to a typical first-order plus dead time system. However, the approximation using the Ziegler-Nichols method (blue curve) proved to be suitable. The transfer function ($G_f(s)$) determined for the flow system can be observed in Equation 2:

$$G_f(s) = \frac{0.93}{0.2s+1}e^{-4.6s}. \tag{2}$$

For a quantitative analysis, the non intrusive performance index (Integral of the Absolute Error (IAE), Integral of the Squared Error (ISE), Integral of Time-weighted Absolute Error (ITAE), Integral of Time-weighted Squared Error (ITSE)) results for the flow system can be obtained: IAE=1.18×10^3, ISE=1.78×10^5, ITSE=1.71×10^5 and ITAE=1.18×10^5.

For the level system, whose reaction curve is depicted in red in Fig. 4, nonlinearity is evident.

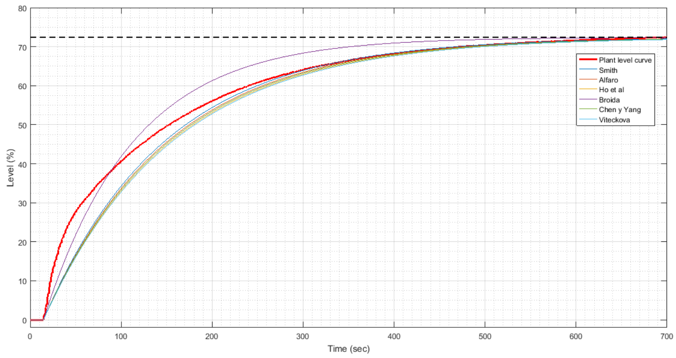

Figure 4: Level open-loop response and some identified transfer functions

The system has at least two time constants; up to approximately 50 seconds, it exhibits a certain behavior, and after 50 seconds, a different behavior becomes apparent. The system approaches a first-order plus dead time system.

The curve generated by the Smith method provides a more visually accurate approximation compared to other methods. In a quantitative analysis, it stands out by achieving the best results, being lower in 3 out of the 4 criteria used, as shown in Table I, thus corroborating the graphical analysis conclusion.

TABLE I: Non intrusive performance index for the level system identification

Method	IAE	ISE	ITAE	ITSE
Alfaro	1.42×10^3	9.27×10^3	1.87×10^5	7.31×10^5
Bröida	1.89×10^3	7.52×10^3	4.82×10^5	1.61×10^6
Chen y Yang	1.55×10^3	1.00×10^4	2.20×10^5	8.28×10^5
Ho et al.	1.69×10^3	1.09×10^4	2.58×10^5	9.47×10^5
Smith	1.25×10^3	8.07×10^3	1.51×10^5	5.89×10^5
Vitecková	1.80×10^3	1.16×10^4	2.88×10^5	1.06×10^6

The level transfer function ($G_l(s)$) that best fits was obtained through the Smith method, as presented in Equation 3:

$$G_l(s) = \frac{0.724}{133.2s+1}e^{-14.6s}. \tag{3}$$

IV. CONTROL STRUCTURES

Control systems aim to achieve objectives such as increasing production, saving energy, and ensuring quality, making it crucial to avoid inadequate configurations to effectively meet desired goals [10].

PID control is widely employed in industry for precision and efficiency, with its proportional, integral, and derivative terms requiring precise adjustments for optimization [10].

Although advanced controllers are available, PID and its variants are still extensively used in industry, often with underutilization, inadequate tuning, and manual operation [11].

Authors such as Ziegler and Nichols (1943), Chien, Hrones, and Reswick (1952), Cohen and Coon (1953) contributed tuning methods for controllers based on the FOPDT model, resulting in the transfer function expression given by Equation 4 [10]:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s, \tag{4}$$

where K_p is the proportional gain, K_i is the integral gain, e K_d is the derivative gain.

The classical method adopted for tuning level controllers in this study is the proposed by Chien, Hrones, and Reswick, offering two criteria: faster response without overshoot and faster response with 20% overshoot. Most industrial processes require stability, opting for the 0% overshoot criterion. This is achieved with a low proportional gain (k_p), making the system more robust and less susceptible to instabilities [12].

For flow control, the Chien, Hrones e Reswick (CHR) method and the Cohen and Coon (CC) method were applied for controller calculation. The choice of the CC method was possible because it meets the controllability factor criterion (θ/τ), which is greater than 0.3 [12].

The following two sections addressed the two propositions for the control structures considered in this work.

A. Traditional Parallel Controller

Summary: Traditional PID control is a common industry practice and serves as a benchmark for comparing with other control strategies [13]. This approach provides a solid foundation for evaluating the performance of more advanced methods, helping determine their suitability for specific applications.

Then, the CHR method was used to tune the conventional controller, showing its results in Table II. Table III consequently presents the respective non-intrusive index errors for better comparison after a 35% SetPoint.

TABLE II: CHR ains obtained after tuning

Method	K_p	K_i	K_d
PI 0%	4.4104	0.0276	-
PID 0%	7.5607	0.0568	55.1934
PI 20%	7.5607	0.0568	-
PID 20%	11.9712	0.0642	82.1461

TABLE III: Non-intrusive index errors for traditional CHR controller

Method	IAE	ISE	ITAE	ITSE
PI 0%	1.98×10^3	3.40×10^4	1.47×10^5	8.52×10^5
PID 0%	1.56×10^2	3.59×10^4	6.53×10^4	6.10×10^5
PI 20%	1.41×10^2	3.41×10^4	5.10×10^4	5.32×10^5
PID 20%	1.52×10^5	3.48×10^4	6.72×10^4	5.75×10^5

V. CASCADE CONTROLLER

The tuning of cascade control occurs from the inner to the outer layer, using recognized techniques. In this study, classical tuning was chosen. Initially, the flow control, internal, is adjusted, followed by the external level control.

In the two-level cascade control system, two controlled variables are managed, monitored by two distinct sensors, and one manipulated variable. Table IV presents clearly the variables involved in the analyzed process.

TABLE IV: Process variables

Type	Variable	Physical Element
Primary	Level (%)	Level Transmitter (LIT31)
Secondary	Flow (%)	Flow Transmitter (FIT31)
Manipulated	Valve Opening (%)	Valve Positioner (FY301)

The correct choice of variables in the cascade system is essential. If this choice is made erroneously, the control result may be ineffective, and/or the system may become unstable.

A fundamental consideration in applying cascade control technique is the necessity for the inner loops to exhibit faster dynamics than the outer loops. This important guideline is emphasized by [14].

For cascade control, typically the inner, secondary controller is a Proportional (P) or PI. The outer, primary controller is generally a PI or PID controller [4]. The block diagram presented in Fig. 5 shows in a general manner the topology of a two-level cascade controller. Where C_1, G_1, H_1, in this order, represent the primary controller, level system, level transmitter; and C_2, G_2, H_2, in this order, represent the secondary controller, flow system, flow transmitter. D_1 and D_2 respectively represent the level and flow disturbances. In this work, H_1 and H_2 were assumed to have unit gain due to the experimental derivation of the system models.

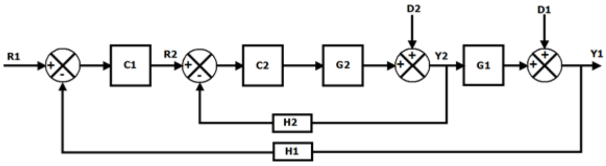

Figure 5: General block diagram of cascade control

A. Tuning of Internal Controller (Flow)

Using the identified flow curve represented by Equation 2, the controller gains were determined using the Cohen and Coon (CC) and Chien, Hrones, and Reswick (CHR) methods, but the results were unsatisfactory, exceeding the 5% tolerance range and exhibiting oscillations in the steady-state regime. Therefore, empirical tuning was chosen, shown in Table V:

TABLE V: Calculated gains for flow system controllers

Method	K_p	K_i
Empirical 1	0.197	0.055
Empirical 2	0.280	0.064

Fig. 6 depicts the controlled response for the system empirically tuned controllers, where their respective non-intrusive index errors are show in Table VI:

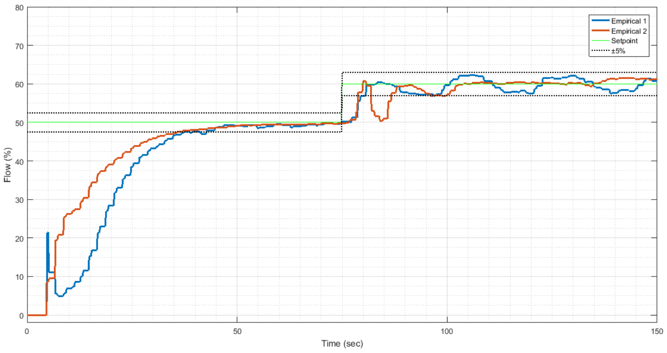

Figure 6: Controlled response for the empirical tuning

TABLE VI: Non-intrusive index errors for flow cascade controller

Method	IAE	ISE	ITAE	ITSE
Cohen and Coon	1.26×10^3	2.30×10^4	6.96×10^4	5.95×10^5
CHR 0%	1.21×10^3	3.53×10^4	4.09×10^4	4.07×10^5
CHR 20%	1.55×10^3	2.87×10^4	8.60×10^4	8.71×10^5
Empirical 1	1.15×10^3	3.59×10^4	2.86×10^4	8.68×10^5
Empirical 2	9.07×10^2	2.39×10^4	2.63×10^4	3.21×10^5

B. Tuning of External Controller (Level)

Using the approximate model obtained for the system with the internal closed-loop (flow), tuning is performed using the CHR method with 0 and 20% overshoot methods. Their gains are found in Table VII and Table III consequently presents the respective non-intrusive index errors for better comparison after a 35% SetPoint:

TABLE VII: CHR gains of the external loop controller

Method	K_p	K_i	K_d
PI 0%	3.1478	0.0187	-
PID 0%	5.3962	0.0384	59.3583
PI 20%	5.3962	0.0384	-
PID CHR 20%	8.5440	0.0434	88.3449

TABLE VIII: Non-intrusive index errors the external control for traditional CHR controller

Method	IAE	ISE	ITAE	ITSE
PI 0%	6.17×10^3	1.54×10^5	6.82×10^5	1.24×10^7
PID 0%	1.99×10^3	5.15×10^4	7.76×10^4	1.17×10^6
PI 20%	2.08×10^3	5.32×10^4	8.60×10^4	1.26×10^6
PID 20%	2.12×10^3	5.22×10^4	9.90×10^4	1.23×10^6

C. Successive Loop Closure Technique

The SLC technique is an advanced control strategy employed in the development of self-adjusting controllers for autonomous systems, such as drones. It involves the sequential closure of control loops, carefully considering the dynamic interactions between these loops. The main idea is to ensure that the inner loops operate faster than the outer loops, typically 5 to 10 times faster, approaching unity gain (Fig. 7). This technique stands out as a valuable tool in the field of robotics and autonomous vehicles, providing an adaptive and effective response in dynamic and challenging environments [15]:

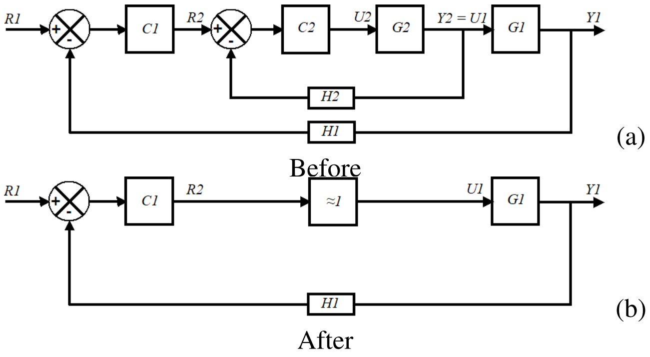

Figure 7: SLC technique diagram of blocks illustration

VI. Experimental Results

The following section will detail the results obtained from the experiment. Based on the error criteria identified for the conventional controllers, cascade control, and cascade control with the SLC technique, the PID controller without overshoot and the PI controller with 20% overshoot exhibited the most promising outcomes.

A. Experiments for Steady-State Analysis in the Level System

In the analysis of steady-state for the best-found controllers, the cascade control strategy, coupled with the use of the SLC technique, demonstrates superior results, as shown in Figs. 8 and 9:

The conventional control strategy reached the 5% tolerance limit in a shorter time interval compared to cascade controls. However, despite cascade controls exhibiting a higher overshoot, they achieved the reference in a shorter time period with lower steady-state error.

For a quantitative analysis, considering a time interval between 150 to 300 seconds, Table IX displays the non intrusive index errors found. The CHR 20% PI controller with SLC technique exhibits the best results, corroborating the graphical analysis from Fig. 9:

TABLE IX: Non-intrusive index errors for the steady-state analysis using CHR technique for 0 and 20% overshoots

Method	IAE	ISE	ITAE	ITSE
Conv. PI 20%	6.51×10^2	2.05×10^3	1.21×10^5	3.57×10^5
Conv. PID 0%	1.97×10^2	1.81×10^2	3.78×10^4	3.39×10^4
Casc. PI 20%	1.25×10^2	7.74×10^1	2.30×10^4	1.35×10^4
Casc. PID 0%	1.10×10^2	6.24×10^1	2.00×10^4	1.06×10^4
SLC PI 20%	1.50×10^1	1.30×10^0	2.87×10^3	2.50×10^2
SLC PID 0%	5.11×10^1	1.43×10^1	9.39×10^3	2.48×10^3

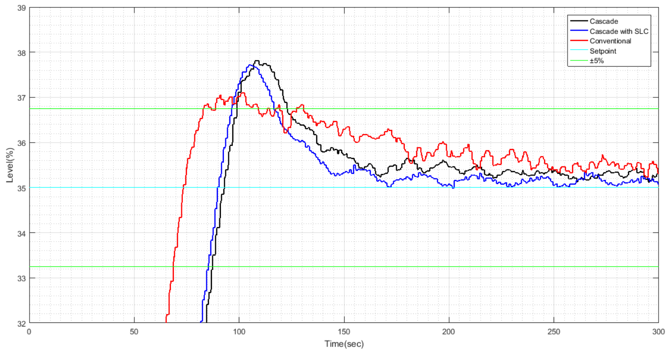

Figure 8: Conventional, cascade and cascade with SLC for CHR 0% PI controller

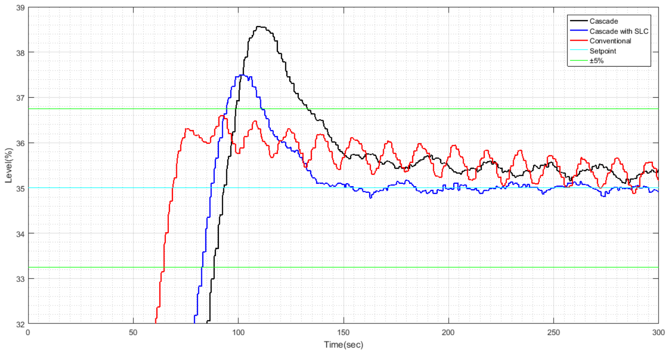

Figure 9: Conventional, cascade and cascade with SLC for CHR 20% PI controller

B. Experiments for Disturbance Analysis in the Flow System

To analyze the response to sudden changes in inlet flow, two scenarios were created. In the first scenario, after 200 seconds, the bypass valve is opened by 50%, allowing for additional flow. In the second scenario, the bypass valve is initially opened, and after 200 seconds, it is closed, leaving the pneumatic valve as the sole source of flow input.

Fig. 10 depicts the system's behavior for the first scenario, comparing conventional CHR 20% PI control with cascade CHR 20% PI controller with SLC. Respectively, Fig. 11 illustrates the behavior for the second scenario:

Cascade control with SLC has demonstrated superior performance in tracking the reference signal, which was expected given one of its main advantages. This control strategy anticipates and addresses deviations in the secondary variable (in this case, flow rate) before they substantially affect the primary variable (the level). As a result, deviations in flow rate are promptly corrected, ensuring minimal impact on the tank level.

Tables X e XI display the non-intrusive index errors, considering a time interval between 150 to 400 seconds, found for the analyzed disturbance scenarios.

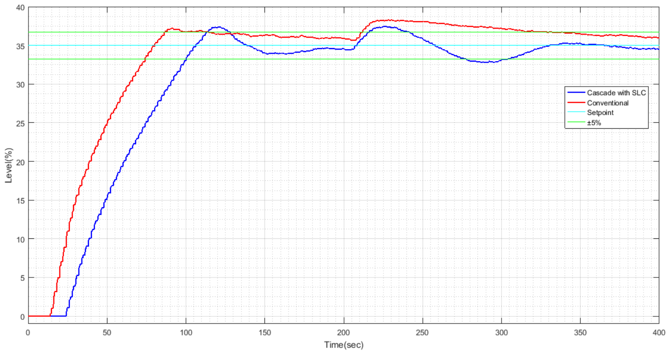

Figure 10: Controlled response for Scenario 1

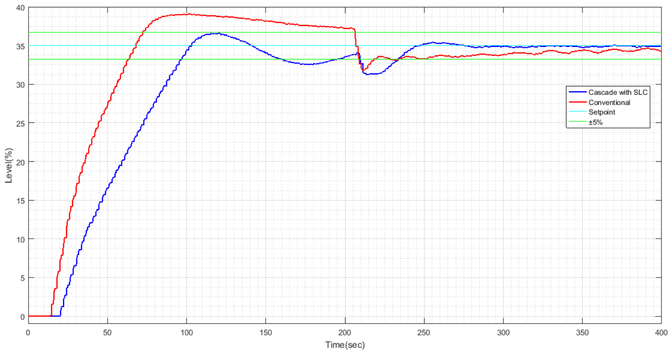

Figure 11: Controlled response for Scenario 2

TABLE X: Non-intrusive index errors for disturbance analysis Scenario 1

Method	**IAE**	**ISE**	**ITAE**	**ITSE**
Conv. PI 20%	4.61×10^2	1.00×10^3	$1,26 \times 10^5$	2.67×10^5
SLC PI 20%	2.31×10^2	3.47×10^2	5.90×10^4	8.84×10^4

TABLE XI: Non-intrusive index errors for disturbance analysis Scenario 2

Method	**IAE**	**ISE**	**ITAE**	**ITSE**
Conv. PI 20%	3.69×10^2	6.94×10^2	8.83×10^4	1.48×10^5
SLC PI 20%	2.17×10^2	4.77×10^2	4.54×10^4	9.64×10^4

VII. CONCLUSIONS

The study highlights the importance of didactic plants like the SMAR PD3 for Control and Automation Engineers' learning process, offering a conducive environment for study and project development.

It demonstrates the effectiveness of cascade control, an advanced method, in regulating tank level using flow rate as a secondary variable. While cascade control proves effective for disturbance rejection and process linearization, drawbacks include increased costs due to an extra sensor and additional tuning requirements.

The SLC technique, commonly used in control systems, notably improves position accuracy, especially in robotics. When combined with cascade control, it enhances steady-state accuracy for the level system. Comparative analysis shows cascade control with SLC technique outperforms conventional strategies, reducing errors by significant margins in two disturbance scenarios.

In conclusion, cascade control with SLC efficiently corrects flow rate deviations, ensuring tank level remains within tolerance and accurately follows the reference signal.

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