Systematic Tuning of PI Averaging Level Control for Recycle Systems

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Abstract: This work examines the use of P-only and PI averaging level control (ALC) of a tanks-in-series recycle process, the most basic model for understanding material balance dynamics in non-reactive recycle systems. We show that P-only ALC tuning for a standalone tank effectively extends to the recycle process. However, directly applying isolated tank PI ALC tuning is not possible due to the complex dynamics and flow amplification that occur along the tank cascade. A systematic procedure for plantwide PI ALC (de)tuning is developed, ensuring acceptable flow amplification while fully utilizing the available surge capacity for the worst-case disturbance. The application of the systematic tuning method to a three-column azeotropic separation process shows that PI ALC achieves significantly higher high-frequency variability attenuation compared to P-only ALC at the expense of mild flow amplification around a small low-frequency resonance peak. These findings suggest that PI level control, which eliminates level offsets, a feature favored by operators, may be applied in plantwide non-reactive systems with systematic detuning.

Keywords: PI ALC, Optimal operation, Plantwide operation

1. INTRODUCTION

Liquid surge drums such as the reflux drum or bottom sump in a distillation column are provided in chemical plants to facilitate start-up/shut-down and also to filter flow transients for 'smooth' operation about the desired steady state. Because the drum overall material balance is not self-regulatory, for the usual case of an independently set drum inflow rate, the outflow rate must be adjusted to exactly match the inflow rate and thus drive the liquid accumulation rate to zero for steady operation. The surge level controller accomplishes this to perfectly balance the flows by manipulating the outflow to stabilize the drum level. The level controller is thus one of the most common control loops in the basic plantwide regulatory control system that drives the process operation to a steady state. Industrial-level controllers (LCs) typically employ proportional (P) or proportional-integral (PI) algorithms. From an operational perspective, 'loose' level control while preventing violations of high/low alarm limits is desired to filter out flow transients. This is referred to as averaging level control (ALC) (Ziegler, 1946; Zotică et al., 2022). For ALC, the P-only/PI LC should be tuned such that the transient level response just touches the alarm limit without violating it for the expected worst-case flow disturbance.

The surge tanks usually exist in a cascade of interconnected units, often inside a material recycle loop. Even as tuning a P-only/PI LC on an isolated surge tank for full surge capacity utilization is straightforward, the same can be significantly more complicated for such plantwide systems due to the dynamic interaction between the interconnected units, including the positive feedback due to recycle. (Cheung and Luyben, 1979) evaluated P-only and PI ALC in a series of connected tanks, showing that for a step increase in the fresh feed rate, P-only ALC results in downstream level and flow transients that are smooth lagged exponentials with no overshoot, which simplifies tuning for maximum surge capacity utilization. The steady-state level then has an offset due to the liquid accumulated/depleted during the transient period where the outflow lags the inflow. The offset is particularly not appreciated by operators when the surge levels settle close to an alarm limit for a large flow disturbance. To remove the level offset, integral (I) action may be coupled with P-action, for a PI LC. The I action causes flow overshoots, which amplifies downstream, potentially leading to operational issues like flooding/weeping in a sieve tray distillation column. While detuning the I action can reduce flow overshoot, especially in systems with positive feedback due to recycle, there is no systematic procedure for PI ALC tuning in such plantwide systems.

It is important to note that operators usually prefer offset-free level control provided by PI controllers. Thus despite the tuning complexity and flow amplification concerns, PI LCs are quite often encountered in industrial plantwide systems. The above overall context raises a few key questions: how can PI LCs be systematically tuned to maximize surge capacity utilization (ALC) for effective high-frequency flow filtering while keeping flow amplification small? Can such tuned PI ALC systems match or even surpass the flow filtering performance of P-only ALC while retaining the advantage of offset-free control? These questions are largely unexplored in plantwide control literature. Addressing this issue is the main motivation behind this work.

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In the following, we study a tanks-in-series recycle process under PI LC, analyzing the effects of recycle fraction and tuning on flow amplification and frequency response. Based on these insights, we propose a systematic PI LC tuning procedure for full surge capacity utilization, improving high-frequency flow attenuation with acceptable low-frequency amplification, to show that such systematically (de)tuned PI ALCs may be used in plantwide systems, despite strong recommendations to the contrary in the literature (Luyben (2020)).

2. TANKS-IN-SERIES WITH RECYCLE PROCESS

The process schematic is shown in Figure 1. The fresh feed rate is flow controlled and the exit stream rate on each tank is manipulated to regulate its level. A fixed fraction r of the outflow from the last tank is recycled back to the first tank using a ratio controller, which is assumed to be perfect. The number of tanks, N, and the recycle fraction, r, are varied as parameters to examine their effects on flow variability attenuation and the impact of positive feedback due to material recycle. It is important to note that as $r \to 0$, the system simplifies to a tanks-in-series without recycle.

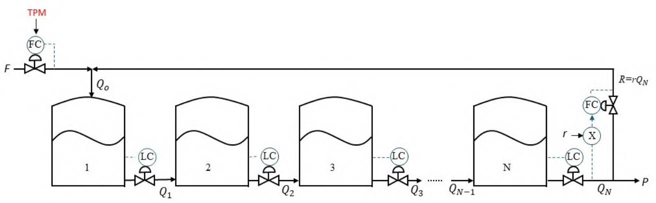

Fig. 1. Tanks-in-series process with recycle

For this system, let $V_{i\%}$ and $Q_{i\%}$ denote the volume and tank exit flow rate from the i^{th} tank in percentage span $(0-100\%)$. The material balance for i^{th} tank gives

$$\tau_i s V_{i\%} = Q_{i-1\%} - Q_{i\%} \tag{1}$$

where $\tau_i = V_i^{MAX}/Q^{MAX}$ is the tank residence time at full flow and full capacity.

For the controller transfer function $G_{ci} = Q_{i\%}/V_{i\%}$, equation (1) gives

$$G_{vi} \equiv \frac{V_{i\%}}{Q_{i-1\%}} = \frac{1}{\tau_i s + G_{ci}} \tag{2a}$$

$$G_{q_i} \equiv \frac{Q_{i\%}}{Q_{i-1\%}} = \frac{G_{ci}}{\tau_i s + G_{ci}} \tag{2b}$$

At the recycle and fresh feed mixing point, the $R+F = Q_0$ constraint, upon normalization by the maximum steady flows, becomes $rR_\% + (1-r)F_\% = Q_{0\%}$, where $r = \bar{R}/\bar{Q}_N = \bar{R}/(\bar{R}+\bar{F})$. The subscript % emphasizes percentage flow deviations. For N tanks-in-series, we also have

$$R_\% = Q_{N\%} = \left[\prod_{i=1}^{N} G_{q_i}\right] Q_{0\%} \tag{3}$$

The transfer functions relating the n^{th} tank exit flow rate $Q_{n\%}$ and level $V_{n\%}$ to $F_\%$ then are

$$G_{Q_n} \equiv \frac{Q_{n\%}}{F_\%} = \frac{(1-r)\prod_{i=1}^{n} G_{q_i}}{1 - r\prod_{i=1}^{N} G_{q_i}} \tag{4}$$

$$G_{V_n} \equiv \frac{V_{n\%}}{F_\%} = \frac{V_{n\%}}{Q_{n-1\%}}\frac{Q_{n-1\%}}{F_\%} = \frac{(1-r)\prod_{i=1}^{n-1} G_{q_i}}{1 - r\prod_{i=1}^{N} G_{q_i}} G_{v_n} \tag{5}$$

For material balance closure, the steady state gain of G_{q_i} is 1. Consequently, the steady-state gain of G_{Q_n} is also 1, meaning that a 1% change in $F_\%$ leads to a corresponding 1% steady-state change in $Q_{n\%}$. This useful property of percentage deviation variables applies only to non-reactive recycle loops.

2.1 P-only Level Control

The controller transfer function is $G_{ci} = K_{ci}$. Equations (2a) and (2b) then become

$$G_{v_i}^{P} = \frac{1/K_{ci}}{\tau_i/K_{ci} s + 1} \tag{6a}$$

$$G_{q_i}^{P} = \frac{1}{\tau_i/K_{ci} s + 1} \tag{6b}$$

The transfer function relating the dependent flow ($Q_{n\%}$) to the independent flow ($F_\%$) is obtained from equation (4) as

$$G_{Q_n} \equiv \frac{Q_{n\%}}{F_\%} = \frac{(1-r)\prod_{i=n+1}^{N}\left(\frac{\tau_i}{K_{ci}}s+1\right)}{\prod_{i=1}^{N}\left(\frac{\tau_i}{K_{ci}}s+1\right) - r} \tag{7}$$

It has been shown that the transfer function can have complex conjugate poles for ($r > 0$) and $N \geqslant 3$ (Kaistha, 2021), but since all poles lie in the left-half-plane (LHP) and the positive feedback loop gain remains less than 1 (as $r < 1$), the system under P-only level control is stable. Simulations confirm that the transient outflow response does not exhibit an overshoot despite the complex conjugate poles that result from the positive feedback due to recycle.

Since there is no overshoot in either flow or volume with P-only LC, the ALC gain for full surge capacity utilization can be directly calculated from the steady-state change in flow and the desired level offset. Application of the final value theorem to equation (5) with G_{q_i} and G_{vi} from equations (6b) and (6a) respectively shows that for a maximum step change of $\Delta F_\%^{MAX}$ in $F_\%$, the steady deviation in $V_{n\%}$ is

$$\Delta V_{n\%}^{HI} = \frac{\Delta F_\%^{MAX}}{K_{cn}}$$

where, $\Delta V_{n\%}^{HI}$ is maximum available surge tank capacity. The minimum gain such that $V_{n\%(t)}$ just touches the level alarm limit for the worst-case disturbance then is

$$K_{c_n\,\mathrm{P}}^{\mathrm{MIN}} = \frac{\Delta F_{\%}^{\mathrm{MAX}}}{\Delta V_{n\%}^{HI}} \tag{8}$$

Typically, at the nominal steady state, the tank level is maintained at 50% of its full capacity, with the high and low alarm limits set equidistant from this level at 75% and 25%, respectively. This tuning expression for the plantwide system is the same as derived by (Marlin, 1995) for an isolated single tank. (Cheung and Luyben, 1979; Luyben, 2020) recommends using $K_c = 2\ \%/\%$, which corresponds to $\Delta V_{\%}^{HI} = 25\%$ and $\Delta Q_{\%}^{MAX} = 50\%$.

2.2 PI Level Control

The controller transfer function is

$$G_{c_i}^{PI} = K_{ci}\frac{\tau_{I\,i}s+1}{\tau_{I\,i}s} \tag{9}$$

Equations (2a) and (2b) then becomes

$$G_{v_i}^{PI} = \frac{\tau_{I\,i}/K_{ci}s}{\tau\tau_{I\,i}/K_{ci}s^2+\tau_{I\,i}s+1} \tag{10a}$$

$$G_{q_i}^{PI} = \frac{\tau_{I\,i}s+1}{\tau\tau_{I\,i}/K_{ci}s^2+\tau_{I\,i}s+1} \tag{10b}$$

The above equation characteristic polynomial is a function of tuning parameter K_{ci} and $\tau_{I\,i}$ and can have real distinct (overdamped), real repeated (critically damped) and complex conjugate (underdamped) roots. The corresponding conditions are

Overdamped: $\frac{K_{ci}\tau_{I\,i}}{\tau_i} > 4$, Critically damped: $\frac{K_{ci}\tau_{I\,i}}{\tau_i} = 4$

Underdamped: $\frac{K_{ci}\tau_{I\,i}}{\tau_i} < 4$

In the literature, a critically damped PI LC tuning is often recommended (Cheung and Luyben (1979)) for the fastest possible return back to a setpoint but it shows a high overshoot which then amplifies down the series cascade system. The positive feedback introduced by recycle can also drive the system unstable. To reduce the maximum flow overshoot and also to remain sufficiently away from instability, one may overdamp the PI ALC. The extent of overdamping is conveniently characterized by the detuning parameter α_i, where $K_{ci}\tau_{I\,i}/\tau = 4\alpha_i$. We then have α_i as an equivalent tuning parameter in lieu of $\tau_{I\,i}$. Note that critically damped and overdamped PI LC tuning corresponds to $\alpha_i = 1$ and $\alpha > 1$, respectively.

As an illustration, we derive the PI ALC tuning for critical damping ($\alpha = 1$). Putting $\tau_I = 4\tau/K_c$, the transfer function in equation (10a) reduces to

$$G_v = \frac{4\tau/K_c^2 s}{\left(2\tau/K_c s+1\right)^2} \tag{11}$$

For the expected worst-case inflow step change of $\Delta Q_{0\%}^{MAX}$, the hold-up response then becomes $V_{1\%} = \frac{t}{\tau}e^{-\frac{K_c}{2\tau}t}\Delta Q_{0\%}^{MAX}$. Differentiating and setting $\dot{V}_{1\%} = 0$, the hold-up response peaks at $t_p = \frac{2\tau}{K_c}$. Setting $V_{\%}(t_p) = \Delta V_{\%}^{HI}$, on solving eq (11) the minimum PI LC gain for full surge capacity utilization is obtained as

$$K_{c\,\mathrm{PI}}^{\mathrm{MIN}} = \frac{2}{e}\frac{\Delta Q_{0\%}^{MAX}}{\Delta V_{\%}^{HI}} \tag{12}$$

which is lower than the corresponding P-only ALC gain in equation (8) by > 25%. In a similar manner, an expression for $K_{c\,PI}^{MIN}$ for an overdamped system with $\alpha > 1$ can be derived such that

$$K_{c\,\mathrm{PI}}^{\mathrm{MIN}} = f_{(\alpha)}\frac{\Delta Q_{0\%}^{\mathrm{MAX}}}{\Delta V_{\%}^{\mathrm{HI}}} \tag{13}$$

where the dependence of f on α for $\alpha > 1$ (overdamped tuning) is given by eq (14). The PI LC approaches a P-only LC with $f \to 1$ for $\alpha \to \infty$. It is highlighted that for finite $\alpha \geqslant 1$, $K_{c\,PI}^{MIN} < K_{c\,P}^{MIN}$. This is because adding I action to P action results in tighter level control so that the maximum level deviation decreases. The gain then must be reduced for the level to just touch the alarm limit. The lower PI ALC gain should improve high-frequency flow variability attenuation, as we shall see later.

$$\begin{aligned} f = &\sqrt{\tfrac{\alpha}{\alpha-1}}\left[\left\{2\alpha\left(1+\sqrt{\tfrac{\alpha-1}{\alpha}}\right)-1\right\}^{-\frac{1}{2}\left(\sqrt{\frac{\alpha}{\alpha-1}}-1\right)}\right] \\ &-\sqrt{\tfrac{\alpha}{\alpha-1}}\left[\left\{2\alpha\left(1+\sqrt{\tfrac{\alpha-1}{\alpha}}\right)-1\right\}^{-\frac{1}{2}\left(\sqrt{\frac{\alpha}{\alpha-1}}+1\right)}\right] \end{aligned} \tag{14}$$

2.3 Exploring System Dynamics

To understand system dynamics using P-only and PI LC, consider the tanks-in-series recycle process (Figure 1) with $N = 5$ identical tanks, each with $\tau = 10$ minutes and a high alarm limit of 75%. At steady state, all flows are 50% of their full range, and the tanks are half full (50% level). A step increase in fresh feed $\Delta F_{\%}^{MAX} = 50\%$ represents the worst-case disturbance. When identically tuned P-only or PI LCs are applied on all tanks, the system transfer functions show that for P-only LC, the optimal gain for maximum surge capacity utilization is $K_{ci\,P}^{MIN} = 2\ \%/\%\ \forall\ i = 1\ldots N$, regardless of recycle fraction r. As seen in Figure 2, P-only ALC produces smooth level and flow responses without overshoot, and all tank levels settle at the high alarm limit (full surge capacity utilization). However, the response slows as r increases, due to some system poles shifting rightward with higher recycle fractions (Kaistha, 2021). For PI LC, achieving full surge capacity utilization is more complex. Applying single-tank tuning ($\alpha = 1$, critical damping) results in significant flow overshoot, which increases down the tank cascade for both $r \to 0$ and $r = 0.5$. The highest overshoot occurs in the last tank's outflow ($Q_{5\%}$), reaching 70% for $r \to 0$ and 52% for $r = 0.5$. These large swings, often unacceptable due to hydraulic constraints, narrow the system's operating window. To reduce the overshoot to an acceptable range (15-25%), the PI LCs may be detuned by increasing α (overdamping).

Another key aspect of the PI LC transient response is that the maximum level deviation increases down the tank cascade, unlike in P-only control. For $r \to 0$, the first tank's level touches the alarm limit, as expected from isolated tank PI ALC tuning, but downstream levels exceed the limit. In the $r = 0.5$ case, although the alarm limits are not violated, the level deviations still increase down the cascade, indicating that isolated tank PI ALC tuning is not directly applicable for full surge capacity utilization. Additionally, the overall response for $r = 0.5$ takes noticeably longer

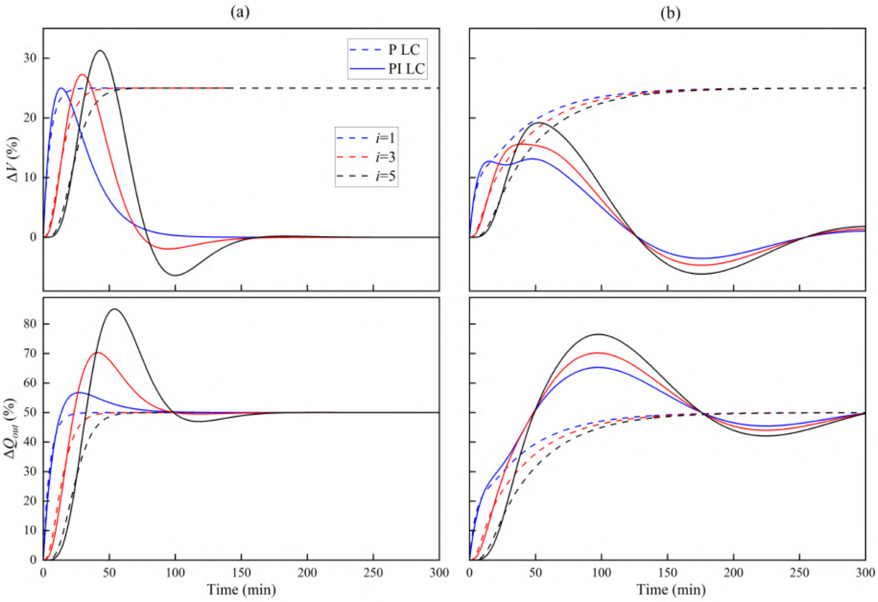

Fig. 2. System transient response to 50% step change in $F_{\%}$ with isolated tank ALC tuning a) $r \to 0$ b) $r = 0.5$

$(N = 5,\ \tau = 10\ \text{min},\ K_c^{PI} = 1.47\ \%/\%,\ \alpha = 1,\ K_c^{P} = 2\ \%/\%)$

to settle due to the rightward movement of some system poles as r increases. For systems with $N \geq 3$ and high recycle fractions, at least two poles can shift into the right half-plane (RHP), causing instability unless the I-action is detuned ($\alpha > 1$). Notably, flow overshoot behavior with recycle depends on PI LC tuning aggressively tuned systems (small α) show reduced overshoot at low to moderate r, while detuned systems (large α) experience increased overshoot as r rises, making the overshoot's dependence on r non-monotonic.

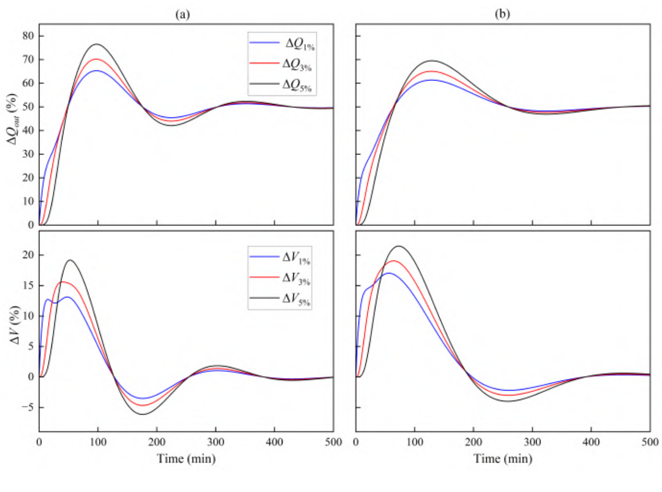

Fig. 3. Effect of α on system transient response for PI LC a) $\alpha = 1$ b) $\alpha = 2$

$(N = 5,\ r = 0.5,\ \tau = 10\ \text{min},\ \Delta F_{\%} = 50\%,\ K_c^{PI} = 1.47\ \%/\%)$

To understand the impact of the detuning factor α on system dynamics, Figure 3 compares the level and outflow responses for critically damped ($\alpha = 1$) and overdamped ($\alpha = 2$) PI LC, with a fixed $K_c = 1.47\%/\%$. As α increases, flow overshoot decreases, but level deviation and the time to return to setpoint increase. At $\alpha \to \infty$, the PI LC behaves like P-only LC, where the level never returns to setpoint, while $\alpha = 1$ leads to the fastest level recovery. Thus, α controls the speed of the level turnaround for a flow disturbance. It's noteworthy that $\alpha < 1$ is not considered due to excessive flow overshoot, which is impractical. Interestingly, for single-tank PI LC, the manipulated flow overshoot depends only on α, so adjusting K_c and τ_I proportionately (keeping α constant) maintains the same flow overshoot while affecting the transient response speed. This principle applies to the tank cascade recycle process as well, as shown in Figure 4, where for $N = 5$ tanks and $r = 0.5$, $\alpha = 4$ modulates the flow overshoot. Therefore, α is used as the tuning parameter in lieu of τ_I, alongside K_c, in an iterative procedure for to systematically tune the PI ALCs in plantwide systems.

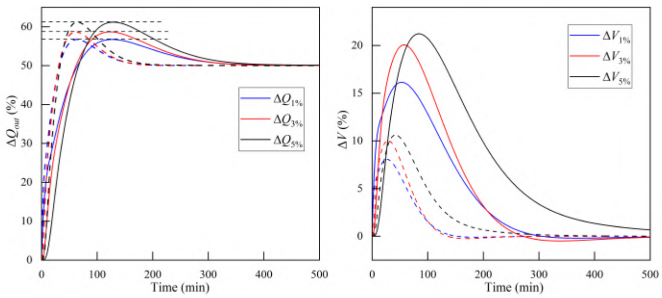

Fig. 4. Illustration of no change in flow overshoot for PI ALC at constant α

(——) Nominal K_c (- - -) High K_c

$(N = 5,\ r = 0.5,\ \tau = 10\ \text{min},\ \alpha = 4,\ \Delta F_{\%} = 50\%)$

3. SYSTEMATIC DETUNING FOR PI ALC

Consider the N-tanks-in-series recycle system shown in Figure 1, where each tank is controlled by a PI level controller (LC), giving us K_{c_i} and α_i as the $2N$ decision variables for $i = 1 \ldots N$. Since offset-free level control is equally important for all tanks, we assume the detuning factor α_i is the same for each tank, i.e., $\alpha_i = \alpha \; \forall \; i = 1 \ldots N$. This reduces the number of decision variables from $2N$ to $N+1$, where we have N controller gains (K_{c_i}) and a common detuning factor α. The factor α, which controls the flow overshoots, can be adjusted to limit the maximum overshoot to an acceptable value (e.g., 15-25%). Meanwhile, the N controller gains K_{c_i} are tuned so that the high alarm limit $V_{\%}^{HI}$ for each tank is just reached from below during the worst-case disturbance. This approach ensures full surge capacity utilization without triggering alarm violations, minimizing the PI ALC gains needed to manage flow transients effectively.

3.1 Detuning Procedure

Figure 5 shows the simple step-by-step (de)tuning procedure that emerges from the discussion for PI ALC with full surge capacity utilization.

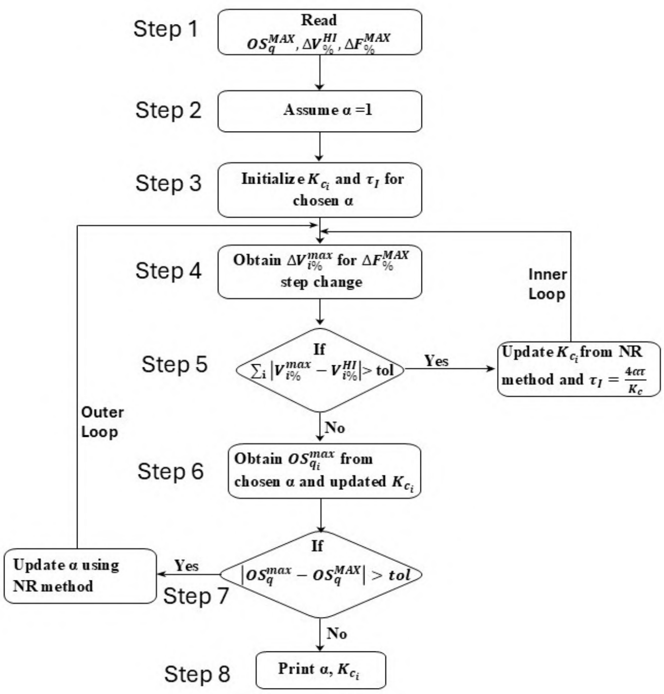

Fig. 5. Systematic detuning procedure of PI ALC

The tuning procedure consists of inner and outer iteration loops. For a given value of α (set by the outer loop), the inner loop adjusts all K_{ci} values using Newton Raphson (NR) so that the high-level alarm limit for each tank is just reached from below for the worst-case step increase in fresh feed rate. The outer loop then adjusts α (PI detuning factor) to meet the maximum flow overshoot constraint. Upon convergence, the result is systematically detuned PI LCs that fully utilize surge capacity while maintaining a specified maximum flow overshoot (e.g., 20%). The method, which assumes identical alarm limits across tanks but can be adapted for tank-specific limits, is applicable to more complex processes as long as their dynamic models are used in Step 5. Figure 6 illustrates this procedure for a system with $N = 5$, $\tau_i = 10$ min for all tanks, $\Delta V_{\%}^{HI} = 25$, $\Delta F_{\%}^{MAX} = 50$, $OS_q^{MAX} = 20\%$, and a recycle fraction of

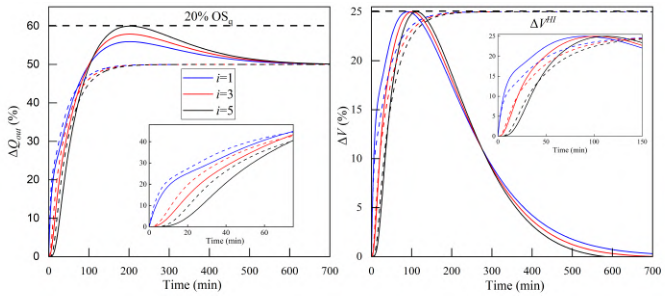

Fig. 6. System transient response for systematically tuned P-only and PI ALC
(——) PI ALC (- - -) P-only ALC
($N = 5$, $r = 0.5$, $\tau = 10$ min, $\Delta F_{\%} = 50\%$)

$r = 0.5$. The results show that all tank levels just touch the 25% alarm limit, while Q_5 exhibits the maximum overshoot of 20%. For comparison, P-only ALC is also shown in Figure 6, demonstrating that PI ALC achieves a lower rate of flow change in the initial transient period due to its lower gains as shown in table 1, thus aiding flow variability attenuation.

Table 1. Systematically tuned PI ALC for $N = 5$ and $OS_q = 20\%$

	$r \to 0$	$r = 0.5$
i	$K_{ci}^{*}(\%/\%)$	$K_{ci}^{\#}(\%/\%)$
1	1.778	1.387
2	1.782	1.413
3	1.804	1.440
4	1.833	1.467
5	1.865	1.495

$^*\alpha = 4.90$, $^\#\alpha = 6.43$
$\tau_{Ii} = \alpha\tau_i / K_{ci}$, $\tau_i = 10$ min, P ALC $K_c = 2\%/\%$

4. PLANTWIDE ALC CASE STUDY

4.1 MeOH-ACN-BZ Separation Process

The nominal design is shown in Figure 7 has been adapted from a recent literature report Zhu et al. (2016). The first column takes in the Methanol (MeOH)-rich ternary fresh feed and an Acetonitrile (ACN) lean MeOH-Benzene (BZ) recycle stream a few trays above the fresh feed tray. Nearly pure ACN product leaves down the bottom and an ACN lean distillate stream leaves up the top. The latter is distilled in the second column to recover nearly pure MeOH product down the bottoms with an ACN lean distillate exiting up the top. The distillate from the second column is further distilled in the third column to recover nearly pure BEN product down the bottoms with an ACN lean distillate stream leaving up the top, which is recycled to the first column. Based on the nearly pure bottom product streams, the first, second, and third columns are also referred to as the ACN, MeOH, and BEN recovery columns, respectively. The plantwide control structure is also shown in figure 7

The LCs may be P-only or PI and are tuned for ALC (full surge capacity utilization). We consider a 12% step change in the fresh feed rate as the worst-case disturbance. Accordingly, the P-only ALC gain is 0.48 %/%. For PI ALC, we note that all the reflux drums are inside the recycle

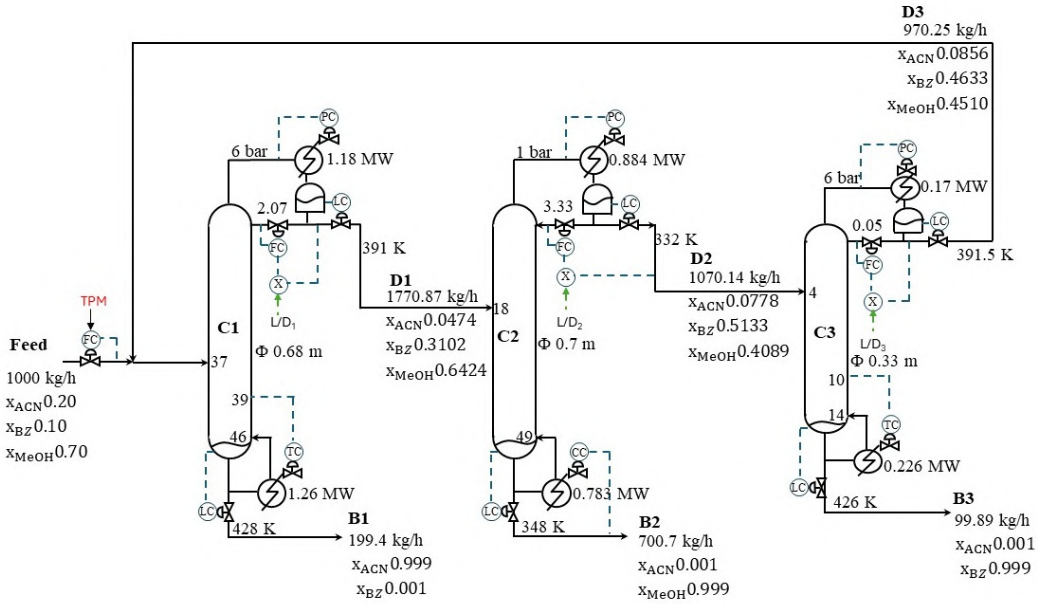

Fig. 7. Nominal design, operating condition (Zhu et al., 2016) and plantwide control structure (Luyben, 2017) of the MeOH-ACN-BZ process

Table 2. Standard deviation for different frequency time-series disturbance for ACN-MeOH-BZ process

Frequency content	**Standard deviation**	
	P	PI
TS1	0.443	0.346
TS2	1.134	0.925
TS3	1.359	1.559

loop so their LCs are tuned using the proposed systematic tuning procedure. The bottom sump LCs, on the other hand, are outside the recycle loop and therefore use the critically damped PI ALC tuning for an isolated tank.

We evaluated the dynamic response to time series flow disturbances with dominant high-frequency content (TS1), intermediate frequency content (TS2), and low-frequency content (TS3). Table 2 shows that PI ALC outperforms P-only ALC in mitigating flow variability for TS1, performs comparably for TS2, and exhibits slightly higher variability for TS3. These findings suggest that PI ALC is more effective at filtering high-frequency disturbances, though it may slightly amplify low-frequency variability.

5. CONCLUSION

This work demonstrates that systematically tuned PI ALC significantly enhances high-frequency flow variability attenuation in plantwide systems compared to P-only ALC. The proposed tuning procedure enables optimal PI ALC tuning for full surge capacity utilization. Applied to a three-column separation process with recycle, the procedure yields effective PI ALC tuning, ensuring near-full surge capacity utilization and superior high-frequency flow attenuation. The findings suggest that the common plantwide heuristic of avoiding PI control due to flow amplification may be misguided. With systematic tuning, flow amplification remains minimal while high-frequency flow attenuation is greatly improved, particularly in systems with recycle for material balance control.

REFERENCES

Cheung, T.F. and Luyben, W. (1979). Liquid-level control in single tanks and cascades of tanks with proportional-only and proportional-integral feedback controllers. *Industrial & Engineering Chemistry Fundamentals*, 18(1), 15–21. doi:10.1021/i160069a004.

Kaistha, N. (2021). Liquid level control in a recycle loop. *Journal of Process Control*, 104, 11–27. doi: 10.1016/j.jprocont.2021.05.014.

Luyben, W.L. (2017). Control of a triple-column pressure-swing distillation process. *Separation and Purification Technology*, 174, 232–244.

Luyben, W. (2020). Liquid level control: Simplicity and complexity. *Journal of Process Control*, 86, 57–64. doi: 10.1016/j.jprocont.2019.12.008.

Marlin, T.E. (1995). *Process control: designing processes and control systems for dynamic perfomance.* McGraw-Hill.

Zhu, Z., Xu, D., Liu, X., Zhang, Z., and Wang, Y. (2016). Separation of acetonitrile/methanol/benzene ternary azeotrope via triple column pressure-swing distillation. *Separation and purification technology*, 169, 66–77.

Ziegler, J. (1946). Averaging liquid level control. *Industrial & Engineering Chemistry*, 38(4), 360–364.

Zotică, C., Forsman, K., and Skogestad, S. (2022). Bidirectional inventory control with optimal use of intermediate storage. *Computers & Chemical Engineering*, 159, 107677.