A Non-linear PI Averaging Level Controller for Plantwide Systems

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Abstract: This work develops a novel non-linear Proportional-Integral (PI) Averaging Level Control (ALC) algorithm designed to optimally utilize the available surge capacity in surge tanks, ensuring that the high and low alarm limits are not breached for the worst-case disturbance scenario. Building upon insights from previous studies, the proposed algorithm incorporates a tunable parameter for an acceptable flow overshoot. The algorithm's performance is compared with existing popular ALC algorithms for a single tank and a realistic methanol dehydration process. The proposed algorithm significantly outperforms these alternatives in mitigating manipulated flow variability for small to moderate disturbances while delivering comparable performance for large disturbances. The significant flow variability mitigation results in up to 8.25% reduction in energy consumption compared to conventional P-only ALC for the methanol dehydration process due to lower back-offs from the active constraint limits. The quantitative results highlight the significant potential of the proposed ALC algorithm towards efficient and sustainable process operation.

Keywords: Averaging Level Control, Non-linear PI Control, Quality Control

1. INTRODUCTION

Averaging level control refers to the 'loose' regulation of liquid level in surge tanks to reduce the severity of the transients in the manipulated flow to the maximum possible extent without violating the high/low level alarm limits. This effectively utilizes the available liquid surge capacity to mitigate the flow variability propagated across the interconnected units in a plant.

The P-only averaging level controller (ALC) with gain $K_c = 2$ (%/%) is often recommended in the literature Cheung and Luyben (1979); Luyben (2020). It however results in a level offset which reduces the distance from the closest level alarm limit and hence the available surge volume for filtering subsequent flow transients. To remove the offset and thus guarantee maximum flow surge handling capacity in either direction, a PI ALC is often used in the industry Buckley (1964); Shinskey (1967). Consider a surge tank with the PI level controller manipulating the outflow. For a step increase in the inflow, the I action causes the outflow to necessarily exceed the inflow in order to discharge the liquid 'accumulated' during the initial transient. The magnitude of the maximum change in the outflow then exceeds the magnitude of the inflow surge. The I action for removing the level offset thus causes a 'bump' in the outflow. The bump size amplifies significantly down a cascade of units, which may further amplify in a material recycle loop due to positive feedback. Therefore Luyben (2020) recommends using P-only level controllers in plantwide systems.

A fundamental issue with P-only or PI ALC is that its tuning is determined by the maximum expected flow surge such that the level closely approaches the alarm limit during the transient and does not violate it. The ALC tuning remains fixed at this 'worst-case' value even as the maximum expected flow surge is a rare occurrence. The maximum flow surge tuning is then too aggressive for the much more common small and moderate flow surges. The manipulated flow transients may be further mitigated by using sluggish tuning for small flow surges and making it progressively more aggressive for large flow surges. This basic idea has been used in innovative advanced ALC algorithms, of which the prominent ones are reported in the table 1. Additionally, passivity-based Sbarbaro and Ortega (2007), filter design based Sanchis et al. (2011) and fuzzy logic based Gupta et al. (2024) ALCs have been developed in the literature. Despite the availability of the above algorithms, the P-only and PI algorithms remain the industrial work-horse for ALC applications as level control is a basic regulatory task and regulatory layer controllers are PID for simplicty and robustness.

There are two major issues with the existing advanced ALC algorithms. The first is that flow overshoot amplification necessarily occurs down a series cascade of units as the level is returned back to setpoint to maximize available surge capacity in either direction at all times. There is no explicit tunable parameter for mitigating the overshoot, if too large. The second is that the tuning is largely heuristic with no clear guidelines for plantwide systems. For example, there are no clear guidelines on what settings to use for K_{C_0}, a, and K_c, τ_I in Shunta and Fehervari (1976) errorsquared PI (PI_{es}) ALC. One then must resort to tedious dynamic simulations to validate the controller tuning. In this overall

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Table 1. Existing algorithm

S No	Highlights	Eqn.
1*	Continuous Time Adapts K_c and τ_I with $\hat{V}_{(t)}$ τ_I chosen for critical damping	$\lvert K_c\rvert = K_{c_0}\left[1 + a\lvert\hat{V}\rvert\right]$
2#	Continuous Time Slowest MV ramp till alarm (OPC) Coupled with highly detuned PI LC	$\dot{Q}_{out(t)} = \frac{\dot{V}_{(t)}^2}{2\Delta V_{(t)}^{max}} + K_c\left[\dot{V}_{(t)} + \frac{\Delta V_{(t)}}{\tau_I}\right]$
3$^\phi$	Discretized OPC (sampling time T) Terminal box constraint for $V_P = V^{sp}$ Prediction horizon P is tuned	$\Delta Q_{out(t)} = \begin{cases}\Delta Q_o^o & \lvert\Delta Q_o^o\rvert > \lvert\Delta Q_o^*\rvert \\ \Delta Q_o^* & \lvert\Delta Q_o^o\rvert \leqslant \lvert\Delta Q_o^*\rvert\end{cases}$ $\Delta Q_o^* = \frac{2\dot{V}_{(t)}}{k^*+1} - \frac{2(V^{lim}-V)}{Tk^*(k^*+1)}$ $\Delta Q_o^o = \frac{2\dot{V}_{(t)}}{P+1} + \frac{2(V-V^{sp})}{TP(P+1)}$ $k^* = N\left[\frac{2(V^{lim}-V_{(t)})}{T\dot{V}_{(t)}}\right]$

* Shunta and Fehervari (1976), # McDonald et al. (1986), ϕ Campo and Morari (1989)

context, it would be highly desirable to develop a general non-linear PI controller with a single tunable parameter for mitigating the flow overshoot and other tuning parameters such as controller gain calculated as a function of the available process measurements and parameters such as the current deviation in level, its rate of change, and distance from the alarm limits. Such a non-linear PI ALC is developed in this work and evaluated for a realistic methanol dehydration process with some very promising flow variability mitigation results when compared with the existing algorithms.

2. NONLINEAR PI ALC

Consider a surge tank with its feed under flow control and outflow set by a level controller as in Figure 1. The level setpoint is 50% of full capacity with high and low level alarm limits at $V_{\%}^{max}$ (say 80%) and $V_{\%}^{min}$ (say 20%), respectively. The system is initially at steady state with $\bar{Q}_{in} = \bar{Q}_{out} = 0.5Q^{max}$ and Q_{in} is increased by a step of magnitude ΔQ at time $t = 0$. For this step disturbance, the optimal utilization of the available surge capacity $(V^{max} - \bar{V})$ to mitigate the severity of the transient in Q_{out} using a PI LC is to choose K_c such that V just touches V^{max} from below for the chosen τ_I.

From the overall tank material balance

$$\tau\frac{d\hat{V}_{\%}}{dt} = \hat{Q}_{in_{\%}} - \hat{Q}_{out_{\%}} \tag{1}$$

where expressing the PVs as $0 - 100\%$ (nominal is 50%) of PV range results in the multiplier $\tau = \bar{V}/\bar{Q}$ (nominal residence time), as well as the PI controller equation

$$\hat{Q}_{out_{\%}} = K_c[\hat{V}_{\%} + \tfrac{1}{\tau_I}\textstyle\int \hat{V}_{\%}dt] \tag{2}$$

we obtain the characteristic equation of the ODE describing the closed-loop system as

$$\tfrac{\tau\tau_I}{K_c}s^2 + \tau_I s + 1 = 0 \tag{3}$$

To mitigate the manipulated flow overshoot that results from I action and amplifies significantly down a series cascade of units Cheung and Luyben (1979), τ_I should be chosen large to sufficiently overdamp the closed-loop response. The condition for overdamping is $\frac{K_c\tau_I}{\tau} > 4\alpha$, where $\alpha > 1$ and captures the extent of overdamping. We then have α as an equivalent tuning parameter in lieu of τ_I.

We wish to develop a non-linear PI ALC algorithm that adapts the controller gain K_c over time t as $K_{c(t)}$ to modulate the aggressiveness of level control action based on the current level, rate of change of level as well as expected flow disturbances. The moving horizon approach is well suited for the purpose, where $K_{c(t)}$ is calculated at the current time t, which in turn gives $\tau_{I\,(t)} = \frac{4\tau\alpha}{K_{c(t)}}$ with α being the user specified overdamping extent (> 1), allowing the calculation of the current manipulated variable (MV) rate of change $\dot{Q}_{out_{\%(t)}}$ from the PI controller velocity form as

$$\dot{Q}_{out\%(t)} = K_{c(t)}\left[\dot{V}_{\%(t)} + \frac{\hat{V}_{\%(t)}}{\tau_{I\,(t)}}\right] \tag{4}$$

$\dot{Q}_{out\%(t)}$ is implemented in the process at the current time t. Similar to MPC, the entire calculation cycle is repeated at the next instant (moving horizon approach).

A systematic procedure for calculating $K_{c(t)}$ is developed in the following two subsections. The next subsection develops the overall framework for $K_{c(t)}$ calculation and the subsequent subsection develops the specific calculations in the overall framework.

2.1 Moving Horizon Controller PI Gain Adaptation

The preceding discussion suggests that the tuning should be 'loose' in the calm operation period and 'tight' in the severe operation period. Qualitatively speaking, the extent of 'loosening'/'tightening' corresponding to decreasing/increasing $K_{c(t)}$, is dictated by the need to just avoid triggering an alarm such that the available surge capacity is fully utilized. The triggering of an alarm depends on

(a) The current level deviation, $\hat{V}_{\%(t)}$, which determines the distance from the nearest alarm limit and hence the remaining available surge capacity for handling a flow disturbance. The closer the level to the alarm limit or alternatively, the further away the level from the nominal setpoint, the lower the remaining available surge capacity.
(b) The current rate of change of level, $\dot{V}_{\%(t)}$, which determines how fast the level is moving towards or away from the nearest alarm limit.
(c) The severity of the expected disturbance in the independent flow to a surge tank. The more severe the disturbance, the more likely the triggering of an alarm.

Whenever the level is not stationary, it is moving either towards the nearer alarm limit or away from the limit towards the setpoint (nominal level). Between the two, depending on the expected disturbance severity, the possibility of alarm limit violation can become a serious concern for the former, particularly when the level is close to the alarm limit. If an alarm violation is predicted, the gain $K_{c(t)}$ must be increased sufficiently such that the predicted transient level response just touches the alarm limit without violating it for full surge capacity utilization. Conversely, if an alarm limit violation is not predicted, $K_{c(t)}$ should be reduced such that the predicted level response just touches the alarm limit for full surge capacity utilization, which indirectly implies minimum flow manipulation using the PI algorithm.

There are two extremes with respect to the severity of the expected disturbance in the independent flow. The optimistic extreme is that the independent flow to the tank remains constant at its current value (ie no further change in the independent flow rate). The pessimistic extreme is that the independent flow rate changes immediately as the worst-case step in the direction that causes the level to move towards the nearest alarm limit.

Let $K_{c(t)}^{lo}$ and $K_{c(t)}^{hi}$ denote the calculated optimum ALC gains for full surge capacity utilization corresponding to the optimistic and pessimistic disturbance scenarios, respectively, at the current time t. The current implemented controller gain $K_{c(t)}$ should be a weighted combination of the two optimum gains. The weighting should trade-off between the conflicting objectives of mitigating the manipulated flow transient by letting the level float versus controlling the level so that an alarm limit is not violated. For the level moving towards the nearer alarm limit, $K_{c(t)}^{lo}$ (optimistic limit) should have higher weightage if the level deviation from setpoint is small ($\hat{V} \to 0$), whereas $K_{c(t)}^{hi}$ (pessimistic limit) should have higher weightage if the level is close to the alarm limit ($V \to V^{HI}$ or V^{LO}). Also, if the level is moving towards setpoint (usually 50%) and therefore away from the nearer alarm limit, only $K_{c(t)}^{hi}$ (pessimistic limit) is relevant. The mixing function

$$K_{c(t)} = u_{(\hat{V}_\% \dot{V}_\%)}[1 - w_{(\hat{V}_\%)}]K_{c(t)}^{lo} + w_{(\hat{V}_\%)}K_{c(t)}^{hi} + b \quad (5)$$

may be used to appropriately combine $K_{c(t)}^{lo}$ and $K_{c(t)}^{hi}$ for ALC, where b is a small bias that ensures a minimum $K_{c(t)}$ at all times and $0 \leqslant u, w \leqslant 1$. The primary weight w is a function of $\hat{V}_\%$. For ALC, we should have $w \to 0$ for $|\hat{V}_\%| \to 0$ and $w \to 1$ for $V_\% \to V_\%^{HI}$ or $V_\%^{LO}$. The $K_{c(t)}^{lo}$ weight modifier u is a function of $\hat{V}_\% \dot{V}_\%$, which captures if the level is moving towards the nearer alarm limit ($\hat{V}_\% \dot{V}_\% > 0$) or if it is moving towards the setpoint and therefore away from the nearer alarm limit ($\hat{V}_\% \dot{V}_\% < 0$). For ALC, we should have $u \to 1$ for $\hat{V}_\% \dot{V}_\% > 0$ and sharply decreasing to zero for $\hat{V}_\% \dot{V}_\% \to 0^+$ with $u \to 0$ for $\hat{V}_\% \dot{V}_\% < 0$. In this work, we use sigmoids for smooth dependence of w and u on the operating conditions with

$$w_{(\hat{V}_\%)} = \frac{1}{1 + e^{-\beta\left(|\hat{V}_{\%(t)}| - |\hat{V}_{\%^c}|\right)}} + b_1 \quad (6a)$$

$$u_{(\hat{V}_\% \dot{V}_\%)} = \frac{1}{1 + e^{-\gamma\left(\hat{V}_\% \dot{V}_\%\right)}} \quad (6b)$$

where b_1 is a small bias that ensures $K_{c(t)}^{hi}$ have some weight all the time.

Once $K_{c(t)}$ is obtained from equation (5) and $\tau_{I(t)}$ is calculated as $\tau_{I(t)} = 4\alpha\tau / K_{c(t)}$, equation (4) gives the control move that is implemented in the process. Similar to MPC, the entire calculation cycle is repeated at the next instant (moving horizon approach). The only missing link is a calculation procedure for obtaining K_c^{lo} and K_c^{hi}, which is developed from first principles in the next subsection.

2.2 Optimistic and Pessimistic ALC Gain Calculation

For the ALC algorithm, we are interested in obtaining $K_{c(t)}^{lo}$ (optimistic gain) and $K_{c(t)}^{hi}$ (pessimistic gain) given $\hat{V}_{\%(t)}$ (usually $\neq 0$) and $\dot{V}_{\%(t)}$ (usually $\neq 0$) at the current time t. To do so, consider the ODE describing the dynamics of $\hat{V}_\%$ obtained by inspection of the characteristic equation (3) and replacing τ_I with $4\alpha\tau/K_c$

$$\frac{4\alpha\tau^2}{K_c^2}\frac{d^2\hat{V}_\%}{dt^2} + \frac{4\alpha\tau}{K_c}\frac{d\hat{V}_\%}{dt} + \hat{V}_\% = \frac{4\alpha\tau}{K_c^2}\frac{d\hat{Q}_\%}{dt} \quad (7)$$

It is convenient to re-label the current time $t = t$ as $t' = 0$ such that t' is the time elapsed from the current time. One may then obtain the analytical solution $\hat{V}_{\%(t')}$ for $Q_{in\%}$ increasing as a step of size $\Delta Q_\%$ at $t' = 0$ (current time) by solving the linear second order ODE in equation (7) as an initial value problem with the two initial conditions $\hat{V}_{\%(t'=0)} = \hat{V}_{\%0}$ (current level deviation) and $\dot{V}_{\%(t'=0)} = \dot{V}_{\%0}$ (current rate of change of level). Applying partial fractions in the Laplace domain with non-zero initial conditions and then transforming back to the time domain, the analytical solution is obtained as

$$\hat{V}_{\%(t')} = \frac{1}{\tau(\lambda_1 - \lambda_2)}\left[c_2 e^{-\lambda_2 t'} - c_1 e^{-\lambda_1 t'}\right] \quad (8)$$

where

$$\lambda_{1,2} = \frac{K_c}{2\tau}\left(1 \pm \sqrt{\frac{\alpha - 1}{\alpha}}\right)$$

$$c_{1,2} = \Delta Q_\% + \tau\dot{V}_{\%0} + (K_c - \tau\lambda_{1,2})\hat{V}_{\%0}$$

Differentiating equation (8) and setting the derivative to 0 gives the $\hat{V}_\%$ response peak time

$$t_p' = \frac{1}{\lambda_1 - \lambda_2}\ln\frac{c_1\lambda_1}{c_2\lambda_2} \quad (9)$$

Substituting t'_p into equation (8) and simplifying gives the maximum $\hat{V}_{\%}$ deviation

$$\hat{V}_{\%}^{max} = \frac{c_1}{\tau\lambda_2}\left(\frac{c_2\lambda_2}{c_1\lambda_1}\right)^{\frac{\lambda_1}{\lambda_1-\lambda_2}} \tag{10}$$

For the standard case of the initially steady nominal system with $\hat{V}_{\%0} = 0$ and $\dot{V}_{\%0} = 0$, we have $c_1 = c_2 = \Delta Q_{\%0}$. The response peak time from equation (9) then is $t'_p = \frac{1}{\lambda_1-\lambda_2}\ln\frac{\lambda_1}{\lambda_2}$. Substituting t'_p into equation (8) and rearranging gives the maximum deviation in level for the initially steady nominal system $\hat{V}^{max} = f_{(\alpha)}\frac{\Delta Q_{\%}}{K_c}$, where

$$f_{(\alpha)} = \left(\frac{2}{1-\sqrt{\frac{\alpha-1}{\alpha}}}\right)\left\{2\alpha\left(1+\sqrt{\frac{\alpha-1}{\alpha}}\right)-1\right\}^{-\frac{1}{2}\left(\sqrt{\frac{\alpha}{\alpha-1}}+1\right)} \tag{11}$$

To fully utilize the available surge capacity towards ALC for an inflow step increase of $\Delta Q_{\%}$, we must have $\hat{V}_{\%}^{max} = V_{\%}^{HI} - \bar{V}_{\%}$. The PI ALC gain K_c^{ALC} for a step increase in $Q_{in_{\%}}$ of magnitude $\Delta Q_{\%}$ with zero initial conditions then is

$$K_c^{ALC} = f_{(\alpha)}\frac{\Delta Q_{\%}}{V_{\%}^{HI} - \bar{V}_{\%}} \tag{12}$$

At the current time $t' = 0$ (or $t = t$), $\hat{V}_{\%0}$ and $\dot{V}_{\%0}$ are known from process measurements. Also α is user specified so that $f_{(\alpha)}$ is known from equation (11). Therefore for specified values of $\Delta Q_{\%0}$ and $\hat{V}_{\%}^{max}$, equation (10) may be solved iteratively for the only unknown K_c. The calculated value of K_c corresponds to the transient $\hat{V}_{\%}$ response just touching $\hat{V}_{\%}^{max}$ and then turning to return back to setpoint. For the optimistic gain $K_{c\,(t)}^{lo}$, $\Delta Q_{\%0} = 0$. For the pessimistic gain $K_{c\,(t)}^{hi}$, the appropriate value of $\Delta Q_{\%0}$ corresponds to the *remaining* maximum step in $Q_{in_{\%}}$ that pushes the level towards the nearest alarm limit. For $\hat{V}_{\%} > 0$ (level above nominal), we have

$$\Delta Q_{\%0} = \min(100 - Q_{in_{\%}\,(t)},\ \Delta Q_{\%}^{max})$$

Similarly, for $\hat{V}_{\%} < 0$ (level below nominal), we have

$$\Delta Q_{\%0} = \max(-Q_{in_{\%}\,(t)},\ -\Delta Q_{\%}^{max})$$

Note that, in case $Q_{in_{\%}\,(t)}$ is not measured, the tank material balance may be used to estimate $Q_{in_{\%}\,(t)}$ as $Q_{in_{\%}\,(t)} = Q_{out_{\%}\,(t)} + \tau\dot{V}_{\%}$.

In our exploratory dynamic simulation studies, we found that $\beta = 0.5$, $|\dot{V}_{c\%}| = 25\%$, $b_1 = 0.07$ and $\gamma = 7$ gave reasonable sigmoids for calculating w and u respectively for combining K_c^{lo} and K_c^{hi} towards ALC. Also $b = 0.1$ is reasonable as it ensures a minimum controller gain of 0.1 %/% at all times. With these controller parameters thus fixed, α (overdamping extent) is the only parameter that the user adjusts to ensure the manipulated flow overshoot due to I action does not become unacceptably large in interconnected plantwide systems. Depending on the process system, we found $2 < \alpha < 6$ achieved excellent ALC in plantwide systems. In the next section, we present the dynamic performance results of thus tuned non-linear PI ALCs on a single tank, and a realistic DME manufacturing plant.

3. DYNAMIC EVALUATION

The proposed nonlinear PI (PI_{nl}) ALC algorithm is evaluated for a single tank and a realistic methanol dehydration process. For comparison, linear P-only and PI ALC as well as MPOC are evaluated.

3.1 Single Surge Tank

Simulation results are obtained for small (5%), moderate (15%), and large (50%) step changes in $Q_{in\%}$ for the single tank in Figure 1. The transient response in Figure 2 shows that to bring $V_{\%}$ back to setpoint using linear/non-linear PI control as well as MPOC, $Q_{out_{\%}}$ overshoots $\Delta Q_{in_{\%}}$. Also, notice that the initial severity of the transient in $Q_{out_{\%}}$ is lower for the proposed non-linear PI ALC for small and moderate magnitude $Q_{in_{\%}}$ step changes. Complementing these less severe transients in $Q_{out_{\%}}$, the deviation in $V_{\%}$ is the larger implying higher surge capacity utilization.

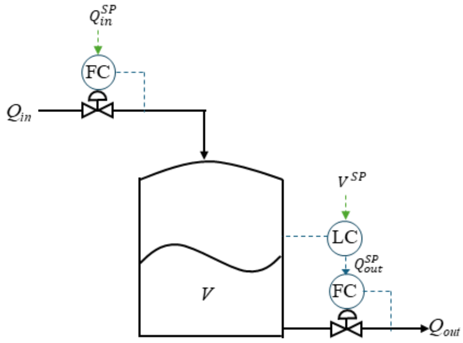

Fig. 1. Single Surge Tank

From the single tank results, the proposed PI nonlinear ALC is expected to more effectively mitigate flow variability for small disturbances via ‘loose’ control action while avoiding alarm limit violation for large disturbances via aggressive control action. The flow variability mitigation can help achieve more economic operation with lower back-offs from active constraints in the operation of real plants. This is demonstrated next.

3.2 Methanol Dehydration Process

The process manufactures dimethyl ether (DME) via dehydration of methanol (MeOH) Luyben (2017). The process flowsheet and design have been adapted from Luyben. A 95 mol% MeOH fresh feed (remaining 5 mol% is water) mixed with pure MeOH recycle stream is vaporized and then superheated to the reactor inlet temperature. The reversible, exothermic dehydration reaction

$$2MeOH \longleftrightarrow \text{DME} + H_2O$$

occurs in a cooled packed bed reactor. The reactor effluent is further cooled and sent to the high-pressure product column that recovers pure DME up the top as the liquid distillate. The DME-free bottoms stream is further separated in the recycle column to recover water down the bottoms with the pure MeOH distillate recycled back to the vaporizer. The nominal process design and operating conditions are shown in Figure 3.

A conventional plantwide regulatory control system with the fresh MeOH feed rate as the throughput manipulator

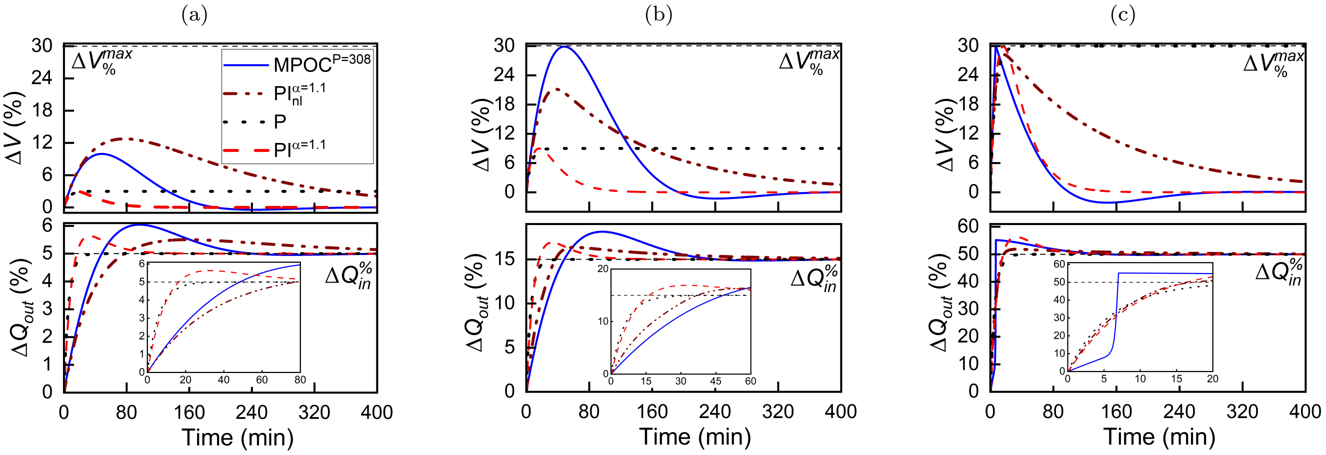

Fig. 2. Transient Response of $Q_{out_{\%}}$ and $V_{\%}$ for step change in $Q_{in_{\%}}$ a) 5% b) 15% c) 50%

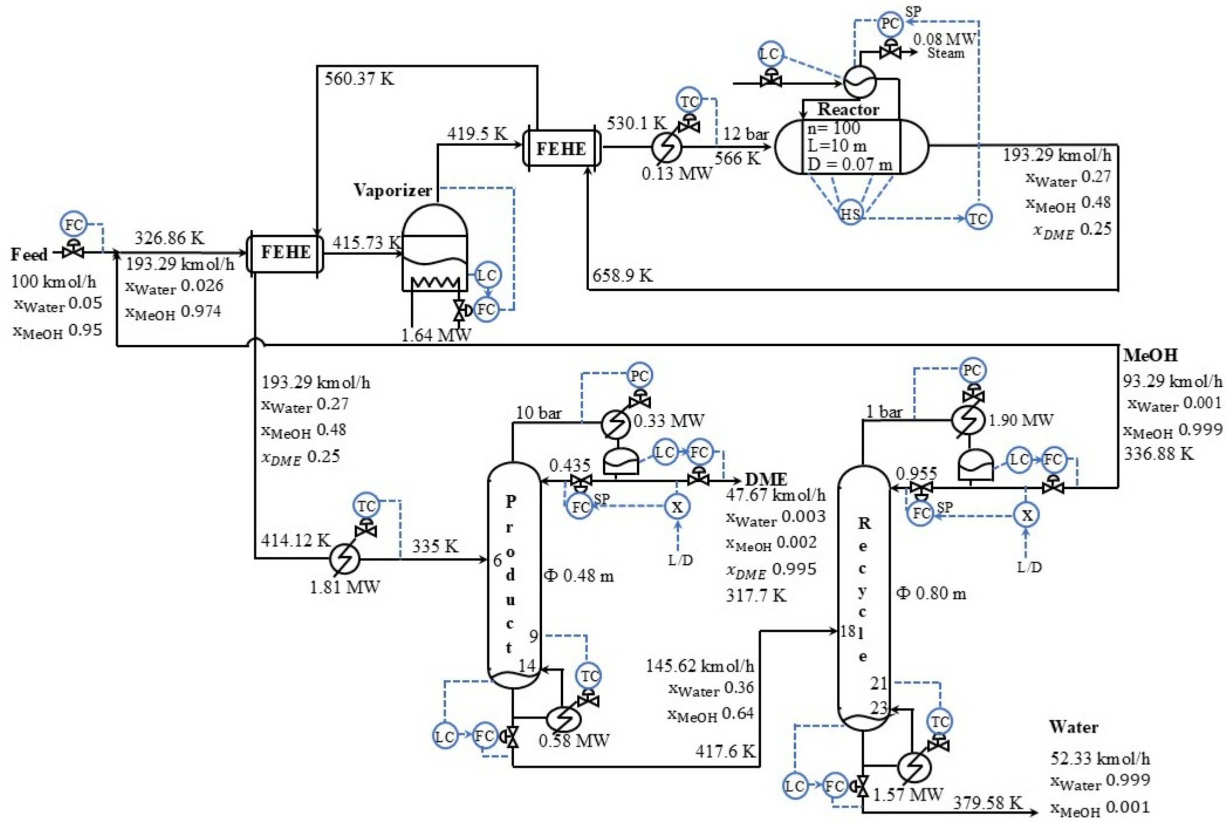

Fig. 3. Nominal design, operating condition and plantwide control structure of the MeOH dehydration process

(TPM) is shown in Figure 3. The vaporizer level is regulated by manipulating the vaporizer duty. The reactor feed temperature is regulated by adjusting the reactor pre-heater duty. The reactor hot-spot temperature is regulated by manipulating the reactor coolant temperature. The reactor effluent cooler duty is adjusted to hold the exit stream temperature. On both columns, the condenser pressure is regulated by adjusting the condenser duty. Also, the reflux drum and bottom sump levels are regulated using the distillate rate and bottoms rate, respectively. A sensitive stripping tray temperature (tray 10 for product column and tray 20 for recycle column) is controlled by manipulating the reboiler duty. The reflux rate is maintained in ratio with distillate rate (L/D control).

The dynamic response of the controlled process is obtained for time series fresh feed composition and reactor coolant and inlet temperature disturbance. To avoid violating the minimum product purity constraint, a suitably backed-off L/D setpoint is chosen on the product column. Similarly, the stripping tray temperature setpoint on the recycle column is suitably backed-off to ensure the wastewater bottoms minimum purity constraint is not violated. Also, the nominal steady state reactor hot-spot temperature hard constraint forces a back-off in the hot-spot temperature controller setpoint. The three backed-off setpoints, product

Table 2. Average backed-off Mode I operation result for methanol dehydration process

Algorithm	$\Delta^{L}/D^{*}_{\textbf{prod}}$ $\times$ **10^{-1}**	**C_1 duty (kW)**	ΔT^{ϕ}_{Rcy} **(K)**	**Total duty (kW)**	$\Delta T^{\#}_{\textbf{react}}$	**Energy savings (%)**
P	0.58	620.47	3.30	4288.12	0.55	0.00
PI	0.47	604.55	2.64	4215.44	0.42	1.70
PI_{es}	0.25	590.90	0.75	4008.11	0.32	6.53
MPOC	0.16	586.90	0.67	3987.97	0.28	6.98
PI_{nl}	0.10	584.22	0.59	3934.30	0.23	8.25

* No back-off $L/D^{SS}_{prod} = 0.44$, $\quad ^{\phi}$ $T^{SS}_{Rcy} = 95.7$ °C, $\quad ^{\#}$ No back-off $T^{Max}_{react} = 386$ °C

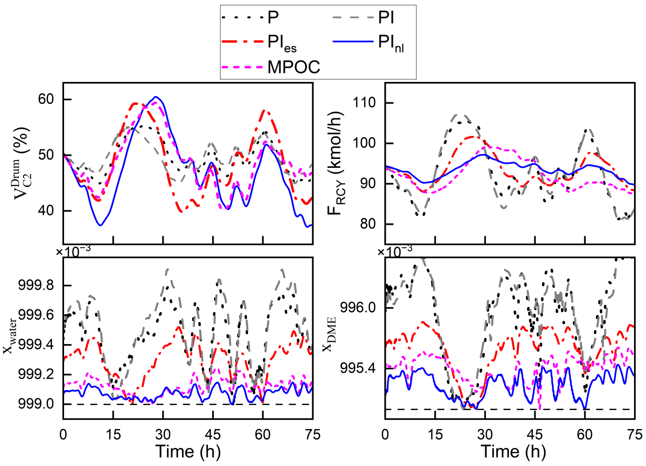

Fig. 4. Transient response of key parameters to time-series disturbance for MeOH dehydration process

column duty and total duty, using the alternative ALCs are reported in Table 2. The % energy savings relative to linear P-only ALC is also reported in the Table. The lowest energy consumption is achieved for non-linear PI ALC, which is a significant $\sim 8.25\%$ less than P-only ALC. Figure 4 plots the backed-off closed-loop operation transients in recycle column reflux drum volume V^{Drum}_{C2}, recycle flow rate F_{RCY}, x_{water}, and x_{DME} using the alternate ALC algorithms with the TPM setpoint fixed at the nominal value. Notice that the variability in V^{Drum}_{C2} is the highest for the proposed ALC algorithm implying the highest available surge capacity utilization. This translates to the lowest variability in F_{RCY} and hence lowest back-offs in the constraint PVs compared to the other algorithms.The quantitative results illustrate the significant potential of surge capacity utilization using ALCs for economic process operation.

4. CONCLUSION

This study develops a non-linear PI averaging ALC algorithm with significantly improved flow variability mitigation characteristics for plantwide systems with material recycle. Quantitative closed-loop results show that the algorithm outperforms existing ALC algorithms for small to moderate flow disturbances with comparable performance for large disturbances while avoiding high/low level alarm limit violation. Up to 8.25 % reduction in energy consumption is achieved due to the reduced back-off in the active constraints that result from the lower flow variability using the developed ALC. Overall, the work highlights the significant potential of surge capacity utilization using ALC for economic process operation.

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