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A Novel Single-Input Two-Output (SITO) Strategy for Split Range Control

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***Abstract* — This paper presents a novel method* for implementing a split range control using a Proportional-Integral (PI) controller where two valves, a big and a small valve, can be used to simultaneously control the underlying process. The proposed control strategy uses proportional action to move the small valve while the integral action is directed to the big valve. Linear stability analysis and design techniques are shown to be applicable to the proposed control strategy. Simulation examples are used to illustrate the advantages of the SITO scheme. The proposed method is demonstrated on a dehydrator drum level at a gas-oil separation plant (GOSP).**

I. Introduction

Achieving operational efficiency, value creation, and risk management are reliant on process control systems - they provide the mechanism to ensure that operating facilities are reliable, efficient and, most importantly, operating in a safe environment. [1] Controllers, simply, are designed with the objective of providing adequate dynamic performance. [2] Fundamental to this approach is often the process operation and economics.

In the case of multi-input, single-output processes, a control philosophy is necessary to effectively handle interactions of a multivariable nature to enhance the process performance. [2, 3] Split range control is a standard control technique considered in processes with several manipulated variables. Typically, the underlying principles of such controllers are used to address effectively operational constrains in the overhead section of distillation columns or jacket outlet temperature of a Continuous Stirred Tank Reactor (CSTR). [4, 1]

The choice of dual split-range control is considered in which two valves are available to control a single process variable. Traditionally, in a single-input single-output (SISO) Proportional-Integral (PI) controller, only one valve is moved at any given time. When two valves are available for control, as shown in Fig. 1, a conventional split range control scheme moves valve A first, till it is 100% open/closed and only then moves valve B till it is 100% open/closed. [5, 6]

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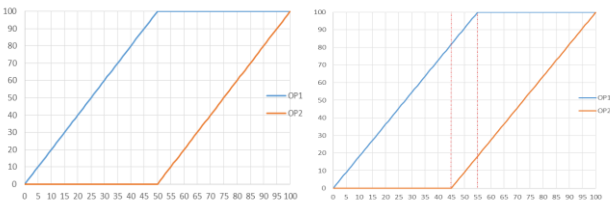
A common application of split range control is one where it is desired to use the first valve under normal conditions to maintain a pressure, for example, and the second valve under abnormal conditions. The first valve can be an inline valve whereas the second valve is typically a vent valve.

In addition to the split point, a dead zone is also used around the split point to avoid excessive switching between the two valves. The dead zone leads to the overall split range scheme behaving in a nonlinear fashion. The presence of the dead zone can also lead to cycling between the two valves as they try to control the process variable at the split point. To prevent this cycling, an overlap can be used between the two valves. Figure 1 shows a typical split arrangement for a two-valve control scheme. Fig. 1 (a) shows a standard split range scheme with a 50% split point and no overlap or deadband. Fig. 1 (b) shows the two valves with a 10% overlap, i.e., in the highlighted area between the two red lines, both valves will be active.

Figure 1. Split Range Control with a Two-valve Arrangement

(a) (b)



Another typical scenario for the split range control scheme is of a flow control system in which a big/small valve arrangement is used with an objective to use the small valve for trimming the system (fine controlling) and the big valve to best handle large disturbances. [2, 4]

The big/small valve arrangement permits use of a single valve at any given time, and so limiting the ability of the feedback loop to improve performance. [2, 4] Implementing, for example, the control scheme illustrated in Fig. 1, would first open valve 1 (small valve) till it is 100% open and only then move valve 2 (big valve). This principle of operation will not cope well with disturbances requiring simultaneous actions from both valves especially when the two valve gains are significantly different.

* The proposed control scheme strategy discussed in this document has been filed for patent with the U.S. Patent Office (Ref: 38136-0156001).

Where both steady-state and dynamic disturbances are common this can lead to cycling in the process variable due to conflict between the big and small valves as both valves try to address the same load changes. Split range control schemes are often known to cycle around the split point as both valves are operated at the end of their respective control ranges.

This paper describes a novel technique to control a process variable using PI control to simultaneously move two valves. The movement of the two valves is coordinated to ensure that there is no interaction due to the simultaneous movement. The rest of this manuscript is organized as follows. The proposed method is described in Section II while the applicability of linear stability analysis and design techniques is shown in Section III. Sections IV and V illustrate the application of the proposed SITO method to simulation and industrial case studies respectively. The main benefits and areas of future research are discussed in Sections VI and VII.

II. Proposed Method

Considering the limitations of implementation mentioned above, the proposed method enables Proportional-Integral (PI) algorithms to manipulate two outputs simultaneously. To overcome the SISO nature of the PI algorithm, a single-input, two-output (SITO) PI controller is proposed. The SITO control algorithm is based on directing the Proportional (P) part of the control action to the small valve (valve 1) for quick response to fast acting disturbances in the flow and the Integral (I) part of the control action to the big valve (valve 2) for steady state response to large disturbances in the flow.

The controller is configured to control both valves, small and big, simultaneously to execute the fluid flow control on the fluid flow process through the pipe system.

Such "split" control action ensures:

- Both valves stay in control range by virtue of the bigger valve always rejecting the slow steady state disturbances and the small valve rejecting fast dynamic disturbances.
- Coordination between the two valves, small and big, as a single control algorithm calculates the action.

While, in the future, there could be a SITO PID block available in the distributed control system (DCS) environment, the implementation of the proposed control scheme can be achieved through the standard functionality available in current DCS's. Consider below block diagram of proposed control scheme strategy of Fig. 2.

One possible approach is to use two control blocks – with a P-only and an I-only controller, respectively. Both controllers will receive the same input of control error. The P-only control action can be achieved by disabling the integral action or by setting the integral time to the maximum allowed in the DCS. I-only control algorithms are available within many DCS. A SITO PI controller could be part of future DCS options.

Figure 2. Proposed Control Strategy for two valves, small and big.

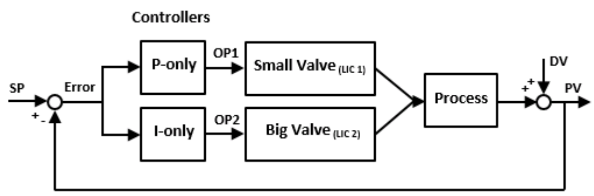


TABLE I. Tuning for LIC_1 and LIC_2

Control	Action	P	I
Small Valve	Old	K_c	K_i
	New	K_c	0
Big Valve	Old	K_c	K_i
	New	0	K_i

III. Stability Analysis And Design

Conventional control loop analysis and design techniques can be directly applied with the proposed method. Instead of splitting the controller output based on the range, it is split into proportional and integral parts and applied to the process.

Case 1: No Time Delay

Let us assume the following relationships between the individual valves and the process:

$$y_1(s) = \frac{K_1}{\tau_1 s+1}u_1(s), y_2(s) = \frac{K_1}{\tau_2 s+1}u_2(s) \ldots.(1)$$

The delay is assumed to negligible for the first case. The controller output is calculated by a standard PI controller.

$$u(s) = K_c\left\{1 + \frac{1}{\tau_I s}\right\}e(s)\ldots(2)$$

The calculated controller output is split into proportional and integral parts to give the changes for the small and large valve, respectively.

$$u_1(s) = K_c e(s), u_2(s) = \frac{K_c}{\tau_I s}e(s)\ldots.(3)$$

Substituting (3) into (1) we get

$$y(s) = y_1(s) + y_2(s) = \left\{\frac{K_1 K_c}{\tau_1 s+1} + \frac{K_2 K_c}{(\tau_2 s+1)\tau_I s}\right\}e(s)\ldots(4)$$

Let us assume the two time constants are the same as the valve dynamics can be expected to be similar and a ratio of the valve gains in the normal operating range.

$$\tau_1 = \tau_2 = \tau, K_2 = \alpha K_1, where\ \alpha > 1$$

Substituting into (4) we get,

$$y(s) = \left\{1 + \frac{\alpha}{\tau_I s}\right\} \frac{K_c K_1}{\tau s+1} e(s) \ldots (5)$$

For the case of setpoint tracking the closed loop transfer function becomes:

$$y(s) = \frac{K_c\left(1+\frac{1}{\tau_I' s}\right)\frac{K_1}{\tau s+1}}{\left(1+K_c\left(1+\frac{1}{\tau_I' s}\right)\frac{K_1}{\tau s+1}\right)} r(s) \ldots (6)$$

$$\mathit{where}\ \tau_I' = \tau_I/\alpha$$

A conventional linear closed loop relationship emerges describing the overall relationship between the two valves and the process output through a single transfer function. Traditional stability analysis techniques such as Bode/Nyquist may be used to determine the gain/phase margins.

Case 2: Similar Time Delay in Both Valves

$$y_1(s) = \frac{K_1}{\tau_1 s+1} e^{-\theta s} u_1(s), y_2(s) = \frac{K_1}{\tau_2 s+1} e^{-\theta s} u_2(s) \ldots (7)$$

Following the same steps as for case 1, we get the following closed loop expression between the setpoint and the output,

$$y(s) = \frac{K_c\left(1+\frac{1}{\tau_I' s}\right)\frac{K_1}{\tau s+1}e^{-\theta s}}{\left(1+K_c\left(1+\frac{1}{\tau_I' s}\right)\frac{K_1}{\tau s+1}e^{-\theta s}\right)} r(s) \ldots (8)$$

which is equivalent to a closed loop relationship for a single input single output (SISO) system with the following process and controller transfer functions:

$$P = \frac{K_1}{\tau s+1} e^{-\theta s}, C = K_c\left(1 + \frac{1}{\tau_I' s}\right) \ldots (9)$$

As such all conventional SISO stability analysis techniques such as Bode, Nyquist can be applied directly. Similarly for controller design purposes, internal model control (IMC) techniques can be applied to calculate the controller parameters for a PI controller. The controller gain can be directly implemented while the integral time has to be scaled to account for relationship in equation (6).

$$K_c = K_{IMC}, \tau = \alpha \tau_{IMC} \ldots (10)$$

Therefore, the proposed technique lends itself naturally to SISO techniques for stability analysis and design. This is made possible by the fact that the proposed approach converts the two input single output problem into a classic SISO problem as shown here. The conventional split range techniques are suitable for cases where the desired operation is to operate at the split point and there are two valves available but you want to preferentially use the full capacity of the first one before opening the second valve. The propose technique is well suited for cases where there are two valves of unequal sizes and you want to use the small valve to reject fast disturbances whereas the big valve is used for slow moving and larger disturbances.

A property of the proposed approach which follows directly from Equation (3) is that the small valve, which moves off the proportional action will always return to its starting point or steady state and the big valve will move its steady state to remove offset. This is clearly seen from the simulation examples that follow.

Case 3: P-PI Control

In some cases, it may be desirable to have some P action on the big valve as well to help with rejection of large fast acting disturbances. The controller equation in this case becomes:

$$u_1(s) = K_c e(s), u_2(s) = Kc(1 + \frac{1}{\tau_I s})e(s) \ldots (10)$$

Assuming the same proportional action is used for the both valves.

Following the same steps as for case 2, we get the following closed loop expression between the setpoint and the output,

$$y(s) = \frac{K_c'\left(1+\frac{1}{\tau_I'' s}\right)\frac{K_1}{\tau s+1}e^{-\theta s}}{\left(1+K_c'\left(1+\frac{1}{\tau_I'' s}\right)\frac{K_1}{\tau s+1}e^{-\theta s}\right)} r(s) \ldots (11)$$

where,

$$K_c' = (1+\alpha)K_c, \tau_I'' = \tau_I\left(1 + \frac{1}{\alpha}\right)$$

This is equivalent to a closed loop relationship for a SISO system with the following process and controller transfer functions:

$$P = \frac{K_1}{\tau s+1} e^{-\theta s}, C = K_c'\left(1 + \frac{1}{\tau_I'' s}\right) \ldots (12)$$

As such all conventional SISO stability analysis techniques such as Bode, Nyquist can be applied directly. Similarly for controller design purposes, internal model control (IMC) techniques can be applied to calculate the controller parameters for a PI controller. The controller gain can be directly implemented while the integral time has to be scaled to account for relationship in equation (6).

$$K_c = \frac{K_{IMC}}{(1+\alpha)}, \tau = \frac{\tau_{IMC}}{(1+\frac{1}{\alpha})} \ldots (13)$$

Note that this is the case where the equal amount of proportional action is applied on both valves. In the ideal case where the proportional action of the big valve was scaled with a scaling factor β (≤ 1), the equivalency result would be the following:

$$K_c' = (1+\alpha\beta)K_c, \tau_I'' = \tau_I\left(\beta + \frac{1}{\alpha}\right) \ldots (14)$$

Once again an IMC controller can be designed for a first order process with the dynamics of the small valve (K, τ, θ)

and the following relationships can be applied to the IMC tuning parameters to determine the tuning parameters to be applied in the field.

$$K_c = \frac{K_{IMC}}{(1+\alpha\beta)}, \tau = \frac{\tau_{IMC}}{(\beta+\frac{1}{\alpha})} \ldots(15)$$

The scaling factor, β, can be a tuning parameter. For example, $\beta = 0.1$, for a big valve, which has twice the gain of the small valve will result in the big valve having proportional action which is 20% of the proportional action of the small valve.

IV. Simulation Case Study

A first order process is used to demonstrate the effectiveness of the new approach. Following process parameters are used:

$$K_1 = 1, K_2 = 2, \tau = 300s, \theta = 2s$$

A large load change is added at initial time. Figure 3 shows the response of the conventional split range scheme. The split point is 66% and the initial controller output (OP) position is 50%. As can be seen from the controller output responses, first the small valve (OP1) opens in response to load change until it reaches 100% (magenta line). Next the big valve comes into action and opens until it is able to reject the load disturbance (blue line).

Figure 3. Load response of a conventional split range control scheme.

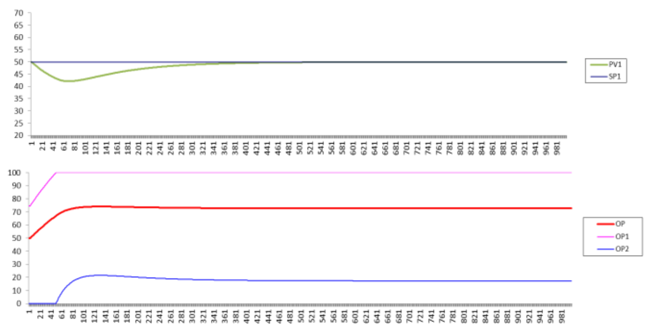
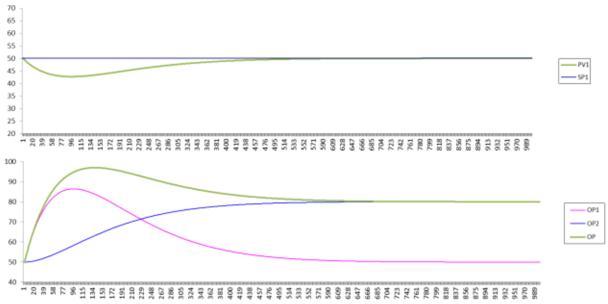


Figure 4 shows the load response of the proposed SITO scheme. While the process variable (PV) behavior is quite similar to the conventional approach, the controller output response is quite different. The small valve (OP1) responds right away while the large valve (OP2) makes measured moves off the integral action. At a steady-state, once the load disturbance is rejected, the small valve (OP1) returns to its starting point while the big valve has absorbed the steady state impact of the disturbance. The overall behavior of the two valves is quite smooth and in coordination with each other.

Figure 5 compares the output behavior for load response in Figs. 3 and 4, on a scatter plot. Figure 5(a) shows the big valve vs. small valve plot for the conventional scheme and the 5(b) shows the behavior for the SITO scheme. The two figures clearly show the difference between the two schemes.

Figure 4. Load response of the proposed SITO control scheme



The conventional scheme moves one input at a time while the SITO scheme is inherently a multi-input single output scheme. Moving the two valves simultaneously also allows the proposed scheme to maintain both the valves in good control ranges. The conventional split range scheme, on the other hand, often operates both the valves at the extremes of their operating ranges making control more challenging. This will be more clearly illustrated in the following example.

Figure 5. Comparison of the two control scheme responses via a scatter plot.

(a) *(b)*

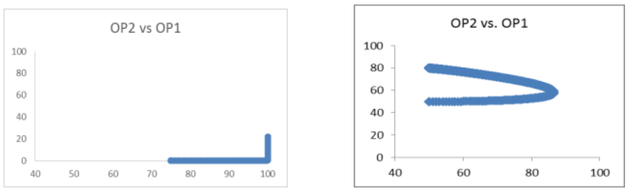
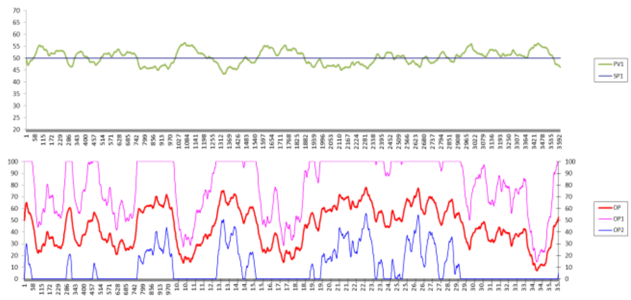


Figure 6 shows the load response of the traditional split range control scheme in the presence of a time varying disturbance.

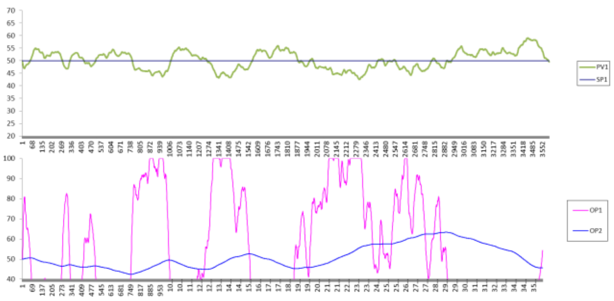
Figure 6. Load response behavior of conventional scheme with time varying disturbances.



The process dynamics were slowed down in this case to emulate a level controller (time constant=1200 seconds). Both the small and large valves are active and varying with similar dynamics in response to the load changes. The small valve is often wide open while the big valve mostly operates at the low end of its range. Significant amount of control energy is consumed in this mode of control as a result.

Figure 7 shows the load response of the SITO scheme in the presence of time varying changes. In this case, both the valves move simultaneously with the small valve making majority of the changes and the big valve responding to the low frequency component of the load disturbance. As a result the control energy is distributed between the two valves while keeping both the control valves in control range.

Figure 7. Load response behavior of SITO scheme with time varying disturbances.



The table below compares the control movement of the two schemes for the load disturbance rejection shown in Figures 6-7. Note the substantially lower variation in the big valve for the SITO case. The PV variation in the SITO case is higher for this set of tuning parameters. This can be reduced with tuning as per the process requirements.

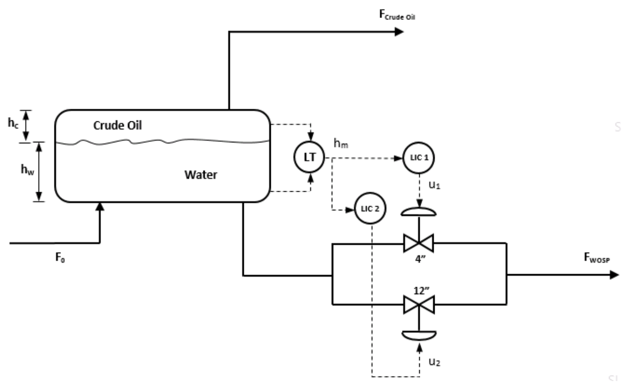
TABLE II. COMPARISON OF THE TWO CONTROL SCHEMES FOR LOAD RESPONSE WITH TIME VARYING DISTURBANCES

	Conventional Split Range Scheme	**SITO Control Scheme**
PV Standard Deviation	2.92	3.61
OP1 Standard Deviation	23.04	33.03
OP2 Standard Deviation	14.22	5.87

V. INDUSTRIAL CASE STUDY

Consider the simple process flow diagram of a basic operation that is used in a dehydrator drum of a gas-oil separation plant (GOSP) as depicted in Fig. 8. The process depicts a dehydrator drum with a configuration of two level control valves, small and big, at a GOSP. As shown, the process includes a dehydrator drum, a level measurement (LT) and two level controllers (LIC_1 and LIC_2, respectively). Wet crude oil feed (F_0) enters the dehydrator drum. The feed water content has to be lowered in the produced crude oil. The removed water is withdrawn from the bottom of the dehydrator drum and the water flows to the downstream facilities of the GOSP (F_{WOSP}).

Figure 8. Dehydrator Drum Level Controls Process



The process minimizes the water content in the wet crude oil leaving the dehydrator drum to be processed in a desalter drum in the downstream facilities of the GOSP. The crude oil flows from the top of the dehydrator drum ($F_{crude\ oil}$) to the desalter drum through water mixing injector valves.

In the dehydrator drum, the interface level between oil (h_c) and water (h_w) is measure by LT and controlled by LIC_1 and LIC_2 to desired operating level (for example, at around 45% (volume)). The level control loop of the process includes two control valves to adjust the interface level between oil and water in the dehydrator drum. The two control valves vary in size in which, for example, the small vale LIC_1 is 4" valve while the big valve LIC_2 is a 12" valve. The two valve gains are significantly different with the gain of the big valve being ~5 times the gain of the small valve. The two valves, small and big, control the water flow rate of the GOSP to adjust the interface level between oil and water in the dehydrator drum.

As illustrated in Fig. 2, both configurations of LIC_1 and LIC_2 include a separate standalone first and second SISO PI controllers, respectively. Both LIC_1 and LIC_2 receive the same input signal, i.e., interface level error (h_m), and each generates a separate output single (u_1 and u_2, respectively). Traditionally the controllers if tuned independently of each other can lead to conflict and cause both the controllers to be turned off with the operators having to manually make movements in each valve.

With the proposed scheme, the controller parameters of the first SISO PI controller (for example, K_p, K_i) are tuned such that the first SISO PI controller functions like a P-only controller. Conversely, the controller parameters of the second SISO PI controller are tuned such that the second SISO PI controller functions like an I-only controller with minimal amount of P-action. Therefore, P control action is mainly applied to the small valve LIC_1 for quick response to fast acting disturbances and I control action is applied to the big valve LIC_2 for steady state response to large disturbances. In the absence of a true SITO block in the DCS, it has to be ensured that the setpoint to both the controllers is identical.

Figure 9 shows the performance of the level control before and after the proposed changes were implemented.

As can be seen from the metrics in Table III, the level variation has been significantly reduced. Additionally, the big valve variation is reduced by 60% as is the small valve variation. The level control was maintained in automatic mode and the operators did not have continuously make adjustments in the two valves in response to level alarms.

It can be seen from Figure 9 that a consistent oscillation appeared once the new strategy was implemented. Upon further investigation, it was realized that this oscillation was due to sticky valve on a downstream process unit. With the interface level under closed loop the oscillation due to the sticky valve was now propagating upstream and could be clearly seen. Previously, since the level was under manual controller, the effect of the downstream disturbance could not be seen as consistently. The valve stiction issue was highlighted to operations for follow-up and maintenance.

Figure 9. Performance improvements: before *vs.* after

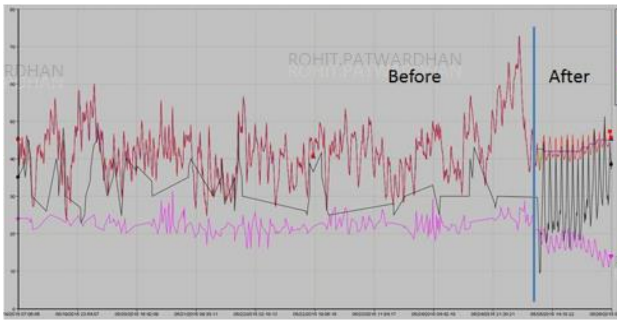


TABLE III. CONTROL PERFORMANCE IMPROVEMENTS

Dehydrator Drum	Standard deviation before and after		
	Before	***After***	***Change***
Interface Level (.PV)	4.041	1.898	-53.03%
LIC_1 (.OP)	13.24	7.723	-41.67%
LIC_2 (.OP)	5.543	2.164	-60.96%

VI. DISCUSSION

The main advantages of the proposed control scheme are discussed below:

- The control is simple to design, analyze, and maintain. From design and analysis point of view, the traditional linear single loop techniques could be used to analyze stability and determine the appropriate sets of controller tuning parameters.
- An improvement is expected in the closed loop performance due to minimizing the invariable interactions between the small and big valves. The technique ensures smooth movement of the big valve while the small valve handles the fast process variations. Techniques of conventional linear system analyses may be used to analyze the stability of the closed loop further. An important point to appreciate is that for analyses purposes, the proposed solution effectively reduces a two-input, single-output problem to a single-input, single-output control scenario.
- The proposed scheme is able to achieve similar process variable (PV) variability with significantly reduced output (OP) variability. This is clearly illustrated by the simulation and industrial case studies. The reduced output variability has a positive impact on downstream units leading to more stable operation.
- Due to the coordinated control between the big and small valves, the same tuning setting can be used at different load conditions. With conventional split range schemes, the tuning can be a function of the load conditions and which valve is in control range.
- The solution is applicable with any two-input, single-output systems. The control strategy has large scale of applicability given that the PI control was thought to be unsuitable due to its SISO nature.

VII. CONCLUSIONS AND FUTURE WORK

The proposed control scheme of SITO PI controller concentrated on overcoming the inherent limitations of the conventional dual split range technique in the use of both valves, small and big, simultaneously. Manipulating two outputs simultaneously is demonstrated on a dehydrator drum level control at a gas oil separation process. Applicability of traditional linear stability analysis and design techniques is shown theoretically and via simulation examples. It is shown that Internal Model Control (IMC) principles can be used in the choice of the PI parameters for the proposed control scheme.

The reset windup behavior and the extension to the case of different dynamics and delays will need to be investigated as a future extension of this work. The presence of two outputs raises interesting questions for the windup behavior, which would need to be addressed in the implementation of the proposed SITO control scheme.

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