Mats Friman*

Tuning of Control Loops with Valve Problems

Abstract: Control valve non-linearities may cause control loop oscillations. Usually, it is not possible to instantly replace a valve in operation just because it causes oscillations in the process, but with proper controller tuning we can minimize valve wear and reduce oscillation amplitudes, and sometimes even eliminate the oscillations. We discuss two major valve non-linearities, backlash and stick-slip, and how to tune the PID controller for such valves.

Keywords: backlash, stick-slip, oscillations, PID tuning

*Corresponding Author: Valmet Automation, E-mail: firstname.lastname@valmet.com

1 Introduction

Control valves play a crucial role in the process industry, regulating the flow of fluids, such as gases, liquids, and slurries. These valves are essential for maintaining the desired process conditions, such as pressure, temperature, and flow rate, ensuring the efficient and safe operation of industrial processes.

An industrial control valve package consists of a valve body, a pneumatic actuator, and a valve positioner. All these components consist of mechanical parts that are subject to wear and dirt (Kirmanen et al. 1997).

Control valves can encounter several problems that may affect their performance and reliability. Example problems include increased friction in valve body and actuator, pneumatic leakage in actuator and positioner, wear in mechanical parts, and design problems, most commonly improper sizing of valve or actuator.

Valve problems frequently cause oscillations in the PID control loop. Instant replacement of a faulty valve because of loop oscillations is usually not an option. Instead, we can re-tune the PID controller to minimize oscillations and reduce valve wear.

In this study we discuss how to decrease the oscillation amplitudes (in both process value (PV) and control output (CO)) to minimize impact of oscillations on the process. Moreover, increasing the period of oscillations reduces valve wear. To our knowledge, PID tuning recommendations for faulty valves have not been previously reported. Still, we believe that special tuning recommendations for faulty valves are useful and that there is a great possibility to stabilize oscillating processes and improve quality and economic performance in the entire process industry.

2 Introductory Example

As an example, consider a simulated level control loop with some 1 % backlash in the control valve. We model the level using a first-order-plus-deadtime model (with gain K = 80, time constant: T = 200, dead time L = 1) and employ a PI controller (with ideal tuning: gain K_p = 1.0, integration time T_i = 10, tuned by SIMC rules, Grimholt and Skogestad, 2012). Simulations suggest that this loop oscillates with a period of 38 and PV oscillation amplitude 0.60, as illustrated in Figure 1 (blue lines).

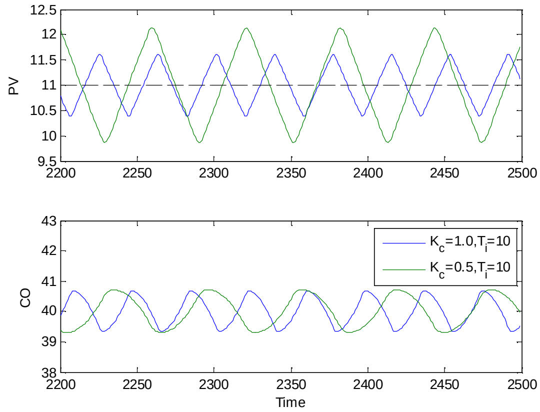


Figure 1. Example control loop oscillating because of backlash in valve. Original tuning in blue and detuned (gain 50% of original) loop in green.

At this point a natural question is: how should we tune the PI controller to reduce impact of oscillation generally on the process (to reduce PV amplitude), and to reduce valve wear (by increasing period of oscillation and decreasing amplitude of CO)? A surprising result, even to experienced control engineers, is that detuning controller gain by 50 % (K_p = 1.0 → 0.5) is a bad option, as it *increases* the amplitude of PV oscillations, in this case by 88% (green trends in Figure 1). A tighter tuning (K_p = 1.0 → 1.5) decreases the PV amplitude, but with a cost of increased valve wear due to faster oscillations (not shown).

In this example case the loop will stabilize when we select a large enough integral time ($T_i = 160$), which is very far from the ideal tuning recommendations ($T_i = 10$).

3 Modeling Common Valve Non-Linearities

In this paper we will consider two valve non-linearities: stick-slip and backlash. Stick-slip is useful to model sticky valves with high friction. In that case, the positioner must increase actuator pressure extensively to move the valve. Stick-slip movement makes it impossible to position the valve properly. Valve stick-slip is also useful to model a control valve with an undersized actuator. On the other hand, valve problems where friction is not an issue are best modeled with simple backlash. A very common example is a worn-out link between the shaft and the body of a rotary valve. Such a case is best modeled using backlash.

To model non-ideal valve behavior, we consider two non-linearities: 1) backlash and 2) stick-slip. These non-linearities are illustrated in Figure 2 below.

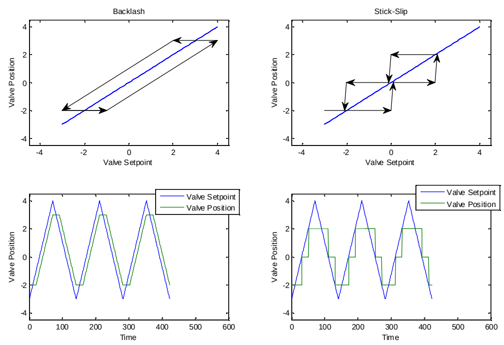


Figure 2. Illustration of backlash (left) and stick-slip motion(right).

Usually, the process dynamics of typical process industry controls are well modeled using simple linear transfer functions. However, control valves with pneumatic actuators don't show such an ideal behavior. For example, valve positioners typically have a hysteresis specification of 0.5 % and a dead-band specification (defined as how much valve setpoint can change before we can expect valve movement) of 0.2 % (Valmet Flow Control, 2024). Hence, PID tuning recommendations based on ideal linear transfer functions, are not necessarily optimal, not even for well-performing control valves.

4 Criteria for Oscillations

A fundamental question is: does backlash or stick-slip in the valve cause control loop oscillations?

For the stick-slip case the answer is quite straight-forward: yes, the loop will oscillate with an amplitude and period that depends on the amount of stick-slip, the PID controller tuning parameters, and process dynamics.

For the backlash case, the situation depends on the PID controller tuning parameters and process dynamics: we may see oscillations in the loop, or we may get a stable loop. Hence, with proper tuning we can minimize oscillations, decrease control error, and reduce valve wear.

To predict limit cycle oscillations due to stick-slip or backlash in the valve, we use describing function analysis (Atherton, 1982). With describing function analysis, we get the amplification and phase angle of the valve, assuming sinusoidal inputs. This assumption means that the analysis is approximative, but it usually predicts oscillations quite well. For backlash, the describing function $N(A)$ depends on backlash d input and amplitude $A>d$ as (Johansson et al. 2012)

$$N(A) = a + bi, \text{ where} \qquad \text{Eq. (1)}$$
$$a = \frac{1}{\pi}\left[\frac{\pi}{2} + \operatorname{asin}\left(1-\frac{2d}{A}\right) + 2\left(1-\frac{2d}{A}\right)\sqrt{\frac{d}{A}\left(1-\frac{d}{A}\right)}\right]$$
$$b = -\frac{4d}{\pi A}\left(1-\frac{d}{A}\right)$$

With stick-slip d, we have (with input amplitude $A>d$) as

$$N(A) = a + bi, \text{ where} \qquad \text{Eq. (2)}$$
$$a = \frac{2d}{\pi A^2}\sqrt{4A^2 - 4d^2}$$
$$b = \frac{-4d^2}{\pi A^2}$$

For a known input amplitude A, the describing function N returns a complex value where $|N(A)| = (a^2+b^2)^{0.5}$ is the amplification and $\angle(N(A)) = \operatorname{atan}(b/a)$ is the phase angle of the valve.

Assuming known transfer functions of process $G_P(s)$ and controller $G_{PI}(s)$, we can predict the existence and details of oscillations. To enter limit cycle oscillations, the following two criteria of the control loop must hold: 1) net amplification of process, controller, and valve equals unity, and 2) net phase angle of process, controller, and valve is –180º. Mathematically this is expressed as

$$G_P(s)G_{PI}(s)N(A) = -1 \qquad \text{Eq. (3)}$$

To investigate oscillations using Eq. (3), we plot $-1/(G_P(s)G_{PI}(s))$ vs. $N(A)$ (with $s=\omega i$, $\omega=2\pi/P$) in the complex plane and look for possible intersections of the curves. The intersection gives the oscillation amplitude A and frequency ω, as illustrated in Figure 3 below. With no intersection of the curves, we can assume a stable loop.

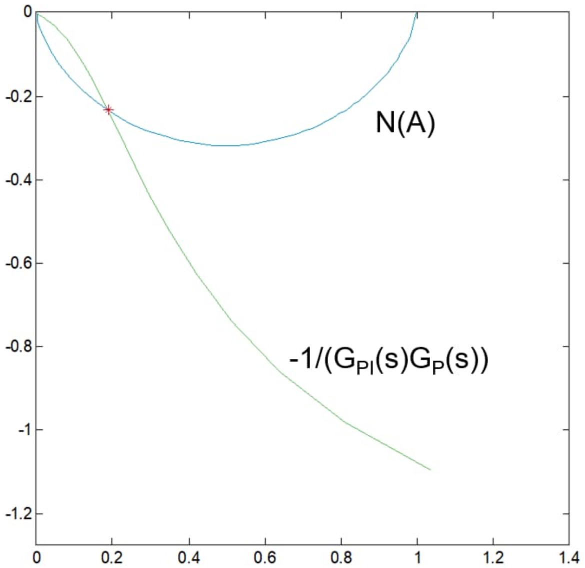


Figure 3. Intersection of backlash describing function N(A) and $-1/(G_P(s)G_{PI}(s))$ predicts limit cycle oscillations.

5 Controller Tuning

To investigate impact of tuning on control performance for control loops with valve problems we simplify the analysis as follows

- We assume first-order-plus-deadtime process models.

$$G_P(s) = \frac{K\exp(-Ls)}{Ts+1} \qquad \text{Eq. (4)}$$

- We assume that PI control is used and employ Skogestad IMC tuning with tuning parameter T_{CL} = 1.5L (called nominal tuning)

$$G_{PI}(s) = \frac{K_c(T_i s+1)}{T_i s} \qquad \text{Eq. (5)}$$

- The amount of backlash/stick-slip d is not important to investigate, as it does not affect the existence of oscillations. Instead, oscillation amplitudes are proportional to the amount of backlash/stick-slip.
- Process gain is also irrelevant because nominal controller gain times process gain is an invariant with fixed tuning recommendations.

Without loss of generality, it is hence enough to investigate various process time constant / dead time ratios T/L to get a good overview of PI tuning impact on control performance. Here we chose two cases: 1) T/L = 2, which we named "Flow loop", and 2) T/L=200, named a "Level loop".

For each 4 cases (Flow & Level loops, backlash & stick-slip), we investigated various PI tuning parameters and used Eq. (1)-(5) to check the existence of oscillations and to calculate oscillation amplitudes and periods. To evaluate the goodness of tuning for oscillating loops, we calculated valve travel (control output amplitude / oscillation period) for each tuning setting.

Figure 4 below illustrates tuning impact on valve travel for the Flow loop with backlash case. This loop works well and remains stable with nominal tuning settings but will oscillate if integral time T_i is chosen too small, as illustrated by the red area in Figure 4.

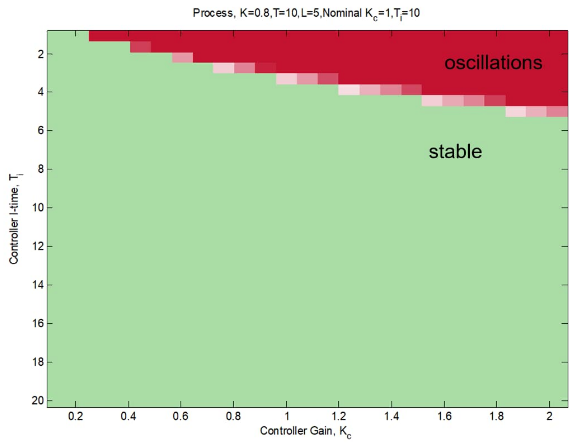


Figure 4. Tuning impact of Flow Loop with backlash case. Color indicates amount of valve travel (control output amplitude divided by oscillation period). This loop is stable with ideal tuning but if a too small Ti is selected, it starts oscillating.

Figure 5 illustrates the Level loop with a backlash case. Here, the loop is oscillating with nominal tuning settings, but we see that increasing T_i reduces valve travel (white color in Figure 5), and that the loop stabilizes with a large enough T_i (green color). Impact of controller gain is small.

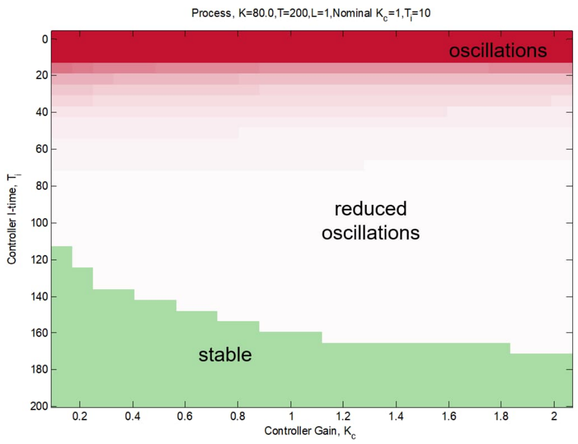


Figure 5. Tuning impact on Level loop with backlash. For this loop valve travel decreases clearly with increased Ti, and it is even possible to stabilize the loop. The impact of controller gain on oscillations is marginal.

For the backlash case we further investigated the impact of integral time T_i on oscillations. As illustrated in Figure 6, integral time must be large enough to avoid oscillations. A good rule of thumb is to have at least at the same level as time constant

$$T_i \geq T \qquad \text{Eq. (6)}$$

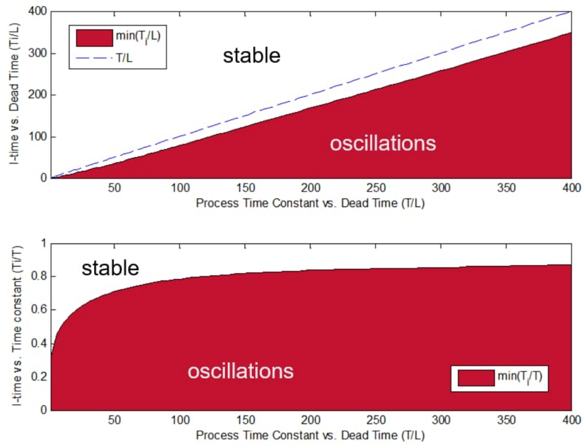


Figure 6. The selection of integral time is important to avoid oscillations for valves with backlash.

Figure 7 shows tuning impact for the Flow loop with stick-slip. Here it is impossible to stabilize the loop by tuning the controller, but we can reduce valve travel by selecting a smaller gain and a larger integral time. For the Level loop with stick-slip (not shown) the results are quite similar, except that the impact of controller integral time T_i is marginal.

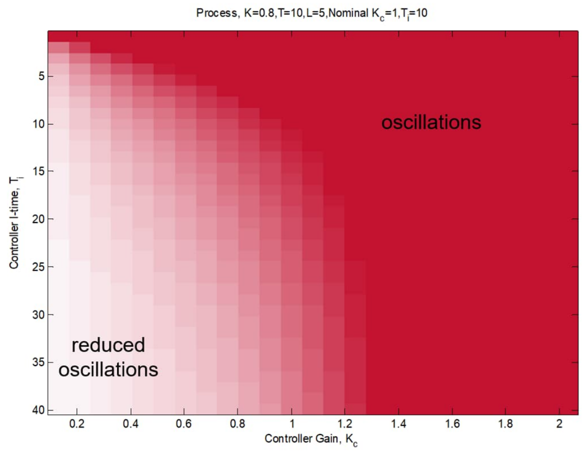


Figure 7. Tuning impact on the Flow loop with stick-slip. Here we can reduce valve travel by decreasing gain and increasing integral time.

6 Controller Tuning Potential and Targets

According to our experience, PID controller tuning usually means finding a good compromise between various performance and economic targets. With improved performance we mean assessments like average control error, variability, and oscillation significance. Cost variables are for example valve travel, valve wear and air consumption.

Typically, it is not possible to obtain improved performance and decreased costs at the same time. With tight aggressive tuning, we can commonly push control error down, with a cost of increased valve travel. On the contrary, selecting a modest tuning setting, we can reduce valve wear, usually with a cost of increased control error.

However, for loops oscillating due to valve problems, the good news is that we can usually expect both increased performance and reduced costs when tuning such loops. These relations are illustrated in Figure 8.

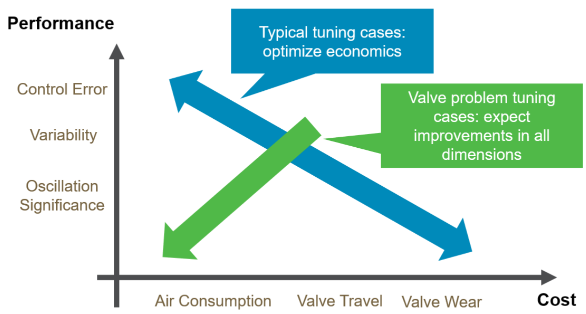
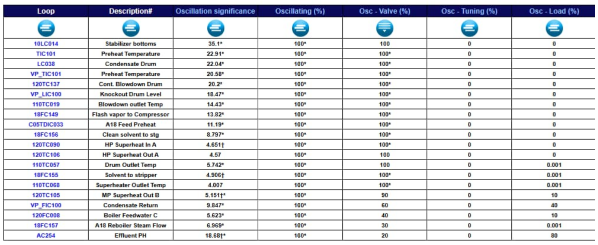


Figure 8. Overview of PID tuning targets.

7 Case Study

To test our idea of tuning loops with valve problems, we performed an industrial case study in a Finnish Pulp Mill. The plant uses PlantTriage (Valmet Automation, 2025) to continuously monitor and analyze 1500 control loops. To find loops that are oscillating due to valve problems, we used Problem Solver "Oscillating Loops" (illustrated in Figure 9) where the most interesting columns are Oscillation Significance (larger value, large influence of oscillations on process) and Osc-Valve (confidence in % that root cause of oscillations is valve). With PlantTriage, we identified around 10 loops, with a good possibility to improve control because of valves that were not performing optimally.

All these loops were classified as having backlash in the valve. Estimated backlash and process parameters (gain, time constant, dead time) were identified from trends (method not discussed in this paper) and new tuning recommendations were implemented on 5 level and 2 temperature control loops.



Loop	Description#	Oscillation significance	Oscillating (%)	Osc - Valve (%)	Osc - Tuning (%)	Osc - Load (%)
10LC014	Stabilizer bottoms	35.1*	100*	100	0	0
TIC101	Preheat Temperature	22.91*	100*	100*	0	0
LC038	Condensate Drum	22.04*	100*	100*	0	0
VP_TIC101	Preheat Temperature	20.58*	100*	100*	0	0
120TC137	Cont. Blowdown Drum	20.2*	100*	100*	0	0
VP_LIC100	Knockout Drum Level	18.47*	100*	100*	0	0
110TC019	Blowdown outlet Temp	14.43*	100*	100*	0	0
18FC149	Flash vapor to Compressor	13.82*	100*	100*	0	0
C05TDIC033	A18 Feed Preheat	11.19*	100*	100*	0	0
18FC156	Clean solvent to stg	8.797*	100*	100*	0	0
120TC090	HP Superheat In A	4.651†	100*	100*	0	0
120TC106	HP Superheat Out A	4.57	100*	100	0	0
110TC057	Drum Outlet Temp	5.742*	100*	100	0	0.001
18FC155	Solvent to stripper	4.906†	100*	100*	0	0.001
110TC068	Superheater Outlet Temp	4.007	100*	100*	0	0.001
120TC105	MP Superheat Out B	5.151†*	100*	90	0	10
VP_FIC100	Condensate Return	9.847*	100*	60	0	40
120FC008	Boiler Feedwater C	5.623*	100*	40	0	10
18FC157	A18 Reboiler Steam Flow	6.969*	100*	30	0	0.001
AC254	Effluent PH	18.68†*	100*	20	0	80

Figure 9. Example screenshot from Problem Solver "Oscillating Loops" of PlantTriage (loops are not from example case).

Figure 10 shows an example loop, where we see a clear improvement in loop performance.

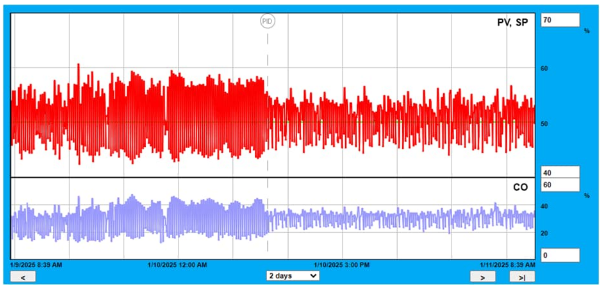


Figure 10. Example loop trends of a tuned control loop.

To estimate the impact of tuning changes, PlantTriage continuously calculates 80 assessments for each loop. Here we studied four PlantTriage assessments one week before, and one week after tuning changes: 1) Average Absolute Error, 2) Valve Travel, 3) Oscillation Significance, and 4) Variability, as shown in an example report in Figure 11 below.

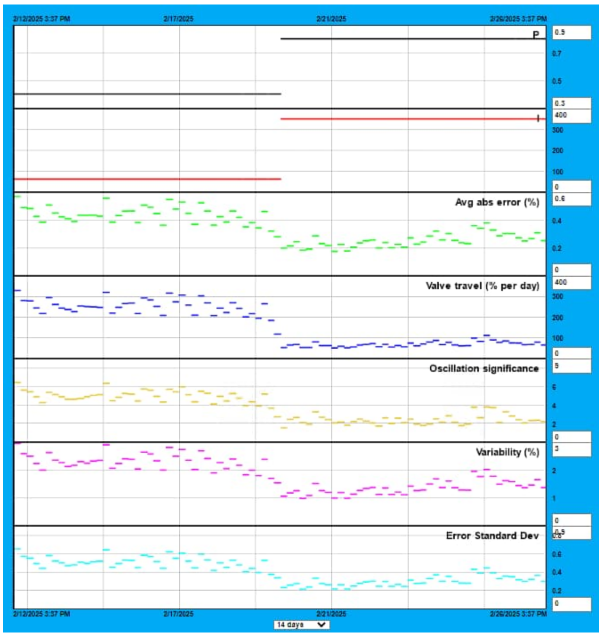


Figure 11. Example PlantTriage Tuning Report showing impact of tuning change on control loops assessments.

The results for the studied control loops are illustrated in Figure 12. We notice that, for most cases, we were able to improve performance in all assessments, except for loop 1, where changes were modest, and loop 3, where only valve travel was improved. For loop 3 we later noticed that the root cause of the oscillations was not in the valve, but in a neighbor loop.

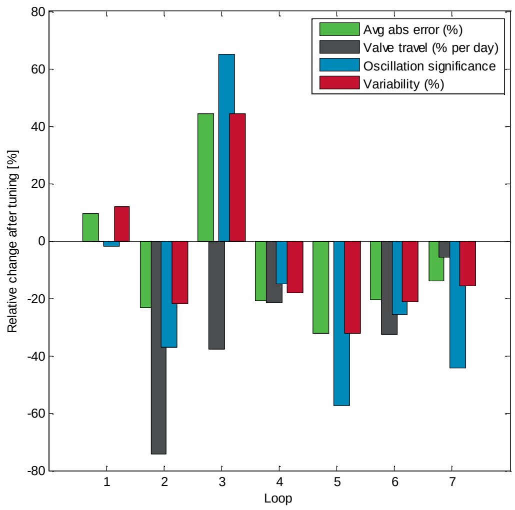


Figure 12. Results of tuning showing change of assessment for each loop after tuning.

These examples demonstrate that with problematic valves, there is usually a great potential to simultaneously reduce oscillations, control errors, and valve wear, as summarized in Figure 13 below.

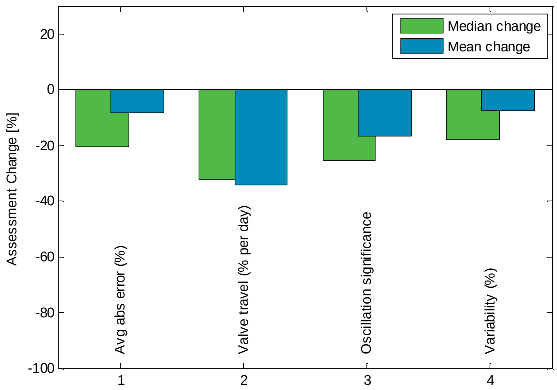


Figure 13. Average control performance change for all tuned loops.

8 Conclusions

We have studied impact of PI controller tuning on control loops with backlash or stick-slip in the valve.

For the stick-slip case, the results suggest that we should decrease controller gain, and increase integral time to reduce valve travel, and extend valve lifetime.

For the backlash case, the tuning rules (Eq. (6)) are very simple: it is important to ensure that integral time is large enough, and there is usually no need to detune gain despite of oscillations.

For loops with backlash, there is a huge potential to reduce oscillations and interactions, and to extend valve lifetime with proper tuning, primarily for loops with large time constants, typically level, pressure, and temperature control loops.

With simple tuning recommendations it is usually easy to improve control performance and reduce valve wear for loops with non-ideal valves. However, it might be difficult to find loops with valve problems if there are thousands of control loop to monitor in the plant. In such cases, good control loop performance monitoring tools that can pick oscillating control loops and determine root cause of oscillations to the valve, are crucial (Valmet Automation, 2025).

An industrial case study demonstrates that we were able to simultaneously minimize oscillations, variability, and to reduce valve travel for loops with valve backlash. In the case study we used PlantTriage, which made it is easy to find loops and valves that needed attention.

9 References

Atherton, D. P., Nonlinear Control Engineering, Van Nostrand Reinhold, 1982

Grimholt, C. and Skogestad, S.. Optimal PI-Control and Verification of the SIMC Tuning Rule. IFAC Conference on Advances in PID Control, PID'12, Brescia Italy. 2012.

Johansson K.H., Wahlberg B. and Jacobsen E.W. EL2620 Nonlinear Control. KTH, Lecture notes. 2012.

Kirmanen J., Niemelä I., Pyötsiä J., Simula M., Hauhia M., Riihilahti J. The Flow Control Manual,.4th ed. Metso Automation. 1997.

Valmet Flow Control. Neles™ NDX™ intelligent valve controller, standard model. Technical Bulletin. 2024.

Valmet Automation. Optimized performance throughout the plant's lifetime. PlantTriage brochure. 2025.