Lambda Tuning—the Universal Method for PID Controllers in Process Control

Lambda tuning gives non-oscillatory response with the response time (Lambda) required by the plant. Seven industrial examples show the relevance and simplicity of this method. Will Lambda tuning work in your process control loop?

by Mark T. Coughran

PID—Proportional+Integral+Derivative--is by far the most common feedback control algorithm in the process industries. Many control engineers are asked to choose the P, I, and D controller tuning parameters. Often we are faced with one or more of these six common challenges:

Process Challenge	**Requirement**	**Lambda (λ) Tuning Solution**
Oscillation with as-found tuning	First-order setpoint response or critically damped load response	Any $\lambda >> T_d$
Need minimum variability on PV	Fast response of control loop; shift variability to Output	$\lambda = 3*T_d$ (minimum robust λ)
Surge vessel to absorb variability; need minimum variability on Output	Slow response of liquid level control loop	λ_{LEVEL} as large as possible
Cascade configuration	Slave loop must respond faster than master loop	$\lambda_{MASTER} >> \lambda_{SLAVE}$
Physically coupled or interacting *processes*	Uncouple the *loop* dynamics	$\lambda_{LOOP\ B} >> \lambda_{LOOP\ A}$
Multiple streams into blending vessel	All inflows respond at same speed to inventory control	$\lambda_{FLOW\ A} = \lambda_{FLOW\ B} = \lambda_{FLOW\ N}$

Given these challenges, what is a systematic and practical way to find the optimal parameters? Don't confuse yourself with arcane statistics; use your knowledge of the plant. Start with the purpose of the loop, possible interactions with other loops, and the ability of the process to respond to the controller (the process dynamics). For example, there are practically no control loops in the process industries whose purpose is to oscillate. To comply with the production objectives of the plant, and to prevent interactions between loops, most loops need to respond in a certain amount of time. Learning which loops need to be fast and which need to be slow will make your tuning efforts more valuable to the plant. Finally, the process dynamics (MANUAL response) will limit how fast you can make the closed loop (AUTO) response.

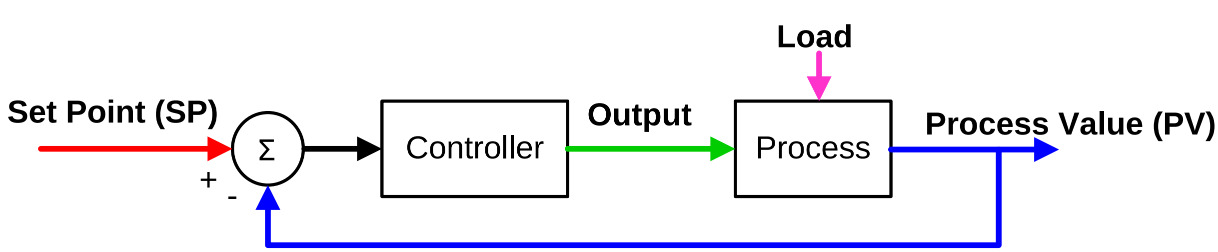


Figure 1. Basic feedback control loop.

Lambda tuning has proven successful in thousands of control loops covering the following process control applications:

- feedback control loops (Figure 1) in continuous and batch processes.
- PID controllers of all types--DCS, PLC, single-loop, pneumatic--from all manufacturers.
- physical processes including flow, pressure (liquids and gases), level (liquids and solids), temperature (heat exchange, mixing, reaction), and composition (density, pH, stack O_2, dissolved oxygen, etc.).
- process industries including chemicals, refining, oil & gas, power, life sciences, pulp & paper, metals & mining, and pipeline.
- the environments of brownfield plant optimization, greenfield plant startup, design and simulation of control systems, and education.

Lambda Tuning Concepts

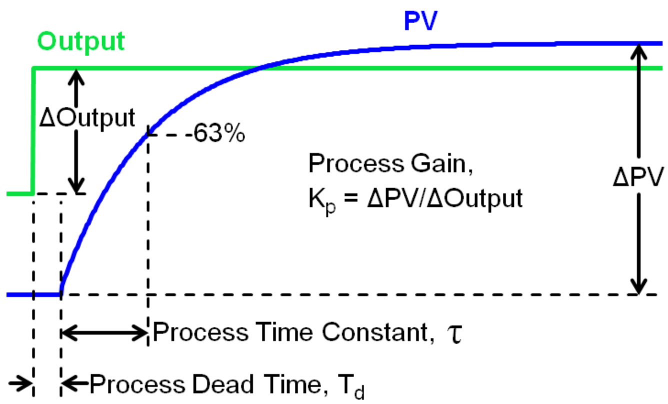
Lambda tuning is a model-based method related to Internal Model Control and Model Predictive Control. The math behind it uses pole-zero cancellation to achieve the desired closed loop response. However, to apply the method you need only simple arithmetic--as in Figure 2--if your process dynamics fit any of the following models:

a) First Order
b) Integrator
c) Integrator, First Order Lag
d) Integrator, First Order Lead
e) Integrator, Non-Minimum Phase
f) Second Order, Overdamped
g) Second Order, Underdamped
h) Second Order, Lead
i) Second Order, Lead with Overshoot
j) Second Order, Non-Minimum-Phase

Each process model includes dead time. Types a) and f)—j) are self-regulating; that is, for an output step, the PV eventually settles at a new value. The process dynamics model is typically identified from step testing in MANUAL mode (open loop). Step tests also help to identify the nonlinearities in the process response, such as dead band in control valves, which may be a greater problem than the as-found controller tuning.

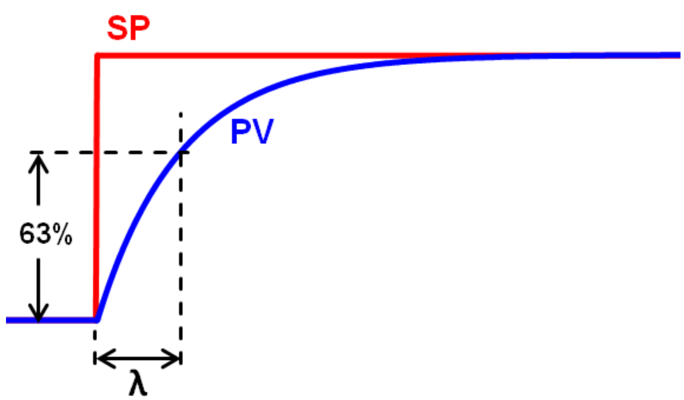
We assume the controller block in Figure 1 contains a PID algorithm. The process block includes the final control element or slave loop, the process to be controlled (chemistry, hydraulics, thermal energy, etc.) and the sensor/transmitter. Lambda tuning gives a non-oscillatory response to setpoint changes and load disturbances. You choose the response time (Lambda or λ) to fit the control strategy and the unit production objectives. Most of the processes in your plant will fit either the first order model or the integrator model.

a) **First-Order Process Dynamics:** if the process has the following self-regulating open loop response



then we define Lambda (λ) as the closed loop time constant after a setpoint step. Time constant has the familiar meaning of the time to reach 63% of the final value.

For simplicity, we show here the closed loop response with negligible dead time:



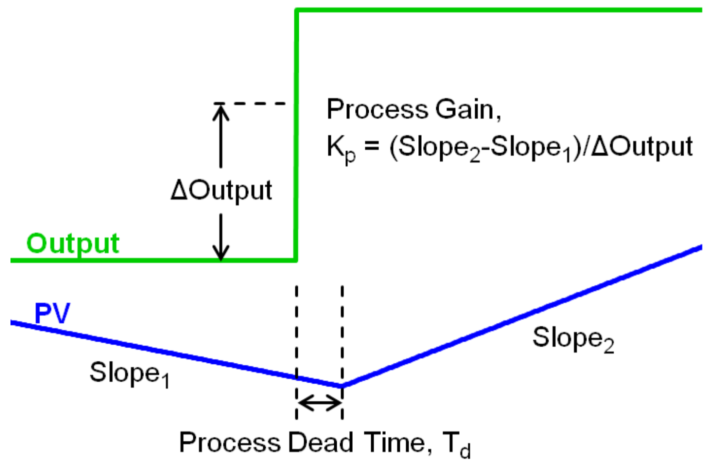
To accomplish this in the PID controller, we set

Proportional Gain = $\frac{\tau}{K_P(\lambda+T_d)}$

Integral Time = τ

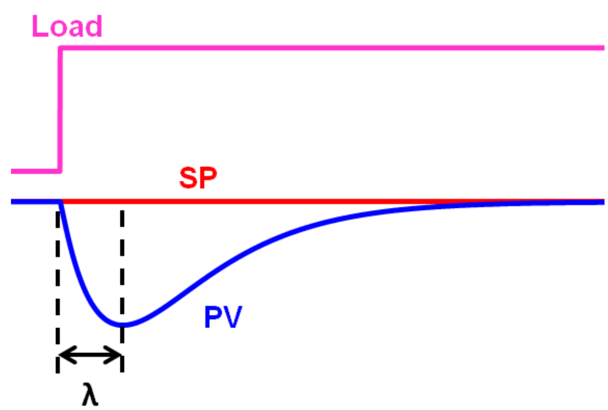
Derivative Time = 0 (none)

b) **Integrator Process Dynamics**: if the process has the following integrating open loop response



then we define a critically damped load response with Lambda (λ) equal to the arrest time.

For simplicity, we show here the closed loop response with negligible dead time:



To accomplish this in the PID controller, we set

Proportional Gain $= \frac{2\lambda+T_d}{K_P(\lambda+T_d)^2}$

Integral Time = $2\lambda+T_d$

Derivative Time = 0 (none)

Figure 2. Lambda tuning method for the two simplest and most common process responses. The process response, in particular the dead time T_d, limits how small you can make λ. For further explanation of the math, see the References.

The process models shown in Figure 2 are built into some control system tuning tools. The ideal tool would include process model identification, the arithmetic for Lambda tuning, recommendations for choice of Lambda, and predicted setpoint and load responses.

Process Plant Examples

Let's look at several examples from process plants. In each example, Lambda has a clear physical meaning. We begin with self-regulating process dynamics. Figure 3 shows a typical result for flow loops.

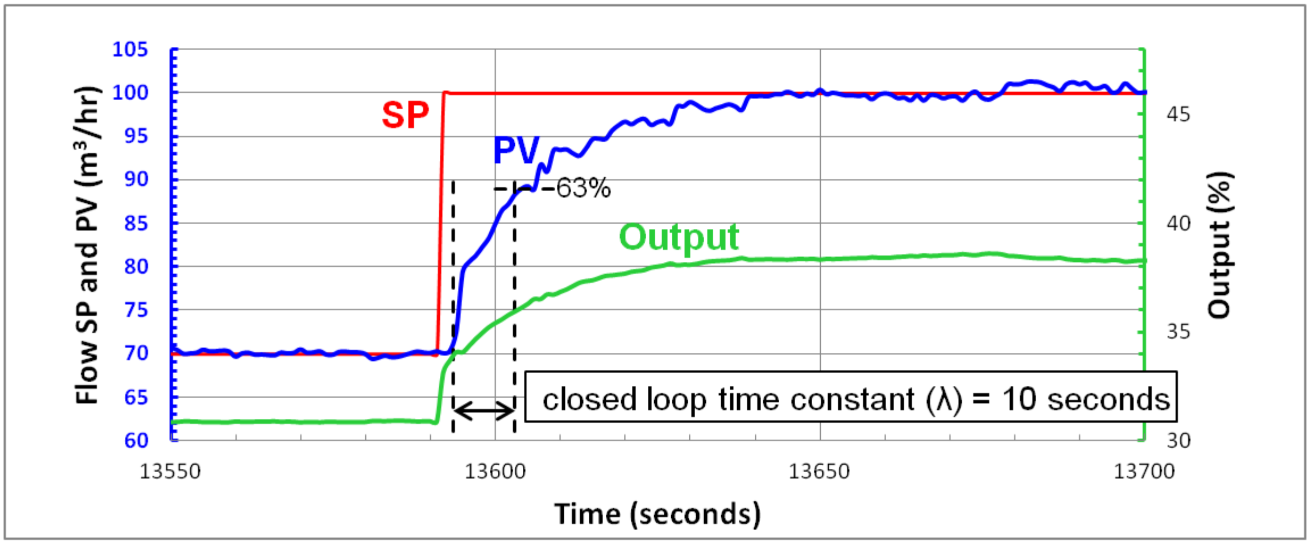


Figure 3. Closed loop flow rate control of Natural Gas Liquids through a control valve into a depropanizer column. The PID controller executes in a DCS. The process model is self-regulating first order plus dead time. The dead time (occurring both in open loop and closed loop) is mostly due to nonlinearity in the response of the control valve.

Robustness of the controller tuning takes into account that the process dynamics (process gain, dead time, and time constant) may change considerably at other process conditions. For robustness it is wise to choose Lambda equal to a generous multiple of the dead time. Note we chose $\lambda=3*T_d$ in the above case.

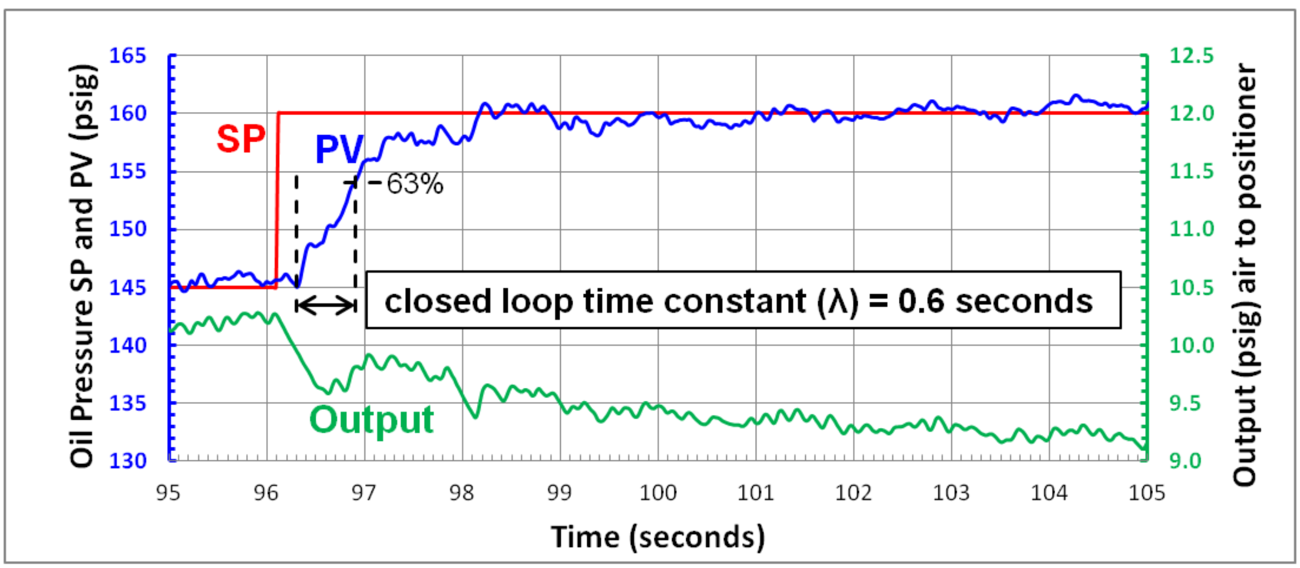


Figure 4. Pressure control of lubricating oil pumped from a reservoir to the propylene compressor of an olefins unit. Maintaining the oil pressure is critical to operation of the unit. The pressure is controlled by routing part of the flow back to the reservoir through a bypass control valve. The PID executes in a pneumatic controller, where the oil is connected directly to the controller sensing element and the output (3-15 psig) goes to a pneumatic positioner on the bypass valve.

This example shows that we can make the closed loop response very fast if the open loop *process* response is fast and the plant requires fast *loop* response. Note however that our choice of Lambda was again no smaller than $3*T_d$.

Integrating processes are often critical to the performance and profitability of the plant. For integrating processes, it is difficult to guess a combination of Proportional and Integral settings that will not cause oscillation. A systematic tuning method is needed to obtain both stability and performance. The first integrating process example is a level controller with no slave flow loop.

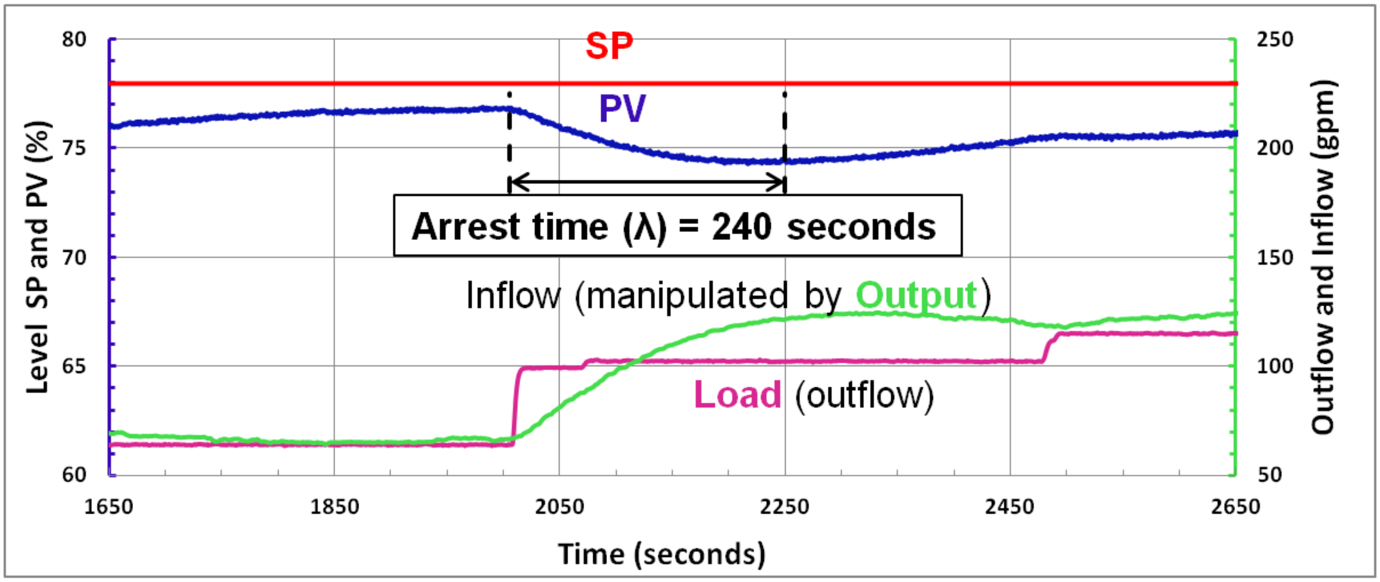


Figure 5. Level control in an oilfield produced water treatment tank. The PID executes in a PLC with output going to a variable speed pump on the inflow piping. The outflow is controlled by a separate pump which establishes the load on the level loop. The process model is integrator.

The as-found tuning caused large oscillations in AUTO, so the operator kept the level controller in MANUAL. For the data shown here with Lambda tuning, the level PV initially is returning to SP after a load disturbance; hence inflow slightly greater than outflow. Then a step occurs on the load flow (outflow); note the inflow responds with a smooth increase. The arrest time or Lambda is the time for the PV to reach maximum deviation and begin returning to SP. After reaching steady state, there will be no oscillation.

We chose Lambda = 240 to keep the level PV away from the alarm limits for large disturbances. For applications where tight level control is needed, a smaller Lambda value can be chosen. In boiler drum level control, for example, the PV alarms are quite close to SP.

The next integrating process example is from a different process industry and a much smaller vessel.

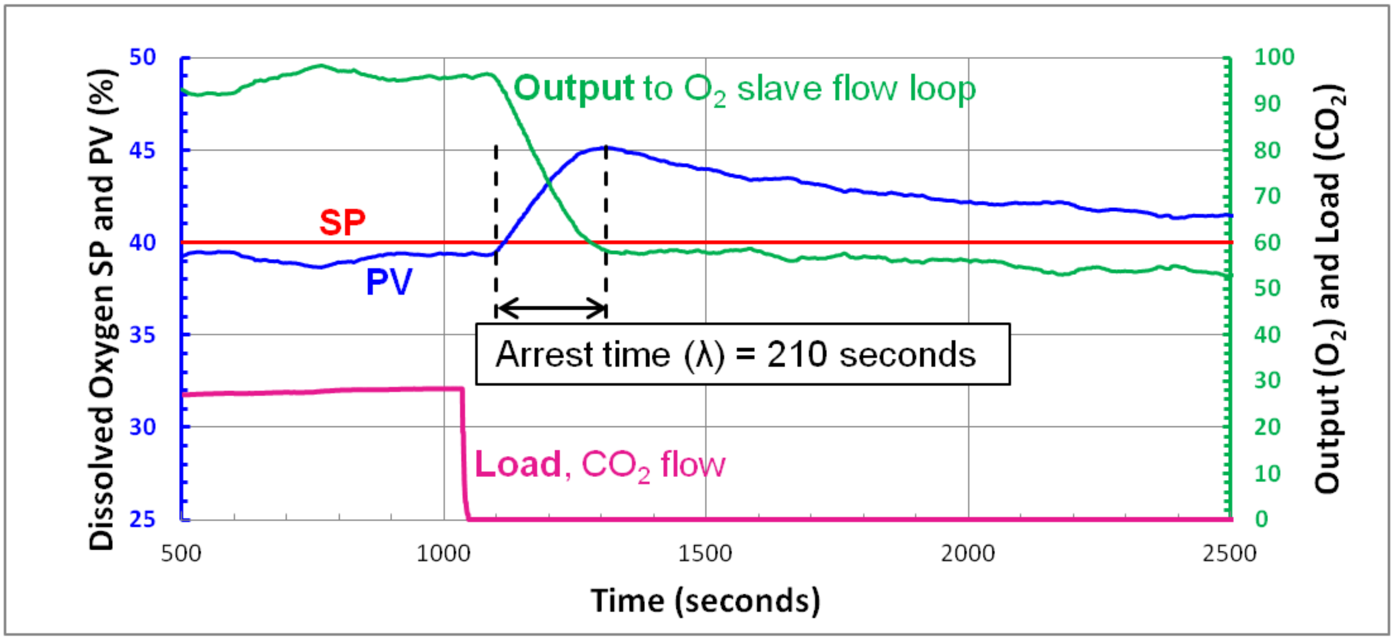


Figure 6. Dissolved Oxygen (DO) control in a 2-liter bioreactor. The PV is measured as % saturation of the solution. Output of the DO controller goes to a slave flow loop that sparges oxygen (O_2) into the bioreactor and is tuned for Lambda = 20 seconds. CO_2 flows into the reactor to control the pH; however, it also tends to displace the O_2, making CO_2 the load variable. The process model (measured in MANUAL) is integrator. The PID controller executes in a DCS.

The chosen Lambda will maintain the DO adequately close to SP as the culture evolves--and the oxygen demand varies--in this batch application. It also complies with the cascade rule, $\lambda_{MASTER} >> \lambda_{SLAVE}$.

So far, for integrating processes, we have only examined the load response. If the controller is any of the default standard PID types, if integral action is used in the controller, and if the process integrates, then a setpoint step will cause an overshoot with any tuning method.

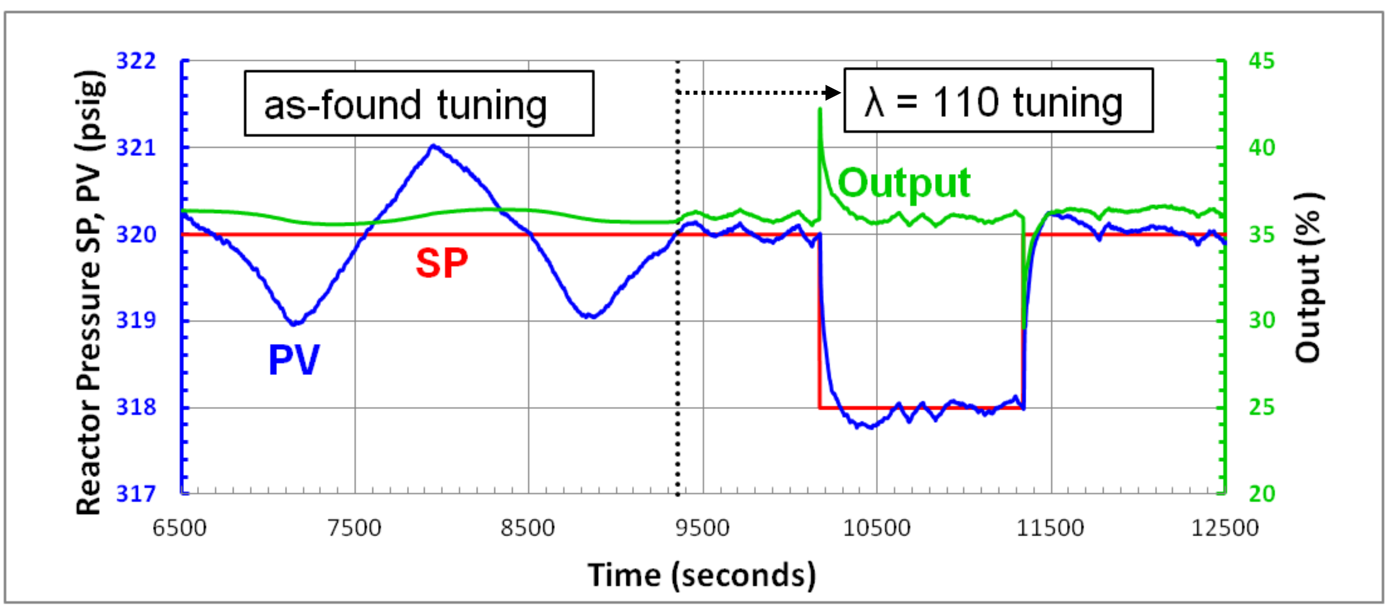


Figure 7. Reactor pressure control in the gasoline hydrotreater unit of a refinery. The PID controller executes in a DCS with standard structure, and output goes to a control valve on the outlet of the reactor. The process model (measured in MANUAL mode) is integrator.

The as-found tuning caused a ±1 psig cycle on the PV. The sharp corners on the cycle indicate the tuning cycle is complicated by dead band in the control valve. Closer examination shows the dead band is approximately 0.7% of controller output. Applying Lambda tuning with λ = 110 seconds eliminates the large tuning cycle; we are left with the small limit cycle caused by dead band. To test the stability of the loop with Lambda tuning, the operators could not make a step in load. However, they could conveniently step the setpoint. The PV crosses SP in approximately 110 seconds and makes a small overshoot before returning to the nonlinear limit cycle.

If SP overshoot is a concern to the plant, it can be easily prevented in the modern controller, either by choosing an alternate PID structure or by adding a setpoint filter. On the other hand, for many integrating processes—including the four examples shown here--the setpoint is rarely changed.

The final graphical example shows a well-tuned surge tank level controller. Your key contribution to this loop is to realize that the control needs to be slow! Then Lambda tuning provides a direct and simple way to achieve this.

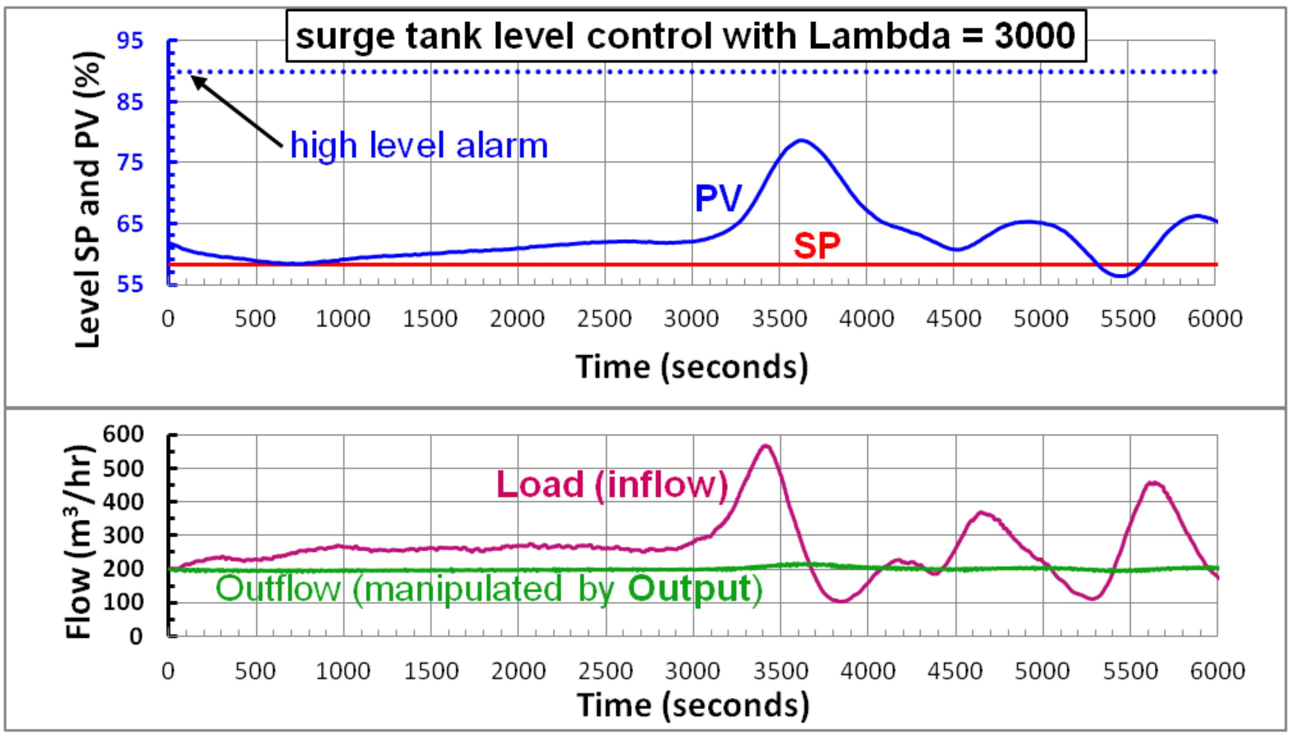


Figure 8. Level control of Natural Gas Liquids in the surge tank that supplies a depropanizer column. The level controller output cascades to a slave flow loop on the surge tank outlet, which we have already seen in Figure 3 with Lambda = 10. The load is the inflow to the tank. The process model is integrator. The PID control executes in a DCS.

The as-found tuning was fast and cyclic; in contrast, Lambda tuning gives no systematic oscillation unless the load oscillates. In this case, we chose a large Lambda to absorb variability; i.e., to minimize the variations on the manipulated flow. Lambda = 3000 is the slowest tuning that will keep the PV away from alarms for the worst-case flow change. Note the steady outflow despite large variations on the inflow that occurred during a plant startup.

The examples with cascade control pointed out the need to prevent interaction between the master and slave loops. Lambda tuning is the only method that provides explicitly for this requirement; we simply choose $\lambda_{MASTER} >> \lambda_{SLAVE}$. Another common type of physical interaction that needs loop decoupling involves multiple control valves piped in series. For example, a chemical plant had process water with a pressure letdown from 2500 to 600 psig, a second letdown from 600 to 150 psig, followed by a flow loop. To get all the loops in AUTO with good system performance, we chose the respective Lambda values at 6 seconds, 30 seconds, and 80 seconds.

Summary

We have illustrated Lambda tuning in several different process plants with various types of PID controllers and various control objectives. In each case, we achieved a smooth response with the appropriate response time (Lambda or λ)—ranging from 0.6 to 3000 seconds. The method accounts for the ability of the process to respond to the controller (process dynamics), the purpose of the loop, and interactions with other loops.

To our initial question, "Will Lambda tuning work in your process control loop?", you should now be able to answer "yes". The most important user requirement is to choose the response time λ according to the unit objectives and the process constraints. The math is simple; training and tools are available. But if you want an oscillatory response or an arbitrary response time, you will need to find a different method.

References

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