# PID Controllers Explained

by
**Jacques Smuts, Ph.D.** - Plant Automation Services, Inc.

PID controllers - named after the Proportional, Integral and Derivative control actions they perform - are used in the vast majority of automatic process control applications in industry today. PID controllers are responsible for regulating flow, temperature, pressure, level, and a host of other industrial process variables. This tutorial reviews the application of PID controllers, explains the P, I and D control modes and units, and highlights the three controller structures used in industrial controllers.

## Manual control

Without automatic controllers, all regulation tasks will have to be done manually. For example: To keep constant the temperature of water discharged from an industrial gas-fired heater, an operator has to watch a temperature gauge and adjust a gas control valve accordingly (Figure 1). If the water temperature becomes too high, the operator has to close the gas control valve a bit - just enough to bring the temperature back to the desired value. If the water becomes too cold, he has to open the valve again.

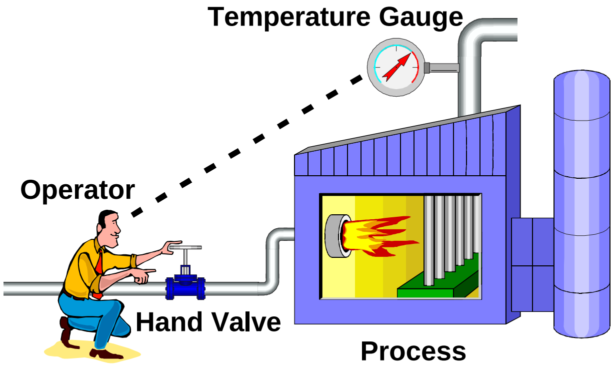

**Figure 1. Manual Control**

## Automatic control

To relieve our operator from the tedious task of manual control, we automate the controls - i.e. we install a PID controller (Figure 2). The controller has a Set Point (SP) that the operator can adjust to the desired temperature. We also have to automate the control valve by installing an actuator (and perhaps a positioner) so that the Controller's Output (CO) can change the valve's position. And finally, we'll provide the controller with an indication of the temperature or Process Variable (PV) by installing a temperature transmitter. The PV and CO are mostly transmitted via 4 - 20mA signals.

So, when everything is up and running, our PID controller compares the process variable to its set point and then calculates the difference between the two signals, also called the Error (E).

Then, based on the error, a few adjustable settings and its internal structure (described below), the controller calculates an output that positions the control valve. If the actual temperature is above its set point, the controller will reduce the valve position and vice versa.

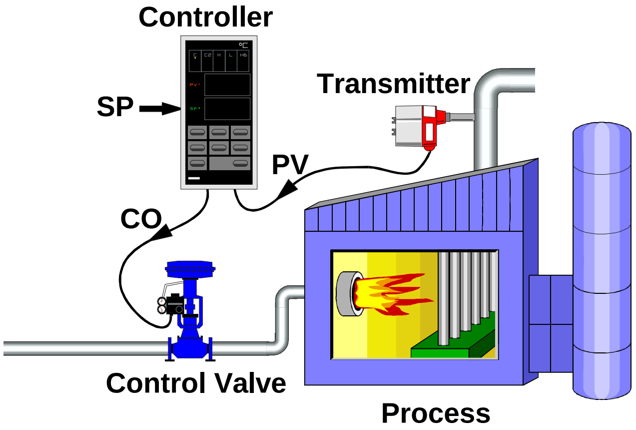

**Figure 2. Automatic Control**

## P, I and D Control Modes

As we said above, a PID controller has proportional, integral and derivative control modes. These modes each react differently to the error, and also, the degree of control action is adjustable for each mode.

### Proportional Control

The proportional control mode changes the controller output in proportion to the error (Figure 3). The adjustable setting here is called the Controller Gain (Kc), sometimes also referred to as a PID controller's P-setting or its proportional setting.

The control action is proportional to both the controller gain and the error. A higher controller gain will increase the amount of output action and so will a larger error.

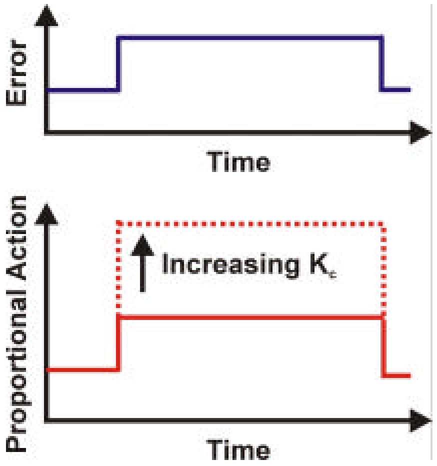

**Figure 3. Proportional Control Action**

Although most controllers use controller gain (Kc) as the proportional setting, some controllers use Proportional Band

Reprinted with permission from *Canadian Process Equipment & Control News*, February 2002

(PB), which is expressed in percent. Table 1 shows the relationship between Kc and PB.

| Controller Gain (Kc) | Proportional Band (PB) % |
|---|---|
| 0.1 | 1000 |
| 0.2 | 500 |
| 0.5 | 200 |
| 1 | 100 |
| 2 | 50 |
| 5 | 20 |
| 10 | 10 |

$$PB = \frac{100\%}{K_c}$$

**Table 1. Relationship between Kc and PB**

The use of proportional control alone has a large drawback - Offset. Offset is a sustained error that cannot be eliminated by proportional control alone. For example, let's consider controlling the water level in the tank in Figure 4 with a proportional-only controller.

As long as the flow out of the tank remains constant, the level (which is our process variable in this case) will remain at its set point.

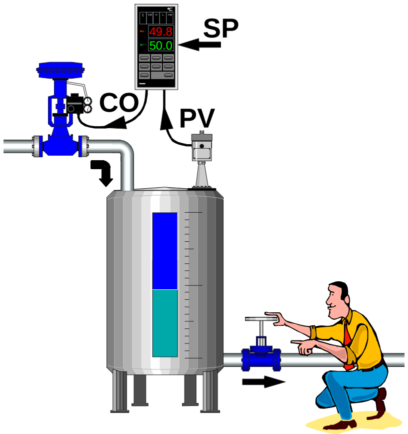

**Figure 4. Level control**

But, if the operator should increase the flow out of the tank, the tank level will begin to decrease due to the imbalance between inflow and outflow. While the tank level decreases the error increases and our proportional controller increases the controller output proportional to this error (Figure 5). Consequently, the valve controlling the flow into the tank opens wider and more water flows into the tank.

As the level continues to decrease, the valve continues to open until it gets to a point where the inflow matches the outflow. At this point the tank level remains constant, and so does the error. Then, because the error remains constant our P-controller will keep its output constant and the control valve will hold its position. The system now remains at balance with the tank level remaining below its set point. This residual error is called Offset.

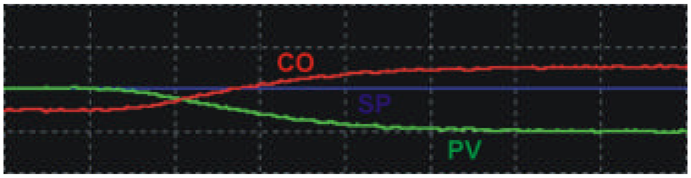

**Figure 5. P-Control**

With our P-controller the offset will remain until the operator manually applies a bias to the controller's output to remove the offset. It is said that the operator has to manually "Reset" the controller. Or… we can add Integral action to our controller.

### Integral Control

The concept of manual reset as described above led to the development of automatic reset or Integral Control, as we know it today. The integral control mode of a controller produces a long-term corrective change in controller output, driving the error or offset to zero.

Integral action appears as a ramp of which the slope is determined by the size of the error, the controller gain and the Integral Time (Ti), also called the I-setting of the controller (Figure 6).

$$I\ Action = K_c \times \frac{1}{T_i} \int E \cdot dt$$

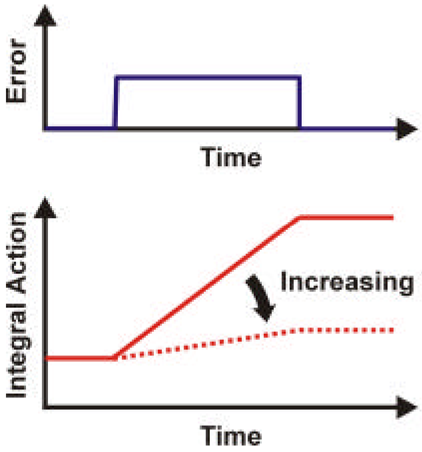

**Figure 6. Integral ControlAction**

Most controllers use integral time in minutes as the unit for integral control, but some others use integral time in seconds, Integral Gain in Repeats / Minute or Repeats / Second. Table 2 compares the different integral units.

| Integral Time | | Integral Gain | |
|---|---|---|---|
| Minutes | Seconds | Rep / Minute | Rep / Second |
| 0.05 | 3 | 20 | 0.333 |
| 0.1 | 6 | 10 | 0.167 |
| 0.2 | 12 | 5 | 0.0833 |
| 0.5 | 30 | 2 | 0.0333 |
| 1 | 60 | 1 | 0.0167 |
| 2 | 120 | 0.5 | 0.00833 |
| 5 | 300 | 0.2 | 0.00333 |
| 10 | 600 | 0.1 | 0.00167 |
| 20 | 1200 | 0.05 | 0.00083 |

**Table 2. Integral Control Units**

Integral control eliminates offset. Figure 7 shows the same level control setup as before, but this time we have used a PI controller. A PI controller simply adds together the output of the P and I modes of the controller. The integral action raises the controller output far enough to bring the level back to its set point.

Reprinted with permission from *Canadian Process Equipment & Control News*, February 2002

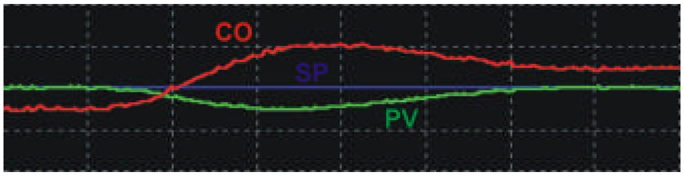

**Figure 7. PI-Control**

### Derivative Control

The third control action in a PID controller is derivative. Derivative control is rarely used in controllers. It is very sensitive to measurement noise and it makes tuning very difficult if trial and error methods are applied. Nevertheless, derivative control can make a control loop respond faster and with less overshoot.

The derivative control mode produces an output based on the rate of change of the error (Figure 8). Derivative action is sometimes called Rate. Its action is dependent on the rate of change (or slope) of the error. It has an adjustable setting called Derivative Time (Td), which is the D-setting of the controller.

$$D\,Action = K_c \times T_d \frac{dE}{dt}$$

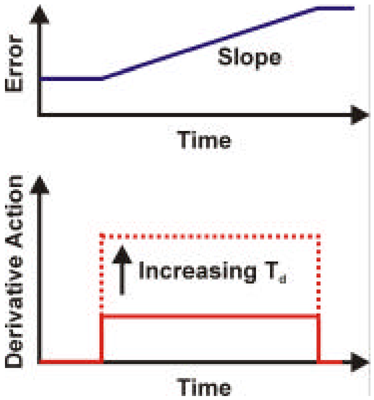

**Figure 8. Derivative ControlAction**

Two units are used for the derivative setting of a controller: minutes and seconds.

Derivative control appears to have predictive or anticipative capabilities. Technically this is not true, but PID control does provide more control action sooner than possible with P or PI control. To see this, compare the initial controller response of Figure 9 (PID control) with that in Figure 7 (PI control). Also note how derivative control reduces the time it takes for the level to return to its set point. Also note that with derivative control the controller output appears noisier. This is due to the derivative control mode's sensitivity to measurement noise.

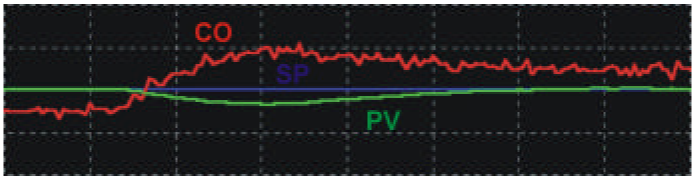

**Figure 9. PID control**

## Controller Structures

Controller manufacturers integrate the P, I and D-modes into three different arrangements or controller structures. These are called Series, Ideal and Parallel controller structures. Some controller manufacturers allow you to choose between different controller structures as a configuration option in the controller software.

### Series

This very popular controller structure is also called the Classical, Real or Interacting structure. The original pneumatic and electronic controllers had this structure and we still find it in most PLCs and DCSs today. Most of the controller tuning rules are based on this controller structure.

$$CO = K_c \left[ E + \frac{1}{T_i} \int E \cdot dt \right] \times \left[ 1 + T_d \frac{d\,\cdot}{dt} \right]$$

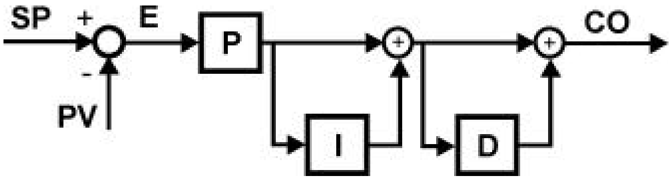

**Figure 10. Series controller structure.**

### Ideal

Also called the Non-Interacting, Standard or ISA structure, this controller structure was popularized with digital control systems. If no derivative is used (i.e. Td = 0), the series and ideal controller structures become identical.

$$CO = K_c \left[ E + \frac{1}{T_i} \int E \cdot dt + T_d \frac{dE}{dt} \right]$$

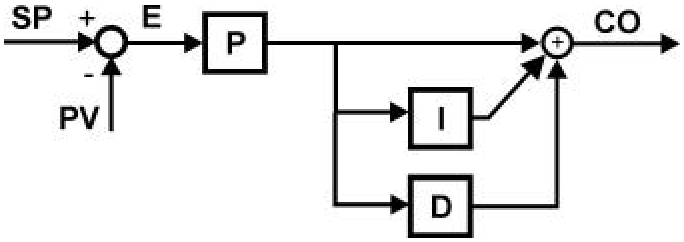

**Figure 11. Ideal controller structure.**

### Parallel

Academic-type textbooks generally use the parallel form of PID controller, but it is also used in some DCSs and PLCs. This structure is simple to understand, but really difficult to tune. The reason is that it has no controller gain, but has a proportional gain instead. Tuning should be done by adjusting all the settings simultaneously. Try not to use this structure if possible.

$$CO = K_p \times E + K_i \int E \cdot dt + K_d \frac{dE}{dt}$$

Reprinted with permission from *Canadian Process Equipment & Control News*, February 2002

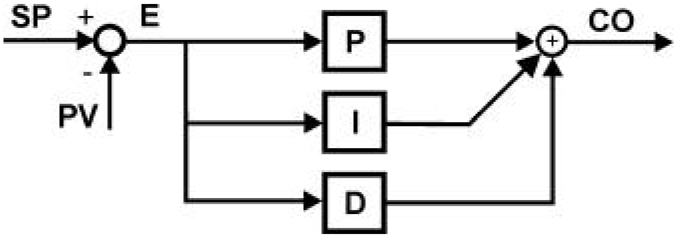

**Figure 12. Parallel controller structure.**

### Parameter Conversion

It is mathematically possible to convert PID parameters between different controller structures to have the controllers behave identically. The only restriction here is that Ti must be at least 4 times Td to convert ideal or parallel controller parameters into series controller parameters.

## Conclusion

With its proportional, integral and derivative modes, the PID controller is the most popular method of control by a great margin. If properly tuned, the three control modes complement each other in the control effort.

It is important to note, however, that there are quite a few different and conflicting options used for P, I and D units and for controller structure. The method of tuning must be adjusted to suite the controller's functional characteristics.

***About the author***

*Jacques Smuts, Ph.D. is the business director of Control.Precision at Plant Automation Services (Houston, TX). He has many years of experience in the design and optimization of industrial control systems and has consulted for clients such as Abitibi, Domtar, Hunstman, Imperial Oil - ESSO, Labatt, Nova Chemicals, Petro-Canada, Stelco, Sunoco and Weyerhaeuser.*

*Plant Automation Services (PAS) is a leading supplier of people and asset solutions to the processing industries worldwide.*

*For more information contact PAS at 281-286-6565 or visit www.pas.com.*

---

*Plant Automation Services (PAS), Inc. of Houston Texas, is a leading supplier of people and asset management solutions to the processing industries worldwide. Software solutions include DOC3000, AMO Suite, Pro Display, and TuneWizard. Services include alarm management optimization projects, system configuration and integration, and the optimization of process control performance.*

*Control.Precision is one of the strategic business units at PAS and provides process control services, control loop optimization software, and process control training. Services include the optimization of regulatory and advanced control systems, control strategy design and improvement, control loop performance diagnostics, and controller tuning.*

*TuneWizard is a leading control loop and valve performance assessment and optimization software product. It provides data acquisition, process diagnostics, controller tuning, control loop simulation, and report writing in one user-friendly Windows application. The software improves control loop performance using a holistic approach - analyzing the loop for critical control performance factors such as tuning parameters, process non-linearity, and control valve performance.*

Plant Automation Services, Inc. 16055 Space Center Blvd, Suite 600, Houston, TX 77062
Phone: 281-286-6565 Fax: 281-286-6767 www.pas.com

Reprinted with permission from *Canadian Process Equipment & Control News*, February 2002