TRANE®

Applications Guide

PID Control

in Tracer Controllers

CNT-APG002-EN

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Contents

Chapter 1

Overview of PID control

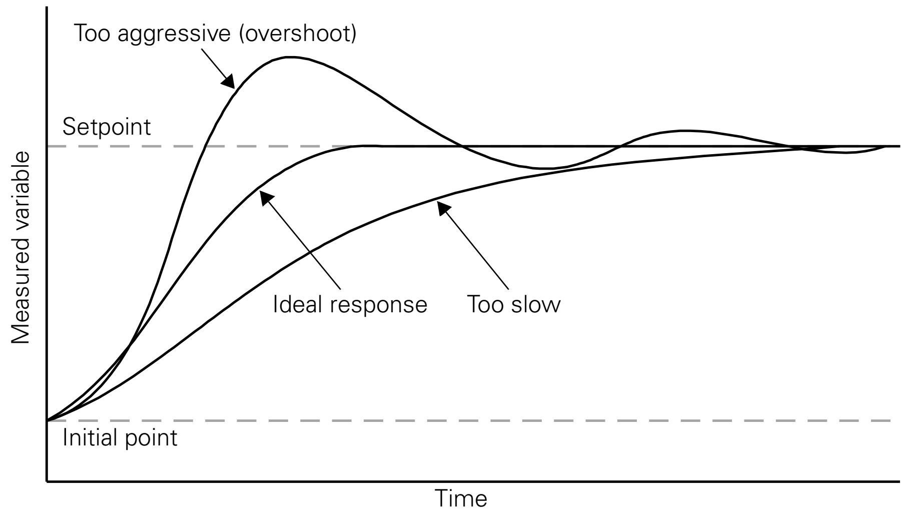
This guide will help you set up, tune, and troubleshoot proportional, integral, derivative (PID) control loops used in Tracer controllers. These controllers include the Tracer MP580/581, AH540/541, and MP501 controllers. This chapter provides an overview of PID control.

What PID loops do

A PID loop is an automatic control system that calculates how far a measured variable is from its setpoint and, usually, controls an output to move the measured variable toward the setpoint. The loop performs proportional, integral, and derivative (PID) calculations to determine how aggressively to change the output.

The goal of PID control is to reach a setpoint as quickly as possible without overshooting the setpoint or destabilizing the system. If the system is too aggressive, it will overshoot the setpoint as shown in Figure 1. If it is not aggressive enough, the time to reach the setpoint will be unacceptably slow.

Figure 1: The effects of PID aggressiveness



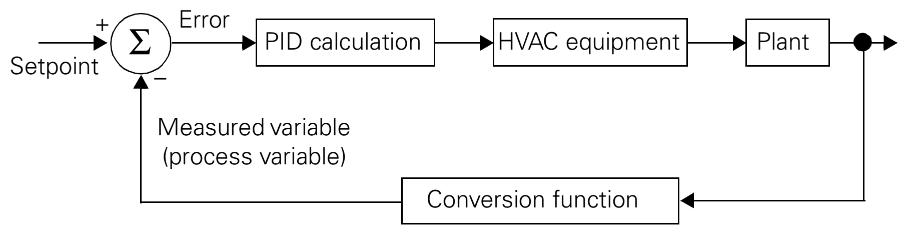
In the heating, ventilating, and air-conditioning (HVAC) industry, PID loops are used to control modulating devices such as valves and dampers. Some common applications include:

- Temperature control
- Humidity control
- Duct static pressure control
- Staging applications

How PID loops work

A PID loop performs proportional, integral, and derivative calculations to calculate system output. Figure 2 illustrates how a typical PID loop works. The sigma (Σ) symbol indicates that a sum is being performed. The plus (+) symbol indicates addition, and the minus (–) symbol indicates subtraction.

Figure 2: PID loop



In an HVAC system, the controller uses a PID calculation to change the output of mechanical equipment to maintain some setpoint. For example, if a space is too cold, the PID calculation controls an actuator to open a hot-water valve some amount, increasing the discharge-air temperature to heat the space.

In classic PID control systems, the controller reacts to a comparison between a setpoint and a measured variable (also called the process variable). The setpoint is often a user-defined setting, such as a room temperature setpoint. The measured variable is the controlled element, in this case the current room temperature.

The difference between the setpoint and the measured variable is called the error, which is the value used to calculate system output. The error is defined as:

Error = setpoint – measured variable

For example, if a room temperature setpoint is 75°F (23.9°C) and the actual temperature is 65°F (18.3°C), then the error is 10°F (5.6°C).

The PID calculation uses the error to calculate an output that moves the measured variable toward the setpoint as quickly as possible without overshooting the setpoint. The output typically controls the position of an actuator over a range of 0% to 100%. In the example above, an actuator would open a hot-water valve some amount to increase the room temperature by 10°F (5.6°C).

The plant is the physical system, such as a room or a duct, that contains the controlled element (the measured variable). The conversion function converts the measured variable to the same units as the setpoint. For example, a thermistor measures space temperature in terms of resistance, which is then converted to a temperature by the analog input of the controller.

PID calculations

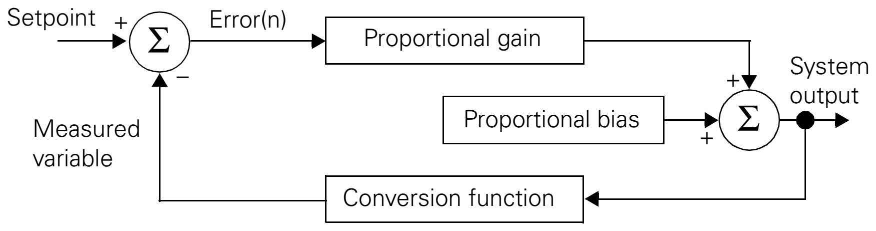
A PID loop performs three calculations: the proportional calculation, the integral calculation, and the derivative calculation. These calculations are independent of each other but are combined to determine the response of the controller to the error.

Proportional calculation

The proportional calculation responds to how far the measured variable is from the setpoint. The larger the error, the larger the output of the calculation. The proportional calculation has a much stronger effect on the result of the PID calculation than either the integral or derivative calculations. It determines the responsiveness (or aggressiveness) of a control system. Though some systems use only proportional control, most Trane controllers use a combination of proportional and integral control.

Proportional-only control (a method of control that does not use the integral and derivative contributions) is traditionally used in pneumatic controllers. It may be used in staging applications because it can be simpler to manage than full PID control. The programmable control module (PCM) and the universal programmable control module (UPCM) assume proportional-only control when the integral and derivative gains are set to zero. Tracer MP580/581 controllers have a unique setting for proportional-only control. Figure 3 illustrates proportional-only control.

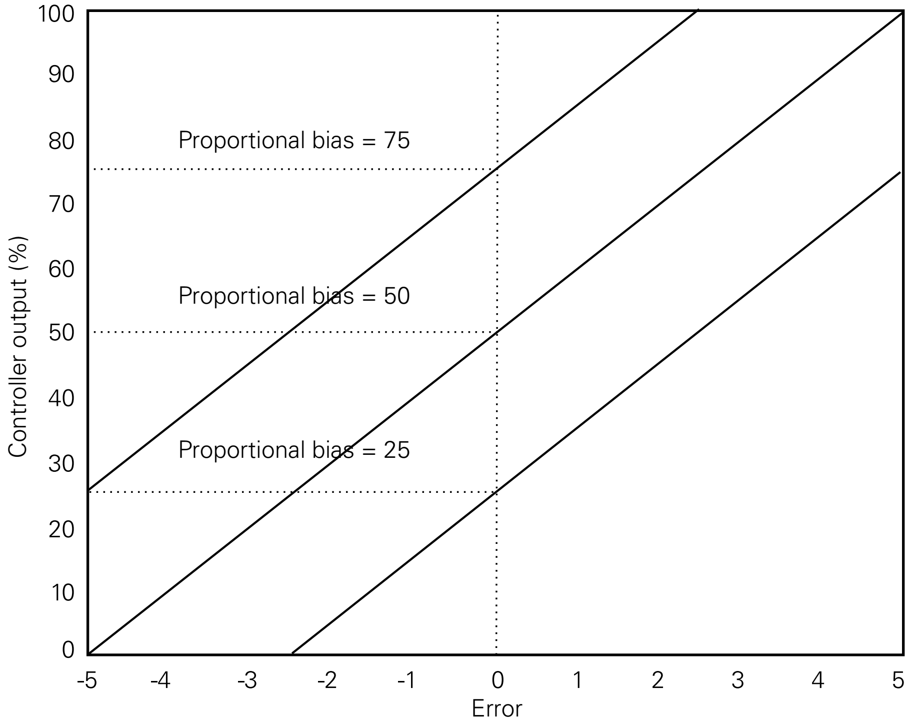
Figure 3: Proportional-only control



One difference between proportional-only control and classic PID control is the use of proportional bias. The proportional bias becomes the output when the error is zero. Thus, you can use the proportional bias to calibrate a controller to some known output. Figure 4 on page 4 shows the effect of proportional bias on PID output. Notice that when the error is zero, the output is equal to the proportional bias.

Note:
The integral calculation automates the process of setting proportional bias. In proportional-only control, the proportional bias lets you decide what the output should be when the error is zero; in PID control, the integral calculation maintains the current output when the error is zero (see "Integral calculation" on page 4).

Figure 4: The effects of proportional bias on system output

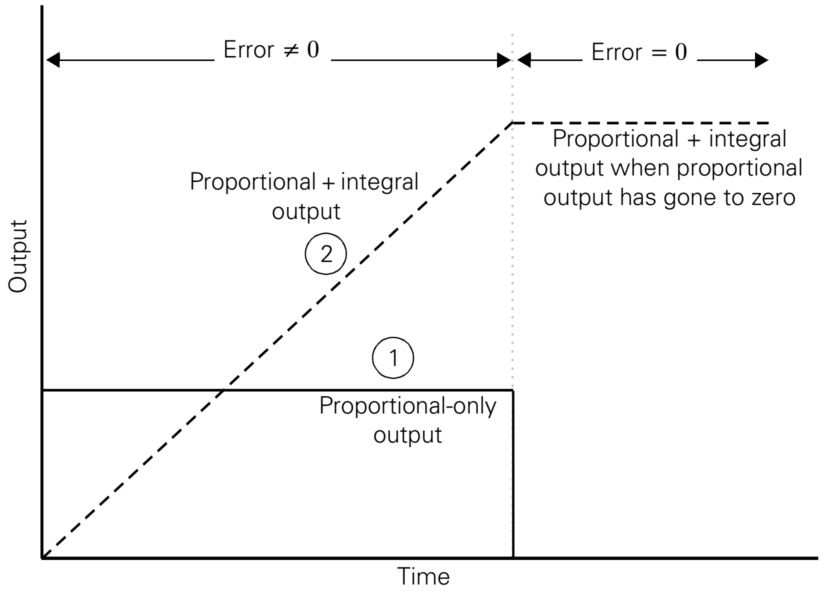


Integral calculation

The integral calculation responds to the length of time the measured variable is not at setpoint. The longer the measured variable is not at setpoint, the larger the output of the integral calculation.

The integral calculation uses the sum of past errors to maintain an output when the error is zero. Line 1 in Figure 5 on page 5 shows that with proportional-only control, when the error becomes zero, the PID output also goes to zero (assuming a proportional bias of zero). Line 2 shows the integral output added to the proportional output. Because the integral calculation is the sum of past errors, the output remains steady rather than dropping to zero when the error is zero. The benefit of this is that the integral calculation keeps the output at an appropriate level to maintain an error of zero.

Figure 5: Integral output added to proportional output



The value of the integral calculation can build up over time (because it is the sum of all past errors), and this built-up value must be overcome before the system can change direction. This prevents the controller from over-reacting to minor changes, but can potentially slow down the response.

One drawback to integral control is the problem of integral windup. Integral windup occurs when the sum of the past errors is too great to overcome. This can happen when the HVAC equipment does not have enough power to reach the setpoint; the integral windup only increases as the equipment struggles to reach the setpoint. To minimize the problem of integral windup, Trane controllers use a method of PID control known as the velocity model, which is described in “Velocity model” on page 7.

Derivative calculation

The derivative calculation responds to the change in error. In other words, it responds to how quickly the measured variable is approaching setpoint. The derivative calculation can be used to smooth an actuator motion or cause an actuator to react faster.

However, derivative control has several disadvantages:

- It can react to noise in the input signal.
- Setting derivative control requires balancing between two extremes; too much derivative gain and the system becomes unstable, too little and the derivative gain has almost no effect.
- The lag in derivative control makes tuning difficult.
- Large error deadbands, common in HVAC applications, render derivative control ineffective.

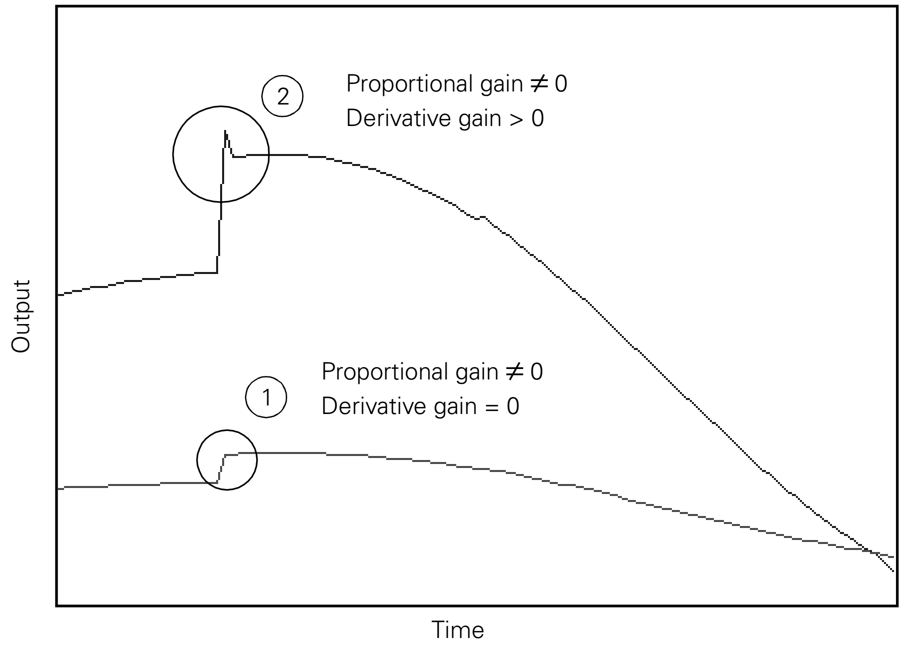
Because of these disadvantages, derivative control is rarely used in HVAC applications (with the exception of steam valve controllers and static pressure control).

Derivative control can affect the output in two ways: it slows the output if the derivative gain is negative and increases the output if the derivative gain is positive.

Slowing (or smoothing) the actuator motion, sometimes known as dynamic braking, can help if there are many quick changes in the input signal. For example, a robot arm moves quickly in mid-motion, but the derivative calculation slows it down at the end of the motion.

The opposite effect occurs when the derivative gain is positive. The output reacts faster to a change in error, resulting in a steeper climb or descent to setpoint. The circled areas in Figure 6 illustrate this effect. Line 1 shows the error without a derivative gain. Line 2 shows the error with a positive derivative gain. The circled sections show what happens during a rapid change in error. Note the spike in line 2 as the system recovers from the effect of derivative control during a sharp change in error. The spike indicates a forceful actuator motion, which is useful for applications such as controlling steam valves.

Figure 6: The effect of positive derivative gain

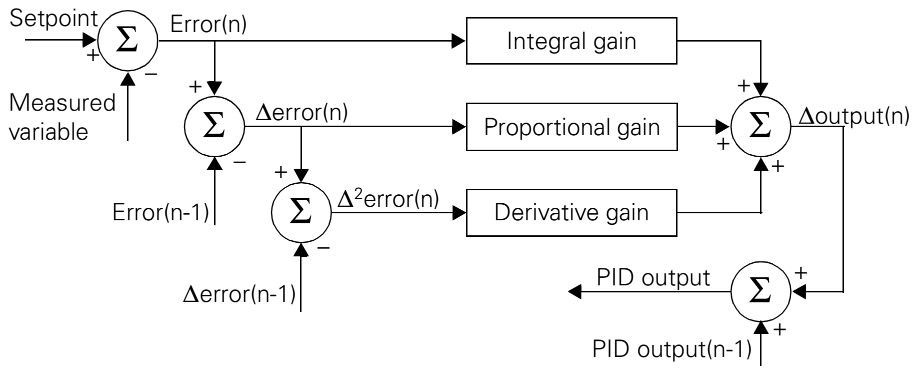


Velocity model

Trane controllers use a type of PID control known as the velocity model. The velocity model minimizes the problem of integral windup, which occurs when the sum of past errors in the integral calculation is too great to allow the controller to change the output at one of the extremes (see “Integral calculation” on page 4).

The velocity model, illustrated in Figure 7, gets its name from the fact that the proportional gain affects the change in error (or error velocity) instead of the error, as in a classic PID model. In the velocity model, the error is multiplied by the integral gain, and the change in error is multiplied by the proportional gain. When the error gets close to zero, the change in error gets close to zero as well. So both the integral and proportional gains are multiplied by a number close to zero. This forces the output of the PID calculation to stop changing when the error becomes zero, minimizing (but not eliminating) integral windup.

Figure 7: Velocity model



Chapter 2

PID settings

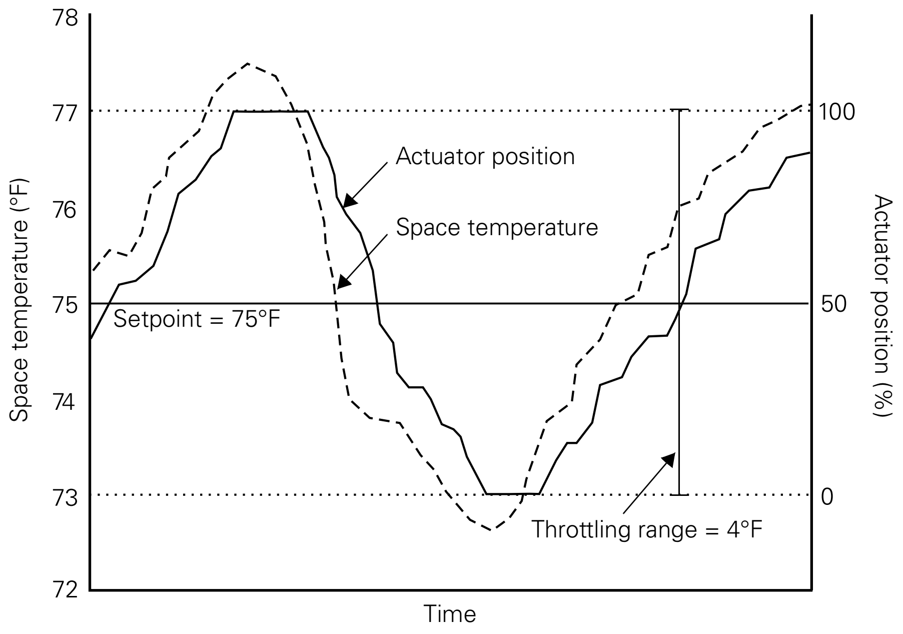
This chapter describes some of the key variables used to set up and tune PID loops. The variables discussed here are:

- Throttling range
- Gain
- Sampling frequency
- Action
- Error deadband

Throttling range

The throttling range is the amount of error it takes to move the output of a system from its minimum to its maximum setting. For example, a throttling range of 4°F (2.2°C) means that a controller fully opens or closes an actuator when the error is ±2°F (1.1°C) or greater, as illustrated in Figure 8. Note how the controller response (actuator position) lags behind the space temperature.

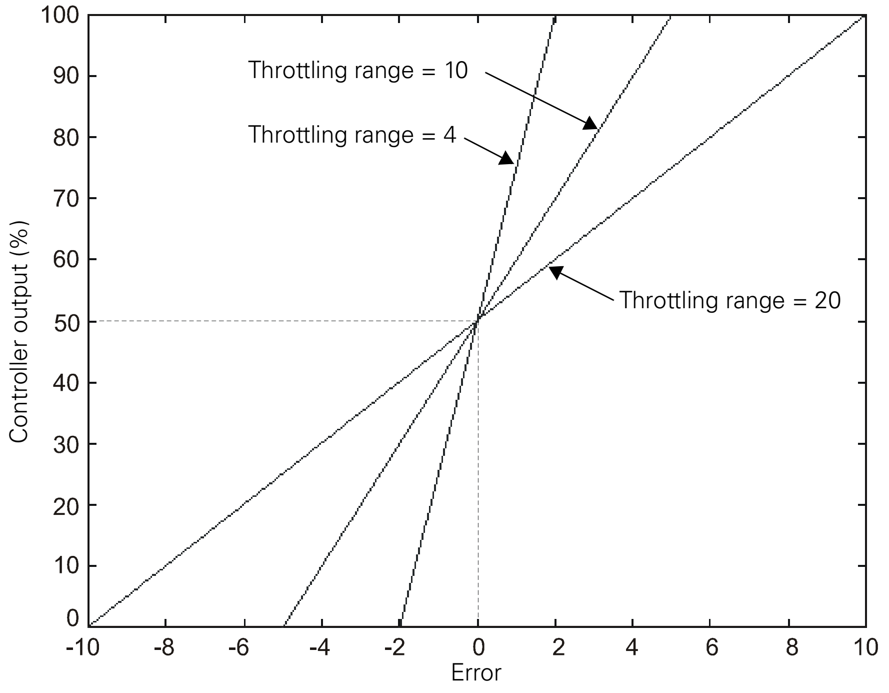
Figure 8: Throttling range



The throttling range determines the responsiveness of a control system to disturbances. The smaller the throttling range, the more responsive the control. You cannot directly program the throttling range in Tracer controllers; rather, the throttling range is used to calculate the gains.

Figure 9 shows that as the throttling range increases, the potential error becomes larger. When the output is at 0% or 100%, the error is equal to one-half of the throttling range. For example, with a 10° throttling range, the potential error is 5° from the setpoint (though the error could exceed 5°).

Figure 9: Throttling range and error with proportional bias = 50



Gains

Gains, which are calculated from the throttling range, determine how fast a measured variable moves toward the setpoint. The larger the gains, the more aggressive the response. The proportional, integral, and derivative calculations each have an associated gain value. The error, the sum of past errors, and the change in error are multiplied by their associated gains to determine the impact that each has on the output.

Calculating the gains

Table 1 shows recommended initial values for the proportional and integral gains for several applications. Most applications do not require a derivative contribution, so the derivative gain is not shown. We recommend using a ratio of 4:1 between the proportional and integral gains, so the proportional gain should be four times as large as the integral gain. You may need to modify the values shown in Table 1 when tuning a PID loop, but try to maintain the 4:1 ratio.

Table 1: Starting gain values for applications

Application	Output	Throttling range	Proportional gain	Integral gain
Discharge-air cooling	Valve position 0–100%	20.0°F (11.1°C)	4.0 (8.0)	1.0 (2.0)
Discharge-air heating	Valve position 0–100%	40.0°F (22.2°C)	2.0 (4.0)	0.5 (1.0)
Space temperature	Discharge setpoint 50–100°F (10–37.8°C)	2.0°F (1.1°C)	20.0 (20.0)	5.0 (5.0)
Duct static pressure	Inlet guide vane or variable-frequency drive (VFD) position 0–100%	2.0 in. wc (0.5 kPa)	40.0 (160)	10.0 (40.0)
Building static pressure	Inlet guide vane or variable-frequency drive (VFD) position 0–100%	20.0 in. wc (5.0 kPa)	4.0 (8.0)	1.0 (2.0)
Discharge-air cooling	Electric/pneumatic 5.0–15.0 psi (34–103 kPa)	20.0°F (11.1°C)	0.4 (4.0)	0.1 (1.0)

You can also calculate proportional and integral gains using the following calculations:

$$\text{Proportional gain} = \frac{0.80 \times \text{output range}}{\text{throttling range}}$$

$$\text{Integral gain} = \frac{0.20 \times \text{output range}}{\text{throttling range}}$$

The proportional gain is scaled by a factor of 0.80, so it contributes 80% of the final output. The integral gain contributes 20% of the final output.

Example

In a duct static pressure system, an actuator can move the inlet guide vanes of an air handler from 0–100%, so the output range is 100. We want a throttling range of 2.0 in. wc (so a change in pressure of 2.0 in. wc or more will drive the output from 0–100% or vice versa). The calculations look like this:

$$\text{Proportional gain} = \frac{0.80 \times \text{output range}}{\text{throttling range}} = \frac{0.80 \times 100}{2.0 \text{ in. wc}} = 40$$

$$\text{Integral gain} = \frac{0.20 \times \text{output range}}{\text{throttling range}} = \frac{0.20 \times 100}{2.0 \text{ in. wc}} = 10$$

So based on the desired throttling range of 2.0 in. wc, the initial proportional gain is 40 and the integral gain is 10.

Sampling frequency

The sampling frequency is the rate at which the input signal is sampled and the PID calculations are performed. Using the right sampling frequency is vital to achieving a responsive and stable system. Problems can arise when the sampling frequency is too slow or too fast in comparison to time lags in the system.

Sampling too slowly can cause an effect called aliasing in which not enough data is sampled to form an accurate picture of changes in the measured variable. The system may miss important information and reach the setpoint slowly or not at all.

Figure 10 and Figure 11 show how aliasing can affect system response. In Figure 10 the sampling frequency is too slow. Because of this, many of the changes in duct static pressure are missed. In Figure 11 the sampling frequency is fast enough that the changes in static pressure are tracked accurately.

Figure 10: Sampling too slowly

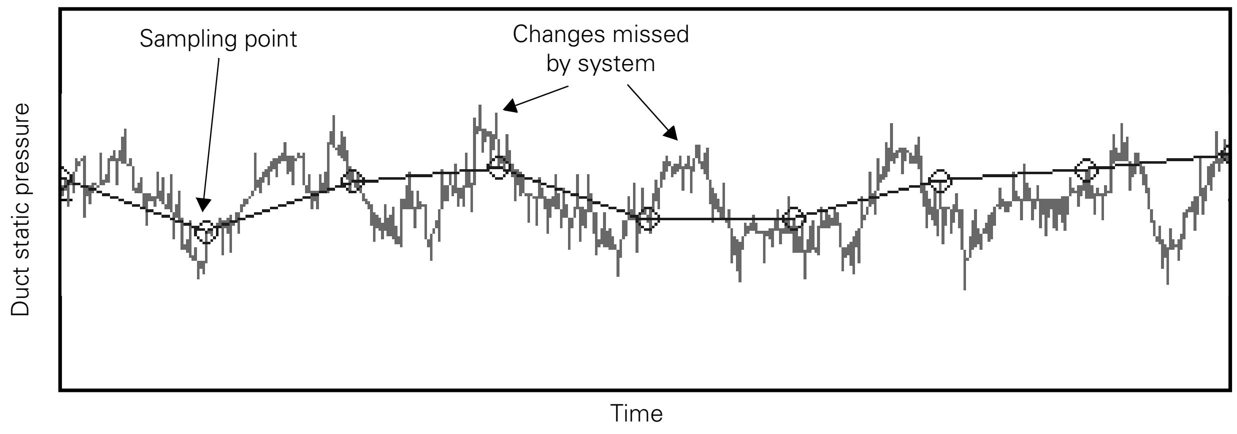
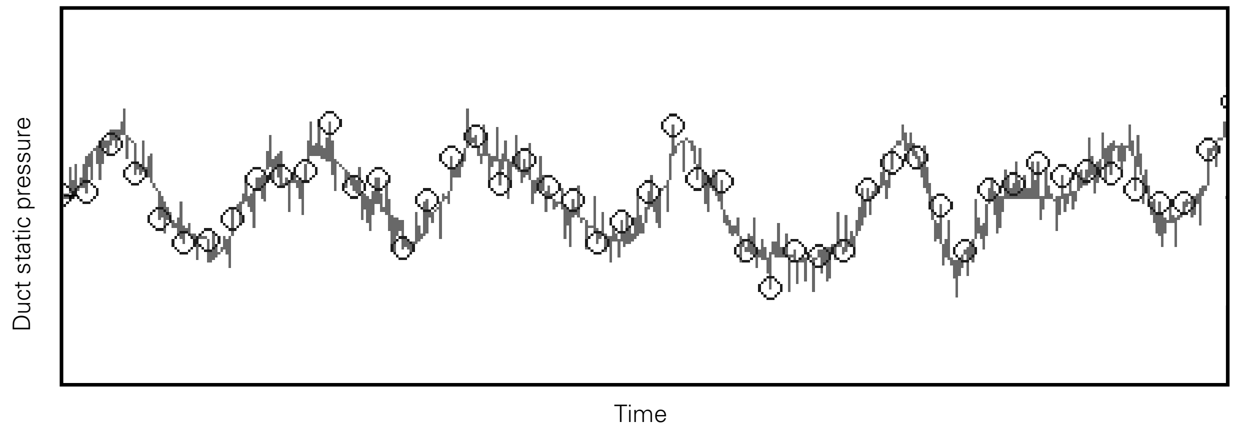


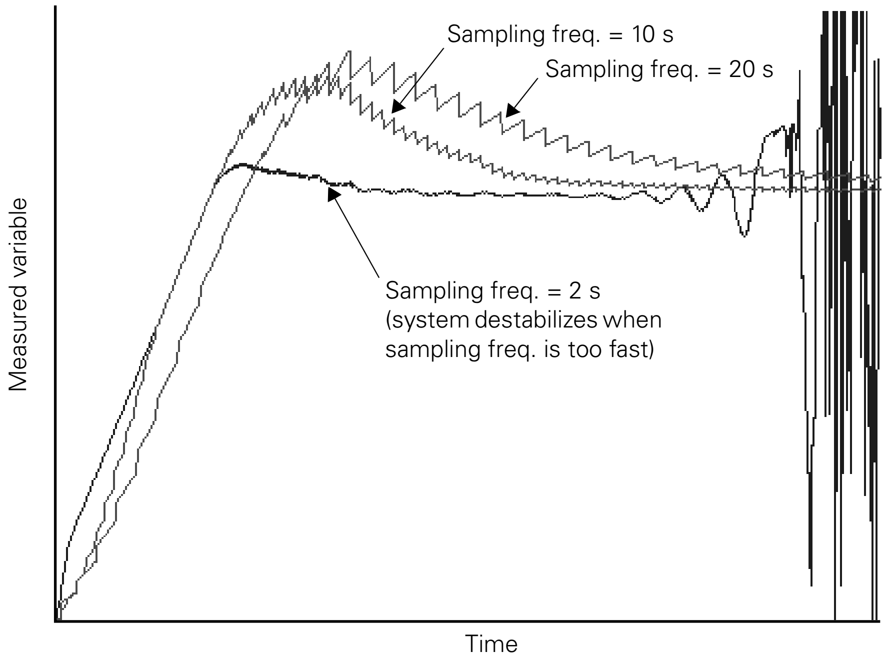
Figure 11: Sampling at the correct rate



Problems also arise from sampling too quickly. Some systems have naturally slow response times, such as when measuring room temperature. Slow response times can also be caused by equipment lags. Since PID loops respond to error and changes in error over time, if the measured variable changes slowly, then the error will remain constant for an extended period of time. If the measured variable is sampled repeatedly during this time, the proportional output remains about the same, but the integral output becomes larger (since it is the sum of past errors). When the control system does respond, the response is out of proportion to the reality of the situation, which can destabilize the system. The control system should always wait to process the result of a change before making another change.

Figure 12 shows the measured variable when sampling frequencies are too fast, acceptable, and barely acceptable. When the sampling frequency is too fast (2 seconds), the measured variable begins to oscillate and finally destabilizes because the PID loop output drives the actuator to extremes. When the sampling frequency is slowed to either 10 or 20 seconds, the system remains stable once setpoint is reached.

Figure 12: System stability with different sampling frequencies



Calculating the sampling frequency

PID loops are carried out by programs, such as process control language (PCL) programs and Tracer graphical programming (TGP) programs. Since the PID calculation occurs when the program executes, the sampling frequency and the program execution frequency are generally the same.

Note:
Tracer controllers have different approaches to using the sampling frequency. For Tracer MP580/581 controllers, the sampling frequency can be a multiple of the program frequency. The Tracer AH540 controller has a pre-determined sampling frequency. The Tracer MP501 controller has a setting for the sampling frequency.

Table 2 shows recommended program execution frequencies for common applications. These are good initial values, but it may take some trial and error to find the best frequency.

Table 2: Recommended initial sampling frequencies

Application	Suggested execution frequency
Duct static pressure	5 seconds
Building static pressure	120 seconds
Discharge-air temperature	10 seconds
Space temperature (typical comfort zone)	60 seconds
Space temperature (high air change zone)	30 seconds
Duct humidity	10 seconds
Space humidity	30–60 seconds

You can also manually calculate the sampling frequency.

To calculate the sampling frequency:

1. Manually control the analog output to 0%.

   For example, control a heating valve closed.
2. Record the measured variable when it stabilizes.

   The temperature stabilizes at 70°F (21°C).
3. Manually control the analog output to 50% or 100%.

   Control the output to 100% (completely opening the heating valve).
4. Record the measured variable when it stabilizes.

   The temperature stabilizes at 120°F (49°C)
5. Subtract the measured variable determined in step 2 from the measured variable determined in step 4. This is the change in the measured variable.

   120 – 70 = 50°F (49 – 21 = 28°C).

6. Calculate two-thirds (66%) of the change in measured variable determined in step 4. Add this value to the initial temperature to determine at what point two-thirds of the total change occurs.

   In the example, 0.66 × 50°F = 33°F, so two thirds of the total change occurs at 70°F + 33°F = 103°F (0.66 × 28°C = 18°C; 21 + 18 = 39°C).

7. Again, set the analog output to 0% and allow the measured variable to stabilize.

   The measured variable stabilizes at 70°F (21°C).

8. Control the output to the value used in step 3 and record the time it takes to reach the two-thirds point determined in step 6. This is the system time constant.

   The time it takes to reach 103°F (39°C) is 2.5 minutes (150 seconds).

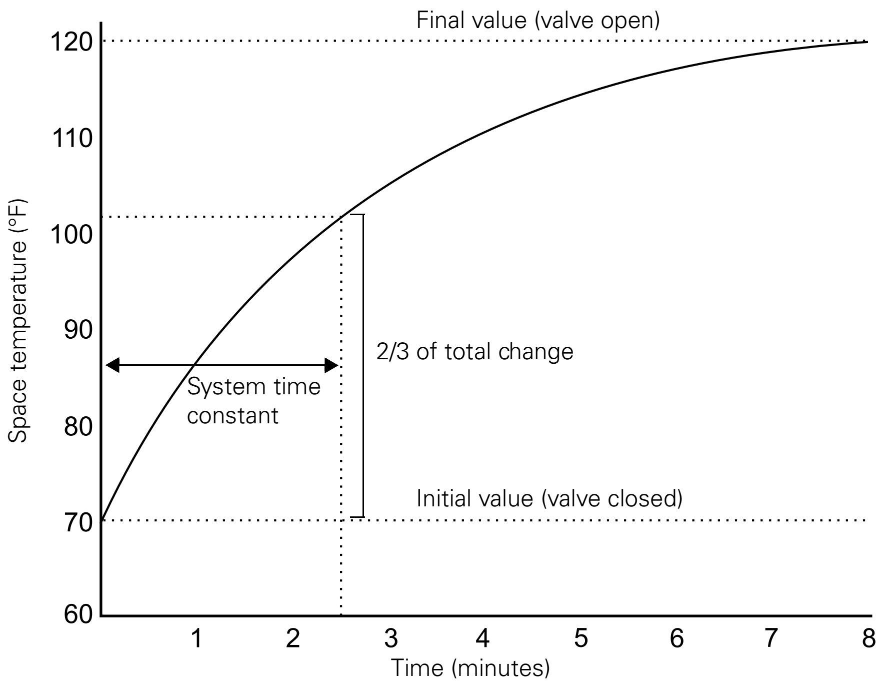
9. Divide the system time constant by 10 to determine the initial sampling frequency.

   150 seconds ÷ 10 = 15 seconds.

Note:
The system time constant is the time it takes to reach 63.21% of the difference between the start point and the end point. However, two-thirds (66%) is accurate enough for most purposes.

Figure 13 illustrates the procedure described above.

Figure 13: Determining the system time constant



Example

In this scenario, we want to find the sampling frequency for a PID loop controlling a heating application.

1. Fully close the output.
2. The stabilized temperature is 60°F (16°C).
3. Fully open the output.
4. The stabilized temperature is 105°F (41°C).
5. The change in temperature is 105°F – 60°F = 45°F (41 – 16 = 25°C).
6. Two-thirds of the change in measured variable is 0.66 × 45°F = 30°F, so two-thirds of the total change has occurred when the temperature is 60°F + 30°F = 90°F (0.66 × 25°C = 17°C; 16 + 17 = 33°C).
7. Close the output. The temperature stabilizes.
8. Fully open the output. The time to reach 90°F (33°C) is 54 seconds (so the system time constant is 54 seconds).
9. Divide the system time constant by ten, resulting in 54 ÷ 10 = 5.4. The best initial sampling frequency is 5 seconds.

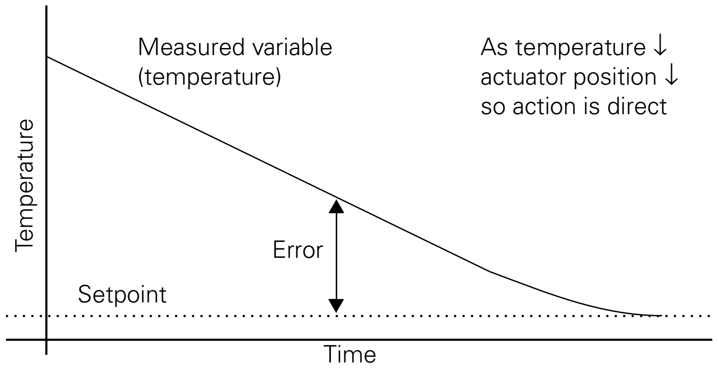
Action

The action of a PID loop determines how it reacts to a change in the measured variable (such as a room temperature). A controller using direct action increases the output when the measured variable increases. A controller using reverse action decreases the output when the measured variable increases.

Direct action

Figure 14 shows the temperature when a system is cooling a space. When the error is large and the PID output is at 100%, the actuator and valve combination are fully open. As the measured variable (room temperature) decreases, the error becomes smaller, and the controller closes the valve to reduce or stop cooling. Because the PID output and measured variable move in the same direction (both decreasing), the loop is direct acting.

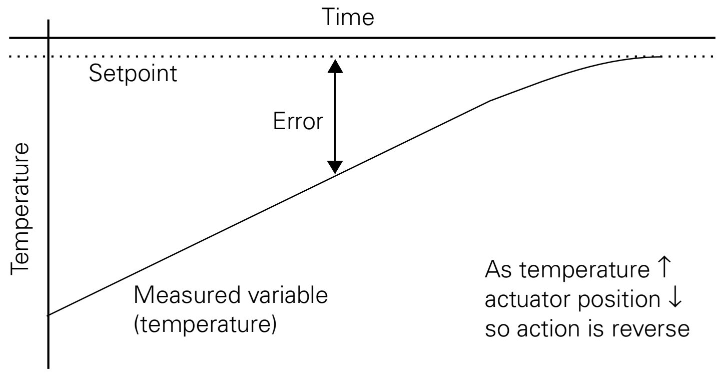
Figure 14: Cooling a space



Reverse action

Figure 15 shows the temperature when a system is heating a space. When the error is large and the PID output is at 100%, the actuator and valve combination are fully open. When the measured variable (room temperature) increases, reducing the error, the controller closes the valve to reduce heating. Because the PID output and measured variable move in opposite directions, the loop is reverse acting.

Figure 15: Heating a space



Determining the action

Table 3 shows the action settings for several applications. These settings are a good starting place for most applications.

Table 3: Action settings

Application	Output	Actuator setting at 100% PID output	Direct or reverse acting
Discharge-air cooling	Valve position 0–100%	Completely open*	Direct
Discharge-air heating	Valve position 0–100%	Completely open*	Reverse
Duct static pressure	Inlet guide vane position 0–100%	Completely open	Reverse
Duct static pressure	variable-frequency drive 0–100%	Completely open	Reverse
Building static pressure	Supply fan control	Maximum fan speed	Reverse
Building static pressure	Exhaust fan control	Maximum fan speed	Direct
Discharge-air cooling	Electric/pneumatic 5.0–15.0 psi (34–103 kPa)	15.0 psi (103 kPa)	Direct
Space temperature	Discharge setpoint 50–100°F (10–37.8°C)	N/A (calculates a setpoint)	Reverse
* These settings may vary by region			

To find the action for other applications, determine whether the actuator and measured variable move in the same direction. If so, then the action is direct. If not, then the PID loop is reverse acting.

Example 1

An exhaust fan controls the static pressure in a building. The exhaust fan operates at its highest speed when the building pressure is too high. When the pressure goes above the setpoint, the exhaust fan should speed up to blow air from the building. So when the measured variable (the building pressure) increases, the actuator increases the fan speed. Because the measured variable and the actuator move in the same direction, the PID loop is direct acting.

Example 2

A supply fan controls the static pressure in ducts supplying variable-air-volume (VAV) boxes. The supply fan operates at its highest speed when the pressure is too low. When the pressure goes above the setpoint, the supply fan should slow down to blow less air to the VAV boxes. So when the measured variable (the pressure) increases, the variable-frequency drive (VFD) decreases the fan speed. Because the measured variable and the control signal to the VFD move in opposite directions, the PID loop is reverse acting.

Error deadband

Error deadband is typically used to minimize actuator activity. It can also be used to allow for some slack in system sensors and actuator mechanics. Error deadband prevents the PID output from changing when the absolute value of the error is less than the error deadband. For example, in Figure 16 the error deadband is set at 2.0°F (1.1°C). As long as the absolute value of the error is less than the 2.0°F (1.1°C), the PID output cannot change. When the absolute value of the error exceeds 2.0°F (1.1°C), the PID output can change.

Figure 16: Error deadband

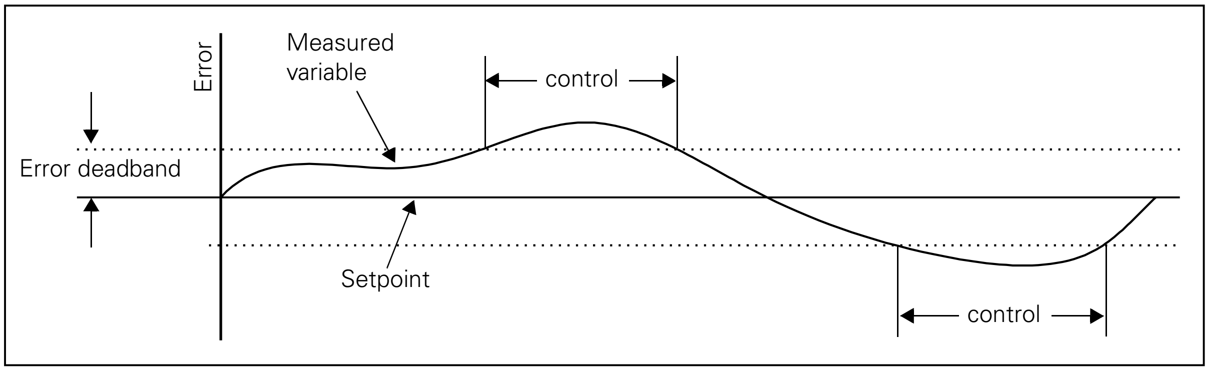


Figure 16 illustrates the way that error deadband limits how often an actuator is controlled. When a PID loop controls a chilled-water valve, limiting control is not so important. But when a PID loop controls how many stages of cooling are being used, it is important to limit equipment cycling.

Typical applications

Table 4 shows reasonable error deadbands for several applications. The error deadband can also be calculated as described in the following sections.

Table 4: Error deadband settings

Application	Suggested error deadband	Notes
Modulating output (analog or floating point binary)	0.5°F (0.3°C) for temperature 0.01 in. wc (2.5 Pa) for duct static pressure 1.0 in. wc (250 Pa) for building static pressure	Dependent on resolution of the measured-variable sensor
Direct expansion (DX) cooling	4.0°F (2.2°C) for temperature	Staging application
Cooling towers—fan staging	2.5°F (1.4°C) for temperature	Staging application

Adjusting error deadband for modulating outputs

In most applications, start with an error deadband of five or ten times the sensor resolution. For example, thermistors have a resolution of approximately 0.1°F (0.06°C), so 0.5°F (0.3°C) is an appropriate error deadband. This error deadband ensures that the sensor reading has changed an adequate amount before the controller responds.

IMPORTANT
The error deadband should not be smaller than the sensor resolution or the controller will react to noise.

Adjusting error deadband for staged outputs

This section shows how to adjust the error deadband for staging applications. Refer to "Staging cooling-tower fans" on page 37 for information on setting other PID properties for staging applications.

Finding the best error deadband for staged output applications is more difficult than for modulating outputs. Instead of using a continuous actuator, such as a chilled-water valve, staged systems use binary outputs to start and stop pieces of equipment, such as fans in a cooling tower. Each piece of equipment contributes a set amount to the final output. When determining the error deadband for staged outputs, the main goal is to reduce equipment cycling.

Table 4 on page 19 provides useful initial values, but the error deadband should be adjusted at the site with the equipment running.

Follow these guidelines when adjusting the error deadband:

- If possible, do not let equipment minimum-on and -off times control how long a particular stage is used. Using minimum-on and -off times to perform system control generally results in unpredictable behavior. The error deadband should be set so that a stage is always on longer than its minimum-on time.
- Ask how tight control should be. A smaller error deadband results in tighter control, but control should not be so tight that minimum-on and -off times affect the stages.

  For example, for a variable-air-volume (VAV) air-handler turning on cooling stages, control can be somewhat loose. The individual VAV boxes control their valve to the space depending on the supply air temperature. If the supply air temperature is relatively warm, the VAV box allows more air flow. If the supply air temperature is somewhat cool, the VAV box constricts the air flow.
- The contribution of each stage can change depending on external circumstances, so make adjustments under worst case conditions. Adjust the error deadband for cooling tower fan stages on very warm days, and adjust the error deadband for boiler stages on very cold days.

With the preceding guidelines in mind, use the following procedure to determine error deadband.

To adjust the error deadband for staged outputs:

1. Run the system manually.

   If possible, do so under worst case conditions for the site. Although it is not always possible for a technician to do this, it is possible for a well-trained customer.
2. Find the smallest change in temperature, ΔT, that the first stage can contribute (the quantity could also be building static pressure for fans or flow for pumps).

   Pay attention to possible changes in external circumstances, such as the amount of water flow. If the system uses a lead-lag approach to the equipment, it will be necessary to find the minimum ΔT for all stages.
3. Multiply ΔT by 0.45 (the error deadband should be slightly less than half of ΔT).

   Keep in mind the resolution of the sensor. You may need to round the error deadband to a more reasonable value.
4. Run the system with the new error deadband.

   Each stage should be on longer than its minimum-on time and cycling should be reduced as much as possible.

Other PID settings

Other PID settings not discussed in this chapter include:

- Proportional bias, which takes the place of derivative gain in proportional-only control (see "Proportional calculation" on page 3)
- Minimum and maximum output, which limit the range of output of the PID loop
- Enabled and disabled modes, which enable the PID output or disable it to a default value
- Fail-safe mode, which sets the PID output to a default value if the controller receives a fail flag from the hardware input that provides the measured variable

Chapter 3, "Programming PID loops," shows how to program these settings for Trane controllers.

Chapter 3

Programming PID loops

This chapter presents programs written in process control language (PCL) and the Tracer graphical programming (TGP) editor. This chapter does not discuss how to use the PCL or TGP editors. For information on using these editors, refer to *Universal Programmable Control Module (UPCM) Programming Guide* (EMTX-PG-5), *Programmable Control Module (PCM) Edit Software Programming Guide* (EMTX-PG-6), and *Tracer Graphical Programming* applications guide (CNT-APG001-EN).

Programming in PCL

PID control is called direct digital control (DDC) in process control language (PCL). Table 5 shows how the DDC function is invoked in PCL. In this example, DDC loop 4 compares the discharge-air temperature to the heating discharge-air setpoint. Line 1 stores the result of the PID function in the analog variable `HEATCALC`. Line 2 controls the valve to the calculated value. You can program specific PID settings in the DDC Loop Parameters screen, shown in Table 6 on page 24.

Table 5: PID (DDC) loop in PCL

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	HEATCALC	=	DISCHTMP	DDC:4	HEATSP	DDC loop 4 compares heat setpoint to discharge-air temp
	<u>Result</u>: analog variable		<u>Measured variable</u>: analog input analog variable	Loop name	<u>Setpoint</u>: analog input analog variable analog setpoint analog parameter	
2	HEATVLV	=		CONTROL	HEATCALC	Output controlled to HEATCALC value

Table 6: PID settings in PCL

```
DDC LOOP # 4           HEAT VALVE
------------
PROPORTIONAL GAIN      4.00
INTEGRAL GAIN          1.00
DERIVATIVE GAIN        0.00
ACTION                 REVERS
PROPORTIONAL BIAS      0.0
MINIMUM OUTPUT VALUE   0.0
MAXIMUM OUTPUT VALUE   100.0
ERROR DIFFERENTIAL     0.5
```

Follow these steps to program PID loops in PCL:

1. Make sure that the setpoint is within reasonable limits.

   Use the `MIN` and `MAX` operators to set a ceiling and floor for the setpoint, as shown in lines 1 and 2 of Table 7 on page 25.

2. Run the PID calculation and store the result in an analog variable.

   Do not place the DDC operation in an `IF` clause (`*IFT` or `*IFF`) because the output can be unpredictable.

3. Define failure and other operation-dependent conditions.

   These checks are called the fail-safe and enable/disable functions. Typically, check for fan status and measured variable input failures.

4. If the failure or enable/disable conditions from step 3 are met, set the analog variable to some default value.

5. Control the analog output with the result of the calculation.

You can follow this procedure for most PID applications. All PID applications require failure-mode conditions.

Table 7 on page 25 shows a PCL program with enable/disable and fail-safe logic. Line 4 checks whether the fan is on. Line 5 checks whether the analog input has failed. Line 6 prevents the PID loop from being used if the fan is off or the analog input has failed. If either condition is met, the analog output is set to –10.0 (closed) in line 7. If the fan is on and the analog input has not failed, the PID loop controls the output in line 9.

Table 7: PCL program for PID loops

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	CALC_SP	=	ROOM_SP	MIN	*80.0	Check that setpoint is reasonable
2	CALC_SP	=	CALC_SP	MAX	*65.0	
3	PID_CALC	=	AIP1	DDC:1	CALC_SP	Run PID calculation
4	*L1	=		NOT	FAN_ON	Is the fan off? (Enable/disable)
5	*L2	=	AIP1	FAIL		Has the input failed? (Fail-safe)
6	*IFT	=	*L1	OR	*L2	If fan is off or input has failed
7	PID_CALC	=	*-10.0			then set output to -10.0 (closed)
8	*END	=				
9	AOP1	=		CONTROL	PID_CALC	Control actuator to calculated value

Table 8 shows a PCL program with separated enable/disable and fail-safe logic. The logic is separated because in this case the enable/disable and fail-safe conditions have different results. In line 4, if the fan is off, then the actuator is closed. In line 6, if the input sensor fails, then the actuator is opened.

Table 8: Separate enable/disable and fail-safe logic

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	CALC_SP	=	ROOM_SP	MIN	*80.0	Check that setpoint is reasonable
2	CALC_SP	=	CALC_SP	MAX	*65.0	
3	PID_CALC	=	AIP1	DDC:1	CALC_SP	Run PID calculation
4	*IFT	=		NOT	FAN_ON	If the fan off (Enable/disable)
5	PID_CALC	=	*-10.0			then set output to -10.0 (closed)
6	*IFT	=	AIP1	FAIL		If the input has failed (Fail-safe)
7	PID_CALC	=	*100.0			then set output to 100.0 (fully open)
8	*END	=				
9	AOP1	=		CONTROL	PID_CALC	Control actuator to calculated value

Programming in TGP

Figure 17 shows the PID block used to program PID loops in TGP editor. The PID block is more flexible than the DDC function in PCL. The enable/disable and failure inputs can accept any binary value, regardless of source. The setpoint, measured variable, p-gain, i-gain, and d-gain inputs can accept any analog value, except analog outputs, including variable (local or from a BAS), hardware input, and network input. You can program PID settings in the PID Properties dialog box, shown in Figure 18.

Figure 17: TGP PID block

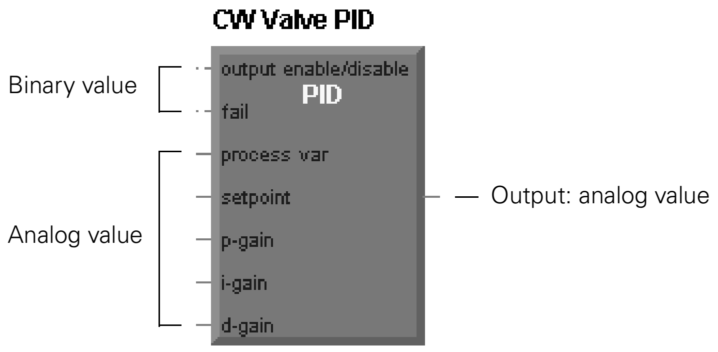
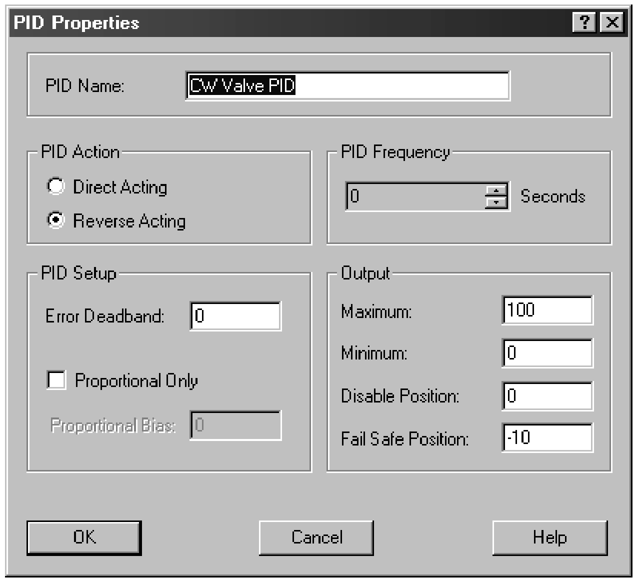


Figure 18: PID Properties dialog box



PID Name: CW Valve PID

PID Action
- ( ) Direct Acting
- (•) Reverse Acting

PID Frequency: 0 Seconds

PID Setup
- Error Deadband: 0
- [ ] Proportional Only
- Proportional Bias: 0

Output
- Maximum: 100
- Minimum: 0
- Disable Position: 0
- Fail Safe Position: -10

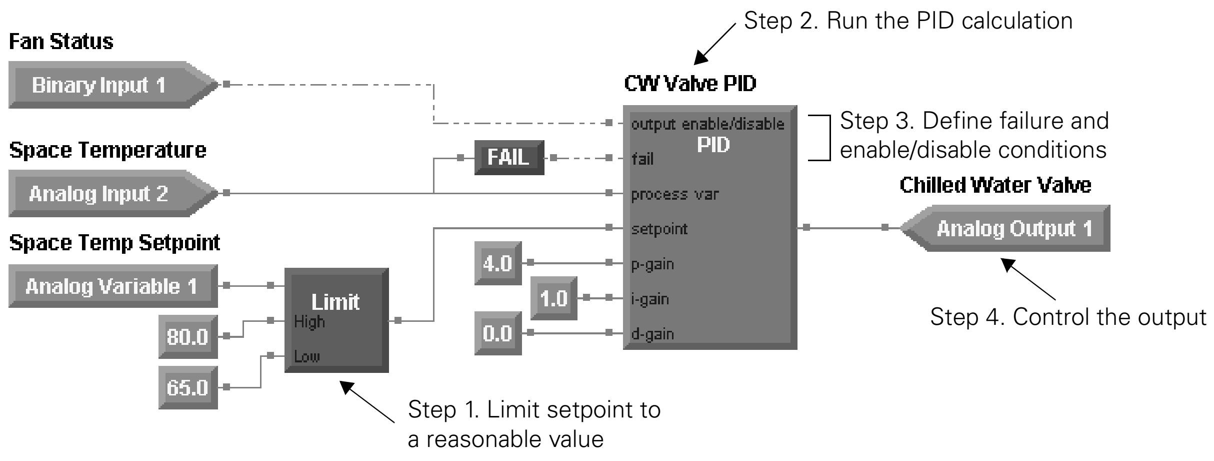
Follow these steps to program PID loops in TGP:

1. Use the Limit block to make sure that the setpoint is within reasonable limits.
2. Run the PID calculation.
3. Define failure and other operation-dependent conditions.

   Check for fan-status and measured-variable input failures. Program sensible actuator positions or behavior for these conditions. To do this, use the Default and Fail Safe fields in the PID Properties dialog box (see Figure 18 on page 26), or use a Switch block for more complex operations.
4. Control the analog output with the result of the calculation.

Figure 19 shows the TGP program for a simple PID loop controlling a chilled-water valve. Compare the TGP program to the PCL program shown in Table 7 on page 25. The Limit block accomplishes the same task as the `MIN` and `MAX` operators in PCL.

Figure 19: TGP program



Chapter 4

Applications

This chapter describes several HVAC applications that use PID control. It includes specific settings and recommendations for each application.

Discharge-air temperature control

When controlling hot/chilled-water valves in discharge-air applications, a PID loop controls the position of a valve to increase or decrease the flow of hot or chilled water. This section focuses on control of hot-water valves, but control of chilled-water valves is almost identical. Seasonal changeover control may be required in these applications, but is not discussed here.

In this application, one hot-water valve and one chilled-water valve control the discharge-air temperature serving a large space. The hot-water valve and chilled-water valve each require a PID loop. Since the two valves should not be open simultaneously, the hot and chilled-water valve programs share valve position data.

Table 9 shows a PCL program for controlling a hot-water valve. Note that the variable `CWVALVE` provides the position of the chilled-water valve.

Table 9: PCL program to control a hot-water valve

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	HEATCALC	=	DISCHTMP	DDC:4	HEATSP	HEATCALC is an analog variable that holds result of PID calculation
2	*L0	=	DISCHTMP	FAIL		Has discharge-air sensor failed?
3	*L1	=	CWVALVE	GT	*0.0	Is chilled-water valve open?
4	*L2	=	*L0	OR	*L1	
5		=	FANOFF			
6	*IFT	=	*L2			If sensor has failed, chilled-water valve is open, or fan is off
7	HEATCALC	=	*-10.0			then close hot-water valve
8	*IFT	=	FANOFF	AND	HEATOPEN	If fan is off and hot-water-valve-open request (override) is true
9	HEATCALC	=	*100.0			then fully open hot-water valve
10	*END	=				
11	HWVALVE	=		CONTROL	HEATCALC	Control hot-water valve to calculated position
12	*END	=				

Figure 20 shows a TGP program to control a hot-water valve. Output Status 1 (an analog output) provides the position of the chilled-water valve. If the chilled-water valve position is greater than zero, the hot-water valve will not open.

Figure 20: TGP program to control a hot-water valve

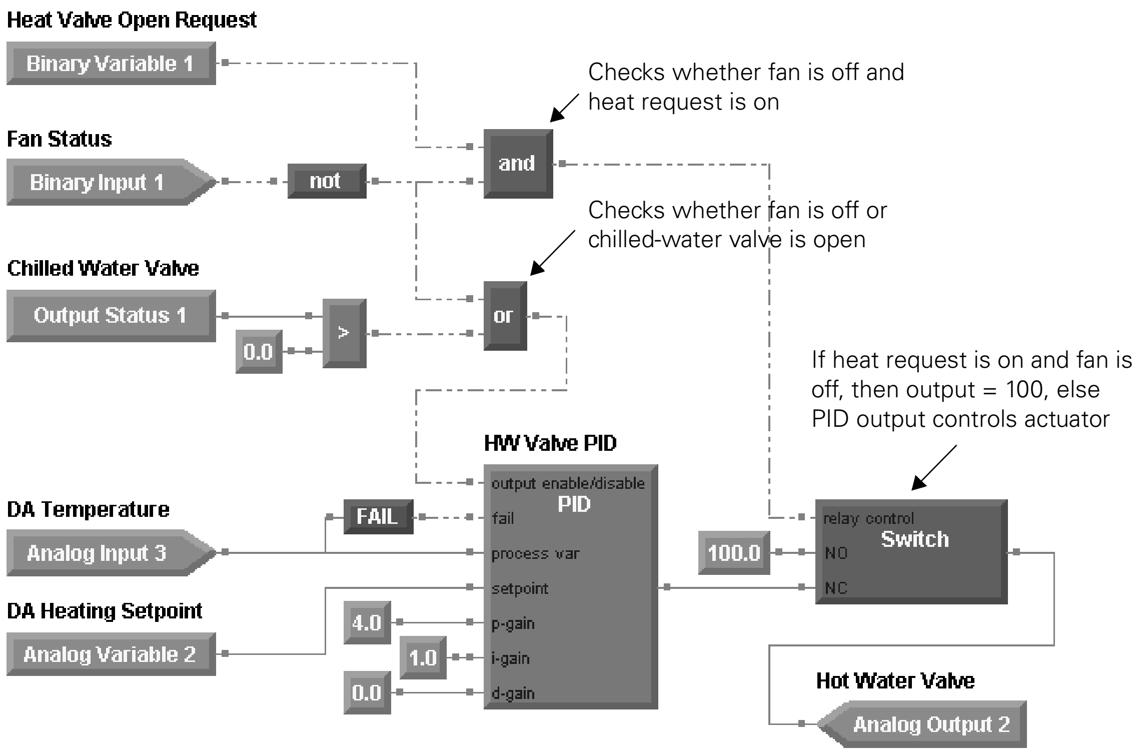


Table 10 shows the initial values the technician used for the hot-water valve PID loop. Chapter 2, "PID settings," explains how to select initial values for various PID applications.

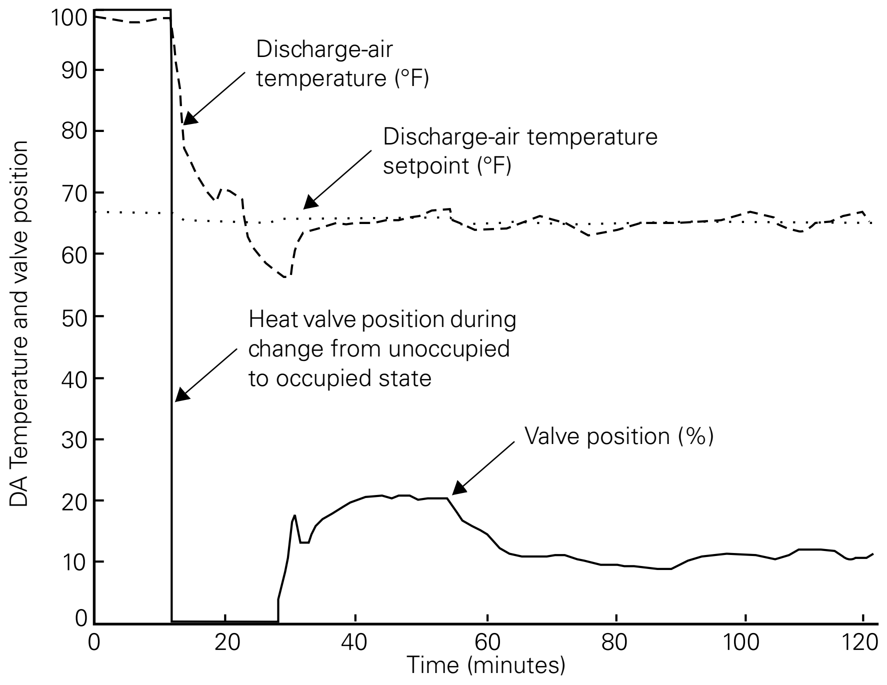
Table 10: Hot-water valve control settings

PID setting	Initial value	Final value
Proportional gain	2.0	4.0
Integral gain	0.5	1.0
Derivative gain	0.0	0.0
Proportional bias	0.0 (not used in PID mode)	0.0
Error deadband	0.5	0.5
Action	Reverse	Reverse
Sampling frequency	10 seconds	30 seconds

After the initial installation and testing, the technician noticed that the discharge-air temperature was oscillating in a 10°F (5.6°C) band around setpoint. Slowing the sampling frequency to 30 seconds stopped the oscillations (see Chapter 5, "Troubleshooting"). The technician also increased the proportional and integral gains to make the discharge-air temperature reach setpoint faster.

Figure 21 shows the discharge-air temperature and valve position over a two-hour period. During the unoccupied period, the hot-water valve is completely open. Eventually the discharge-air temperature rises to almost 100°F (37.8°C). At the twelve-minute point, the HVAC system changes from the unoccupied to the occupied state, and the hot-water valve is adjusted to meet the discharge-air setpoint. The valve closes completely for nearly 20 minutes until the discharge-air temperature drops below setpoint. Achieving a stable discharge-air temperature takes approximately 30 minutes. Note that once setpoint is reached, the valve position remains stable between 10% and 15%. A stable valve position over time indicates that the loop has been tuned for optimal performance.

Figure 21: Hot-water valve position and discharge-air temperature



Building pressure control

Space pressure is typically controlled by opening and closing relief dampers. A PID loop controls these dampers based on a space pressure setpoint and the measured space pressure. The space pressure in the building should remain slightly positive to keep dust particles out, but not so positive that outside doors are difficult to open.

Table 11 shows a PCL program to control a relief damper. Figure 22 shows the same program in TGP. In PCL, the space pressure and other values are scaled by a factor of 100 because the software resolution is 0.1 and the sensor resolution is 0.01. Values are not scaled in TGP.

Table 11: PCL program for relief damper control

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	PRSPX100	=	SPACEPR	*	*100.0	Scale the measured space pressure
2	RELCALC	=	PRSPX100	DDC:2	SPACPRSP	Call the PID (or DDC) function
3	*L0	=	SPACEPR	FAIL		Has pressure sensor failed?
4	*IFT	=	*L0	OR	FANOFF	If sensor has failed or fan is off
5	RELCALC	=	*-10.0			then set output to -10 to close valve
6	*END	=				
7	RELDAMPR	=		CONTROL	RELCALC	Control damper to calculated position
8	*END	=				

Figure 22: TGP program for relief damper control

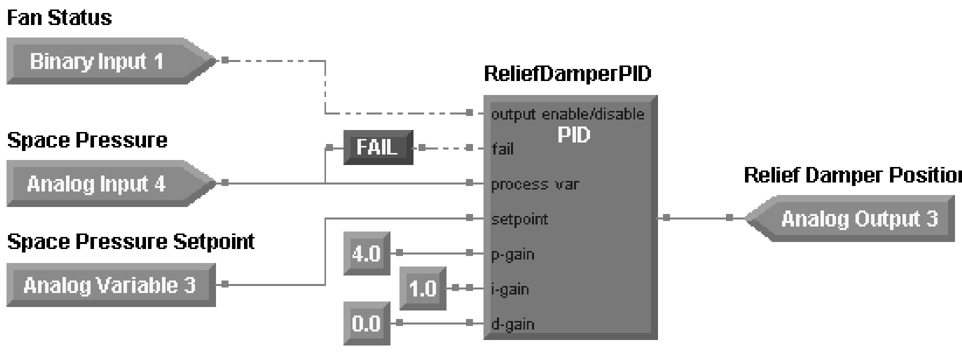


Table 12 lists the settings for the PID loop controlling building pressure. The sampling frequency is slow because building pressure changes slowly. For programs written in PCL, the error deadband is 1.0, which is equal to 100 times the minimum resolution of the pressure sensor.

Table 12: Settings for building pressure control

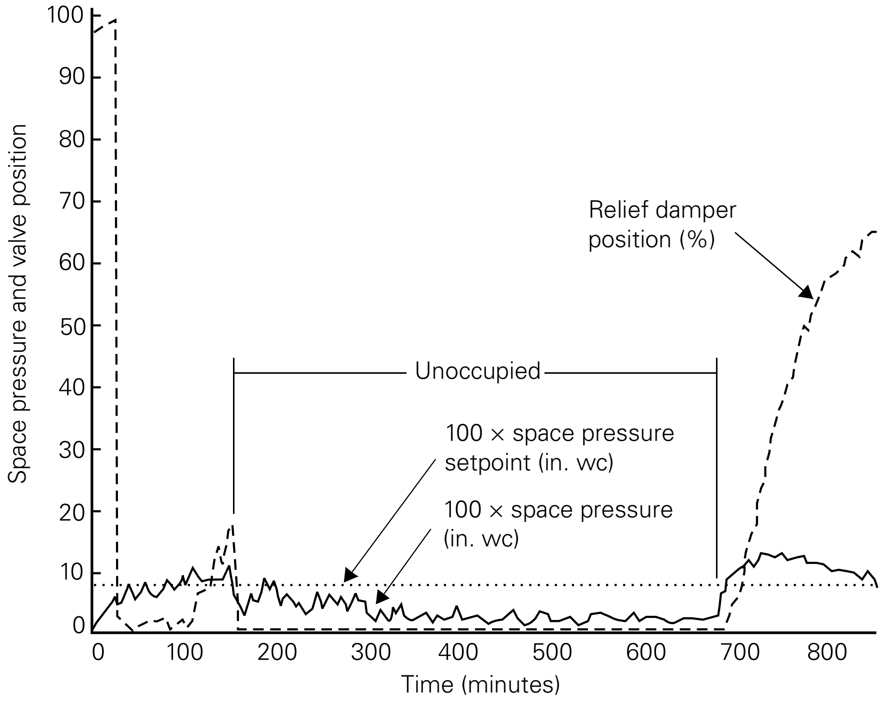
PID setting	Initial value
Proportional gain	4.0
Integral gain	1.0
Derivative gain	0.0
Error deadband	PCL: 1.0, TGP: 0.01
Action	Direct
Sampling frequency	2 minutes

Figure 23 shows system response over a 14-hour period. During the unoccupied period (from 150 to 650 minutes) a different type of control, which decreases pressure, is being used. After the control mode changes from occupied to unoccupied, the PID loop still attempts to increase space pressure by closing the relief damper.

When the space is again occupied, the rapid change in the damper position indicates that the system is being aggressively controlled.

You may find that during occupied operation, the relief damper is controlled to a fully open position. This is usually the result of pressure in an adjacent space influencing pressure in the measured space.

Figure 23: Space pressure and damper position

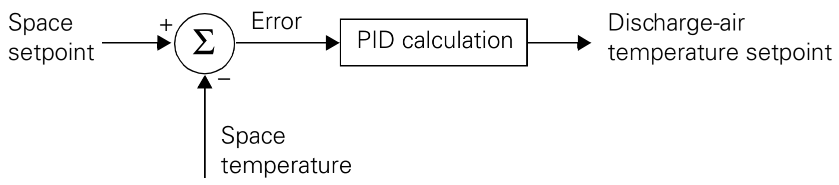


Cascade control—first stage

A PID loop can be used to automatically determine a discharge-air temperature setpoint. Other programs or control systems can then make use of this calculated setpoint. This type of control, called cascade control, results in very tight control of space temperature. Calculating the discharge-air temperature setpoint is the first stage of cascade control.

Figure 24 illustrates how a PID loop calculates the discharge-air temperature setpoint. The calculated discharge-air temperature is changed based on the difference between the space temperature setpoint and the space temperature.

Figure 24: Calculating the discharge-air temperature setpoint



Cascade control requires two sensors, one for the space temperature and one for the discharge-air temperature. The PCL or TGP program must be programmed to respond to a failure of either of the sensors. Suggested failure conditions are:

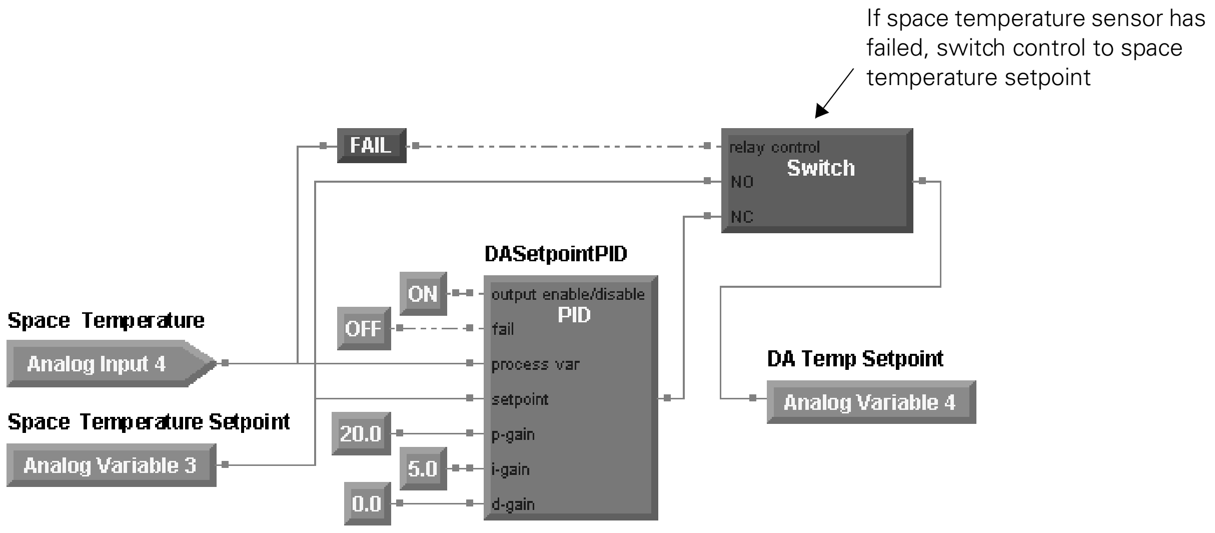
- If the space temperature sensor fails, set the discharge-air temperature setpoint to the space temperature setpoint. Other limits for the discharge-air temperature setpoint may need to be defined. Inform the operator of the sensor failure.
- If the discharge-air temperature sensor fails, control the hot or chilled-water valve as appropriate to the climate in your region. Inform the operator of the sensor failure.

Table 13 shows a PCL program to calculate the discharge-air temperature setpoint, and Figure 25 on page 35 shows the same program in TGP. Most of the programming occurs in the DDC Loop Parameters screen. Use the values shown in Table 14 on page 35.

Table 13: PCL program for discharge-air temperature setpoint in cascade control

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	DATSTPT	=	SP_TEMP	DDC:1	SP_STPT	Call the PID function
2	*IFT	=	SP_TEMP	FAIL		If the space sensor has failed
3	DATSTPT	=	SP_STPT			set the disch air setpt to space setpt
4	*END	=				(Note: the discharge-air temp sensor is checked in another program.)

Figure 25: TGP program for discharge-air temperature setpoint in cascade control



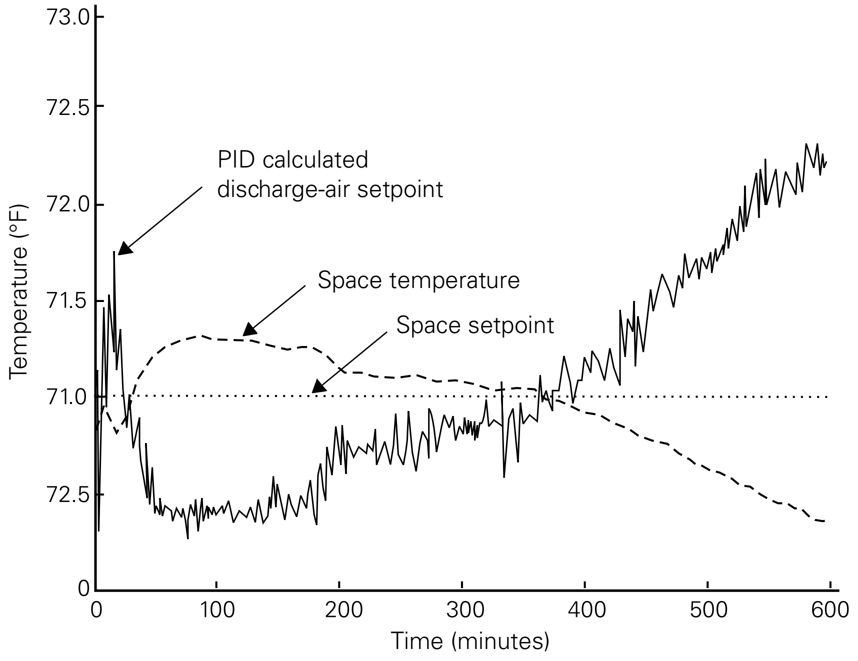
If you use the settings shown in Table 14, you should not have to tune the loop. These values can be used in almost any cascade control application without change. The proportional and integral gains are high to respond aggressively to the error and change in error. The minimum and maximum output values keep the output between 50°F (10°C) and 120°F (49°C).

Table 14: Settings for discharge-air temperature setpoint

PID setting	Initial value
Proportional gain	20.0
Integral gain	5.0
Derivative gain	0.0
Error deadband	0.5
Action	Reverse
Sampling frequency	60 seconds
Minimum output	50°F
Maximum output	120°F

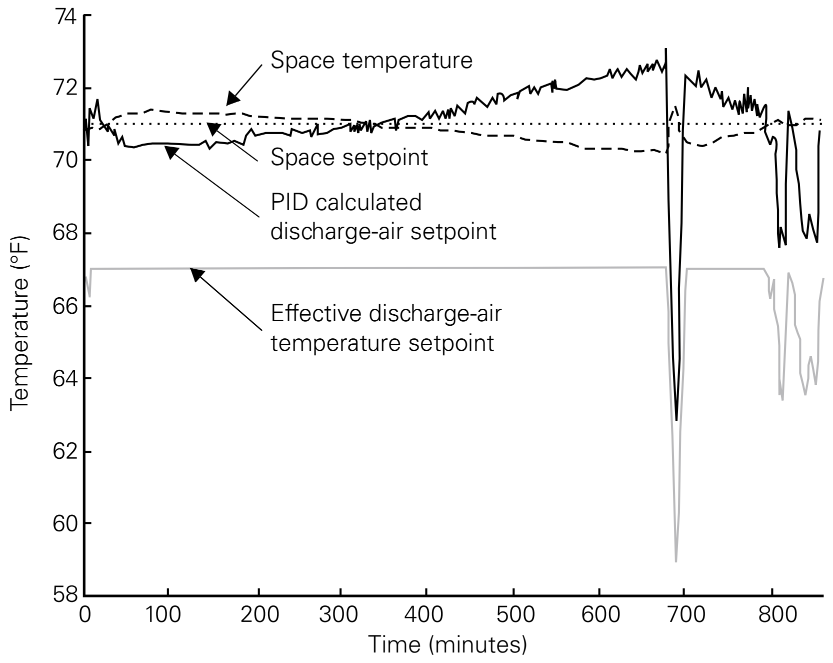
Figure 26 on page 36 shows an example of the relationship between the calculated discharge-air temperature setpoint and the space temperature. The discharge-air temperature setpoint reacts strongly to small changes in error because of the high proportional gain.

Figure 26: Space temperature and calculated discharge-air setpoint



The discharge-air temperature setpoint calculated by the PID loop may not control the discharge-air temperature depending on other conditions that have priority, such as high and low setpoint limits. The high limit controls the discharge-air temperature for much of the time in Figure 27 (because the calculated setpoint is too high). Also, Figure 27 shows how aggressively the PID loop responds to disturbances in space temperature.

Figure 27: Effective discharge-air temperature setpoint



Staging cooling-tower fans

Staging applications organize individual pieces of equipment into a group to accomplish a single task. For example, several fans might be used to maintain the supply water temperature in a cooling tower. Staging applications control a series of binary outputs on and off at specific times based on an analog value. This value can be generated by a linear equation, a PID calculation, a reset block, and so on.

The advantage of using PID control for staging applications is that you can use the error deadband to optimize the system so that stages cycle less often (see “Adjusting error deadband for staged outputs” on page 20). Another advantage is that PID control is built into Trane controllers, making settings easy to enter and adjust.

This section describes how to use a proportional-only PID loop to control supply water temperature in a cooling tower with several fans instead of a variable-frequency drive.

Setting up the PID loop

Proportional-only control works well in staging applications because the output is linear and predictable, and therefore easy to manage. Integral control can also be used but is much more complex to set up and tune.

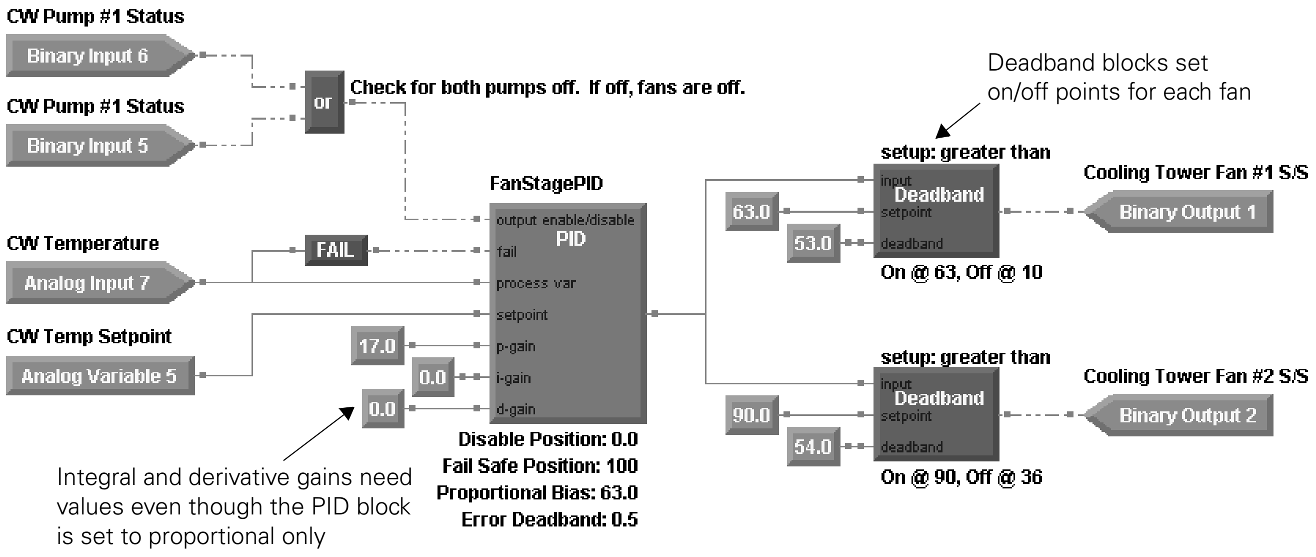
To use proportional-only control in process control language (PCL), set the integral and derivative gains to zero. In Tracer graphical programming (TGP) editor, select Proportional Only in the PID Properties dialog box (see “Programming in TGP” on page 26).

The PCL program in Table 15 stages two cooling-tower fans. Figure 28 shows the same program in TGP. The behavior of the stages programmed in this program is illustrated in Figure 30 on page 41.

Table 15: PCL program for staging cooling-tower fans

Line	Result		1st Arg	Operator	2nd Arg	Description of Statement
1	FAN_CALC	=	CWST	DDC:1	CW_SETP	DDC loop compares water temp to setpt
2	*IFF	=	CDWP1ST	OR	CDWP2ST	If both chilled-water pumps are off
3	FAN_CALC	=	*0.0			set output to 0 to turn off all fans
4	*IFT	=	CWST	FAIL		If sensor has failed
5	FAN_CALC	=	*100.0			set output to 100 to turn on all fans
6	*IFT	=	FAN_CALC	GT	*63.0	If PID result > 63
7	CT1SS	=		CONTROL	ON	then turn on stage 1
8	*IFT	=	FAN_CALC	LT	*10.0	If PID result < 10
9	CT1SS	=		CONTROL	OFF	then turn off stage 1
10	*IFT	=	FAN_CALC	GT	*90.0	If PID result > 90
11	CT2SS	=		CONTROL	ON	then turn on stage 2
12	*IFT	=	FAN_CALC	LT	*36.0	If PID result < 36
13	CT2SS	=		CONTROL	OFF	then turn off stage 2
14	*END					

Figure 28: TGP program for staging cooling tower fans



The TGP program follows this sequence of operation:

1. Chilled-water pump status is checked. If there is flow, the cooling towers are allowed to operate.
2. Based on the error (the difference between the chilled-water setpoint and the chilled-water temperature), the controller turns cooling-tower fans on or off as needed to ensure efficient cooling tower operation.
3. If the chilled-water temperature sensor fails, all cooling-tower fans are turned on.

Note that:

- A 2-input Or block (a TGP block) checks the status of the chilled-water pumps. Both fan stages are turned off if neither chilled-water pump is operating.
- A PID calculation generates an output based on the difference between the chilled-water setpoint and the chilled-water temperature. If both pumps are off, the PID calculation is disabled and the output set to the default of zero.
- If the chilled-water temperature sensor fails, the PID output defaults to the fail-safe value of 100, which turns both fan stages on.

Specific settings are listed in Table 16.

Table 16: Settings for staging cooling-tower fans

PID setting	Initial value
Proportional gain	17 (midrange between 10 and 26)
Integral gain	0
Derivative gain	0
Proportional bias	63% (set the same as the first stage enable value)
Error deadband	2.0°F (1.1°C)
Action	Direct
Sampling frequency	At least 1 minute

The throttling range is fairly wide—from 10°F to 25°F (6°C to 14°C). The large throttling range keeps control loose to prevent stages from cycling too often. Assuming an output range from 0 to 100, the throttling range translates to a proportional gain of 26 to 10 respectively (see “Calculating the gains” on page 11). The proportional gain chosen for this application is in the middle of that range at 17. The gain may need to be adjusted to optimize the system.

The temperature of the water flowing through a cooling tower responds fairly slowly, so the sampling frequency should be set to at least 1 minute. The sampling frequency may need to be adjusted to a slower rate if the temperature oscillates around the setpoint (see “Calculating the sampling frequency” on page 14). The goal in this case is to effectively control the water temperature while limiting equipment cycling.

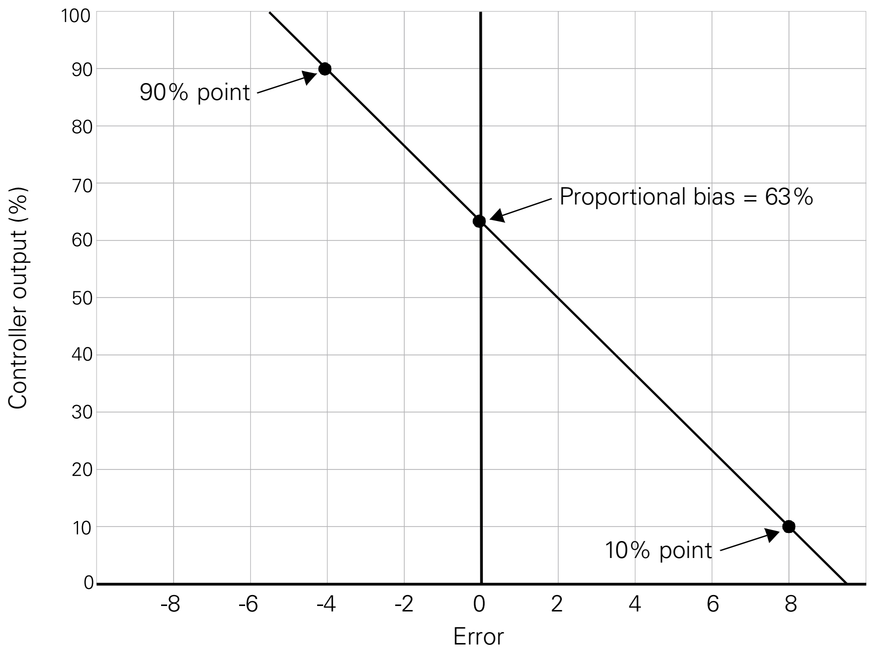
The challenge in staging applications is to find the correct proportional bias. This value determines the output when the error is zero. The proportional bias should have the same value as the point at which the first stage turns on (see "Determining the staging points" on page 42). In this case, the first stage turns on at an output of 63%, so the proportional bias is set to 63%.

Figure 29 shows the output versus error when the proportional bias is 63%. This graph can help us determine the error deadband setting. We know that the first-stage fan turns on when the error becomes negative. The second stage should not turn on until the output reaches 90% or an error of –4°F (–2.2°C). Following the procedure presented in "Adjusting error deadband for staged outputs" on page 20, the error deadband is:

0.45 × 4°F (2.2°C) = 1.8°F (1°C)

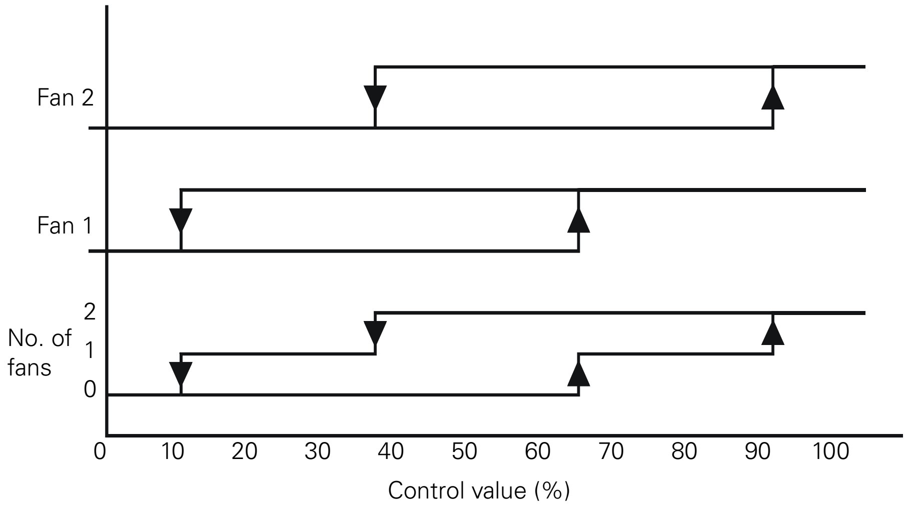
We can round the error deadband to 2.0°F or 1.5°F. Either choice should ensure that the second stage does not turn on until the error is relatively large.

Figure 29: Controller output versus error: proportional bias = 63%



For staging applications, the result of the PID calculation controls binary outputs rather than an analog output. For this kind of staging application, it is typical to use the deadband to make sure that the binary output state is maintained for some specific range. Figure 30 illustrates the staging points for two cooling-tower fans. The three lines indicate (from bottom to top): the number of fans versus the control value, fan 1 on and off points, and fan 2 on and off points. Fan 1 is turned on at 63% and off at 10%. Fan 2 is turned on at 90% and off at 36%.

Figure 30: Cooling tower fan on and off points



Determining the staging points

This section describes how to find the points at which stages are turned on and off.

Start with these guidelines:

- To avoid having a stage turn off at the lowest extreme, always have at least one stage on at 10% of the output range. Turn that stage off when the control value is less than 10%. Due to hysteresis (the programming of equipment to react in a different way depending on whether the control value is increasing or decreasing), this stage may be on only when the output is decreasing.
- To avoid having a stage turn on at the PID maximum value, have all stages on at 90% of the output range.
- To reduce equipment cycling, stages should overlap.
- As a starting point, assume that the overlap range is the same for all stages. You can adjust the staging points later to optimize the system.

To determine the staging points:

1. Use the following formula to find the overlap range:

$$\text{Overlap range} = \frac{\text{highest extreme} - \text{lowest extreme}}{\text{stage count} + 1}$$

$$\text{Overlap range} = \frac{90\% - 10\%}{\text{stage count} + 1} = \frac{80\%}{3 + 1} = 20\%$$

(assuming the system has three fans).

2. To create overlap, the first stage should turn on at the lowest extreme plus 2 times the overlap range and turn off at the lowest extreme, or:

$$\text{Stage 1} = \begin{cases} \text{On: control value} \geq 10\% + (2 \times \text{overlap range}) = 50\% \\ \text{Off: control value} < 10\% \end{cases}$$

For a three-fan system, the first stage should turn on at 50% and turn off at less than 10%.

3. For each subsequent stage, the on and off points are described by:

$$\text{Stage n} = \begin{cases} \text{On: control value} \geq 10\% + (n + 1) \times \text{overlap range} \\ \text{Off: control value} < 10\% + (n - 1) \times \text{overlap range} \end{cases}$$

Although not discussed in this section, equipment minimum-on and -off times become a factor as more stages are added to the system. The higher stages may be on for shorter periods of time. System behavior may become erratic if a stage control is dominated by minimum-on and -off times instead of the calculated control value.

Example 1: Two-stage fan system

The staging points are calculated as follows:

1. Calculate the overlap range.

$$\text{Overlap range} = \frac{80\%}{\text{stage count} + 1} = \frac{80\%}{2+1} = 26.7\%$$

2. Calculate the first stage control points.

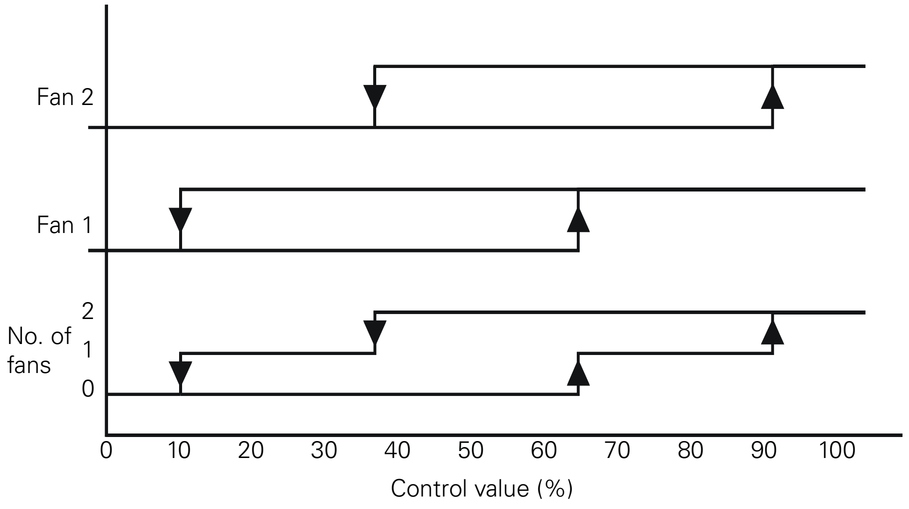
$$\text{Stage 1} = \begin{cases} \text{On: control value} \geq 10\% + (2 \times 26.7\%) \approx 63\% \\ \text{Off: control value} < 10\% \end{cases}$$

3. Calculate the second stage control points.

$$\text{Stage 2} = \begin{cases} \text{On: control value} \geq 10\% + (3 \times 26.7\%) = 90\% \\ \text{Off: control value} < 10\% + (1 \times 26.7\%) \approx 36\% \end{cases}$$

The staging points are illustrated in Figure 31. You should not have to adjust the extremes at 10% and 90%, but you may need to adjust the middle staging points to optimize the system.

Figure 31: Two-stage fan on and off points



Example 2: Three-stage fan system

The staging points are calculated as follows:

1. Calculate the overlap range.

$$\text{Overlap range} = \frac{80\%}{\text{stage count} + 1} = \frac{80\%}{3+1} = 20\%$$

2. Calculate the first stage control points.

$$\text{Stage 1} = \begin{cases} \text{On: control value} \geq 10\% + (2 \times 20\%) = 50\% \\ \text{Off: control value} < 10\% \end{cases}$$

3. Calculate the second stage control points.

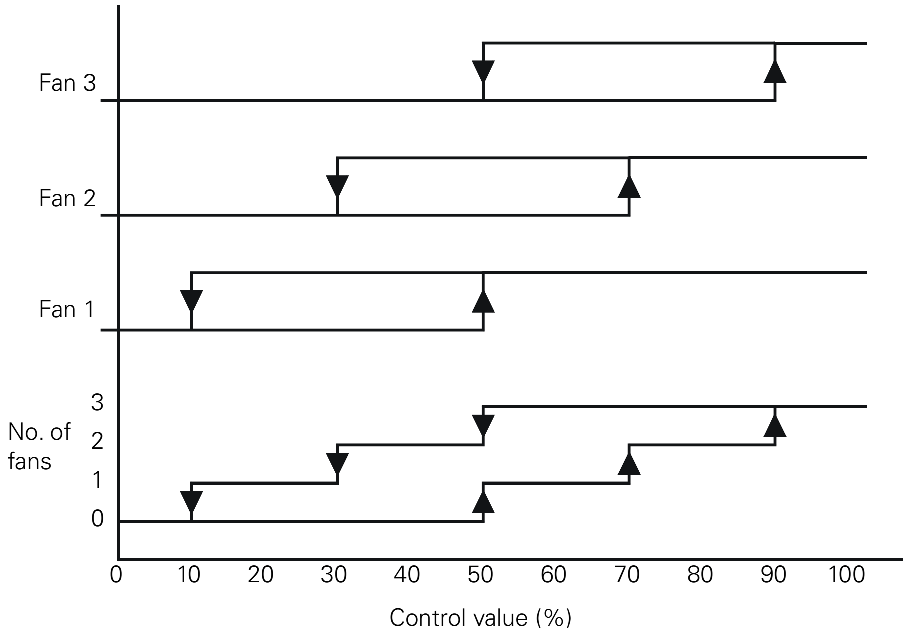
$$\text{Stage 2} = \begin{cases} \text{On: control value} \geq 10\% + (3 \times 20\%) = 70\% \\ \text{Off: control value} < 10\% + (1 \times 20\%) = 30\% \end{cases}$$

4. Calculate the third stage control points.

$$\text{Stage 3} = \begin{cases} \text{On: control value} \geq 10\% + (4 \times 20\%) = 90\% \\ \text{Off: control value} < 10\% + (2 \times 20\%) = 50\% \end{cases}$$

The results are summarized in Figure 32.

Figure 32: Three-stage fan on and off points



Chapter 5
Troubleshooting

This chapter offers a general troubleshooting procedure and tips for specific problems.

Troubleshooting procedure

When following this troubleshooting procedure, change only one thing at a time, then wait to see the effect the change has on the system.

Follow these steps to troubleshoot a PID loop:

1. Make sure that the system is not in override.
2. Graph the measured variable, setpoint, and valve position over time to determine how the system performs.

   Look at the big picture. Can the system actually accomplish what it needs to? What is happening to the measured variable? Is it oscillating or failing to reach setpoint?
3. Check the programming logic for:
   - DDC statement in an `*IFT` or `*IFF` clause
   - Failure conditions that are always true
   - Output connected to the wrong part of a Switch block in TGP
   - Conflicting programming demands, such as bad logic interlocks between program modules
4. Check PID property settings for:
   - Output minimum incorrectly set to 100%
   - Output maximum incorrectly set to 0%
   - Sampling frequency that is too fast
5. Check the system for disturbances from:
   - Outside air intake
   - Bad actuator linkages
   - Faulty sensors
6. Change PID gains.
   - Reduce gains when experiencing system overshoot, output at minimum or maximum, or cycling of output around setpoint
   - Increase gains when experiencing system undershoot

Tips for specific problems

Table 17 provides tips for troubleshooting specific problems.

Table 17: Tips for specific problems

Problem	Tips
Measured variable is cycling around setpoint	• Slow the sampling frequency • Decrease PID gains • Check programming for conflicting actuator commands • Actuators may be overridden by minimum-on and -off times
Overshooting setpoint	Reduce gains
Undershooting setpoint	Increase gains
Output at maximum	Ensure that minimum output is not set to 100%
Output at minimum	Ensure that maximum output is not set to 0%

Changing the sampling frequency

The major cause of actuator cycling is time lags in the system. If a 10% change in PID output requires two minutes to affect the measured variable, it does no good to have the sampling frequency set to two seconds. The integral contribution will build up before any significant change in error can be measured. A sampling frequency of 30 to 60 seconds would work much better in this situation. In other words, to fix a cycling system, slow down the loop. See “Sampling frequency” on page 12 for more information.

Changing the gains

Be careful when changing PID gains. Never change the gains unless the effects can be measured. Use a doubling/halving technique when increasing or decreasing gains. If the PID gains are set to 4, 1, and 0 respectively, and you are going to reduce them, try 2, 0.5, and 0. If the system now undershoots, try gains of 3, 0.75, and 0 respectively. Refer to “Throttling range” on page 9 for more information.

Examples

This section presents troubleshooting scenarios from a hot-water valve application. The three examples have the same symptom but different solutions to the problem.

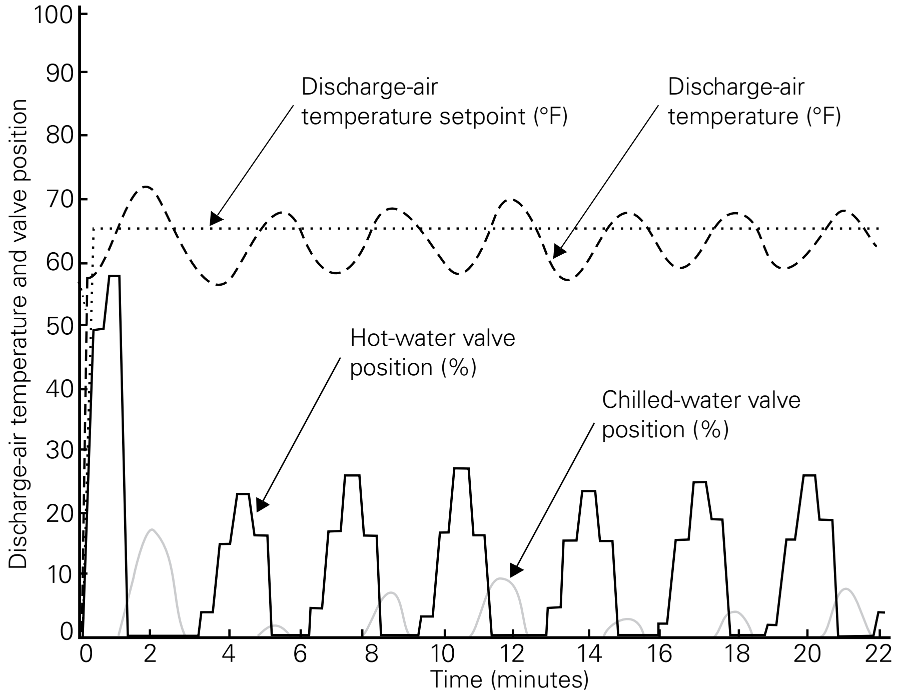
Example 1

A hot-water valve cycles closed every few minutes. Although the space temperature remains fairly stable, the discharge-air temperature swings across a range of 10°F (5.6°C).

The technician follows the troubleshooting procedure described in this chapter. However, nothing seems to work. The program is the same as the one used in "Discharge-air temperature control" on page 29, and is known to work well. Reducing the sampling frequency reduces the cycling, but does not eliminate it. Reducing the gains helps reduce the cycling further, but now the discharge-air temperature takes too long to reach setpoint. The valve continues to cycle closed, though not as often.

The technician goes back through the troubleshooting steps and notices when checking the programming logic that the hot-water valve closes when the chilled-water valve is open. The technician decides to check the position of the chilled-water valve while the application is running with its original settings. Figure 33 illustrates what the technician found. The chilled-water valve opens when the discharge-air temperature goes above setpoint, thus forcing the hot-water valve to close.

Figure 33: Hot and chilled-water valve positions



The application is running in a cold climate during winter, so the chilled-water valve should not open at all (because chilled water is not being used). However, it might open in the following cases:

- The building automation system has information that chilled water is available.
- The program logic is wrong, and the hot-water valve should depend only on the heat/cool mode, not on the position of the chilled-water valve.

Before reprogramming the controller, the technician checks to see if the building automation system has information that chilled water is available. The technician finds that the building automation system had been configured incorrectly and is sending the controller information that chilled water was available. To fix the problem, the technician resets the building automation data point. The controller no longer opens the chilled-water valve, which in turn prevents the hot-water valve from cycling closed every few minutes.

Example 2

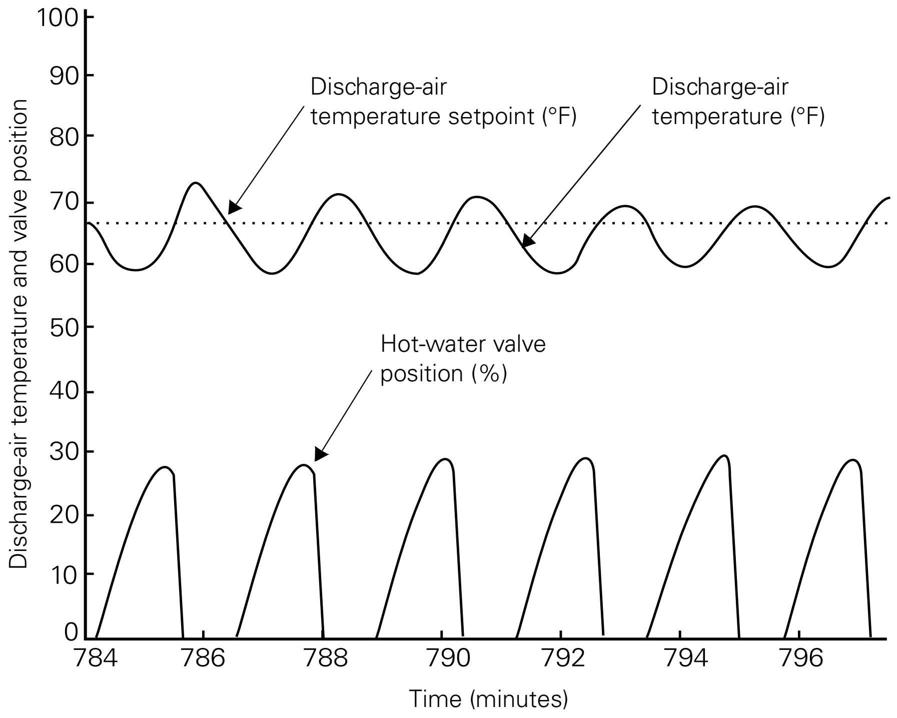
The technician experiences the same problem as in the first example: a hot-water valve cycles closed every few minutes, and the discharge-air temperature swings across a range of 10°F (5.6°C).

Again, the technician follows the troubleshooting procedure. The programming logic looks correct. The mixed air temperature and outdoor air temperature remain steady, indicating that outside disturbances are not causing the problem. The cycling stops only when the technician slows the sampling frequency from 10 seconds to 30 seconds.

When the sampling frequency is 10 seconds, the hot-water valve cycles because the fast sampling frequency does not take into account the natural lag involved in trying to change air temperature. The change in the discharge-air temperature over 10 seconds is so small that the controller responds more aggressively to reduce the error. The controller opens the hot-water valve too much, which causes the discharge-air temperature to overshoot the setpoint (see Figure 34 on page 49). Again, the controller over-reacts, shutting the hot-water valve to cool the discharge-air temperature, which causes the discharge-air temperature to overshoot the setpoint in the opposite direction. This cycle repeats indefinitely.

Slowing the sampling frequency to 30 seconds gives the discharge-air temperature enough time to change so that the PID loop can calculate the valve position based on a reasonable error.

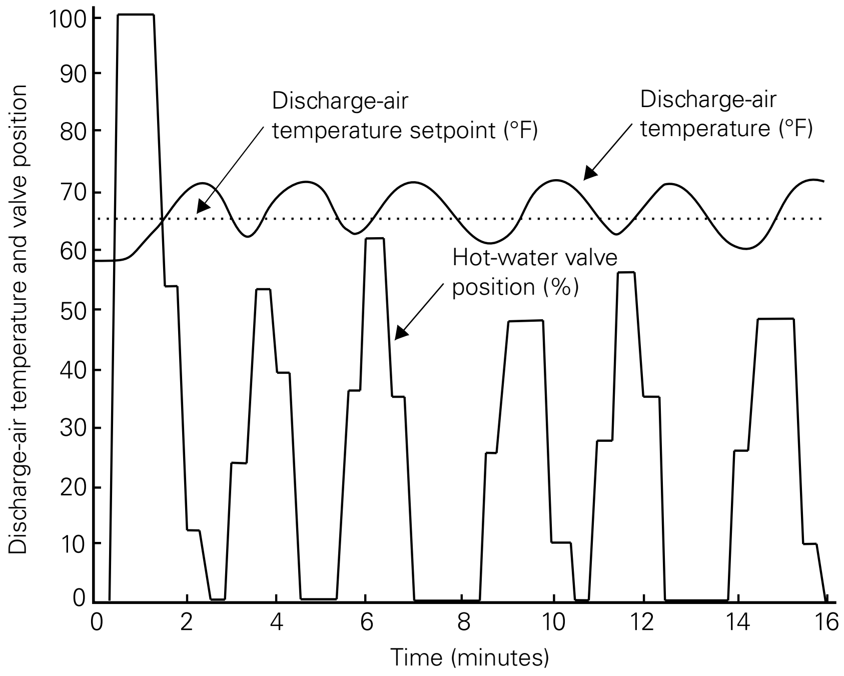
Figure 34: Hot-water valve position, sampling frequency too short



Example 3

The technician experiences the same problem as in the first two examples: a hot-water valve cycles closed every few minutes, and the discharge-air temperature swings across a range of 10°F (5.6°C). The technician graphs the discharge-air temperature setpoint and the hot-water valve position, as shown in Figure 35.

Figure 35: Hot-water valve position, gains too high



The dramatic changes in the hot-water valve position indicate that the gains are too high. The technician reduces the proportional gain from 16 to 1 and the integral gain from 4 to 0.25. This stops the hot-water valve from cycling but increases the time to reach setpoint to more than 20 minutes. The technician then increases the proportional gain to 4 and the integral gain to 1, which brings the discharge-air temperature to setpoint more quickly while still preventing the hot-water valve from cycling.

Chapter 6

Frequently asked questions

Why is the output of my PID loop always zero?

- Maximum PID output may be set to zero.
- PID action setting may need to be changed.
- Setpoint may be zero or negative, driving the output to zero. Change the setpoint to a reasonable value manually or add a limit block to the PID loop to keep the setpoint within a reasonable range.
- Physical output may not have enough power to achieve the setpoint, leaving the output at the low end of its range. This problem is known as integral windup (see “Integral calculation” on page 4 for more information).
- Measured-variable input may have failed and the fail-safe may be set to zero.
- Fan status is off so the program has set the output to zero.
- Scaling may be inconsistent for setpoints and inputs.

Why is the output of my PID loop always at its maximum value?

- Minimum PID output may be set to the maximum value.
- PID action setting may need to be changed.
- Setpoint may be high enough that the output stays at its maximum output. Change the setpoint to a reasonable value or add a limit block to the PID loop to keep the setpoint within a reasonable range.
- Physical output may not have enough power to achieve the setpoint, leaving the output at the high end of its range. This problem is known as integral windup (see “Integral calculation” on page 4 for more information).
- Measured-variable input may have failed and the fail-safe may be set to the maximum value.
- Scaling may be inconsistent for setpoints and inputs.

Why is the output of my PID loop oscillating?

- PID action setting may be wrong. If the action is reverse when it should be direct, the system may start oscillating as the output changes around setpoint.
- Sampling frequency may be too slow or too fast. See “Sampling frequency” on page 12 for instructions on setting an appropriate sampling frequency.
- Proportional, integral, or derivative gains may be set too high. Reduce the gains until the oscillation subsides.

I tried the 4:1 ratio for proportional and integral gains, but this did not optimize my system. Can I try another ratio?

We recommend maintaining a 4:1 ratio between the proportional and integral gains. Changing the gains may slightly improve the speed and stability of a system, but the 4:1 ratio has proven to work effectively. See "Calculating the gains" on page 11 for more information.

Why is the derivative gain usually zero?

Derivative control is rarely used in HVAC applications because the large error deadbands used in HVAC applications make derivative control ineffective. Also, derivative control can react to noise in the input signal, and the lag in derivative control makes tuning difficult. Setting the derivative gain to zero prevents derivative control from being used. See "Derivative calculation" on page 5 for more information.

What is the difference between direct acting and reverse acting?

Reverse acting loops decrease the output as the measured variable increases. Discharge-air heating, duct static pressure control, and space temperature control applications are typically reverse acting. Direct acting PID loops increase the output as the measured variable increases. Discharge-air cooling and building static pressure (with exhaust fans) applications are typically direct acting. See "Action" on page 17 for more information.

When should I use proportional-only control?

Proportional-only control works well in staging applications because it can be simpler to manage than full PID control. Proportional-only control is also used in pneumatic controllers. To use proportional-only control, set the integral and derivative gains to zero. See "Proportional calculation" on page 3 for more information.

Why should I use PID control in staging applications?

Most Trane controllers have built-in PID functions, making settings easy to enter and adjust. See "Staging cooling-tower fans" on page 37 for more information.

How can I tell if a PID loop is working well?

Graph the measured variable, setpoint, and valve position over time, especially during periods of change, such as when changing from unoccupied to occupied mode. The setpoint should be achieved in a reasonable time and the valve position should remain fairly stable once setpoint has been reached. If the measured variable oscillates around the setpoint, fails to reach setpoint, or takes too long to reach setpoint, follow the guidelines in Chapter 5, "Troubleshooting."

What's the best sampling frequency?

The best sampling frequency depends on the application. See “Calculating the sampling frequency” on page 14 for recommended sampling frequencies. You may need to adjust the sampling frequency (usually to slow it down). If the measured variable is oscillating around setpoint, the sampling frequency may be too fast or the gains may be too big.

Do I need to worry about the throttling range?

You probably do not need to worry about the throttling range. The throttling range cannot be programmed as a PID setting. Instead, it is used to help calculate the gains. The throttling range is the amount of error it takes to move the output of a system from its minimum to its maximum setting. Most PID applications have recommended gain settings, but if these gains do not fit your application, an understanding of throttling range can help you find more appropriate gain settings. See “Throttling range” on page 9 and “Calculating the gains” on page 11 for more information.

Appendix A

The math behind PID loops

This appendix presents the mathematical formulas used for PID control in Tracer MP580/581 controllers, the programmable control module (PCM), and the universal programmable control module (UPCM).

Velocity model formula

The formula used to calculate the output in the velocity model is shown below. It uses the integral and proportional gain, but not the derivative gain. The same formula is used in the PCM and the UPCM.

$$\Delta\text{output}(n) = \left[\frac{K_{prop}}{c} \times \Delta\text{error}(n)\right] + \frac{K_{int} \times \text{error}(n)}{c} + \left[\frac{K_{diff}}{c} \times \Delta^2\text{error}(n)\right]$$

Where:

K_{prop} = proportional gain

K_{int} = integral gain

K_{diff} = integral gain

c = 2.56 for the PCM and UPCM

c = 1.00 for Tracer MP580/581 controllers

$\Delta\text{error}(n)$ = change in error

$\Delta^2\text{error}(n)$ = change in the change squared

The factor 2.56 scales the PID output to a range of 0–100% in the PCM and UPCM.

Proportional control formula

The following formula shows the relationship between the error and the output in proportional-only control:

$$\text{Output}(n) = \frac{K_{prop}}{c} \times \text{error}(n) + \text{proportional bias}$$

The proportional bias calibrates the controller to some known output. So when the error is zero (which makes the proportional gain zero), the output is equal to the proportional bias.

Glossary

action
A PID setting that determines how the PID loop reacts to a change in the measured variable (such as a room temperature). A controller using direct action increases the output when the measured variable increases. A controller using reverse action decreases the output when the measured variable increases. *See also* measured variable.

actuator
Electric, hydraulic, or pneumatic motor that changes the position of moveable devices such as valves and dampers.

cascade control
A method of control in which one PID loop calculates a setpoint for use by other PID loops or control systems. Cascade control is used in applications that require tight control; the response to error is aggressive.

conversion function
The part of a PID loop that converts the measured variable to the same units of measurement as the setpoint. The result of the conversion function is called the measured variable or process variable.

deadband
See error deadband.

derivative control
Control action based on the rate of change of the error. Used to smooth an actuator motion or cause an actuator to react faster. Derivative control is rarely used in HVAC applications.

direct action
See action.

direct digital control (DDC)
A term used at Trane as a synonym for PID control.

error
In PID control, the difference between the setpoint and the measured variable. For example, if the setpoint is 75°F (23.9°C) and the measured variable is 65°F (18.3°C), then the error is 10°F (5.6°C). This means that the HVAC system must heat the space by 10°F (5.6°C). The error is the basis of all PID calculations. *Also called* offset.

error deadband
A PID setting that defines how much the error must change before the PID loop reacts. Used to compensate for bearings, linkages, and other mechanical items.

gain
The primary tool for tuning PID loops, gain determines how a particular part of the PID calculation contributes to the final output. The bigger the gain, the more a part contributes. The proportional, integral, and derivative calculations each have an associated gain setting. Gain is defined as the output range divided by the throttling range (multiplied by a scaling factor for each part of the PID calculation). *See also* throttling range.

hysteresis
The programming of equipment to react in a different way depending on whether the control value is increasing or decreasing (Figure 31 on page 43 illustrates hysteresis).

integral control
Control action based on the sum of past errors. Used to maintain an output when the error is zero. *See also* integral windup, error. *Also called* reset control, automatic reset.

integral windup
A condition that can occur when the result of the integral calculation becomes too great for the system to change direction. This is typically caused when the system does not have the power to reach setpoint. Trane uses the velocity model to minimize the problem of integral windup. *See also* integral control, velocity model.

measured variable
Typically, a value read by a sensor, such as space temperature, discharge-air temperature, or duct static pressure. The measured variable is subtracted from the setpoint to determine the error. *See also* error. *Also called* process variable.

overshoot
When a controller responds too aggressively to error, it can push the controlled variable past the setpoint. The overshoot is the amount by which the system passes the setpoint.

PID loop
See proportional, integral, derivative (PID) loop.

process variable
See measured variable.

program frequency
The rate at which a program executes or cycles.

proportional control
Control action based on the error. The most important determinant in how quickly the system responds to the error. Some applications use proportional-only control.

proportional, integral, derivative (PID) calculation
The mathematical process that determines how quickly a controller reaches setpoint. *Compare* proportional, integral, derivative loop.

proportional, integral, derivative (PID) loop
A control system that compares the setpoint and the measured variable to calculate system output. *See also* measured variable. *Compare* proportional, integral, derivative calculation.

resolution
See sensor resolution.

reverse action
See action.

sampling frequency
The rate at which the input signal in a PID loop is sampled. For Tracer MP580/581 controllers, this occurs at the same rate or a multiple of the rate of the program frequency. *See also* program frequency.

sensor resolution
The minimum change of a physical quantity, such as temperature or airflow, that causes a reliable reaction in the sensor. Typically, this value is provided by the sensor manufacturer. If a thermistor can reliably report a temperature change of 0.1°F (0.06°C), then any change less than that should be considered noise.

setpoint
The point at which the desired value of the controlled variable is set. For example, if the controlled variable is space temperature, then the cooling setpoint might be 75°F (42°C).

staging
The process of organizing individual pieces of equipment into a group to produce a single result. For example, a cooling tower might have three fans used in stages to cool water. On a hot day, all three fans would be needed to cool the water, but on a cooler day one or two fans would be enough.

system time constant

The time it takes to reach 63.21% of the difference between the start point and the end point when controlling an output over a known range. Used to calculate the sampling frequency. Using $^2/_3$ (66%) rather than 63.21% provides a good approximation of the system time constant.

throttling range

For an HVAC controller, the range of input that drives the output from the minimum output to the maximum output (typically 0% and 100%). The gains are calculated from the throttling range. *See also* error, gain.

velocity model

A type of PID control used in Trane controllers to minimize the problem of integral windup. *See also* integral windup.

windup

See integral windup.

Index

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