Controllers

Other than the operator, the brain of any controlled process loop is the controller. It is the controller that takes an input signal from a sensor/transmitter, compares it to a desired set point, and applies a corrective output signal to some end device. For our purpose, we will define the following configurations of controller logic.

- Two-position
- Timed Two-position
- Floating Control
- Proportional Control

This section will concentrate on proportional control with feedback. However, let's briefly discuss two-position and floating control.

Two-position Control

As the name implies, two-position control is the on-off control of some device. Such a device could be a motor, an electric heater, a gas-fired kiln, or other such device. Two-position control is characterized by a rather large operating differential. Although Figure 1 shows a 24-volt control circuit, two-position controllers may operate from any power source.

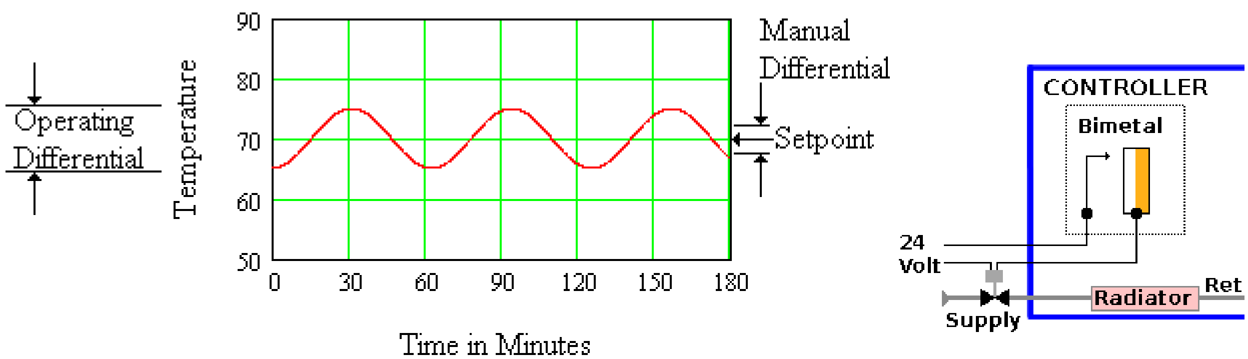


Figure 1 Response of a hot water radiator under two-position control

In Figure 1, a two-position controller is being used to control space temperature by opening and closing a two-position motorized valve. The controller has an adjustable manual differential. This manual differential prevents the end device from chattering should the controlled variable be hovering at set point. A bimetal senses space temperature and completes the electrical circuit when the space temperature rises to set point plus one-half the manual differential. At this time, the valve is energized and closes to prevent hot water flow. However, the thermal mass continues to heat the space. Eventually, space temperature begins to drop. When the space temperature drops below set point minus one-half the manual differential, the valve is commanded open. The now cooled thermal mass must heat up before heat is radiated to the space thus accounting for the low temperature swing. Although two-position control is suitable for many applications where a large operating differential is tolerable, there are also many where more sophisticated control is warranted.

Timed Two-position Control

If we could power the controlled device at predetermined times to allow the manipulated variable to impact the controlled environment with ‘packets’ of energy, we could minimize the inherent operating differential. This is done through the use of some form of timer. Consider the system in Figure 2. In this system, we add a resistor to the bimetal element of the controller. Since the resistor is powered, it radiates heat to the bimetal thus forcing the bimetal to close sooner than without the resistor. This is typical of a mechanical thermostat used for residential heating and air conditioning. This resistor, known as a heating anticipator, minimizes the operating differential by allowing the control valve to cycle on and off more frequently.

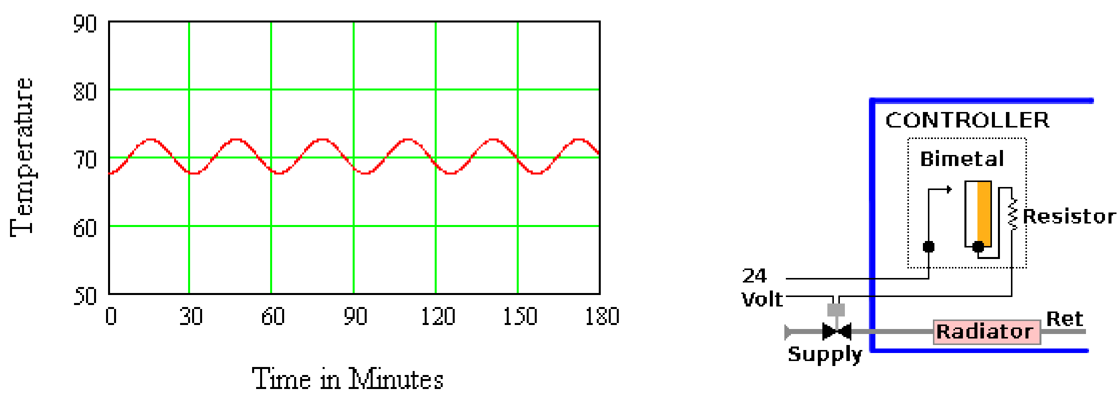


Figure 2 Use of timed two-position control to control a hot water radiator

Floating Control

Floating control is a modification of two-position control except that the operator can stop at intermediate positions. Consider the hydraulic tank in Figure 3. Assume the system is at steady state where inflow is equal to outflow. Now open the hand valve to allow more water to exit the tank. When the float drops sufficiently, the inlet valve begins to open allowing more water into the tank. As the float rises, the electrical connection breaks and the valve will remain in its last commanded position. The opposite happens as the water level in the tank rises. To apply this form of control, one must recognize the following limitations.

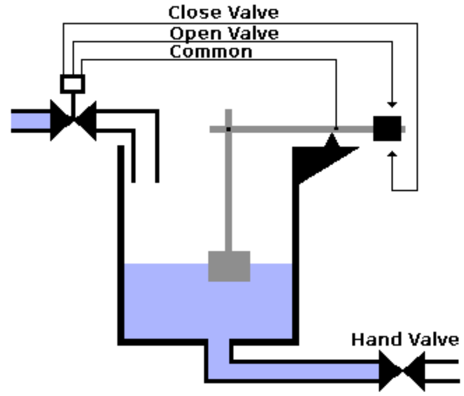


Figure 3 Illustration of floating control

- This is not a failsafe condition. If the control system fails, the valve will remain in its last commanded position
- The end device must move at some predetermined and constant rate in response to a corrective signal from the controller
- The speed of the actuator must be adjustable so one can match control system response to system response
- System load changes must be constant rate of the control response cannot be matched to system response
- The end device must react and move faster than the controlled variable
- The control system must immediately sense the result of a corrective action

An example of misapplication is room temperature control. This is because of the significant time lag inherent in such control. In other words, the controller will not see immediately a change in room temperature as a result of operator movement. On the other hand, an application where floating control could be used is the control of water flow by sensing differential pressure across the supply/return mains. Any change to operator position will have an immediate impact on the differential pressure across the mains.

Proportional Control

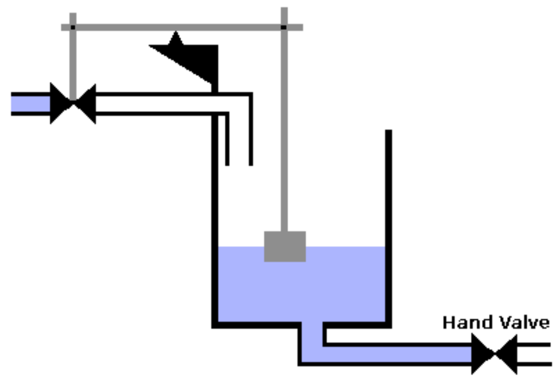


Figure 4 Illustration of proportional control

In most systems, there is a time lag between the change in the controlled variable and the output of the controller. Timed two-position attempts to handle this lag to some extent by introducing heat anticipation, but cannot provide modulating control. Floating control will modulate, but cannot be used where there are significant time lags. In order to provide modulating control while preventing overshoot of the set point, we introduce proportional control. Proportional control is a modification of floating control by adding continuous feedback to the controller. In proportional control, the output signal of the controller is mathematically related, or proportional to, the controller input signal. Proportional control is also characterized by the fact that the value of the controlled variable seldom equals set point.

To explain this last statement, consider the tank shown in Figure 4. Assume the volume of water entering and leaving the tank is equal such that everything is in equilibrium. This is known as a bias condition. It is sometimes called the calibration condition since this is the point at which the controller is calibrated. Yet another term for the bias condition is manual reset. In any case, it is that point at which everything is in equilibrium and the control point is equal to the set point.

Now let's open the hand valve and allow water to flow from the tank. In order for the inlet valve to open sufficiently to replace the amount of water leaving the tank, the water level must drop. In other words, the control point MUST fall below set point. When this happens and inflow equals outflow, the system will remain at this new equilibrium state. However, the water level is not at its original level or set point, nor can it ever regain the original set point condition unless the position of the hand valve is returned to its original position. This difference in water levels is an error condition referred to as offset or droop.

Direct or Reverse Acting

The first thing one must determine when setting up any proportional controller is determine whether or not the controller is direct or reverse acting. A direct acting controller means the output signal of the controller will increase with a corresponding increase in the value of the controlled variable. If a controller is reverse acting, the output signal will decrease with an increase in the value of the controlled variable (Fig. 5).

For example, suppose a heating valve is normally open. If the space temperature rises, we want the valve to close to allow space temperature to fall to the desired set point. For a normally open heating valve to close, the controller output signal must increase with an increase in space temperature. A direct acting controller is required. However, if the heating valve is a normally closed valve and space temperature is rising, then the controller must reduce its output signal allowing the normally closed valve to close and bring the space temperature down. This requires a reverse acting controller.

As one can see from the example, the selection of reverse or direct action is dependent upon whether or not the actuating device is normally open or normally closed. This, in turn, is based upon what you determine as the 'fail-safe' condition for the system.
Fail-safe was discussed in the section on valves.

For example, in most cases, the fail-safe condition of a heating valve is for the valve to fail open. One reason for this is to allow full flow through a coil to prevent freezing the coil in the event of a control system failure. This requires a normally open heating valve, thus a direct acting controller.

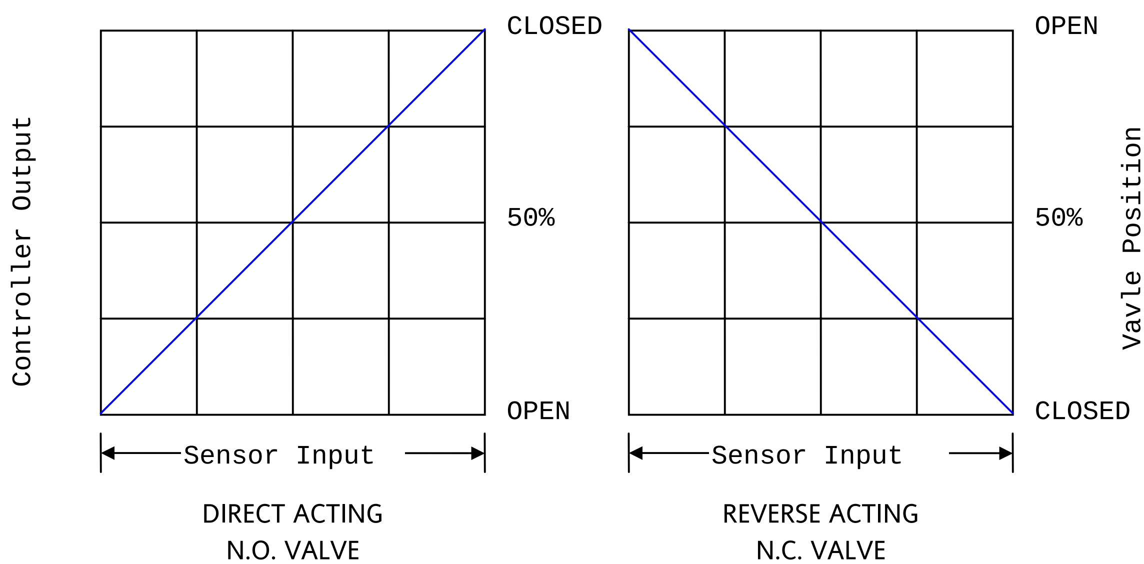


Figure 5 Direct vs. Reverse Acting Control

On the other hand, one may want the heating valve on a reheat coil serving a data processing center to fail closed to prevent overheating the center in the case of a control system failure.

The fail-safe condition selected is up to the judgment of the designer and the specific application under design.

Controller Sensitivity

A typical closed-loop control schematic is shown in Fig. 6. In Fig. 6(a), the sensor is shown in the feedback loop as providing feedback to the controller as to the effect of a change in the manipulated variable. This information is provided as a control signal. Figure 6(b) rearranges the schematic shown in Fig. 2(a) to separate the controller from the process. In Fig. 6(c), we break the loop as shown. If we measure the change in the process variable and the change in output signal from the controller as a result of the change in the process variable, we can define controller sensitivity as:

$$CS = \frac{Change\ in\ output\ signal}{Change\ in\ input\ variable}$$

For example, suppose a temperature control loop is setup so a 5 ^oF change in the process variable causes a 4 ma change in output signal from the controller. The controller sensitivity is then calculated as:

$$CS = \frac{4ma}{5\,^oF} = 0.80\frac{ma}{^oF}$$

Proper controller adjustment is crucial to obtain the desired control loop sensitivity so the control system will react properly. Unfortunately, different manufacturers use different methods of setting control loop sensitivity. Some manufacturers use the concept of gain while others use the concept of percent proportional band. Whichever method is used, the adjustment of the controller gain or percent proportional band dial or slide is the controller adjustment allowing one to establish the desired controller sensitivity.

Gain

The concept of controller gain is slightly different from controller sensitivity. Referring again to Fig. 6(c), consider breaking the loop at two points as shown. If we were to measure the input signal to the controller (transmitter output signal) and the output signal from the controller (actuator input signal), we can define controller gain as:

$$Gain = \frac{Change\ in\ output\ signal}{Change\ in\ input\ signal}$$

Suppose the range of the sensor in the example above is 50 ^oF – 150 ^oF (100 ^oF span) with a standard output of 4 – 20 ma (16 ma span). The sensor has a sensitivity of 16 ma/100 ^oF or 0.16 ma/^oF. This means a 5 ^oF change in temperature will result in a 5 ^oF x 0.16 ma/^oF = 0.80 ma change in input signal to the controller. Assuming the same

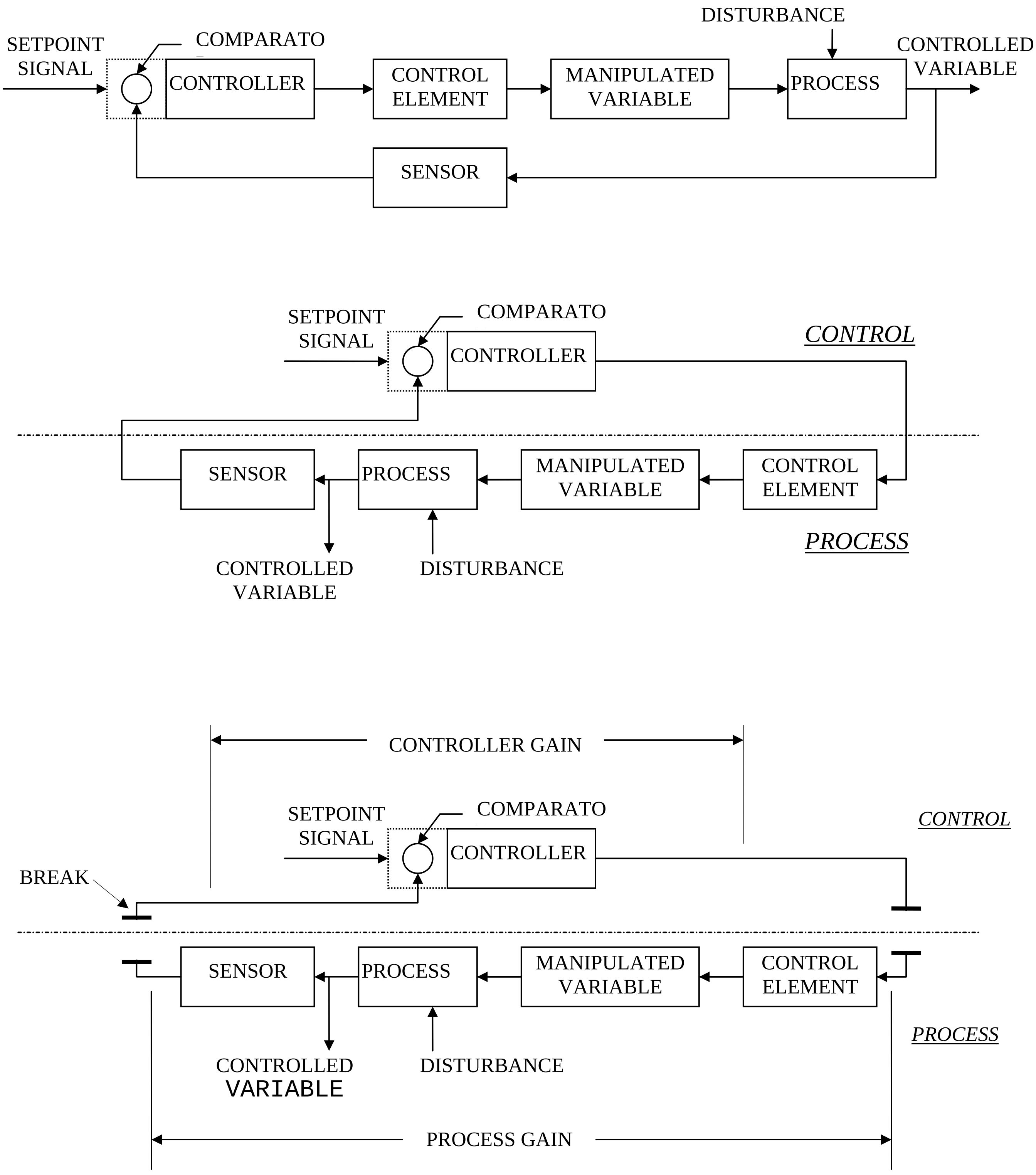


Figure 6 Control System Block Diagram

4 ma change in controller output, controller gain is easily calculated as:

$$Gain = \frac{4\,ma}{0.80ma} = 5$$

Notice the value of gain is dimensionless as opposed to the value of controller sensitivity.

Percent Proportional Band

Although many manufacturers require you to directly input the value of controller gain as a tuning parameter, many require you to set the controller gain by inputting a parameter known as percent proportional band. Some manufacturers use the term percent throttling range in lieu of percent proportional band, but both have the same meaning. The definition of proportional band is the amount of change in the controlled variable required to move the actuator from one end of its stroke to the other. Percent proportional band simply expresses the proportional band as a percentage of primary sensor span. In other words:

$$\%PB = \frac{Proportional\ Band}{Sensor\ Span} \times 100\%$$

In the above example, the controller provided a 4 ma change in output signal for a 5 °F change in input when a 50 °F to 150 °F sensor was connected to the controller. The full output of a typical current-based controller is 4 – 20 ma, a 16 ma span. This means that it would take a 20 °F change in input to cause a full 16 ma change in output, the full stroke signal of an electronic actuator. In other words, the proportional band for this example is 20 °F. With a sensor span of 100 °F, we can calculate a proportional band of:

$$\%PB = \frac{20^{o}F}{100^{o}F} \times 100\% = 20\%$$

Notice that %PB is the reciprocal of gain.

$$\%PB = \frac{100\%}{Gain} = \frac{100\%}{5} = 20\%$$

Control Action Diagrams

At this point, it is worth introducing the control action diagram. This diagram is shown below for the example control loop described above. The intent of the control action diagram is to concisely and graphically depict the design goals of the control loop, thus allowing one to easily see or calculate initial control loop parameters.

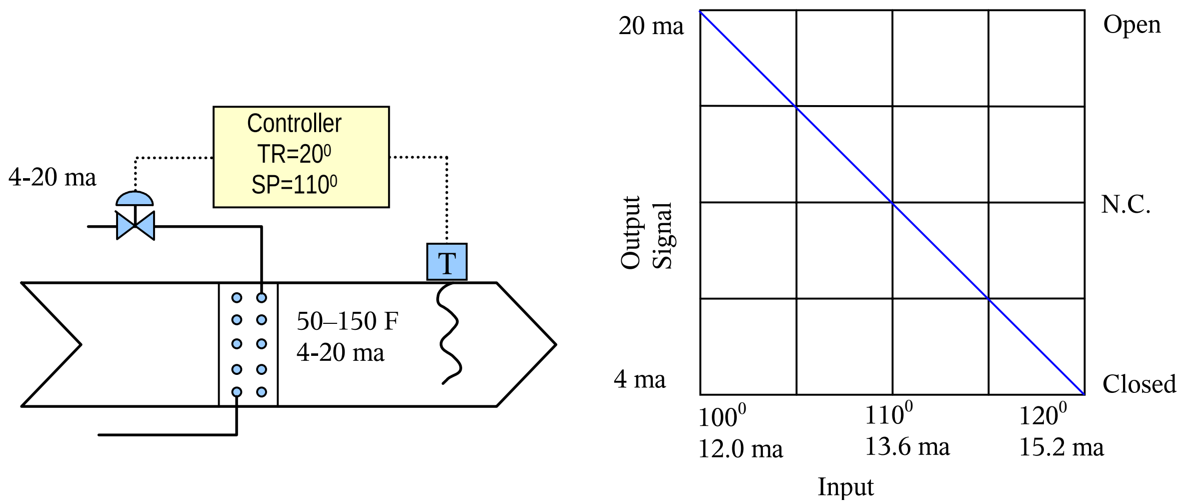


Figure 7 Development of control action diagram for a control loop

The control loop shown in Figure 7 depicts the control of discharge air leaving a heating coil. The set point is 110 °F and the throttling range is 20 °F. The controller receives a 4 - 20 ma signal from a 50 – 150 °F sensor/transmitter and drives a 4 - 20 ma actuator. The control valve is selected to fail closed. Controller action is determined from the following table.

Sensor	Valve Position	Controller Output
120 °F	CLOSED	4 ma
100 °F	OPEN	20 ma

Table 1 Determining Controller Action

From the control action table, note that as temperature increases, controller output decreases. This requires a reverse acting controller. We now have enough information to construct the control action diagram.

The left y-axis indicates the controller output signal, 4 – 20 ma in this case. The right y-axis indicates valve position and the failsafe condition as shown. The x-axis is used to indicate the controller input signal. This input signal is displayed in engineering units and in terms of a control signal. The midpoint of the x-axis is the controller set point. The width of the x-axis represents the desired throttling range. Finally, one can draw a curve representing the controller output over the throttling range. In the majority of cases, this curve will be linear. A negative slope indicates a reverse acting controller while a positive slope indicates a direct acting controller.

From the control action diagram, one can determine controller gain. The y-axis represents a change in output. The x-axis represents the corresponding change in input. From this, we can determine controller gain as:

$$Gain = \frac{\Delta output}{\Delta input} = \frac{(20-4)ma}{(15.2-12)ma} = 5$$

It is worth pointing out that controller gain represents the slope of the controller curve as shown on the action diagram. This is an important revelation, one we will use to describe the difficulties

Gain vs. Proportional Band

The relationship between gain and percent proportional band:

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

is one that is well known. However, what is not well understood is the fact this relationship is based upon the assumption the input and output ranges of the controller are equal. In other words, assume you have an electronic controller with an input range of 4-20 ma and an output range of 4-20 ma. Further assume the controller is driving an electronic actuator with a full stroke that occurs with an input signal (to the actuator) of 4-20 ma. In such a case, the above relationship holds true. But what about the following cases:

- An electronic controller driving an electronic actuator where the signal necessary to do so is only a percentage of the output range of the controller.
- An electronic controller driving a pneumatic actuator through an I/EP valve
- A pneumatic control system

In these cases, the gain and percent proportional band are not necessarily reciprocals as generally stated in the typical textbook. We will address these situations by example later. For now, let's determine how to convert from gain to percent proportional band in the general case. To do so, we need to review the definitions of gain, proportional band, and percent proportional band.

Gain: The ratio of the change in output signal to the change in input signal defines controller gain. As an example, suppose you have a controller that accepts a 4-20 ma current signal and provides a 4-20 ma output signal. Further assume you apply a step change of 2 ma to the input terminals of the controller and you measure a change of 5 ma at the output terminals. The controller gain is then:

$$K_c = \frac{5\,ma}{2\,ma} = 2.5$$

Proportional Band: The amount of change in the controlled variable, expressed in engineering units, required to move the actuator from one end of its stroke to the other. This is also referred to as throttling range.

%PB: Percent proportional band is the proportional band expressed as a percentage of the sensor span. It is sometimes called percent throttling range (%TR). For example, if you had a room temperature process with a throttling range of 5 ^oF and a sensor with a range of 60 to 85 ^oF, then the percent proportional band would be:

$$\%PB = \frac{5\,^oF \times 100\%}{(85-60)\,^oF} = 20\%$$

Using these basic definitions, let's consider three separate controllers. Each controller accepts a 4-20 ma input signal. However, one has an output capability of 4-20 ma, another outputs 4-16 ma, while a third outputs 4-12 ma.

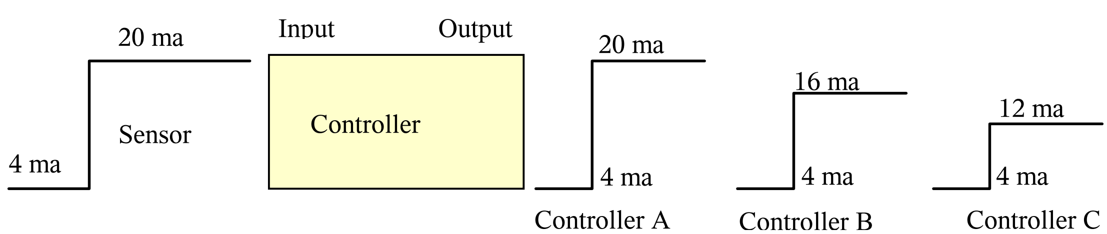


Figure 8 Illustration of proportional band

Assume each controller has a percent proportional band slide and this slide is set to 100% on each controller. By definition, a 100% proportional band means the throttling range equals the sensor span. Since the entire sensor span is also the throttling range, it follows that as the input signal is stepped by 100%, the controller output will also change 100%. Note that in each case, even though the %PB is the same in each case, the change in output is quite different. This is because each has a different output range.

The gain for each controller is also quite different. The observed gain for each controller is as follows:

Controller A: $$K_c = \frac{(20-4)ma}{(20-4)ma} = 1.0$$

Controller B: $$K_c = \frac{(16-4)ma}{(20-4)ma} = 0.75$$

Controller C: $$K_c = \frac{(12-4)ma}{(20-4)ma} = 0.50$$

Obviously, only the first value of gain is the reciprocal of the controller's percent proportional band setting while the other two are not. In order to determine the proper proportional band setting from the value of gain for controllers B and C, we must normalize the controller output to the controller input as follows:

$$\%PB = \frac{100\%}{K_c} \times \frac{Actuator\ Span}{Input\ Span}$$

So we can now calculate the %PB for each of the above three controllers as follows:

Controller A: $$\%PB = \frac{100\%}{1} \times \frac{(20-4)ma}{(20-4)ma} = 100\%$$

Controller B: $$\%PB = \frac{100\%}{1} \times \frac{(16-4)ma}{(20-4)ma} = 100\%$$

Controller C: $$\%PB = \frac{100\%}{1} \times \frac{(12-4)ma}{(20-4)ma} = 100\%$$

For illustration, the above examples assumed the actual output of the controller was limited to something less than 4 - 20 ma. Of course, the typical electronic controller always has an output range equal to its input range, both of which are standardized to some standardized process signal (i.e.: 4-20 ma, 0-5 volt, 0-50 mV, etc.) However, when an end-device requires an input current (or voltage) range less than the output capability of the controller, the result is the same as described above.

For example, shown below is a single loop electronic controller receiving a signal from a 70 to 150 ^{o}F temperature sensor. The sensor outputs 4 - 20 ma over its sensing range.

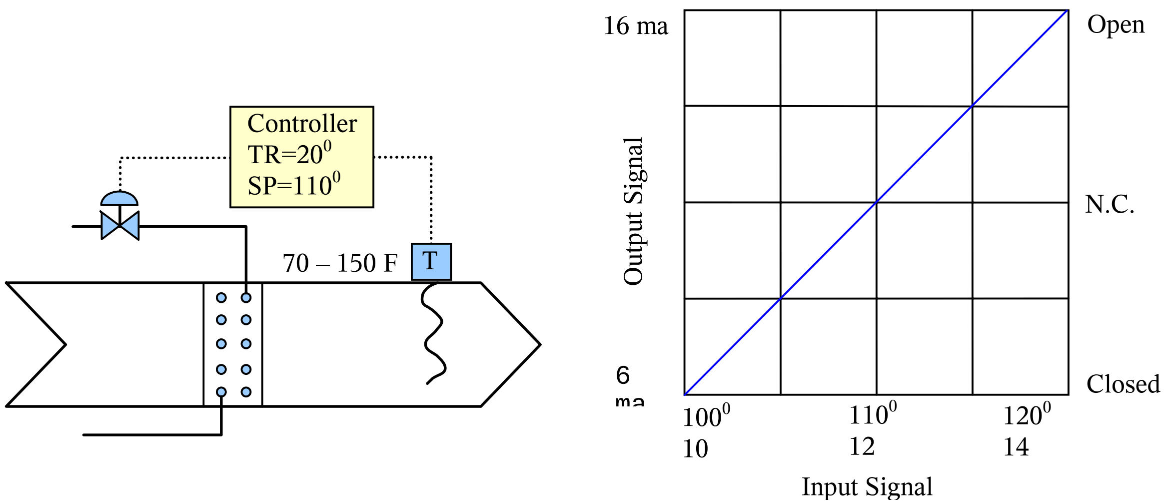


Figure 9 Control loop and control diagram for example problem

Although the controller is capable of an output of 4 - 20 ma, the actuator strokes the normally closed heating valve full closed to full open with a 6 - 16 ma input signal.

Using the fundamental definition of gain, we can define controller gain by expressing the entire proportional band (controller input) in terms of current and the controller output as 6 to 16 ma. Then:

$$Gain = \frac{(16-6)\,ma}{(14-10)\,ma}$$

Realizing the input and output ranges are not equal, we can calculate the %PB as follows:

$$\%PB = \frac{100\%}{2.5} \times \frac{(16-6)\,ma}{(20-4)\,ma} = 25\%$$

The above example assumed an electronic actuator with an input range less than that of the controller output range. What is more common is the use of an I/P or E/P valve driving a pneumatic actuator. In most cases, the I/P or E/P transducer will output a 3 - 15 psi signal with a 1 - 5 v, a 2 - 10 v, or a 4 - 20 ma signal. However, the I/P (E/P) generally drives an actuator with a spring range less than the maximum output range of the I/P (E/P). In such a case, the effective output of the controller is reduced. This results in an analysis virtually identical to the above analysis.

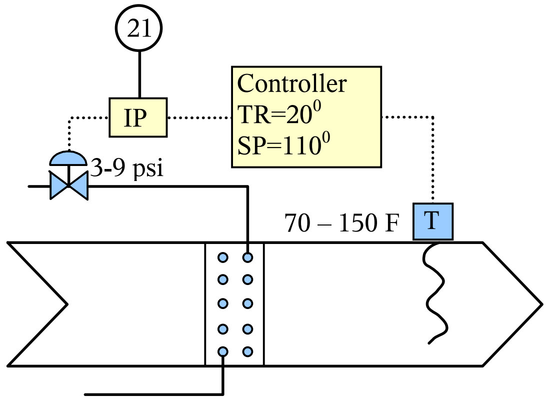


Figure 10 Example control loop with I/P and pneumatic valve

Take, for example, the above system, but replace the electronic valve actuator with an I/P and a 3 - 9 psi pneumatic valve actuator. A typical I/P will output a 3 - 15 psi pressure with a 4 - 20 ma input current. The 3 - 9 psi actuator has a 6 psi span and represents 50% of the output capability of the I/P. It is easily shown that the corresponding controller output is 4 - 12 ma. This is identical to Controller 'C' in the above example. In other words, the ratio of the effective controller output to the controller input is ½. Thus, the reciprocal of gain must be multiplied by this ratio to obtain a proper %PB setting.

Pneumatic Controllers

Pneumatic controllers are handled in a similar fashion, but there is one major difference between pneumatics and electronics. The pneumatic controller is powered with a compressed air source with a line pressure usually somewhere between 18 and 25 psi. This compressed air source is also the source of power for pneumatic transmitters (similar to electronic loop powered transmitters). It is also the source of power for actuators if the actuator is equipped with a pilot positioner. In the end, the output capability of any pneumatic controller will be 0 psi to line pressure. Since line pressure is somewhat variable, the output range of any given controller will also be variable. However, even if line pressure was standardized such that the output range of the pneumatic controller was constant, pneumatic actuators are available with varying spring ranges. Thus the effective output of any controller is dependent upon the selection of the actuator.

The adjustment of most pneumatic controllers is via a slider or a rotary knob calibrated in percent proportional band. Remember that proportional band is defined as:

> "The amount of change in the controlled variable…"

This is a temperature, pressure, or humidity range, in engineering units, over which we wish to control. But this may be expressed as a pressure change in sensor output rather than engineering units. In other words, a change in [controller] input pressure.

"...required to run the actuator over its full stroke."

> In other words, this is the actuator spring range expressed in units of pressure and refers to a change in [controller] output pressure.

This means the output range of all pneumatic controllers would have to be standardized so the manufacturer can provide a calibrated proportional band scale indexed to this standard output. Herein lies the problem; manufacturers never agreed upon a single standard controller output. Every manufacturer calibrates their controller based upon their idea of what this should be. Table 2 lists standard outputs adopted by some manufacturers for some of their controller models.

However, if we know what this standard output range is, we can use it to rewrite the equation for percent proportional band by indexing the sensor to both the controller output range and the actuator range as follows:

$$\%PB = \frac{Proportional\ \ Band}{Sensor\ \ Span} \times \frac{Std.Controller\,Output}{Actuator\,Spring\,Range} \times 100\%$$

MANUFACTURER	STANDARD OUTPUT
Powers	5 psi
Honeywell	10 psi
Barber Colman	10 psi
Robertshaw	12 psi
Kreuter	12 psi

Table 2 Standard Controller Outputs

If we use the previous example, we note the sensor has a range of 70 ^{o}F - 150 ^{o}F (80 ^{o}F span). The throttling range is 20 ^{o}F and the actuator has a 6 psi spring span. We can determine the value of controller gain as follows.

$$Sensor\ Sensitivity = \frac{(15-3)\ psi}{(150-70)\ ^{o}F} = 0.15\frac{psi}{^{o}F}$$

$$Proportional\ Band\ (in\ psi) = 0.15\frac{psi}{^{o}F} \times 20\,^{o}F = 3\,psi\ \ (Controller\ input)$$

$$Controller\ Output = Spring\ Range = 9-3 = 6\,psi$$

$$Controller\ Gain = \frac{6\,psi}{3\,psi} = 2$$

This value of gain is correct regardless of the controller being used. However, we must now convert this to a proportional band setting for our particular controller. Using the above equation for %PB, as developed for pneumatic controllers, we can determine the correct value of %PB to which we must set each controller in order to obtain the desired value of gain. Using the standard outputs listed in Table 2.

(Powers)

$$\%PB = \frac{20^oF}{80^oF} \times \frac{5\,psi}{6\,psi} = 0.208 = 21\%$$

(Honeywell)
(Barber Colman)

$$\%PB = \frac{20^oF}{80^oF} \times \frac{10\,psi}{6\,psi} = 0.416 = 42\%$$

(Krueter)
(Robertshaw)

$$\%PB = \frac{20^oF}{80^oF} \times \frac{12\,psi}{6\,psi} = 0.50 = 50\%$$

Note the reciprocal of the percent proportional band matches the gain calculation only in the last case when the standard controller output is equal to the input span.

The Controller equation

Whether the controller is pneumatic or hydraulic, whether it is electronic analog or microprocessor-based, all controllers are mathematical in nature. The basic controller equation used to predict the output of a controller at any time is:

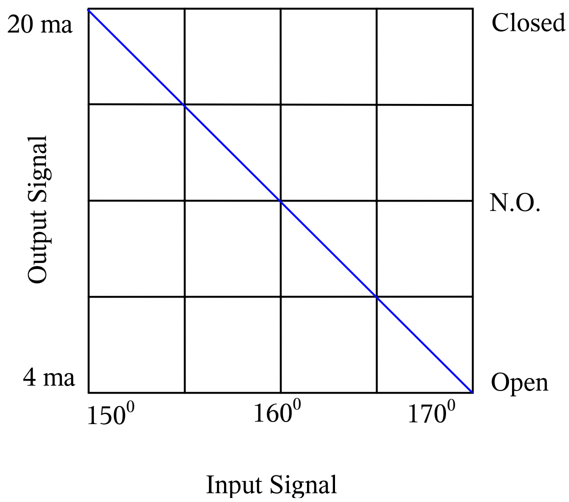
$$output = bias \pm (pv - sp)\left[\frac{SR}{TR}\right]$$

where:

$bias = controller\ output\ at\ calibration\ point$
$pv = engineering\ value\ of\ controlled\ variable$
$sp = engineering\ value\ of\ set\ point$
$SR = actuator\ range\ units\ of\ controller\ output$
$TR = throttling\ range\ in\ engineering\ units$
$+ = add\ if\ controller\ is\ direct\ acting$
$- = subtract\ if\ controller\ is\ reverse\ acting$

Assume you have a shell and tube heat exchanger and are controlling the outlet temperature on the tube side. The set point is 160 ^oF and the throttling range is 20 ^oF. The controller drives a normally closed valve with a 4 – 20 ma actuator. The controller is setup with a 50% bias. Determine the controller output when the process variable is 150 °F.

The first thing to do is develop the controller action diagram as shown below. Since the valve is normally open on a heating system, the controller will be reverse acting. A 50%



bias means the controller is calibrated at (20 – 4) x 50% + 4 = 12 ma. We can then write the controller equation as:

$$output = 12ma - \left(pv - 160^oF\right)\left[\frac{16ma}{20^oF}\right]$$

Thus, if the process variable is at 150 °F, the controller output will be:

$$12ma - \left(155 - 160\right)^oF\left[\frac{16ma}{20^oF}\right] = 16ma$$