Process Control Primer

At the onset of the Industrial Revolution, processes were controlled manually. Men turned valves, pulled levers or changed switches based on the need to turn devices on or off. As the technology of process control evolved, the human links in the process were replaced by products that could automatically make the mechanical adjustments that were necessary, and make them accurately and consistently. This resulted in increased efficiency and greater productivity from the machine, process and operator.

Today, the process industry experiences greater demands for productivity and efficiency. The request for more exotic materials have enhanced the development of products that provide more exacting control. Process control techniques have advanced to include PID, or three-mode, control. Three-mode control (Proportional, Integral and Derivative) furnishes energy in exact accordance with the load of your process instead of in steps that may not match the load requirements. PID control is further defined in this article to explain how it may provide the exacting control necessary for many industrial processes.

PROCESS CONTROL-HOME FURNACE.

The fundamentals of process control affect your daily life in many ways. For example, the furnace that heats your home operates under the principles of process control. To elaborate, you control the temperature of the air in your home by choosing a setting on the thermostat, which in turn controls the furnace. In process control, a setting is referred to as a "setpoint." A setpoint is defined as "the desired value of a process variable." In this example, the process variable is the temperature of the air.

By establishing a desired air temperature setting for your home (setpoint), you expect that gas or oil will be supplied to the furnace to heat the air. The furnace is turned on when the temperature rises above the setpoint. This type of control action is often referred to as two position or "on and off" control.

In more sophisticated thermostats, the amount of fuel delivered to the furnace is regulated according to the number of degrees the actual air temperature differs from the desired temperature. This difference is called the "error or deviation." The deviation is detected by the thermostat. The thermostat controls the amount of heat delivered by the furnace by controlling the amount of fuel burned. For a large deviation, the thermostat sends a proportionately strong regulating signal to the valve that controls the amount of fuel going into the burner. The valve in turn opens proportionately. If the setpoint is reached, the valve receives a weak signal or no signal at all. It closes, and very little heat, if any, is generated.

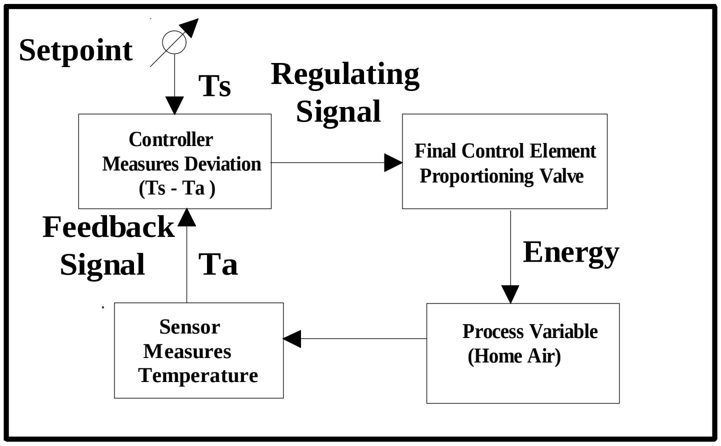

Figure 1-1

The device that senses the air temperature in your home (sensor) sends a signal (feedback signal) to the temperature controller (thermostat). The signal portrays the actual air temperature(At). The thermostat compares the signal received with the setpoint (Ts). A corresponding action (valve opens or closes) occurs depending on the magnitude of the deviation (Ts-At). This Process is called a "Closed Loop" process because there is a feedback signal and the controller adjusts the output automatically (figure 1).

The home furnace uses mostly fossil fuels as a source of energy. Many industrial processes utilize electric heaters as the source of energy. The following paragraphs describe process control in electric heat applications.

PID CONTROL-ELECTRIC HEAT

The amount of heat obtained from an electric heater depends on the voltage applied on the heater. It is desirable in many processes to deliver a portion of the available voltage, thus decreasing the wattage, to meet the process heat-up requirements. In some processes, it is desirable to have extremely tight control on the process temperature. This is achieved through a well-designed thermal system, a precise method of throttling electric heat.

The most precise method used to control energy in a process is referred to as three-mode control, or the PID method. The letters PID stand for Proportional, Integral, and Derivative. These factors are also known as proportional band or gain, reset, and rate. These factors can be entered into a controller and function as a set of instructions to control the release of energy to the process. Each factor is described below.

PROPORTIONAL FACTOR (GAIN OR PROPORTIONAL BAND)

When a proportional instruction is entered into a controller, the amount of energy that is sent to the process changes as the process variable approaches the setpoint. This means that the energy output is affected by the amount of error (deviation) from the setpoint.

A similar situation occurs when most car drivers approach a stop sign. A driver may approach a stop sign (same as setpoint process control) at a high speed using a lot of gas (output). If he waits until he is right at the stop sign (setpoint) to slow down, he will overshoot his mark (move beyond setpoint) and move into the intersection. Therefore, as he approaches the stop sign, he decreases his gas and speed in proportion to the distance he is from the stop sign. The closer he is to the stop sign, the more he decreases the amount of gas sent to the engine. Just as the driver determines the point where he will decrease his speed to control his car's movement toward the stop sign, the proportional setting of the controller in an industrial process determines the point where output should be less than 100% and steadily decreases as the process variable approaches setpoint. The area between the setpoint and the temperature where output is less than 100% is called the proportional band.

In the example below, a heater has ample power (kW capacity) to bring the process temperature to a 300ºF setpoint within an hour. Thereafter, only a fraction of the available power is used to maintain temperature.

The controller used has a temperature range of 0 to 400ºF; hence, its span is 400ºF. In a heating process, the proportional band is defined as the range of temperatures below the setpoint in which proportional control takes place. The band is defined as a percentage of the span. We will assume the proportional band is 15% of the span (i.e., 15% of 400ºF, or, 60ºF). Therefore, with a setpoint of 300ºF, the low limit of the proportional band is 240ºF. The proportioning band and its direction of function varies with the type of process controller used. Our example involves a heating process; proportional action occurs when the process variable is below the setpoint (reverse action) and within the 60º proportional band. Conversely, a cooling process would require proportional band action when the process variable is above the setpoint (direct acting).

In a cooling process with a 300º setpoint and a 15% proportional band, proportional action would be through the range of 300º to 360ºF. The heater heats at full capacity
(100% energy output) until the temperature (process variable) reaches 240ºF, the low limit of the proportional band. When the process variable becomes greater than 240ºF (i.e., entering the proportional band), the energy output delivered by the heater steadily decreases as the process variable approaches the setpoint. Notice that the thermal system finds its own equilibrium at the temperature where the energy needed will be whatever is required to offset the systems heat losses.

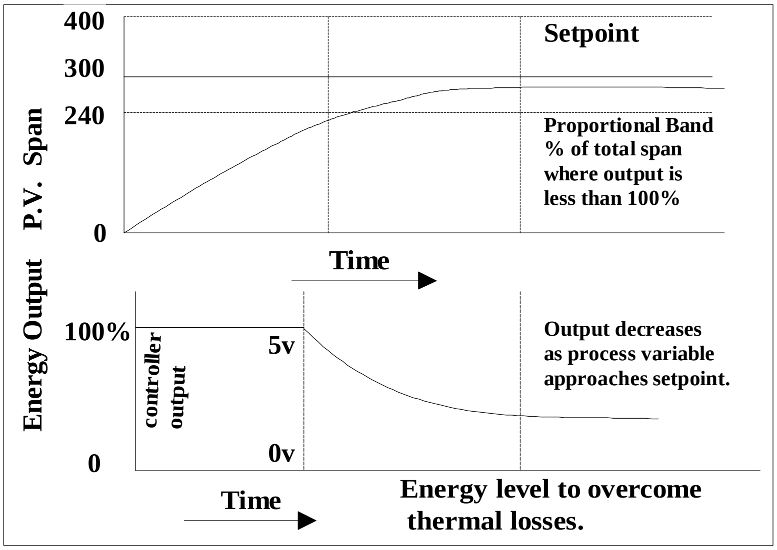

Figure 1-2

Two methods can be used to calculate proportioning action of a controller:

1. Proportioning band (PB)

Proportional bandwidth can be expressed as a relationship with the percentage of the error and the process variable from the setpoint divided by the percentage of the output. By definition 100% PB is the situation where deviation is 100% and output is 100%.

$$100\%\ \text{PB} = \frac{100\%\ \text{input deviation from setpoint}}{\text{input span}}$$

$$\text{From previous example: PB} = \frac{60^{\circ}}{400^{\circ}} = 15\%$$

Since all parameters of this proportional band expression are related to their total spans, they clarify how the process will respond to the controllers proportional term due to the error.

2. GAIN (K)

An alternate expression which is used to describe this proportioning mode (proportional band) on the controller is **GAIN**. Gain is a multiplication term (K) expressing how the controller output varies with respect to a change in input error. To be calculated, both input and output parameters must be expressed in similar engineering units.

$$K = \frac{\text{output}}{\text{input error}}$$

$$\text{From previous example: } K = \frac{100}{15} = 6.66$$

If we express output and input as a percent of their total (as in the case of our previous discussion of proportional band) we can relate GAIN to PB as follows.

$$\text{GAIN} = \frac{\text{change output(\%)}}{\text{change input error(\%)}} = \frac{100\%}{\text{PB\%}}$$

In the practical controller where many varying input ranges can be available, the GAIN term (K) may vary with each different range selected (if expressed in other than its percentage of span) and must be rescaled accordingly to like engineering units for input errors and outputs. For this reason, defining proportional control in terms of the gain expression is often not as convenient as expressing proportional control in terms of proportional band (PB).

Additionally, gain is less decriptive of the process since it does not relate directly to the process span as does percentage PB that tells the user directly over what portion of his total process span the controller proportions.

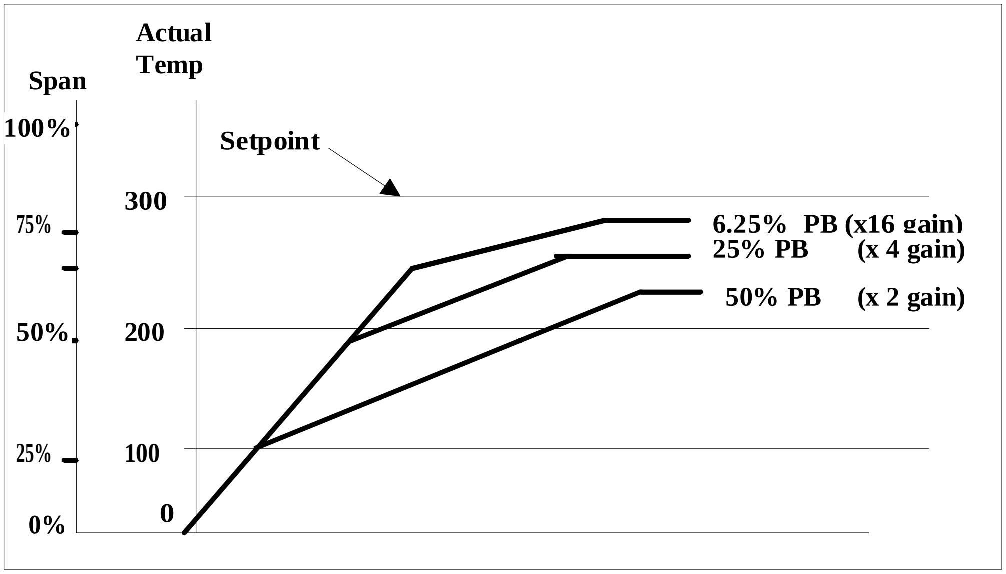

FIGURE 1-3.

EFFECTS OF THE PROPORTIONAL SETTING

If the Gain is set low, the Proportional Band will be wide and the process will reach setpoint more slowly than if the Gain is set high. If the Gain is set high, the proportional band will be narrower.

In order to determine when proportional action will take over during the process (what percent of span the proportional band is equal to), a percentage of the inverse function of the gain is calculated. For example, if a gain term of 25 is entered, the proportional band will be equal to 1/25, or 4% of the total span. If the entire span of the process is equal to 400º, 400 * .04 = 16º. Proportional will begin 16º below setpoint.

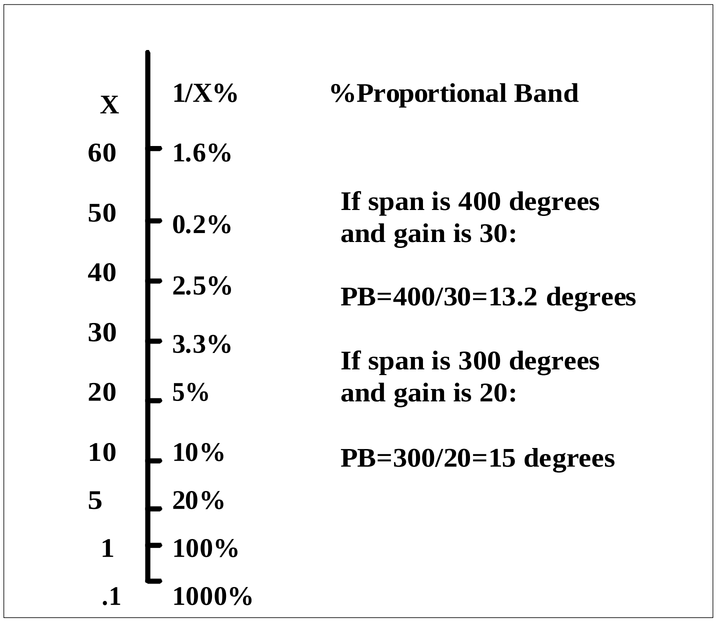

FIGURE 1-4

In summary, proportional control means that the output changes as the deviation (setpoint minus the process variable) changes. Proportional control is only active during part of the process. The point at which it begins is determined by the gain setting. The lower the setting, the lower the temperature point at which proportional action begins.

If the gain is high for the process, the process variable will reach the setpoint, but it will also rise higher (overshoot) than the setpoint, causing the output to return to 0%. If this occurs, the process variable will drop below setpoint, creating a deviation tat will cause the output to rise again. The process would once again exceed setpoint and the output would return to 0%. Oscillation occurs and the process is out of control. In most processes, oscillation may not be permitted due to possible product loss.

For a given process, the point just below where the process variable begins to oscillate defines the maximum proportional band entry.

NOTE: One-mode Proportioning only control can never reach true setpoint since at the true setpoint, the output is zero. An error called **PROPORTIONAL DROOP** is present. To realize an output to the final control element, offset of the setpoint is required.

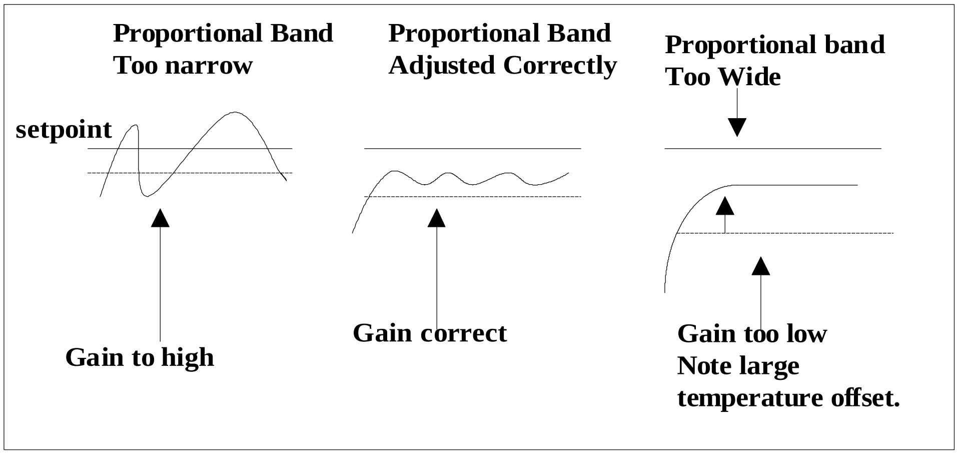

FIGURE 1-5

In order to avoid the on/off cycling of the output signal (oscillation) and the " out of control" condition, the gain term can be lowered so that proportional action begins at a lower temperature and the decreased output causes the output variable to fall within the proportional band. Losses, such as heat escaping from the process, will also cause a steady deviation from setpoint.

The system will reach equilibrium. The temperature at which it reaches equilibrium will be within the proportional band, but may be different from the setpoint. The difference is called "offset". Often this offset is called "droop", as in most applications the equilibrium temperature falls below the setpoint.

Integral Factor (Reset)

Steady state error (offset) is adjusted by adding a second factor in three-mode control. The integral, or reset factor, simply adds or subtracts from the output; it adjusts for the droop caused by the proportional term. Integral is derived from the word "integrate", which means to blend with something or to add something.

In graphs A1 and A2 of figure 1-6, the process variable has reached equilibrium, and due to the heat losses there was not enough heat (as obtained through the proportional setting) to reach the setpoint. The setpoint can be attained (Graph B1) when a reset output (Graph B3) is added to the gain output (Graph B2) to add more heat (Graph B4). This counteracts droop and helps to bring and maintain the process variable at the setpoint. Reset output is actually added to the proportional output only within the proportional band and reset action continues until the process reaches the setpoint (no deviation error).
In tuning the control loop, Reset is enabled after the initial proportioning mode. Its result overcomes the droop.

The reset output is specified in "repeats per minute".

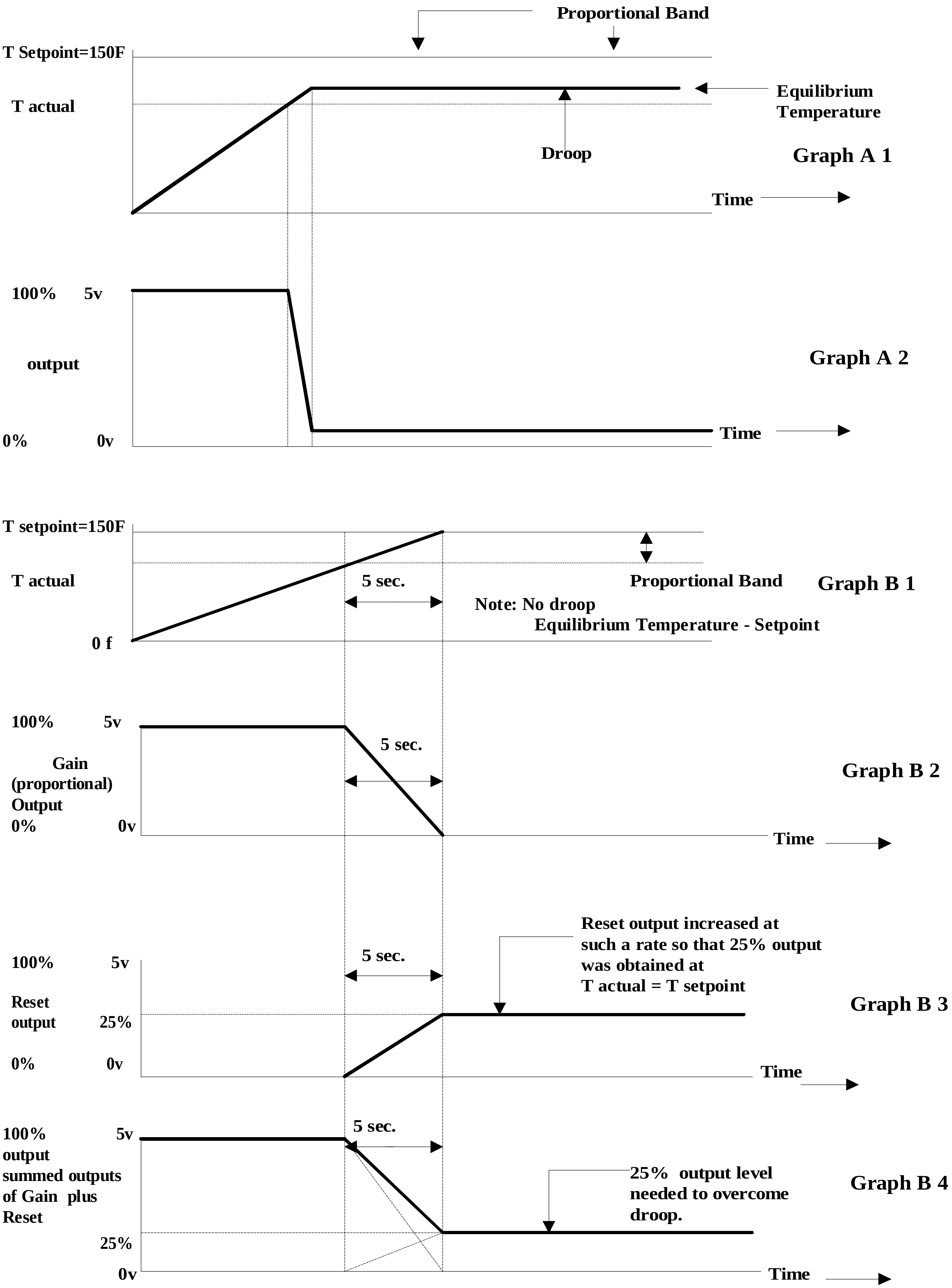
Proportional Band
T Setpoint=150F
T actual
Equilibrium
Temperature
Droop
Graph A 1
Time
100%
5v
output
Graph A 2
0%
0v
Time
T setpoint=150F
T actual
5 sec.
Proportional Band
Graph B 1
Note: No droop
Equilibrium Temperature - Setpoint
0 f
100%
5v
5 sec.
Gain
(proportional)
Output
Graph B 2
0%
0v
Time
Reset output increased at
such a rate so that 25% output
was obtained at
T actual = T setpoint
5 sec.
100%
5v
Graph B 3
Reset
output
25%
0%
0v
Time
5 sec.
100%
5v
output
summed outputs
of Gain plus
Reset
25% output level
needed to overcome
droop.
Graph B 4
25%
0v
Time

Figure 1-6

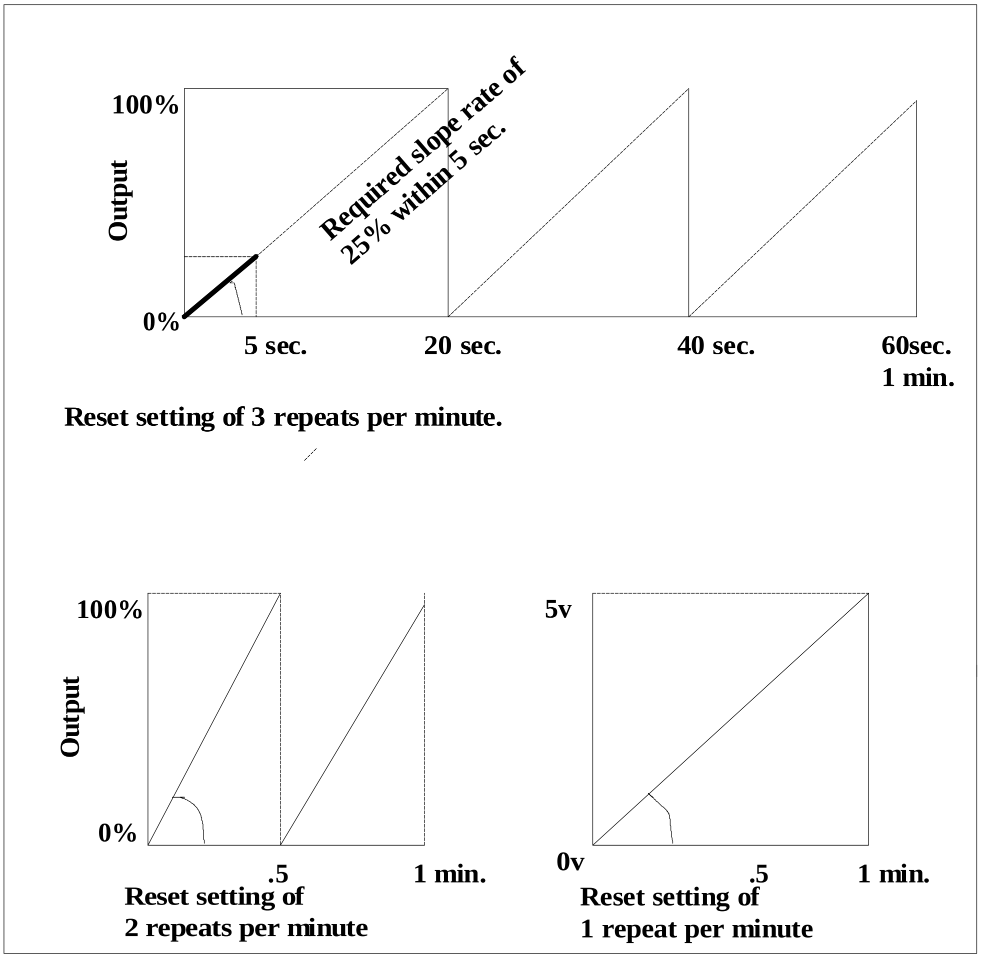

Figure 1-7

To illustrate, let us state that the reset output of our example is three repeats per minute.
This means that 100% of output will be reached three times in one minute (per definition of repeats per minute). It follows that 100% of output will be reached in 20 seconds and 25% of output will be reached in 5 seconds. If 25% output represents the amount of output required to overcome an offset and reach the setpoint, the amount of time required by the process variable to reach setpoint within the proportional band (corresponding to 25% of output) is 5 second. The "repeats per minute" is just a way of specifying the speed at which the reset action overcomes the droop and brings the process to the setpoint.

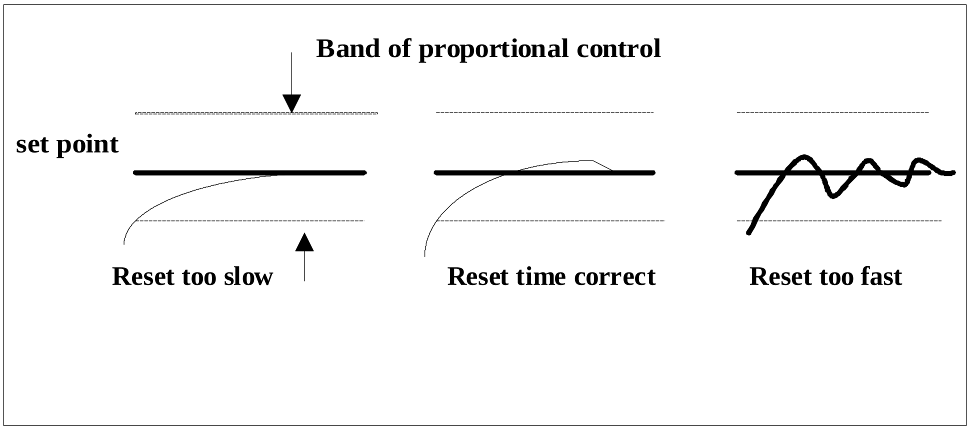

Figure 1-8

Just as too much proportional action causes the process variable to oscillate, a reset setting of to many repeats per minute also causes oscillation. The higher the repeats per minute, the faster the setpoint is reached.

The addition of reset action to proportional action is usually sufficient to stabilize most closed loop processes.

In most heating applications, there is a lag between the time heat is called for by the controller and the time its effects are detected (i.e., rise in temperature). The presence of a lag tends to create overshoots of temperature, as there is to much heat in the system. In the processes where it is necessary to have close control and a lag is present, the tendency for overshoot can be reduced or eliminated by anticipating its presence and correcting the energy output prior to the overshoot. The rate function is introduced to adjust for such a condition.

Derivative Factor (Rate)

Rate differs from the proportional and reset terms in that it opposes change and thus is used to stabilize a process. It increases or decreases the output by responding to the speed and direction of change of the process variable. Often there is a time lag between the time that a change in the proportional or reset terms or a product load change is entered into a system and the time that a process variable is affected by the change. Derivative action advances the effect that proportional action alone has on the final control mechanism, and is expressed in time.

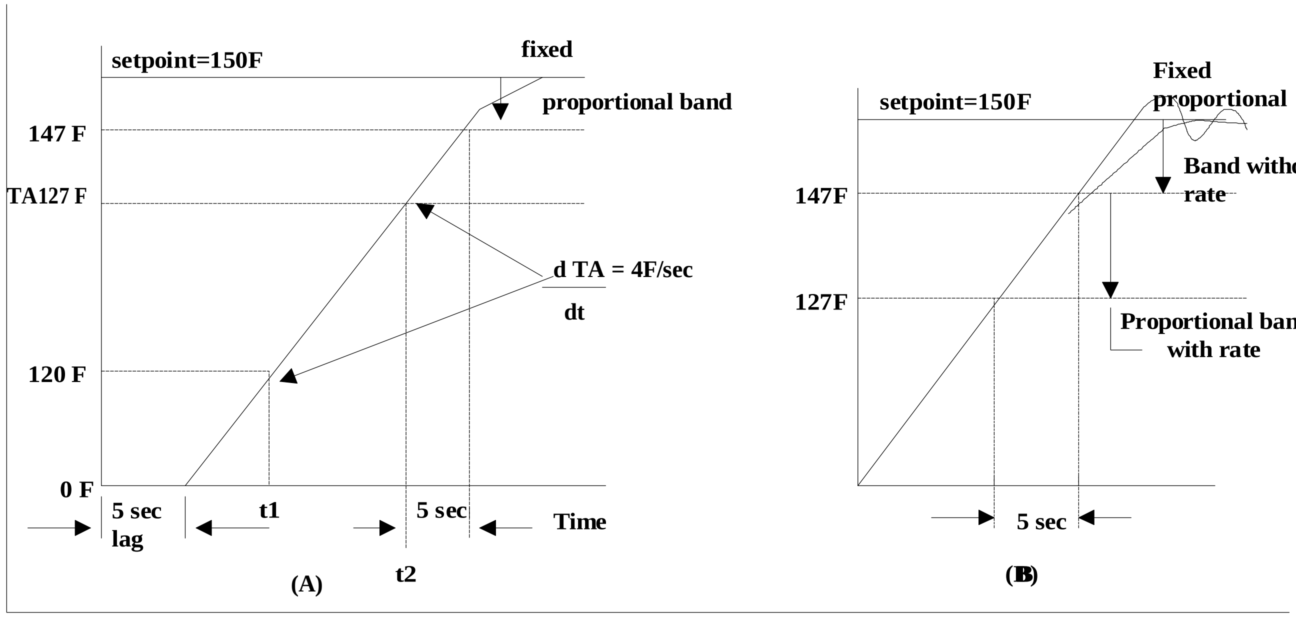

Figure 1-9

The rate factor is often added to processes to anticipate and correct for the process lag and adjust the output to avoid the overshoot occurrence. The rate factor is proportional to the "rate of change" of the actual process variable temperature Ta in figure 1-9a. For example, a rapid temperature change indicates that something drastic is happening. The rate factor would sense this change and cause the process controller to make less corrective action than with the fixed proportional band.

In effect, it causes proportional action to occur by an amount directly proportional to the rate of temperature change and the thermal lag time. The result is corrective action permitting maximum allowable rise rates commensurate with the anticipated time lag of the system (see figure 1-9b).

As an example, let us assume there is a 5 second lag in our system controlled (PD controller) from the moment heat is applied to the moment a temperature rise begins (see figure 1-9a). The value of rate (Kd) set on the controller is equal to the lag (five seconds). There is also a rate of change of actual temperature of 4ºF/second as the process variable rises toward the setpoint of 150ºF. The proportional band is equal to 3ºF. The factor is derived as follows:

$$\frac{dTa}{dt} \quad x \quad Kd \quad = \quad \frac{4^{\circ}F}{sec} \quad x \quad 5\ sec \quad = \quad 20^{\circ}F$$

When this rate factor is subtracted from the deviation, the output will only be affected when the result is less than the proportional band. For example, at time t1, the setpoint is 150ºF and the process variable is 120ºF. The result is:

$$T\ setpoint - T\ actual - 20^{\circ}F = 150^{\circ}F - 120 - 20 = 10^{\circ}F$$

At this time, the rate factor would not affect the output. However, at time t2 (figure 1-9a), if the process variable is at 127ºF, the result is:

$$150^{\circ}F \ - \ 127^{\circ}F \ - \ 20^{\circ}F \ = \ 3^{\circ}F$$

At this time, corrective rate action begins to affect system operations. The corrected error signal now falls inside the edge of the proportional band, and dynamic proportioning action will begin slowing the systems thermal rise rate to prevent overshoot. Thus, proportioning action starts 23ºF from setpoint (20ºF rate factor plus 3ºF PB) rather than 3ºF from setpoint.

Rate is measured in seconds of anticipation or seconds of thermal lag. It should be added only after initial Gain and Reset adjustments have been made.

Summary

1. In closed loop process control, a feedback signal is sent to the temperature controller to adjust the amount of energy that is sent to the process. The amount of the deviation of the process variable from the setpoint determines the amount of energy that is sent to the process.

2. Proportional control takes place within the proportional band. This means that the output of the controller changes in proportion to the amount of deviation of the process variable from the setpoint.

3. The proportional band is defined as the range of temperature around the setpoint in which proportional action takes place. It is the percent of the total span of the controller where the output is less than 100%. Proportional bandwidth is expressed as a relationship of the percentage of the error of the process variable from the setpoint divided by the percentage of output.

4. Gain is alternate expression used to describe the proportioning mode. Gain is a multiplication term (A) (see page 4).

5. If the Gain is set low, the Proportional Band will be wide and the process may never reach setpoint. If the Gain setting is high, the Proportional Band will be narrower.

6. A temperature control process which the output is set by the proportional only control will reach thermal equilibrium. The temperature at which it reaches equilibrium will be within the proportional band, but will be different from the setpoint. In proportional only control, the process variable cannot equal the setpoint because by definition there would be no output at true setpoint.

7. The integral or "reset" output (expressed in repeats per minute) adds to the proportional output to adjust for the droop caused by thermal losses.

8. Reset action is actually added to the proportional output only within the proportional band. Reset action continues until the process reaches setpoint (no deviation error).

9. Rate differs from the gain and reset factors in that it opposes change when the process variable is within the proportional band. It increases or decreases the output by responding to the speed and direction of change of the process variable. In effect, it causes proportional action to occur outside the proportional band by an amount directly proportional to the rate and direction of temperature change.

10. Rate is measured in seconds of anticipation or seconds of thermal lag.

Definition Of Terms

Bi-Modal Control - A control arrangement that provides both direct acting and reverse acting control. See direct action control and reverse acting control.

Closed loop - A signal path which includes a final control element for the process and a process feedback which is compared to the setpoint to determine the deviation. A deviation signal addresses the final control element and provides automatic control of the process. Called the AUTO mode.

Controller - A device which controls the amount of energy sent to a process within specific limits of time, load, and process equipment capabilities. A controller accepts an input (thermocouple, RTD) which is connected directly to the process sensing element and must provide all the necessary signal conditioning internally, i.e. amplification, linearization, and reference junction compensation.

Derivative - See Rate

Deviation - The difference of the actual temperature of the process as compared to the desired temperature (setpoint - process variable).

Direct Acting Control - A control arrangement in which the process controller output increases if the process variable rises above the setpoint. Typically used to control cooling equipment. See reverse acting control and bi-modal control.

Feedback Element - Provides a signal analogous to the process variable magnitude that can be compared with the desired value or setpoint. This element modifies and conveys the information back to the controller.

Feedback Signal - In closed loop control, the signal which causes the controller to adjust its output to cause the deviation to decrease. Also called process variable.

Final Control Element - Provides the force to do the work of the control loop. It is a device used to modulate the energy for the process which may be addressed by the process controller output. Examples are electric power controllers (SCR thyristors, saturable core reactors, or valves in wet systems.

Gain - An alternate expression which is used to describe the proportioning mode (Proportional Band) on the controller is Gain. Gain is a multiplication term (K) expressing how the controller output varies with respect to a change in input error. To be calculated, both input and output parameters must be expressed in similar engineering units.

$$K = \frac{\text{output}}{\text{input error}}$$

If we expressed output and input as a percent of their total (as in the case of our discussion of proportional band). We can relate Gain to PB as follows.

$$\text{Gain} = \frac{\text{change output (\%)}}{\text{change input error(\%)}} = \frac{100\%}{\text{PB\%}}$$

Integral Control - See Reset

Offset - A condition which occurs when the process has reached equilibrium but has not reached the setpoint. Called droop.

Open Loop - In open loop Manual control the operator adjusts the final control element to send energy to the process for the result desired. The result is not automatic and requires constant operator attention to correct for outside influences that tend to affect the process result. Examples of such conditions are drafts, changes in the energy source supply of voltage, stream pressure, etc.

Oscillation - Cycling of the process variable signal above and below the setpoint.

Output - The signal delivered from the controller to the final controller (actuator) on the process.

Primary Element - Any device such as a thermocouple or RTD (resistant temperature device) which senses the controlled variable within the process.

Process - Any work function in which energy is added to or removed from which results in a change in the process state. For convenience, some measurable parameter is derived from a process variable sensor that provides an indication of the process state.

Process Variable - A process quantity, property or condition which is measured. Common measured variables are temperature, pressure, rate of flow, thickness, speeds, etc.

Proportional Band (PB) - The range of the process variable around the setpoint in which the output changes as the deviation (difference of the process variable temperature and the setpoint temperature) changes. Proportional band can be expressed as a relationship of the percentage of the error of the process variable from the setpoint divided by the percentage of the output. By definition 100% PB is the situation where deviation is 100% and output is 100%.

$$\text{PB} = \frac{\text{100\% input deviation from setpoint}}{\text{Input Span}} = 100\%$$

The proportioning bandwidth and its direction of function varies with the type of process controller used. A heating process requires proportional action below the setpoint (reverse action). Conversely, a cooling process would require proportional band action when the process variable is above the setpoint (direct acting).

Proportional Control - Proportional control means that the output changes as the deviation (setpoint minus the process variable) changes. Proportional control is only active during part of the process. The point at which it begins is determined by the gain setting. This setting determines how fast the process will react and whether setpoint will be achieved.

Range - The region of output or process variable movement between the minimum and maximum range values.

Rate (derivative)(D) - Rate differs from the proportional and reset terms in that it opposes change and thus is used to stabilize a process. It increases or decreases the output by responding to the speed and direction of change of the process variable. The control action responds inversely to the rate of change of the process variable instead of its deviation from setpoint.

Reset (integral)(I) - Reset adds to the gain output only when the process is in the proportional band range. Reset acts on the deviation of the process variable from the setpoint and adds its output to the proportional output to counter the offset which naturally occurs when the system reaches thermal equilibrium in proportional control.
When the process variable equals the setpoint (no deviation), all the output is due to the reset factor.

Reverse Acting Control - A control arrangement in which the process controller output increases if the process variable drops below the setpoint. Typically used to control heating equipment. See direct acting and bi-modal control.

Setpoint - The desired value of a process variable.

Signal Conditioner - A device which performs scaling and arithmetic functions. Some examples are square root extractors, summers, multiplier/dividers, and scalers.

Span - The difference between the upper and lower range values of the process variable. Defined by the limits of the controller sensing devices (thermocouples, RTD's, etc.). For example, a range of -100º to +900º ... has a span of 1000º.