Controller Algorithms and Tuning

The previous sections of this module described the purpose of control, defined individual elements within control loops, and demonstrated the symbology used to represent those elements in an engineering drawing. The examples of control loops used thus far have been very basic. In practice, control loops can be fairly complex. The strategies used to hold a process at setpoint are not always simple, and the interaction of numerous setpoints in an overall process control plan can be subtle and complex. In this section, you will be introduced to some of the strategies and methods used in complex process control loops.
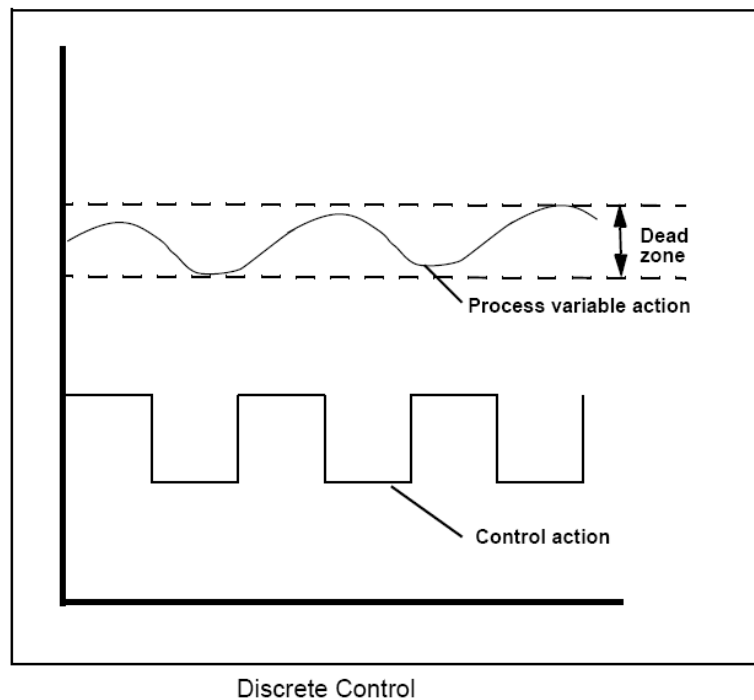
Controller Algorithms

The actions of controllers can be divided into groups based upon the functions of their control mechanism. Each type of contoller has advantages and disadvantages and will meet the needs of different applications. Grouped by control mechanism function, the three types of controllers are:

- ❏ Discrete controllers
- ❏ Multistep controllers
- ❏ Continuous controllers

DISCRETE CONTROLLERS

Discrete controllers are controllers that have only two modes or positions: on and off. A common example of a discrete controller is a home hot water heater. When the temperature of the water in the tank falls below setpoint, the burner turns on. When the water in the tank reaches setpoint, the burner turns off. Because the water starts cooling again when the burner turns off, it is only a matter of time before the cycle begins again. This type of control doesn't actually hold the variable at setpoint, but keeps the variable within proximity of setpoint in what is known as a *dead zone* (Figure 7.15).

Discrete Control

Controller Algorithms

MULTISTEP CONTROLLERS

Multistep controllers are controllers that have at least one other possible position in addition to on and off. Multistep controllers operate similarly to discrete controllers, but as setpoint is approached, the multistep controller takes intermediate steps. Therefore, the oscillation around setpoint can be less dramatic when multistep controllers are employed than when discrete controllers are used (Figure 7.16).
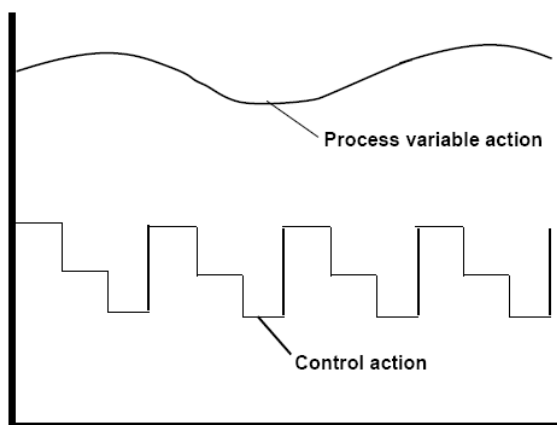
Process variable action

Control action

Figure 7.16: Multistep Control Profile

CONTINUOUS CONTROLLERS

Controllers automatically compare the value of the PV to the SP to determine if an error exists. If there is an error, the controller adjusts its output according to the parameters that have been set in the controller. The tuning parameters essentially determine:

How much correction should be made? The *magnitude* of the correction(change in controller output) is determined by the proportional mode of the controller.
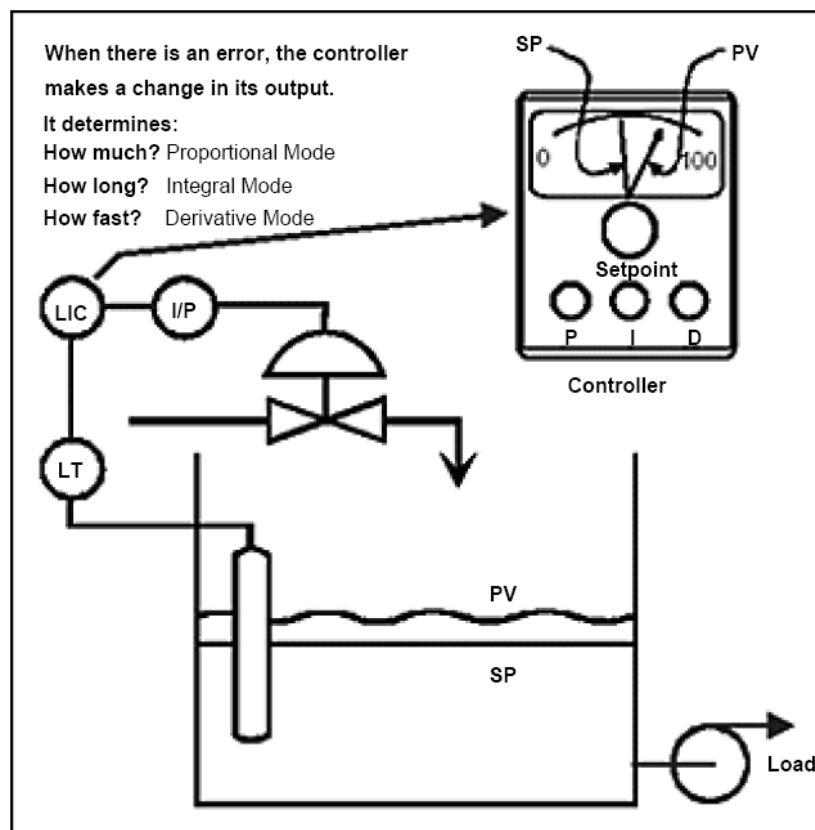
How long should the correction be applied? The *duration* of the adjustment to the controller output is determined by the integral mode of the controller

How fast should the correction be applied? The *speed* at which a correction is made is determined by the derivative mode of the controller.

Controller Algorithms

When there is an error, the controller makes a change in its output.

It determines:
How much? Proportional Mode
How long? Integral Mode
How fast? Derivative Mode

SP

PV

0   100

Setpoint

P   I   D

Controller

LIC   I/P

LT

PV

SP

Load

Automatic Feedback Control

Why Controllers Need Tuning?

Controllers are tuned in an effort to match the characteristics of the control equipment to the process so that two goals are achieved: is the foundation of process control measurement in that electricity:

❑ The system responds quickly to errors.
❑ The system remains stable (PV does not oscillate around the SP).

GAIN

Controller tuning is performed to adjust the manner in which a control valve (or other final control element) responds to a change in error. In particular, we are interested in adjusting the *gain* of the controller such that a change in controller input will result in a change in controller output that will, in turn, cause sufficient change in valve position to eliminate error, but not so great a change as to cause instability or cycling.

Gain is defined simply as the change in output divided by the change in input.

Examples:
Change in Input to Controller - 10%
Change in Controller Output - 20%
   Gain = 20% / 10% = 2

Change in Input to Controller - 10%
Change in Controller Output - 5%
   Gain = 5% / 10% = 0.5
convey measurements and instructions to other instruments in a control loop to maintain the highest level of safety and efficiency.

The next three sections in this module discuss electricity, circuits, transmitters, and signals in greater detail so you can understand the importance of electricity in process control.
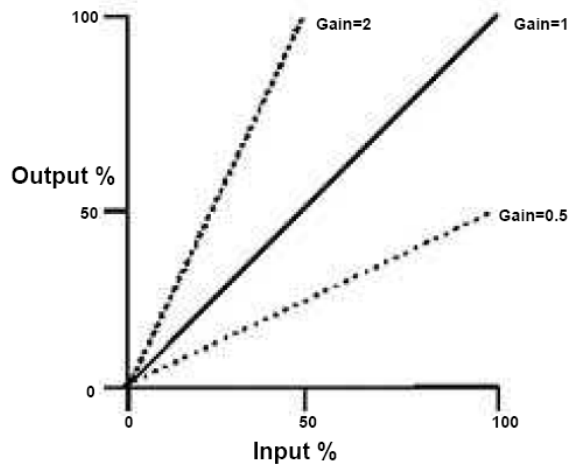
Why Controllers Need Tuning?

Gain Plot - The Figure below is simply another graphical way of representing the concept of gain.

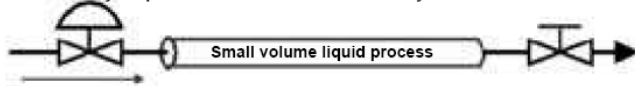$$\text{Gain Kc} = \Delta \text{ Output \% } / \Delta \text{ Input \%}$$

Activities

4. Fast or slow processes have no impact on controller gain settings. Is this statement true or false?

Graphical Representaion of Gain Concept

Examples - The following examples help to illustrate the purpose of setting the controller gain to different values.
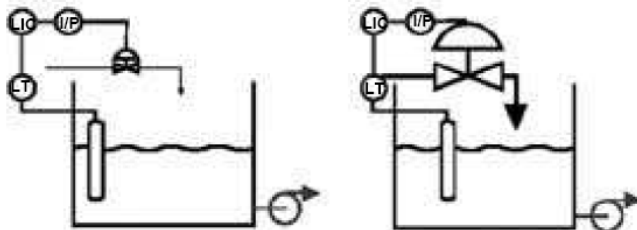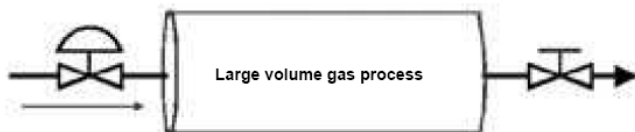
Controllers May be Tuned to Help Match the Valve to the Process

Fast Process May Require Less Gain To Achieve Stability

Small volume liquid process

Slow Process May Require Higher Gain To Achieve Responsiveness

Large volume gas process

Fast and Slow Processes May Require Different Controller Gain Settings

Proportional Mode

PROPORTIONAL ACTION

The proportional mode is used to set the basic gain value of the controller. The setting for the proportional mode may be expressed as either:
1. Proportional Gain
2. Proportional Band

PROPORTIONAL GAIN

In electronic controllers, proportional action is typically expressed as proportional *gain*. Proportional Gain (Kc) answers the question:
"What is the percentage change of the controller output relative to the percentage change in controller input?"
Proportional Gain is expressed as:

$$\text{Gain, } (Kc) = \Delta Output\% / \Delta Input \%$$

PROPORTIONAL BAND

Proportional Band (PB) is another way of representing the same information and answers this question:
"What percentage of change of the controller input span will cause a 100% change in controller output?"

$$PB = \Delta Input (\% \text{ Span}) \text{ For } 100\% \Delta Output$$

Converting Between PB and Gain

A simple equation converts *gain to proportional Band:*
added.

PB = 100/Gain

Also recall that:

Gain = 100%/PB

$$\text{Proportional Gain, } (Kc) = \Delta Output\% / \Delta Input \%$$

$$PB = \Delta Input(\%Span) \text{ For } 100\% \Delta Output$$
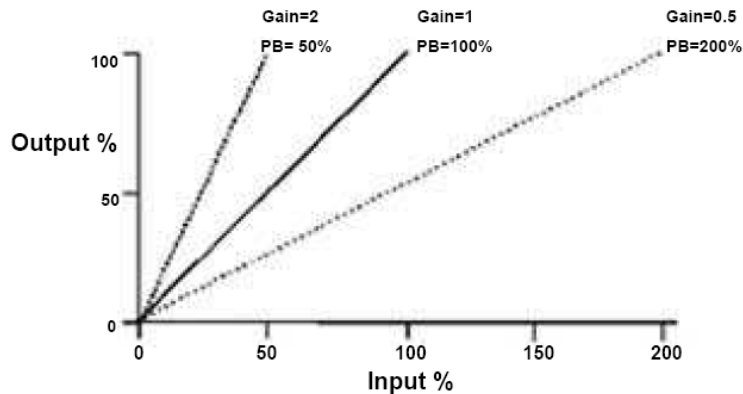
Proportional Mode

Relationship of Proportional Gain and Proportional Band

LIMITS OF PROPORTIONAL ACTION

Responds Only to a Change in error - Proportional action responds *only* to a *change in the magnitude* of the error.

Does Not Return the PV to Setpoint - Proportional action will *not* return the PV to setpoint. It will, however, return the PV to a value that is within a defined span (PB) around the PV.

DETERMINING THE CONTROLLER OUTPUT

Controller Output - In a proportional only controller, the output is a function of the change in error and controller gain.

Output Change, % = (Error Change, %) (Gain)

Example: If the setpoint is suddenly changed 10% with a proportional band setting of 50%, the output will change as follows:

Calculating Controller Output

ΔController Output = ΔInput, % X Gain
Gain = 100%/PB

EXAMPLE

ΔInput = 10%
PB = 50%, so Gain = 100%/50% = 2

Proportional Mode

ΔController Output = Δ Input X Gain
ΔController Output = 10% X 2 = 20%

Expressed in Units:
Controller Output Change = (0.2)(12 psi span) = 2.4 psi OR
(0.2)(16 mA span) = 3.2 mA

PROPORTIONAL ACTION - CLOSED LOOP

Loop Gain - Every loop has a critical or natural frequency. This is the frequency at which cycling may exist. This critical frequency is determined by all of the loop components. If the loop gain is too high at this frequency, the PV will cycle around the SP; i.e., the process will become unstable.

Low Gain Example - In the example below, the proportional band is high (gain is low). The loop is very stable, but an error remains between SP and PV.

Proportional Control Closed Loop - Low Gain Example
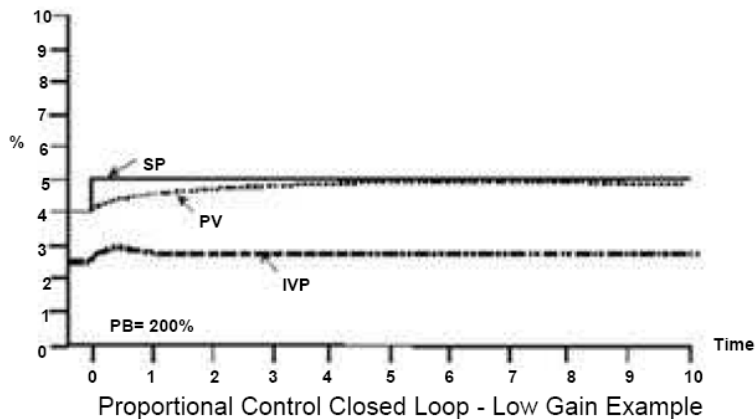
High Gain Example - In the example, the proportional band is small resulting in high gain, which is causing instability. Notice that the process variable is still not on set point.

Proportional Mode
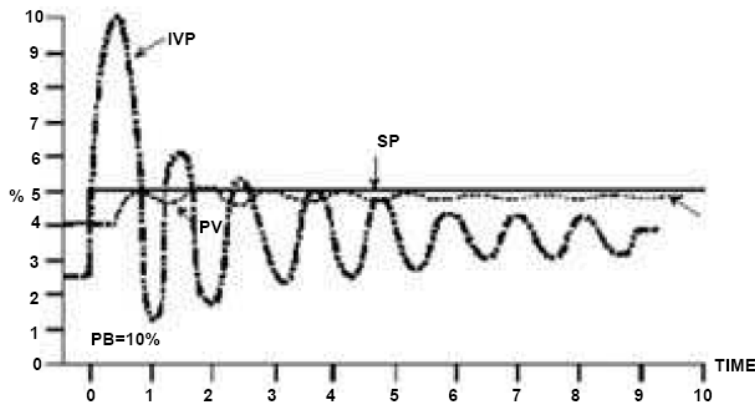
Proportional Control Closed Loop - High Gain example

Proportional Summary - For the proportional mode, controller output is a function of a change in error. Proportional band is expressed in terms of the percentage change in error that will cause 100% change in controller output. Proportional gain is expressed as the percentage change in output divided by the percentage change in input.

$$PB = (\Delta Input, \% / \Delta Output, \%) \times 100 = 100/Gain$$

$$Gain = \Delta Input \% / \Delta Output \%$$

Δ Controller Output = (Change in Error)(Gain)
1. Proportional Mode Responds only to a change in error
2. Proportional mode alone will not return the PV to SP.
Advantages - Simple
Disadvantages - Error
Settings - PB settings have the following effects:

Small PB (%)   Minimize Offset
High Gain (%)   Possible cycling

Large PB (%)   Large Offset
Low Gain   Stable Loop

Tuning - reduce PB (increase gain) until the process cycles following a disturbance, then double the PB (reduce gain by 50%).

Activities

7. What will be the result if the proportional gain is set too high?
   Select all options that apply.

   1   Large offset
   2   Minimized offset
   3   Possible cycling
   4   Stable loop

Integral Mode

INTEGRAL ACTION

Duration of Error and Integral Mode - Another component of error is the *duration* of the error, i.e., how long has the error existed? The controller output from the integral or reset mode is a function of the duration of the error.

INTEGRAL(RESET)
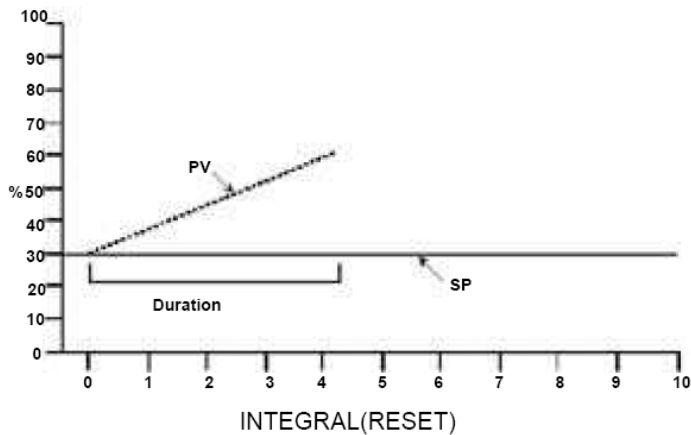
OPEN LOOP ANALYSIS

Purpose- The purpose of integral action is to return the PV to SP. This is accomplished by repeating the action of the proportional mode as long as an error exists. With the exception of some electronic controllers, the integral or reset mode is always used with the proportional mode.

Setting - Integral, or reset action, may be expressed in terms of:
> **Repeats Per Minute -** How many times the proportional action is repeated each minute.
> **Minutes Per Repeat -** How many minutes are required for 1 repeat to occur.

8. _____ action is the type of control algorithm that eliminates offset.
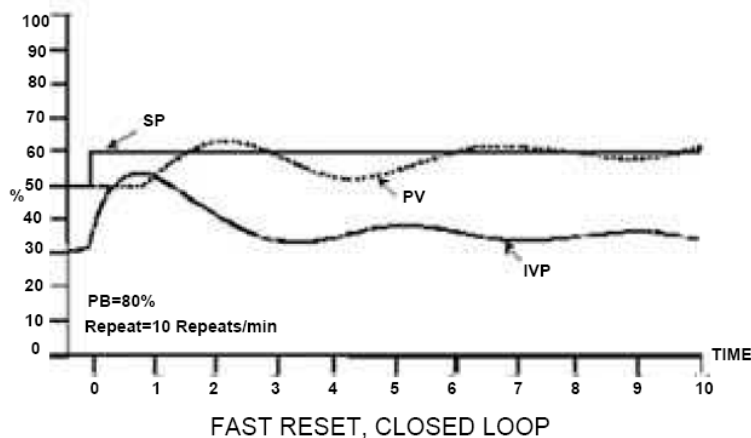
Integral Mode

CLOSED LOOP ANALYSIS

Closed Loop With Reset - Adding reset to the controller adds one more gain component to the loop. The faster the reset action, the greater the gain.

Slow Reset Example - In this example the loop is stable because the total loop gain is not too high at the loop critical frequency. Notice thatthe process variable does reach set point due to the reset action.

SLOW RESET, CLOSED LOOP
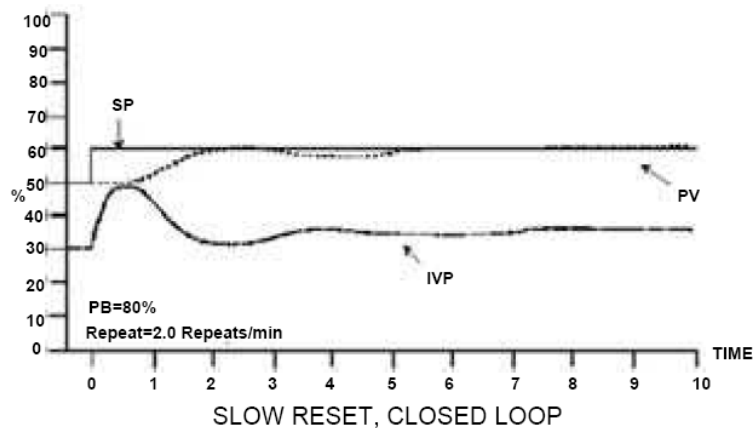
Fast Reset Example - In the example the rest is too fast and the PV is cycling around the SP.

FAST RESET, CLOSED LOOP

Activities

9. Which of the following are integral or reset actions expressed in terms of?
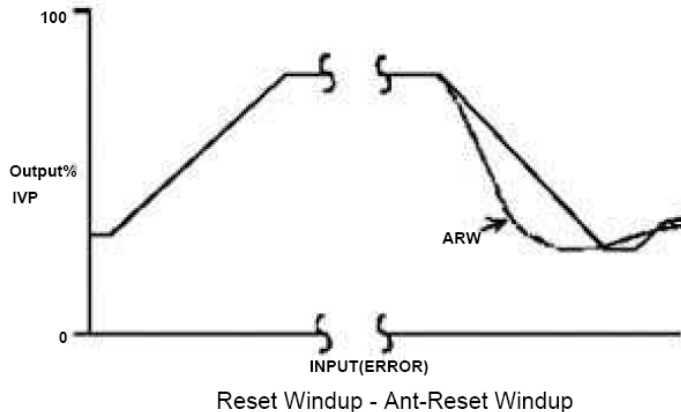   Select all options that apply.

 | 1 | Repeats per setting |
2	Repeats per minute
3	Repeats per loop
4	Minutes per repeat

Integral Mode

RESET WINDUP

Defined - Reset windup is described as a situation where the controller output is driven from a desired output level because of a large difference between the set point and the process variable.

Reset Windup - Ant-Reset Windup

Shutdown - Reset windup is common on shut down because the process variable may go to zero but the set point has not changed, therefore this large error will drive the output to one extreme.

Reset Windup - Shutdown and Startup
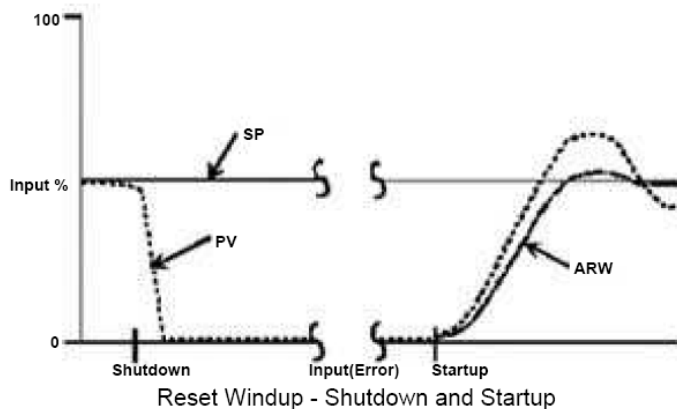
Startup - At start up, large process variable overshoot may occur because the reset speed prevents the output from reaching its desired value fast enough.

Anti Reset Windup - Controllers can be modified with an anti-reset

Activities

10. Identify the major disadvantages of integral action.
    Select all options that apply.

    1   Tends to leave an offset
    2   Reset windup during shutdown
    3   Possible overshoot during start up
    4   Can cause cycling in fast process by amplifying noisy signals

Integral Mode

windup (ARW) device. The purpose of an anti-reset option is to allow the output to reach its desired value quicker, therefore minimizing the overshoot.

SUMMARY

Integral (Reset) Summary - Output is a repeat of the proportional action as long as error exists. The units are in terms of repeats per minute or minutes per repeat.

Advantages - Eliminates error

Disadvantages - Reset windup and possible overshoot

Fast Reset
(Large Repeats/Min.,Small Min./Repeat)

1. High Gain
2. Fast Return To Setpoint
3. Possible Cycling

Slow Reset
(Small Repeats/Min.,Large Min./Repeats)

1. Low Gain
2. Slow Return To Setpoint
3. Stable Loop

Trailing and Error Tuning - Increase repeats per minute until the PV cycles following a disturbance, then slow the reset action to a value that is 1/3 of the initial setting.
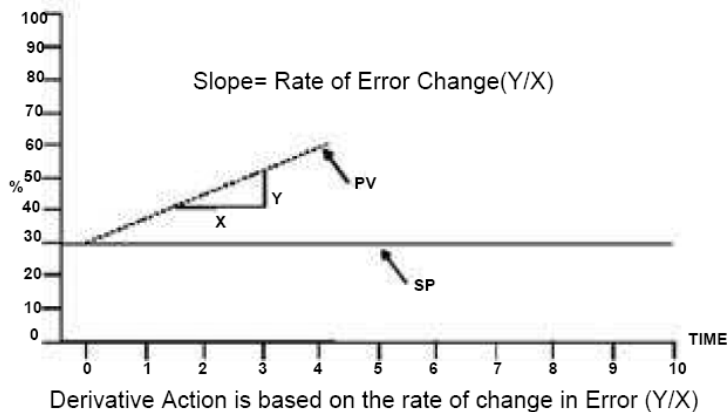
Derivative Mode

DERIVATIVE ACTION

Derivative Mode Basics - Some large and/or slow process do not respond well to small changes in controller output. For example, a large liquid level process or a large thermal process (a heat exchanger) may react very slowly to a small change in controller output. To improve response, a large initial change in controller output may be applied. This action is the role of the derivative mode.

The derivative action is initiated whenever there is a *change in the rate of change of the error* (the slope of the PV). The magnitude of the derivative action is determined by the setting of the derivative . The mode of a PID controller and the rate of change of the PV. The Derivative setting is expressed in terms of *minutes*. In operation, the the controller first compares the current PV with the last value of the PV. If there is a change in the slope of the PV, the controller etermines what its output would be at a future point in time (the future point in time is determined by the value of the derivative setting, in minutes). The derivative mode *immediately* increases the output by that amount.

Derivative Action is based on the rate of change in Error (Y/X)

Activities

11. _____ action is a control algorithm that is tied to the rate of change in the error.

12. Which of the following are derivative or rate actions expressed in terms of?

  1   Repeats per minute
  2   Hours
  3   Seconds
  4   Minutes
  5   Milliseconds

Derivative Mode

Example - Let's start a closed loop example by looking at a temperature control system. IN this example, the time scale has been lengthened to help illustrate controller actions in a slow process. Assume a proportional band settingof 50%. There is no reset at this time. The proportional gain of 2 acting on a 10% change in set pint results in a change in controller output of 20%. Because temperature is a slow process the setting time after a change in error is quite long. And, in this example, the PV never becomes equal to the SP because there is no reset.

Rate Effect - To illustrate the effect of rate action, we will add the are mode with a setting of 1 minute. Notice the very large controller output at time 0. The output spike is the result of rate action. Recall that the change in output due to rate action is a function of the *speed (rate) of change of error,* which in a step is nearly infinite. The addition of rate alone will not cause the process variable to match the set point.
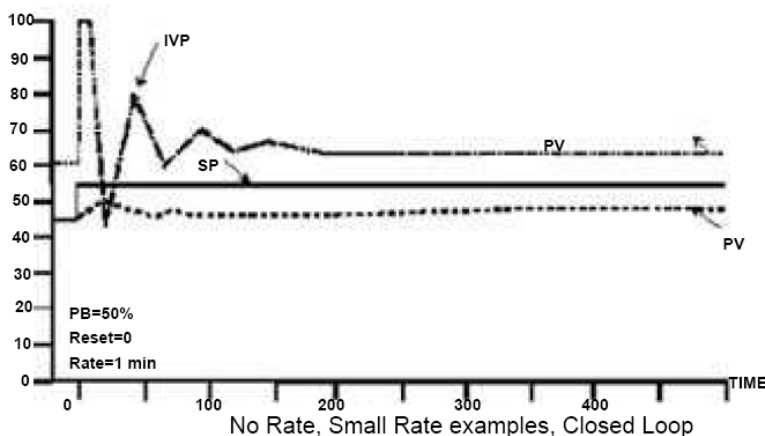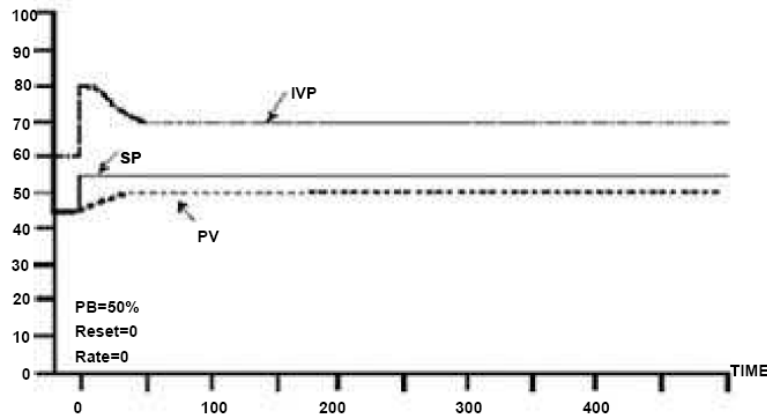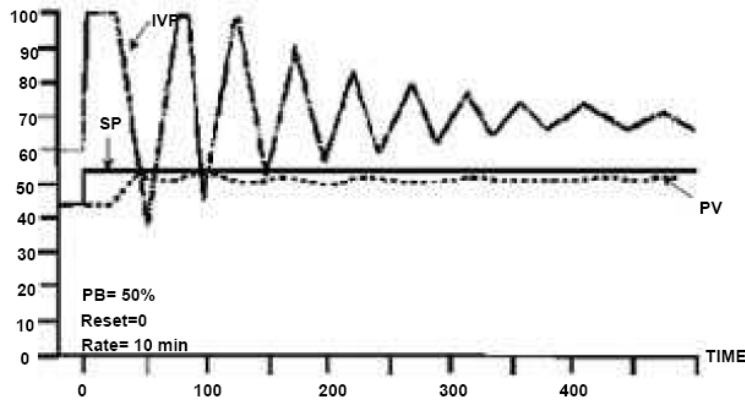
No Rate, Small Rate examples, Closed Loop

Derivative Mode

Effect of Fast Rate - Let's now increase the rate setting to 10 minutes. The controller gain is now much higher. As a result, both the IVP (controller output) and the PV are cycling. The point here is that increasing the rate setting will not cause the PV to settle at the SP.

P+D, High Rate Setting, Closed Loop Analysis

Need for Reset Action - It is now clear that reset must be added to bring process variable back to set point.

Applications - Because this component of the controller output is dependent on the *speed of change* of the input or error, the output will be very erratic if rate is used on fast process or one with noisy signals. The controller output, as a result of rate, will have the greatest change when the input changes rapidly.

Controller Option to Ignore Change in SP - Many controllers, especially digital types, are designed to respond to changes in the PV only, and to ignore changes in SP. This feature eliminates a major upset upset that would occur following a change in the setpoint.

Derivative Mode

SUMMARY

Derivative (Rate) Sumary - Rate action is a function of the *speed of change* of the error. The units are *minutes*. The action is to apply an immediate response that is equal to the proportional plus reset action that would have occurred some number of minutes I the future.

Advantages - Rapid output reduces the time that is required to return PV to SP in slow process.

Disadvantage - Dramatically amplifies noisy signals; can cause cycling in fast processes.

Settings

Large (Minutes)	1.High Gain
	2.Large Output Change
	3.Possible Cycling
Small (Minutes)	1.Low Gain
	2.Small Output Change
	3.Stable Loop

Trial-and-Error Tuning

Increase the rate setting until the process cycles following a disturbance, then reduce the rate setting to one-third of the initial value.

Controller Algorithms

Proportional, PI, and PID Control

By using all three control algorithms together, process operators can:

- ❏ Achieve rapid response to major disturbances with derivative control
- ❏ Hold the process near setpoint without major fluctuations with proportional control
- ❏ Eliminate offset with integral control

Not every process requires a full PID control strategy. If a small offset has no impact on the process, then proportional control alone may be sufficient.

PI control is used where no offset can be tolerated, where *noise* (temporary error readings that do not reflect the true process variable condition) may be present, and where excessive *dead time* (time after a disturbance before control action takes place) is not a problem.

In processes where no offset can be tolerated, no noise is present, and where dead time is an issue, customers can use full PID control. Table 7.2 shows common types of control loops and which types of control algorithms are typically used.

Controlled Variable	Proportional Control	PI Control	PID Control
Flow	Yes	Yes	No
Level	Yes	Yes	Rare
Temperature	Yes	Yes	Yes
Pressure	Yes	Yes	Rare
Analytical	Yes	Yes	Rare

Table 7.2: Control Loops and Control Algorithms

Activities

14. What type of control is used in an application where noise is present, but where no offset can be tolerated?

1   P only
2   PD
3   PI
4   PID