CONTROLLERS

FOR PROCESS APPLICATIONS

What is a Controller??

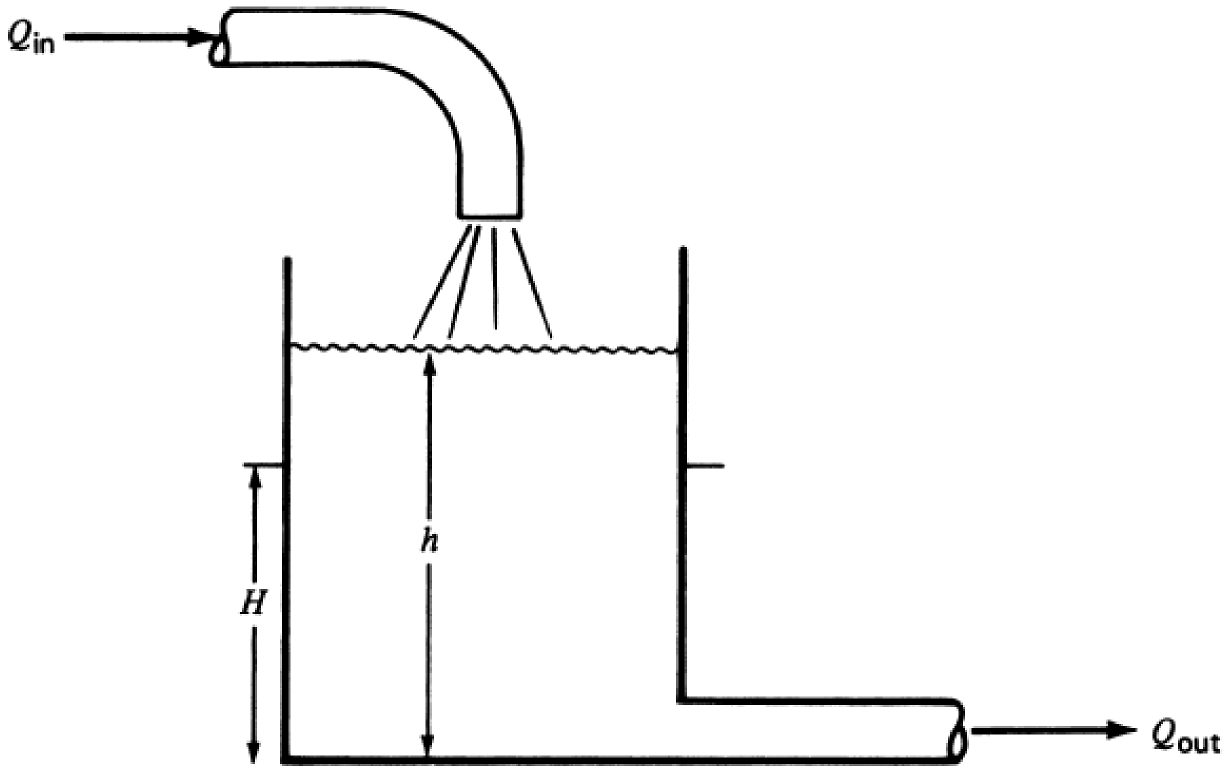


FIGURE 1
The objective is to regulate the level of liquid in the tank, *h*, to the value *H*.

What is a Controller??

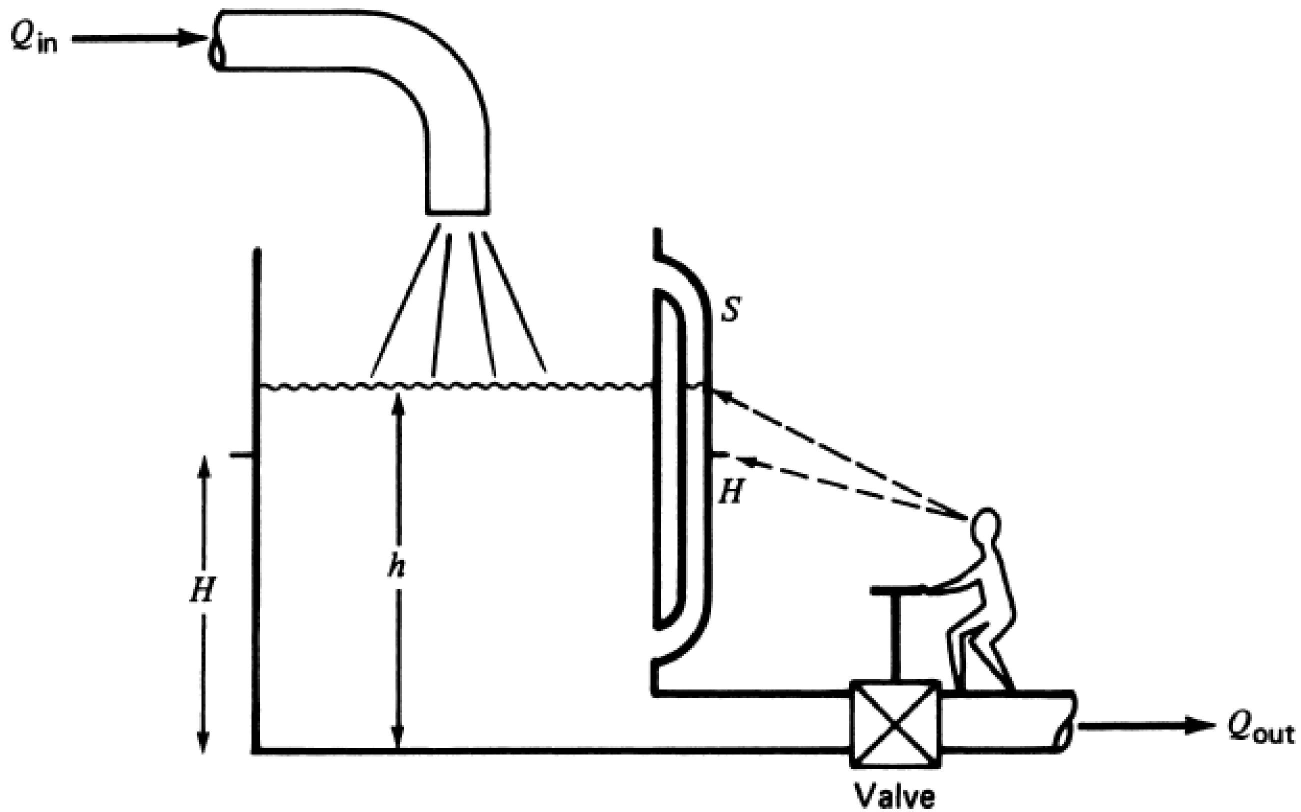


FIGURE 2
A human can regulate the level using a sight tube, *S,* to compare the level, *h,* to the objective, *H,* and adjust a valve to change the level.

What is a Controller??

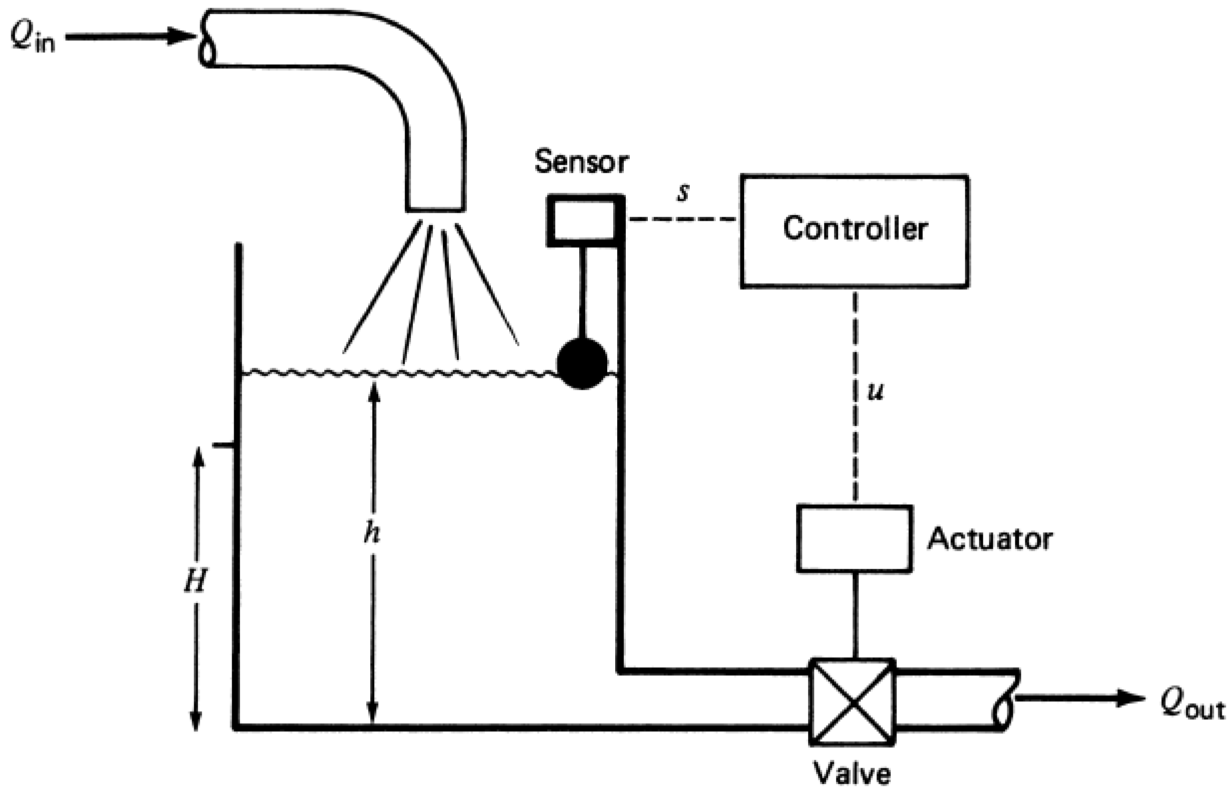
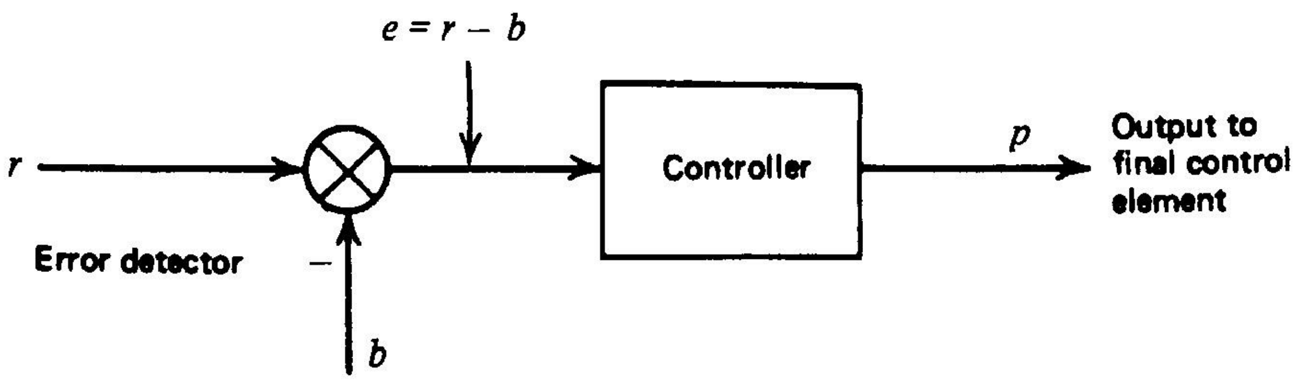


FIGURE 3
An automatic level-control system replaces the human with a controller and uses a sensor to measure the level.

What is a Controller??



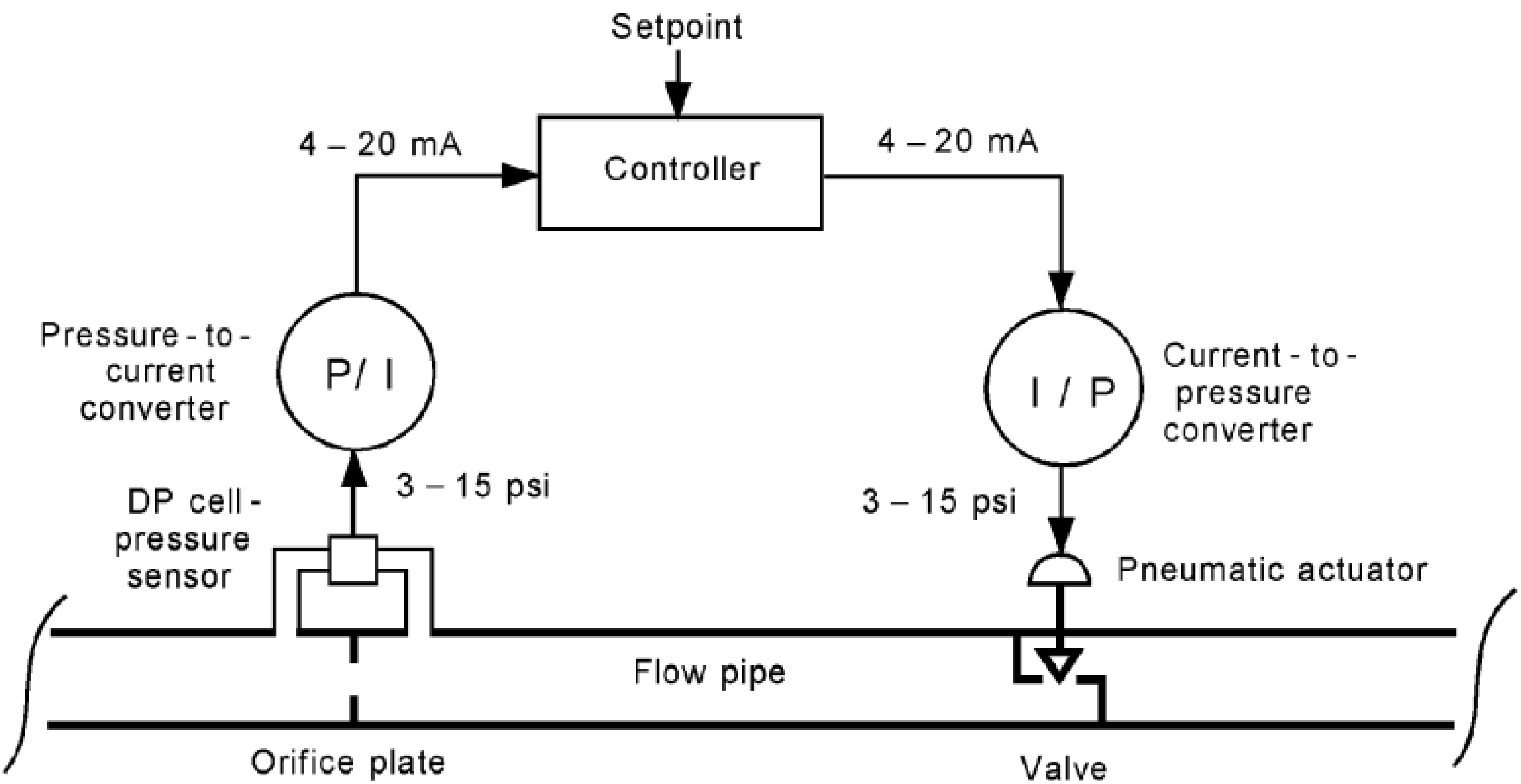
The deviation or error of the controlled variable from the setpoint is given by

$$e = r - b$$

where

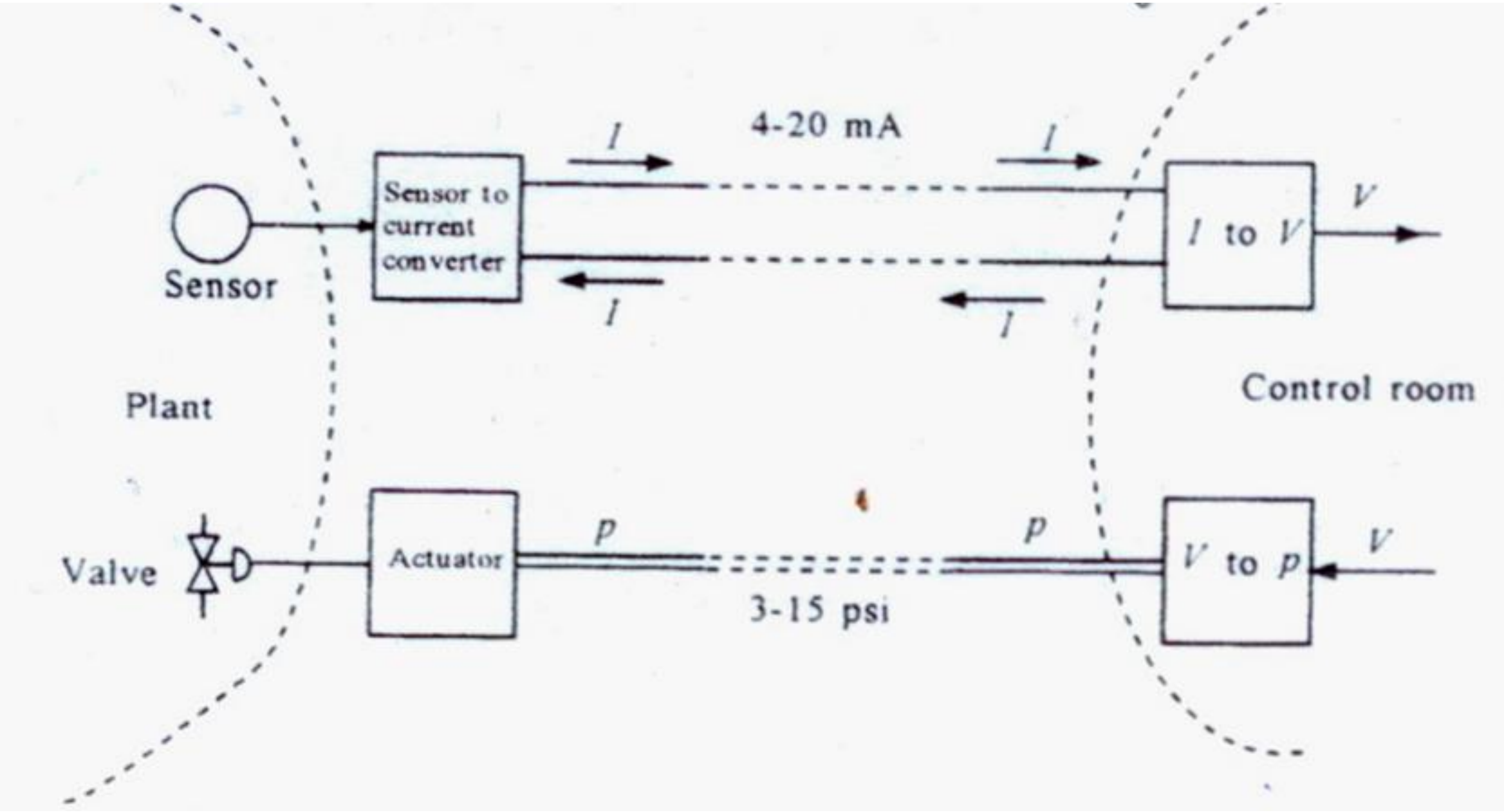
e = error
b = measured indication of variable
r = setpoint of variable (reference)

What is a Controller??

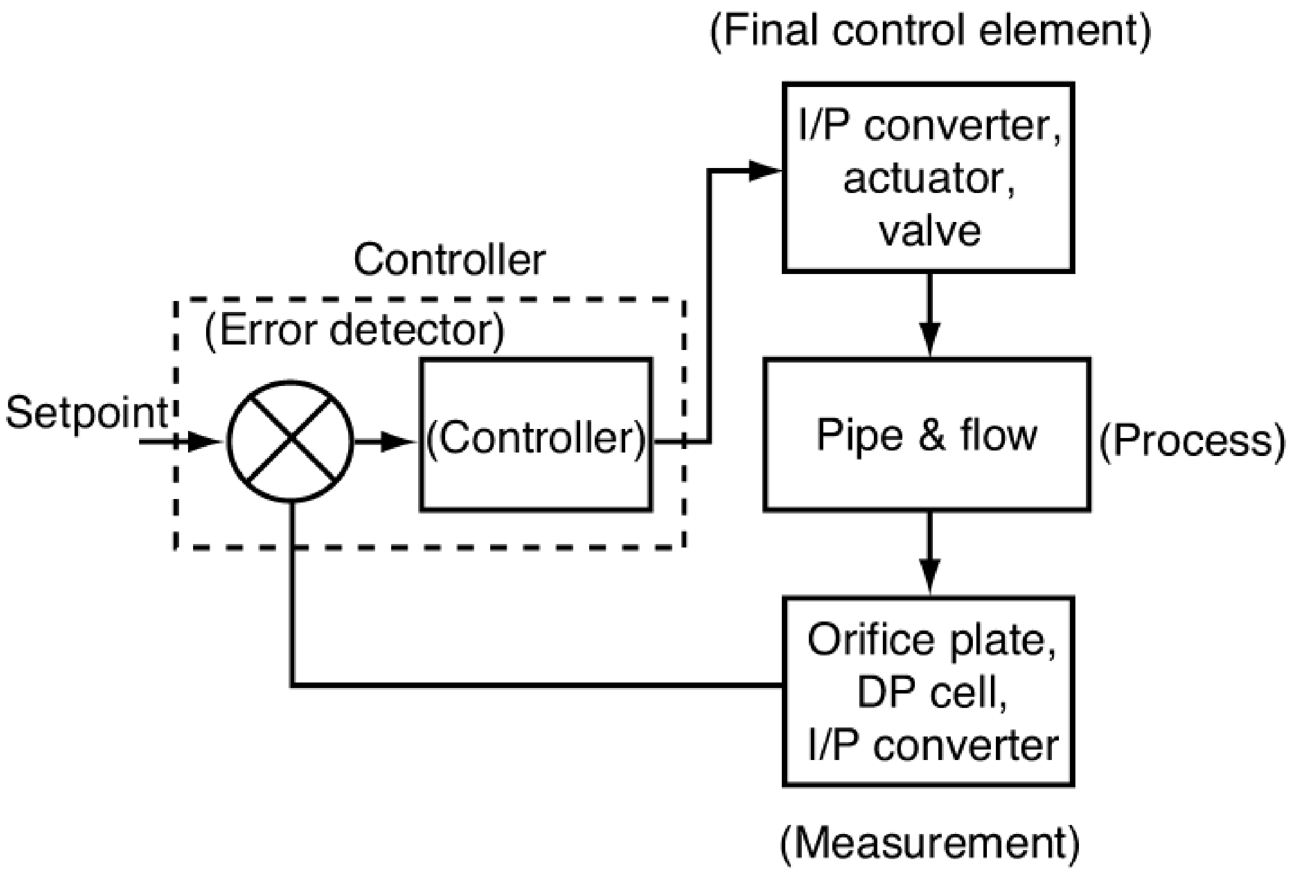


(a) Physical diagram of a process-control loop

What is a Controller??

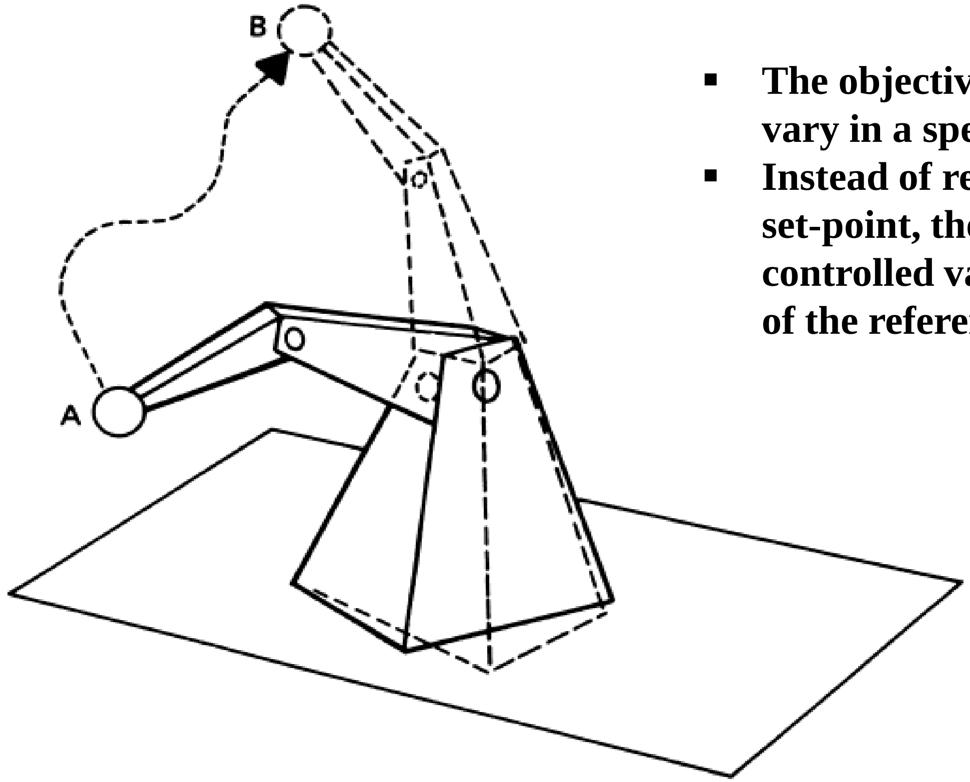


What is a Controller??



(b) Block diagram of the process-control loop

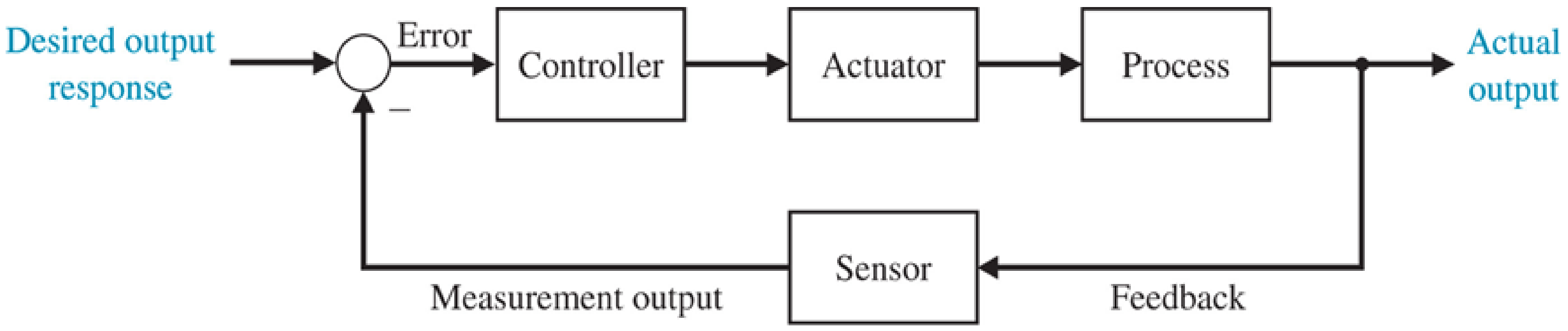
Servo-Mechanisms/ Tracking Control System

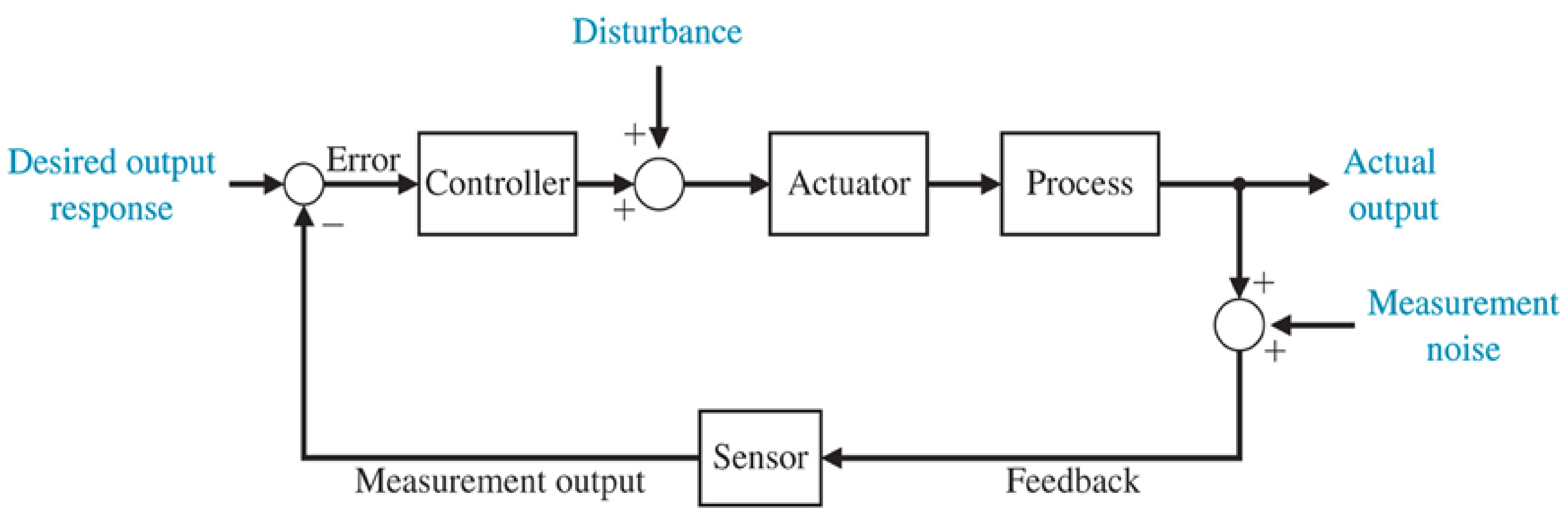


- **The objective is to force some parameter to vary in a specific manner.**
- **Instead of regulating a variable value to a set-point, the servomechanism forces the controlled variable value to follow variation of the reference value.**

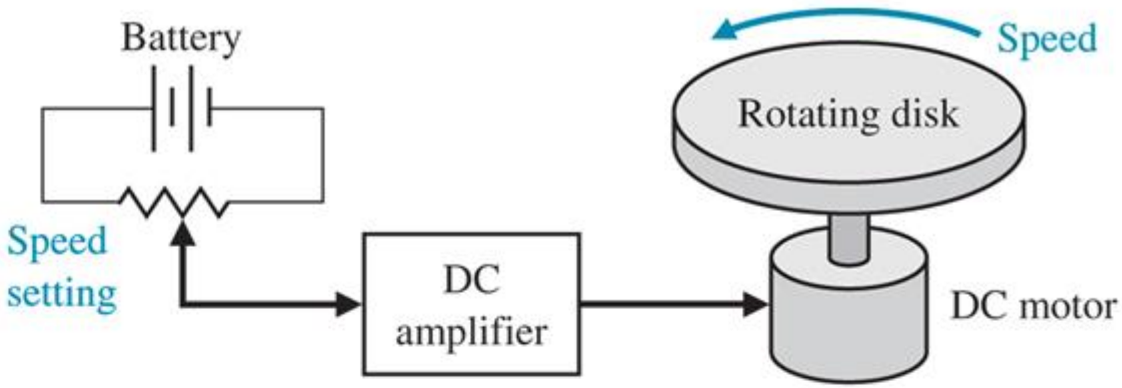
FIGURE 4
Servomechanism-type control systems are used to move a robot arm from point *A* to point *B* in a controlled fashion.

Closed Loop Feedback Control System

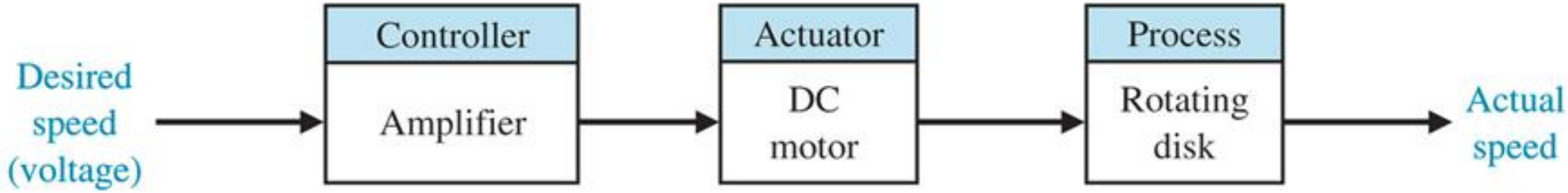




Open Loop Control System

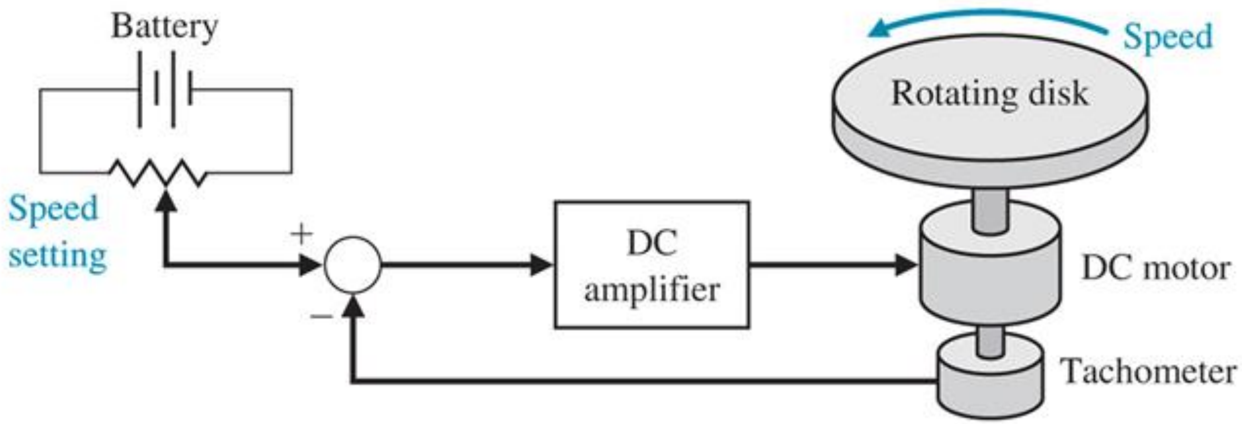


(a)

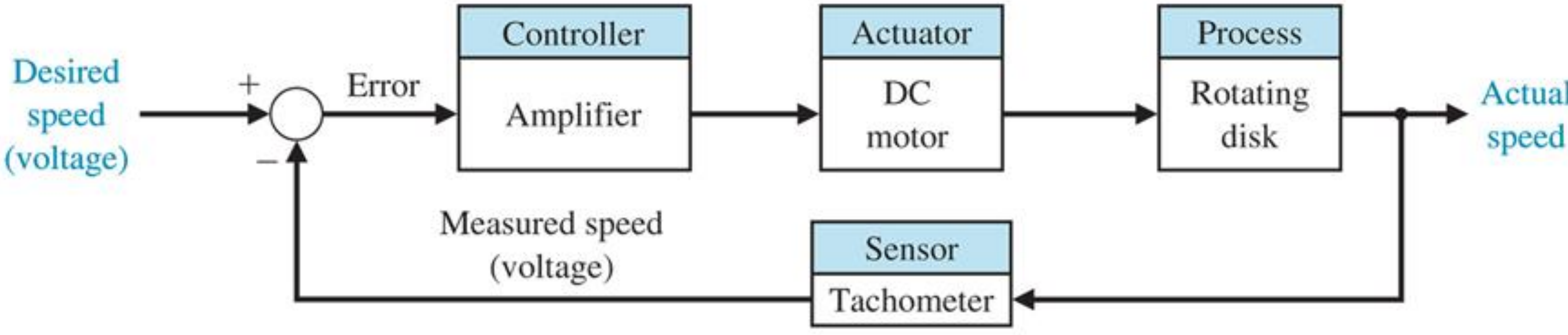


(b)

Closed Loop/Feedback Control System

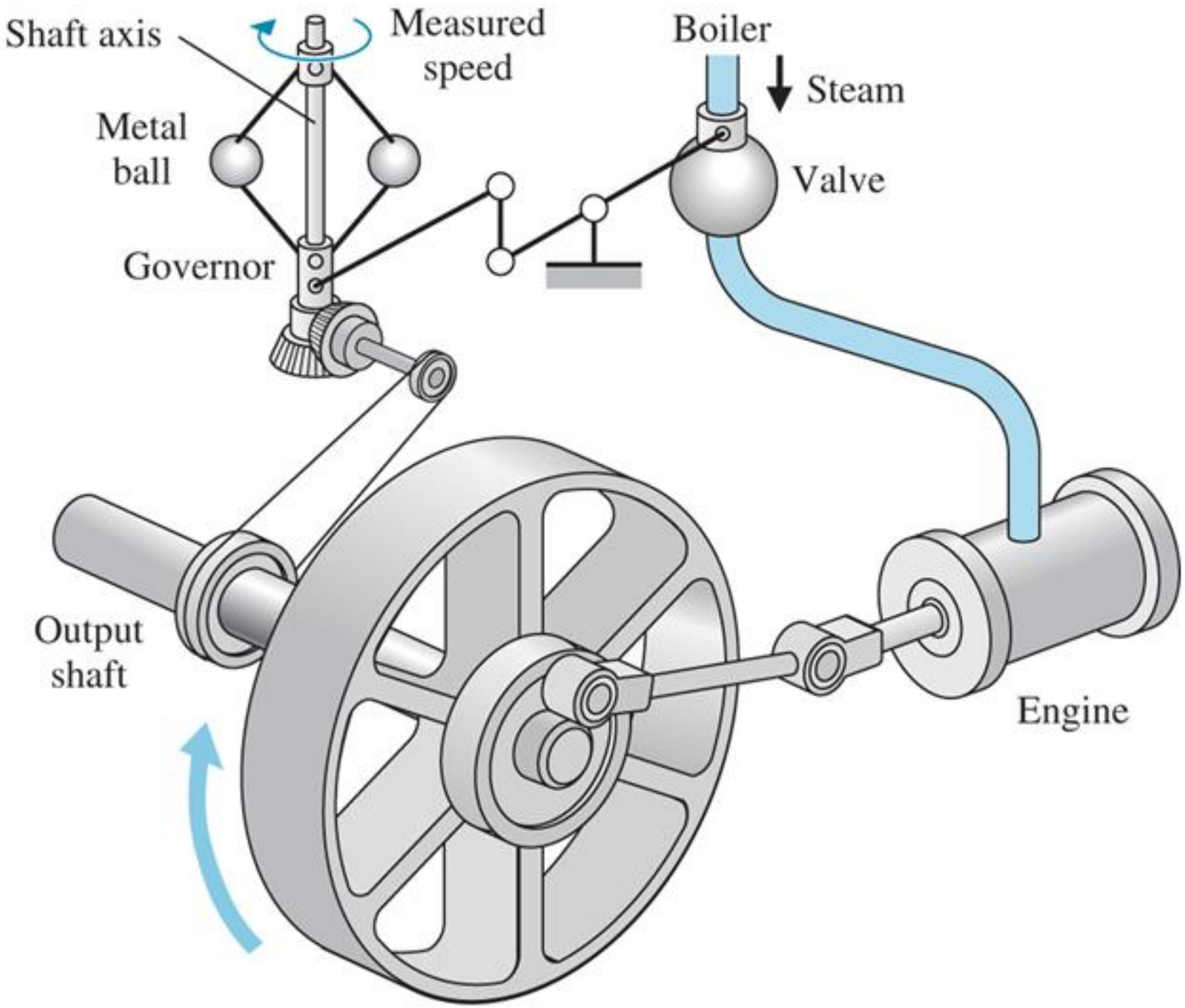


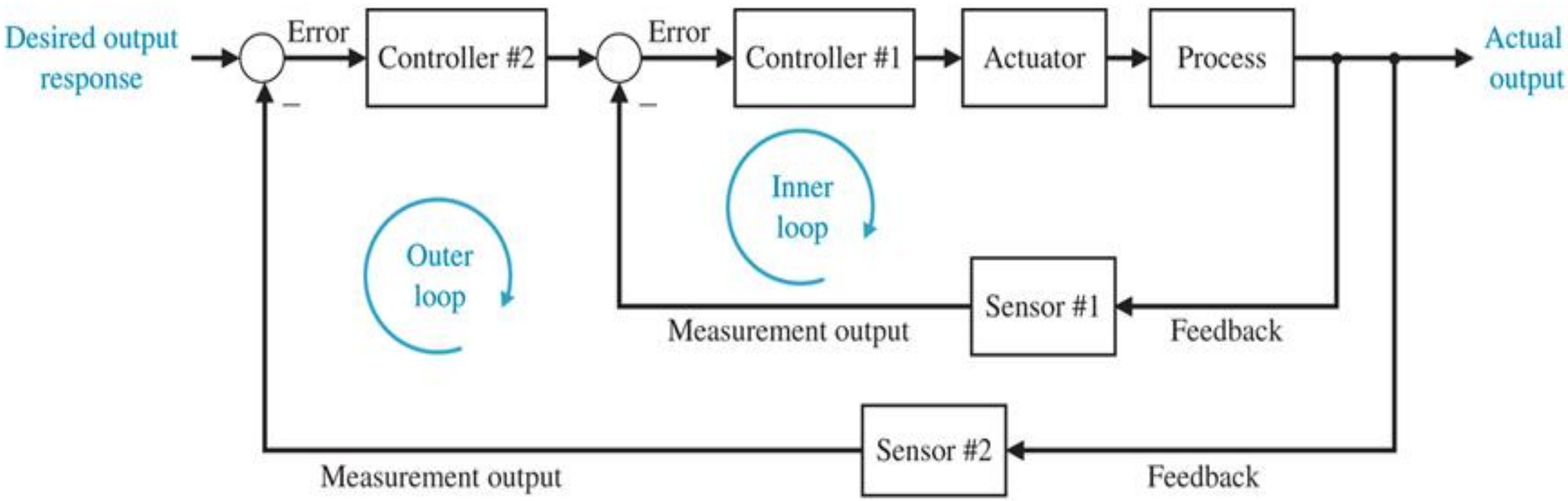
(a)



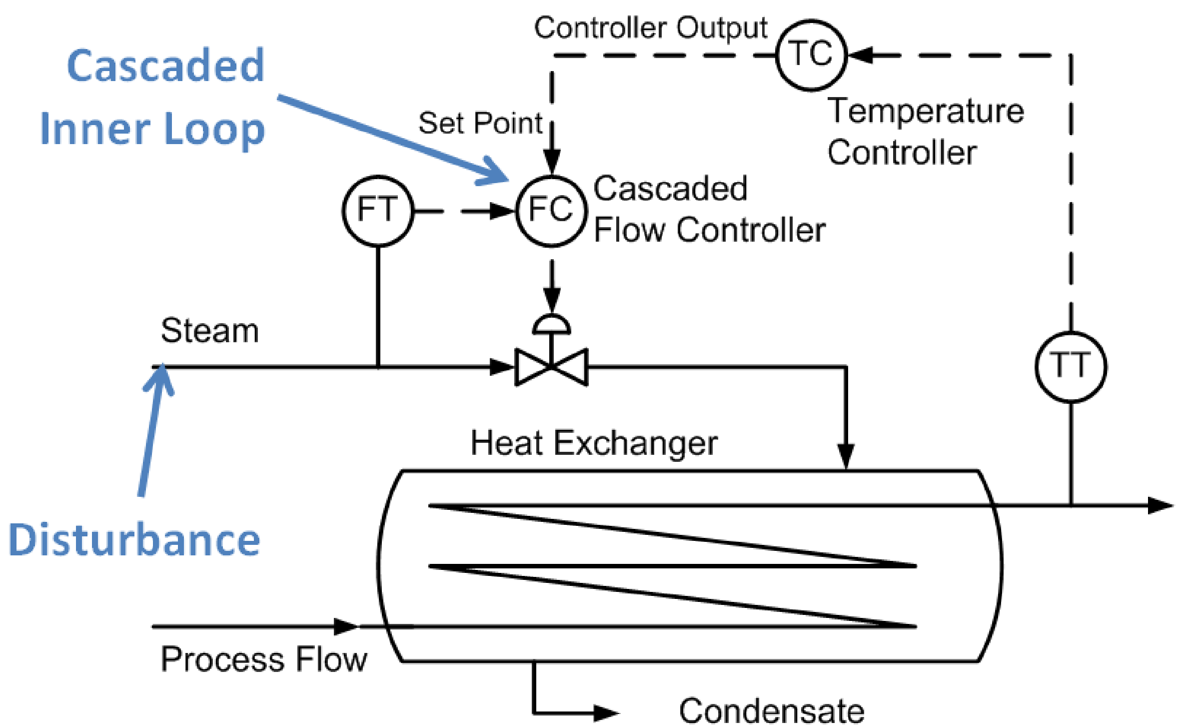
(b)

Closed Loop/Feedback Control System

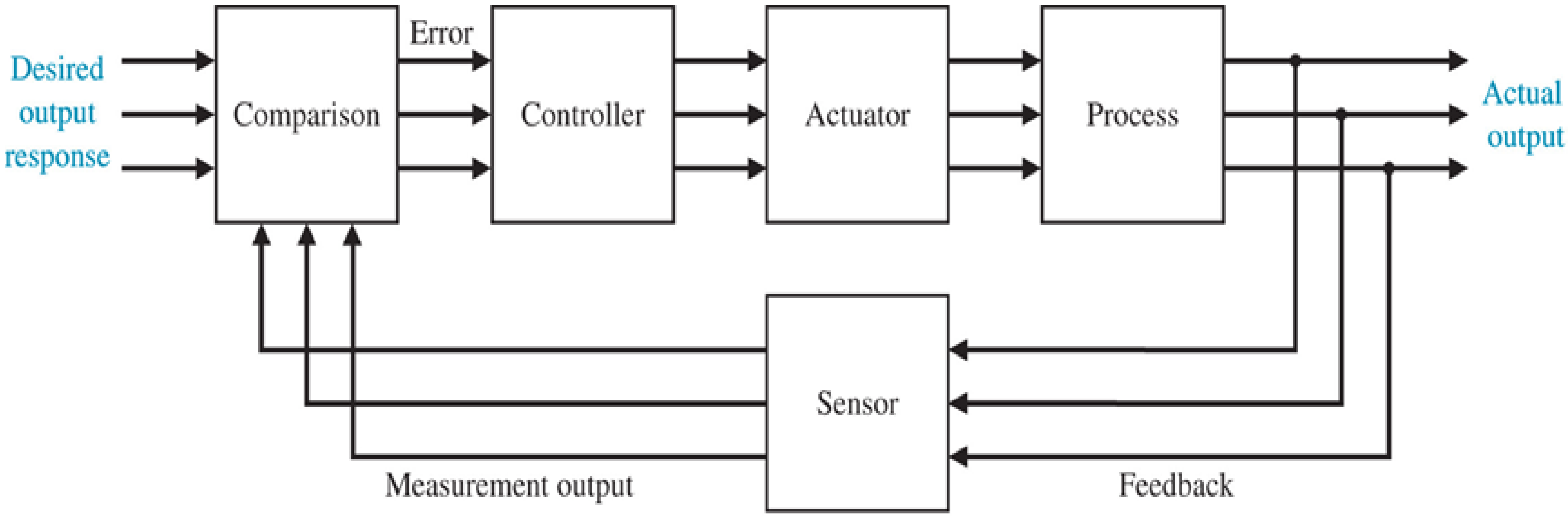




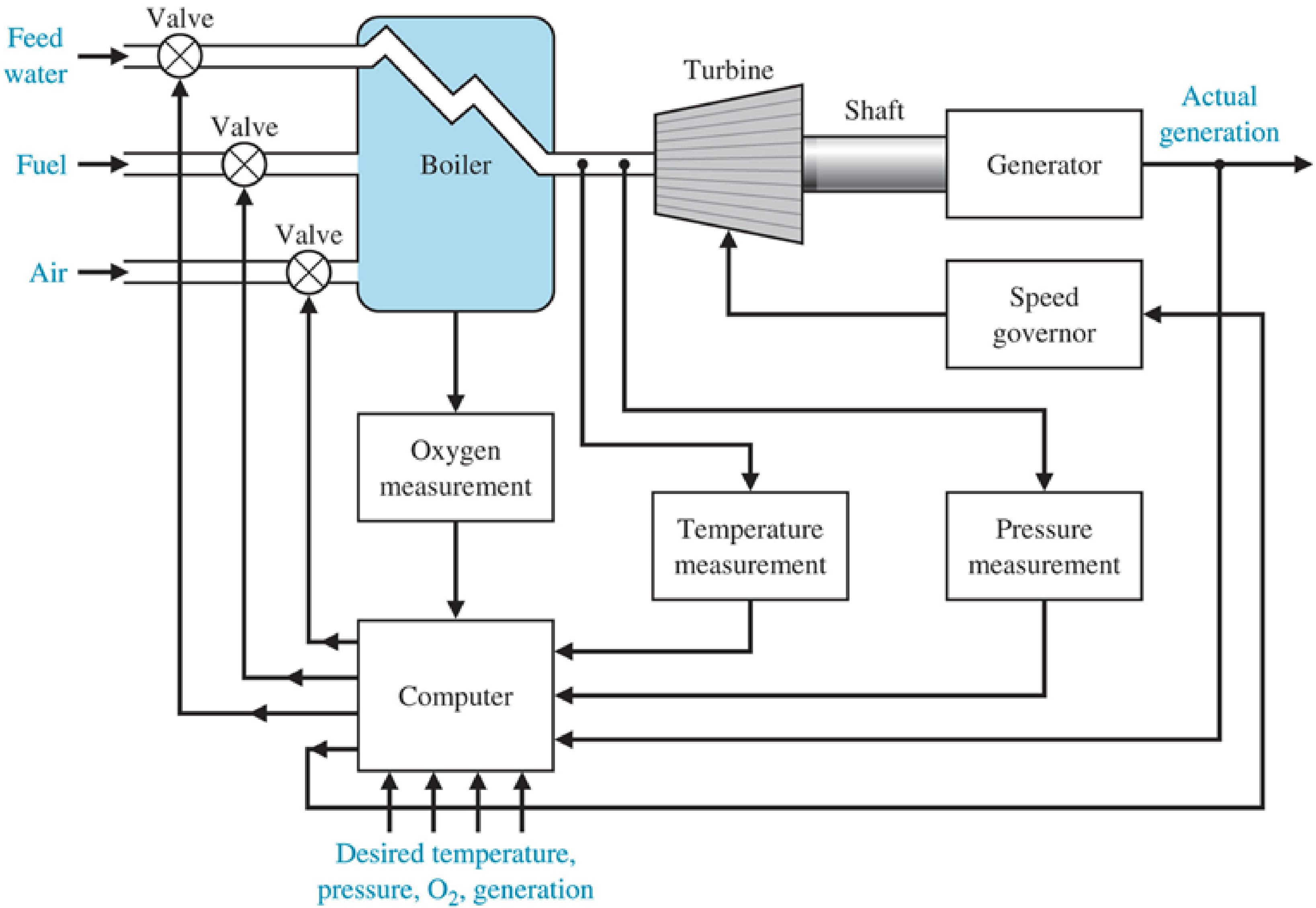
Multiloop Feedback Control System



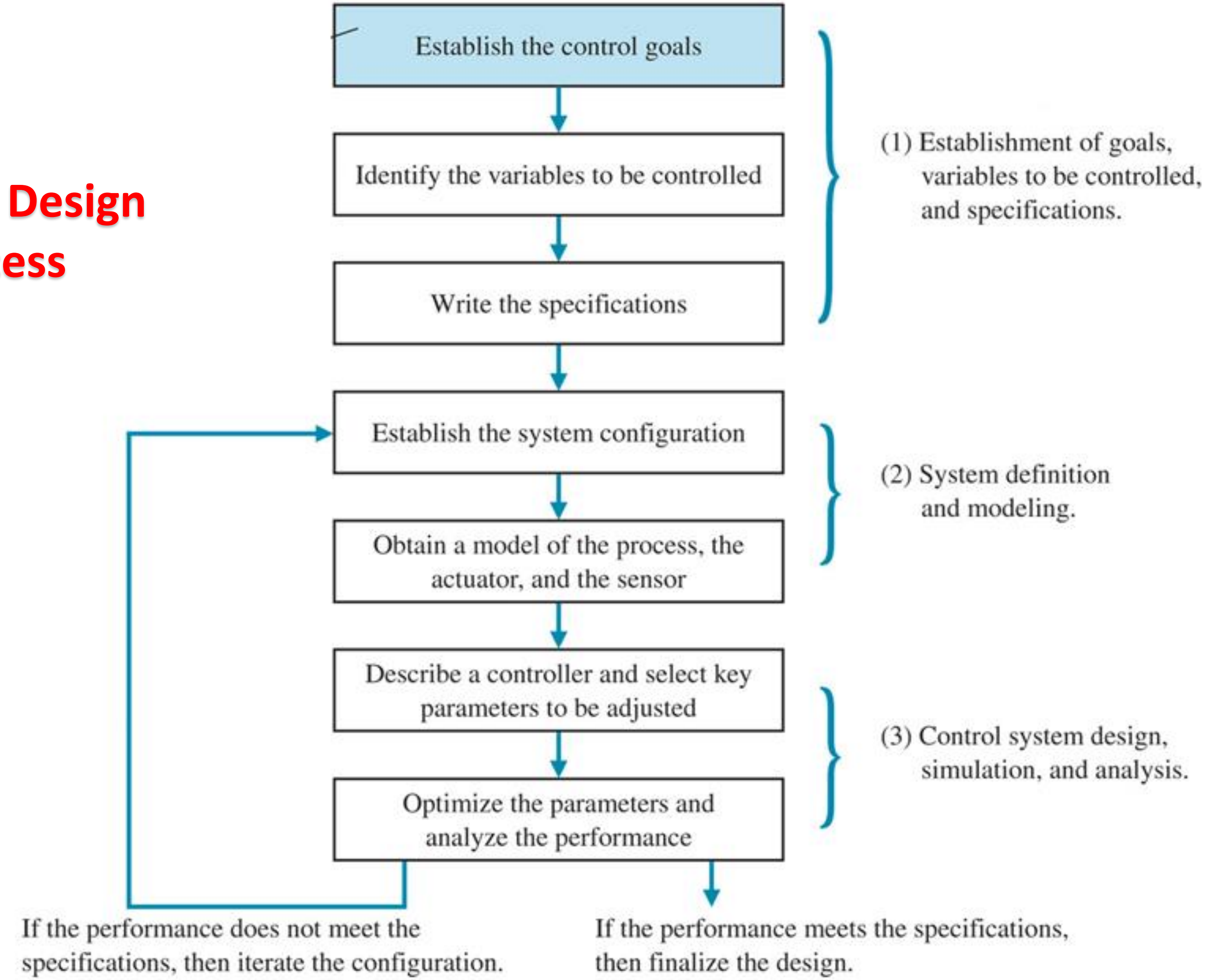
Multi-variable Feedback Control System



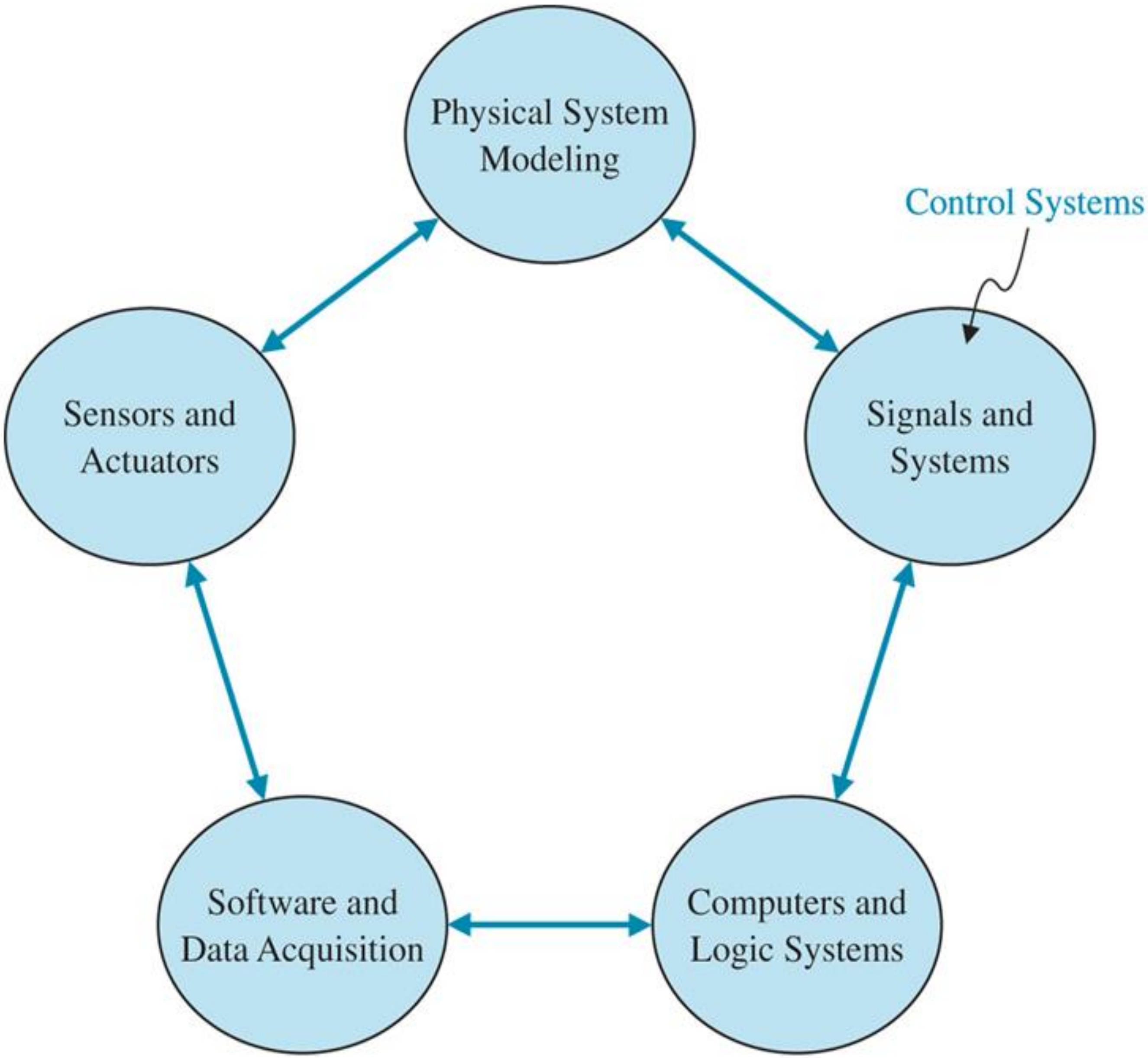
Example: Feedback Control System



Control Design Process



Control Design Process



Controllers Modes

- Continuous Controller Action
- Discontinuous Controller Action

Each of the Above Classification can be written as:

- Direct Action and
- Reverse Action

Types of Controllers

- ✓ On-Off or Two Position Controller
- ✓ Multi-Position Controller
- ✓ Floating mode Controller
- ✓ Proportional Controller
- ✓ Integral Controller
- ✓ Derivative Controller
- ✓ PI Controller
- ✓ PD Controller
- ✓ PID Controller

Discontinuous Controller Modes

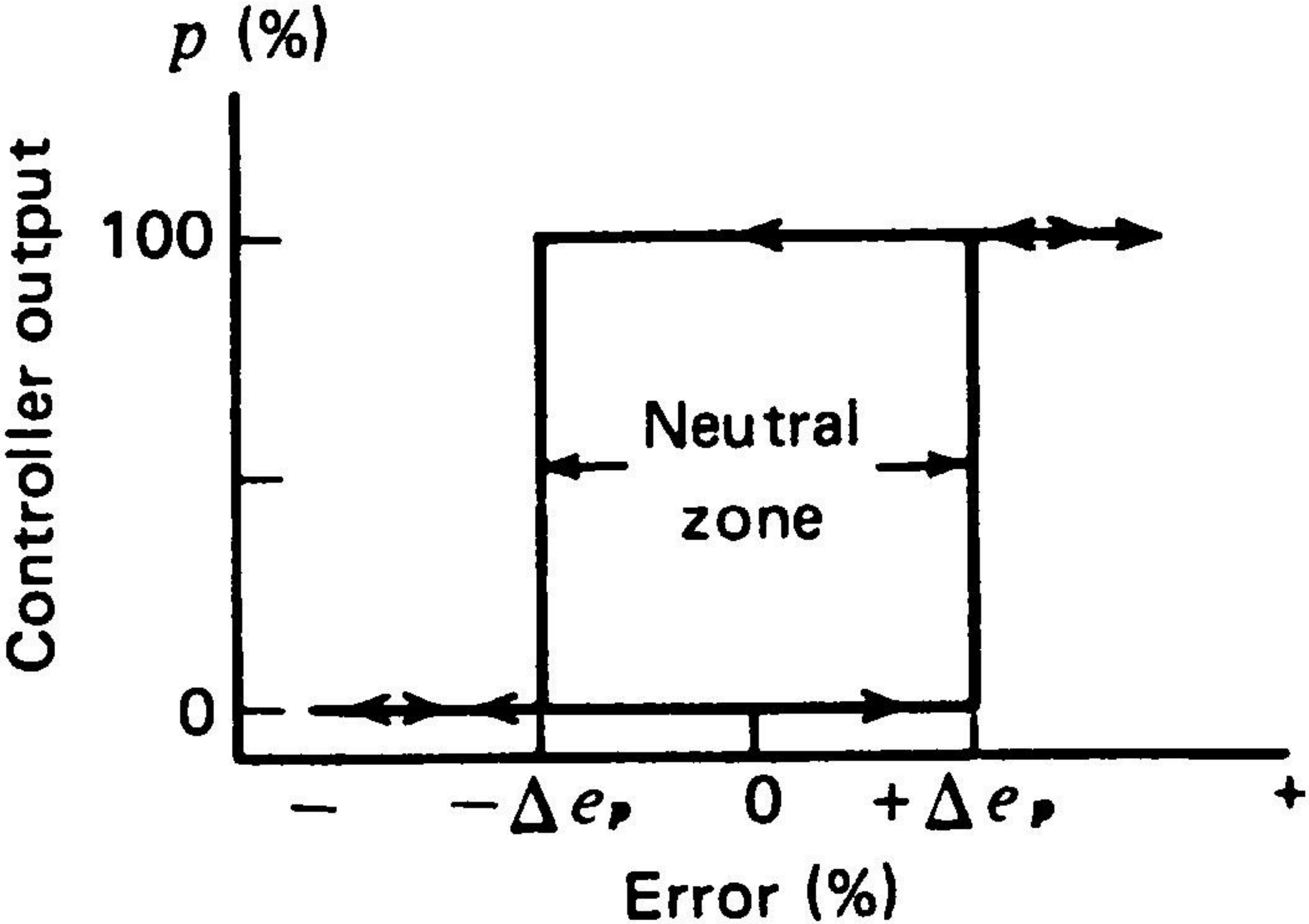
TWO POSITION MODE:

Controller Output p is given by

$$p = \begin{cases} 0\% & e_p < 0 \\ 100\% & e_p > 0 \end{cases}$$

WATER HEATER EXAMPLE………………

Neutral Zone in Two Position Controller Mode



MULTIPOSITION CONTROL MODE

An extension of two position controller mode to provide several intermediate rather than just two settings for the controller output

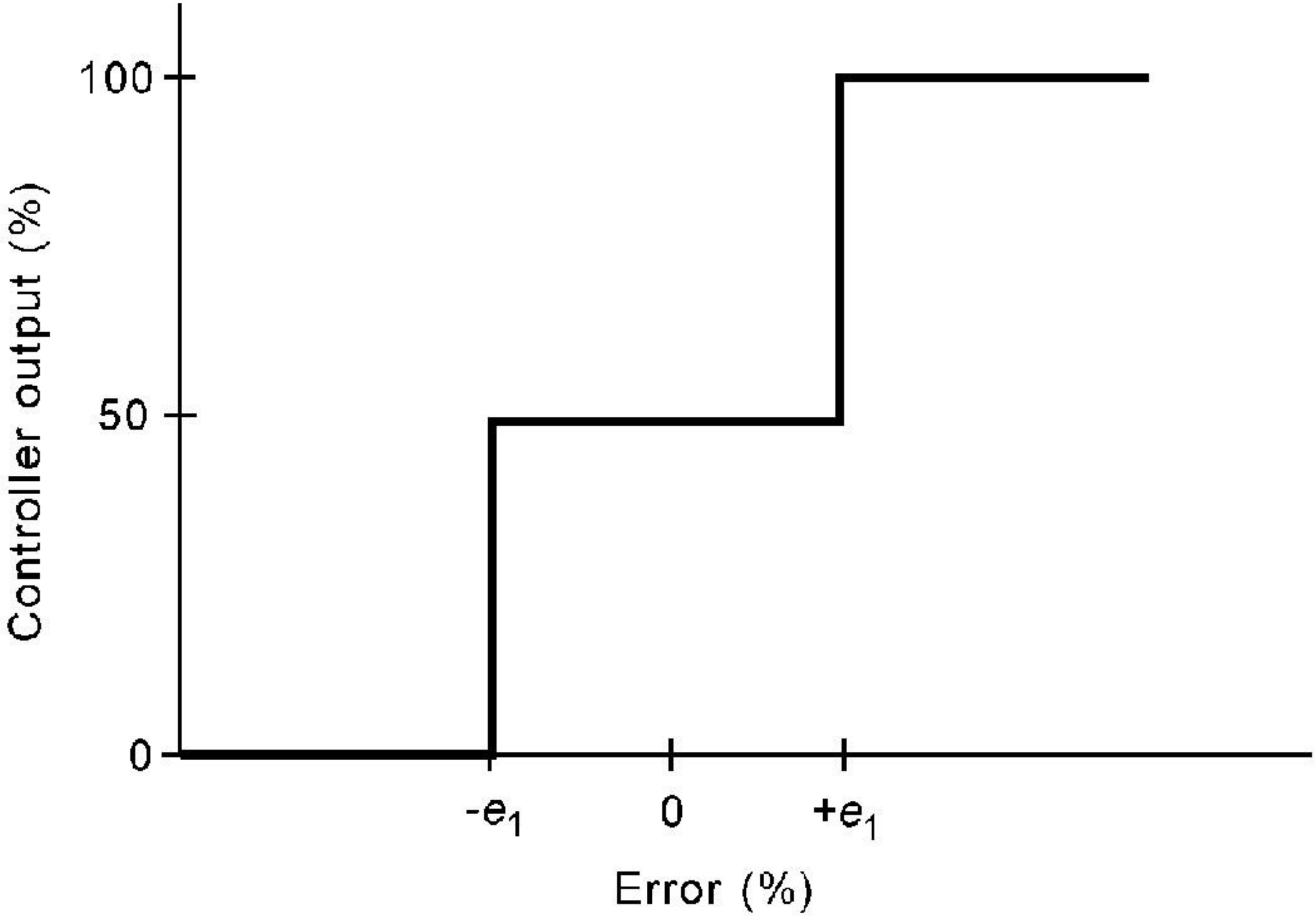
This mode is represented by

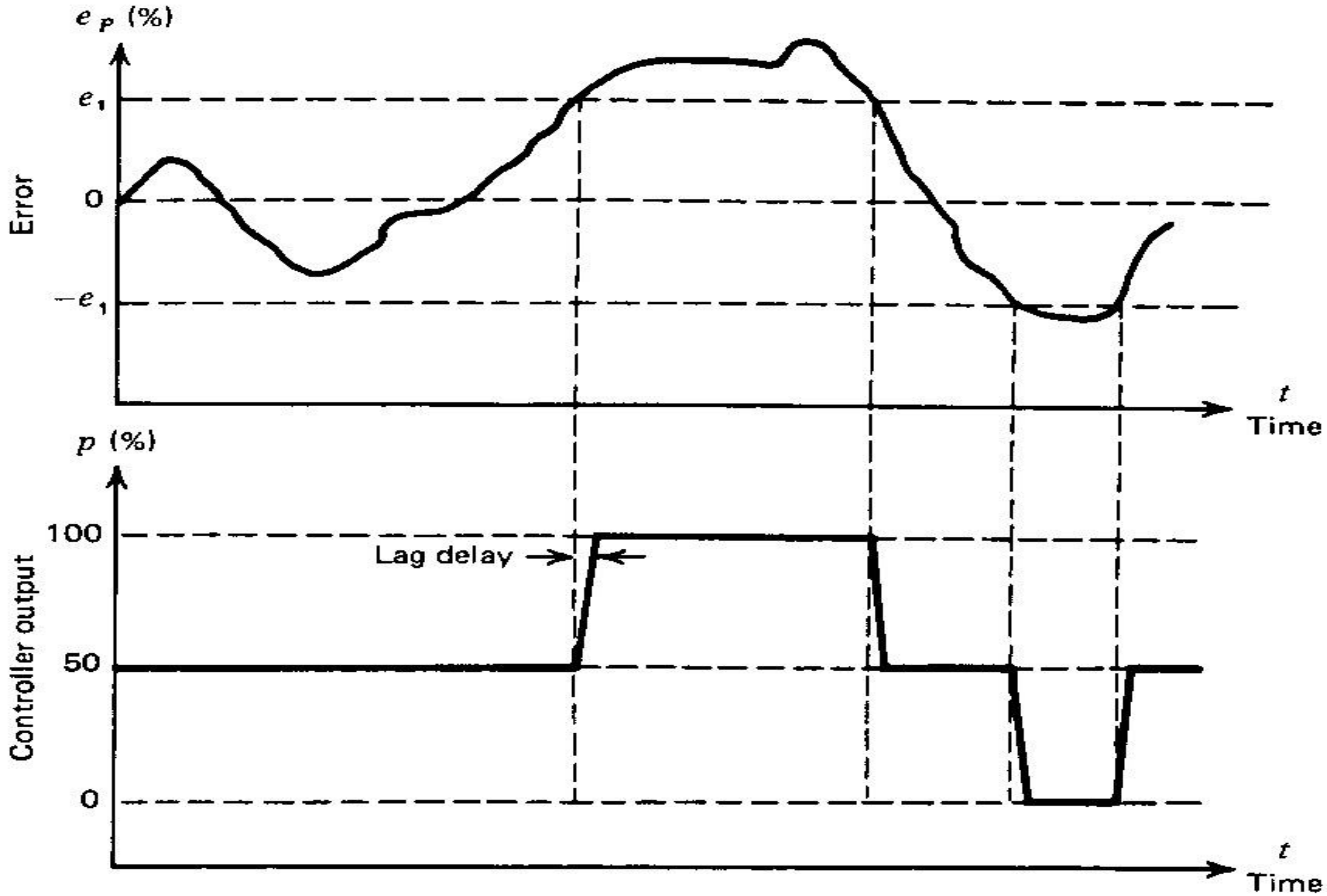
$$p = p_i \qquad e_p > |e_i| \; i = 1, 2, \cdots n$$

The most common example is the three-position controller where

$$p = \begin{cases} 100 & e_p > e_2 \\ 50 & -e_1 < e_p < e_2 \\ 0 & e_p < -e_1 \end{cases}$$

MULTIPOSITION CONTROL MODE





Relationship between error and three-position controller action, including the effects of lag due to final control element and controller

FLOATING CONTROL MODE

In this mode the specific Controller output is not uniquely determined by the error, here When error is zero the controller output will not change but floats at the value at whatever Setting it went to zero.
When error moves off the zero the controller output begins to change.

Single Speed:

In the single-speed floating-control mode, the output of the control element changes at a fixed rate when the error exceeds the neutral zone. An equation for this action is

$$\frac{dp}{dt} = \pm K_F \qquad |e_p| > \Delta e_p \tag{9.11}$$

where

$\frac{dp}{dt}$ = rate of change of controller output with time

K_F = rate constant (%/s)

Δe_p = half the neutral zone

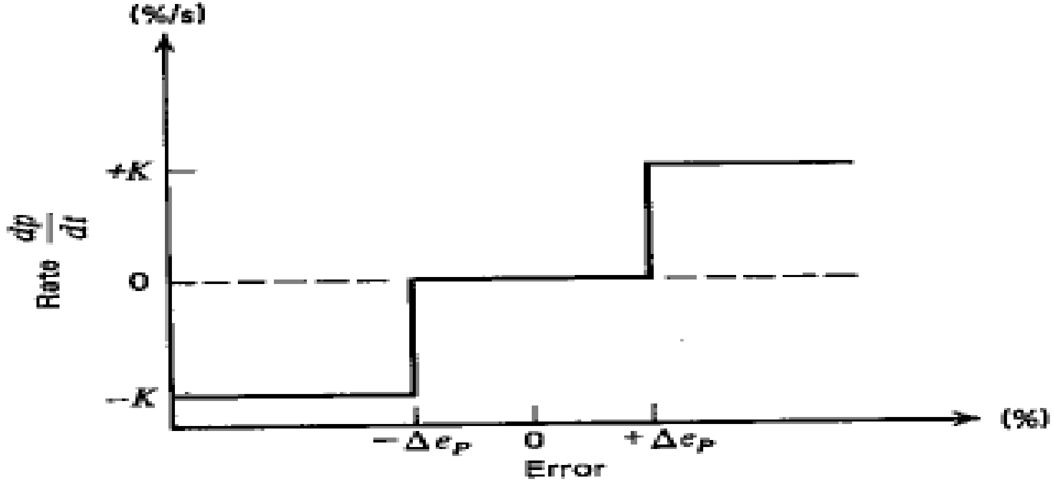
If Equation (9.11) is integrated for the actual controller output, we get

$$p = \pm K_F t + p(0) \qquad |e_p| > \Delta e_p \tag{9.12}$$

where

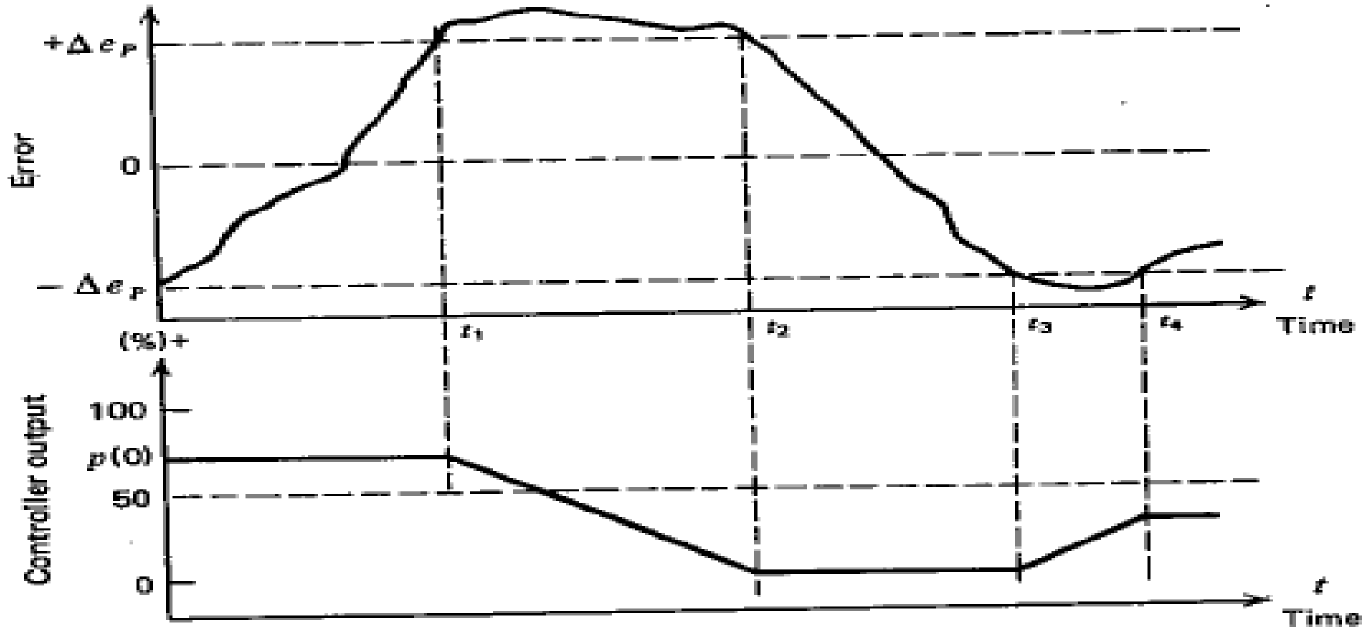
$p(0)$ = controller output at $t = 0$

which shows that the present output depends on the time history of errors that have previously occurred. Because such a history usually is not known, the actual value of p floats at an *undetermined* value. If the deviation persists, then Equation (9.11) shows that the controller saturates at either 100% or 0% and remains there until an error drives it toward the opposite extreme. A graph of single-speed floating control is shown in Figure 9.7a.



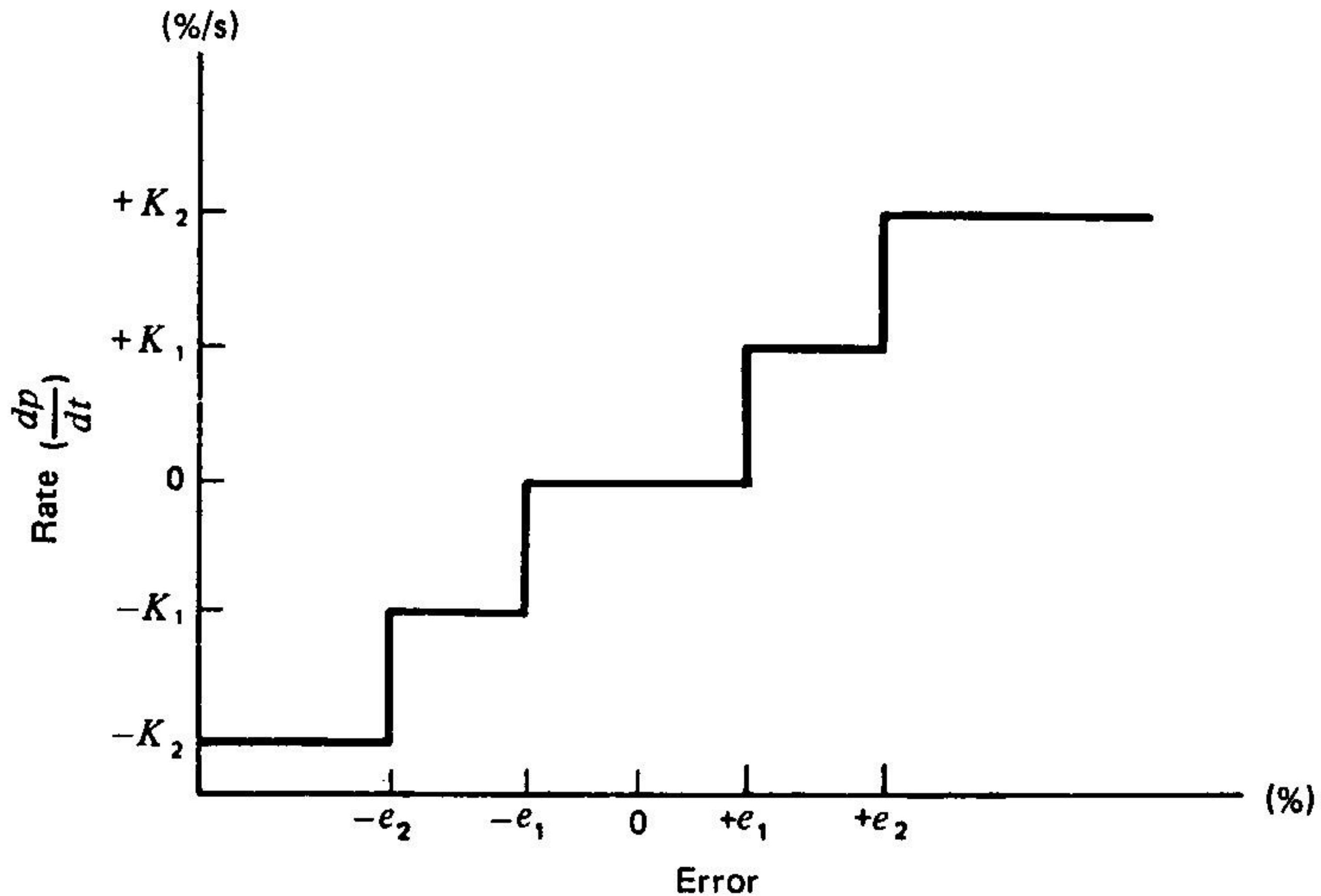
a) Single-speed floating controller action. The ordinate is the rate of change of controller output with time

Here Controller is Reverse Acting

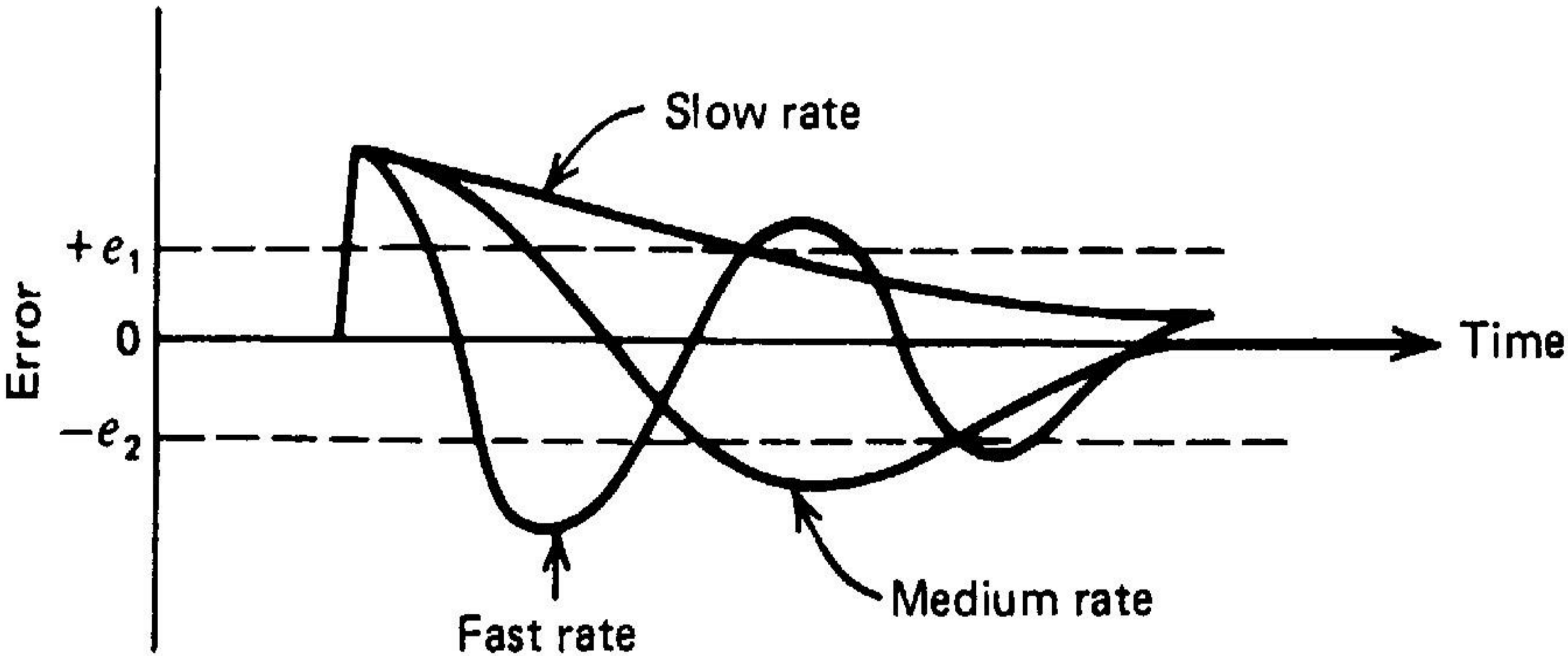


b) Error and controller output for single-speed floating action.

Figure 9.7 Single-speed floating controller.



Multiple-speed floating-control mode action.



The rate of controller output change has a strong effect on error recovery in a floating controller.

At higher rate of change of Controller output instability or Oscillations may occur similar to ON-OFF Control

Continuous Controller Modes

Proportional Controller Mode:

The two-position mode had the controller output of either 100% or 0% depending on the error being greater or less than the neutral zone. In multiple-step modes, more divisions of controller outputs versus error are developed. The natural extension of this concept is the *proportional mode*, where a smooth, linear relationship exists between the controller output and the error. Thus, over some range of errors about the setpoint, each value of error has a unique value of controller output in one-to-one correspondence. The range of error to cover the 0% to 100% controller output is called the *proportional band* because the one-to-one correspondence exists only for errors in this range. This mode can be expressed by

$$p = K_P e_p + p_0 \tag{9.14}$$

where

K_P = proportional gain between error and controller output (% per %)
p_0 = controller output with no error (%)

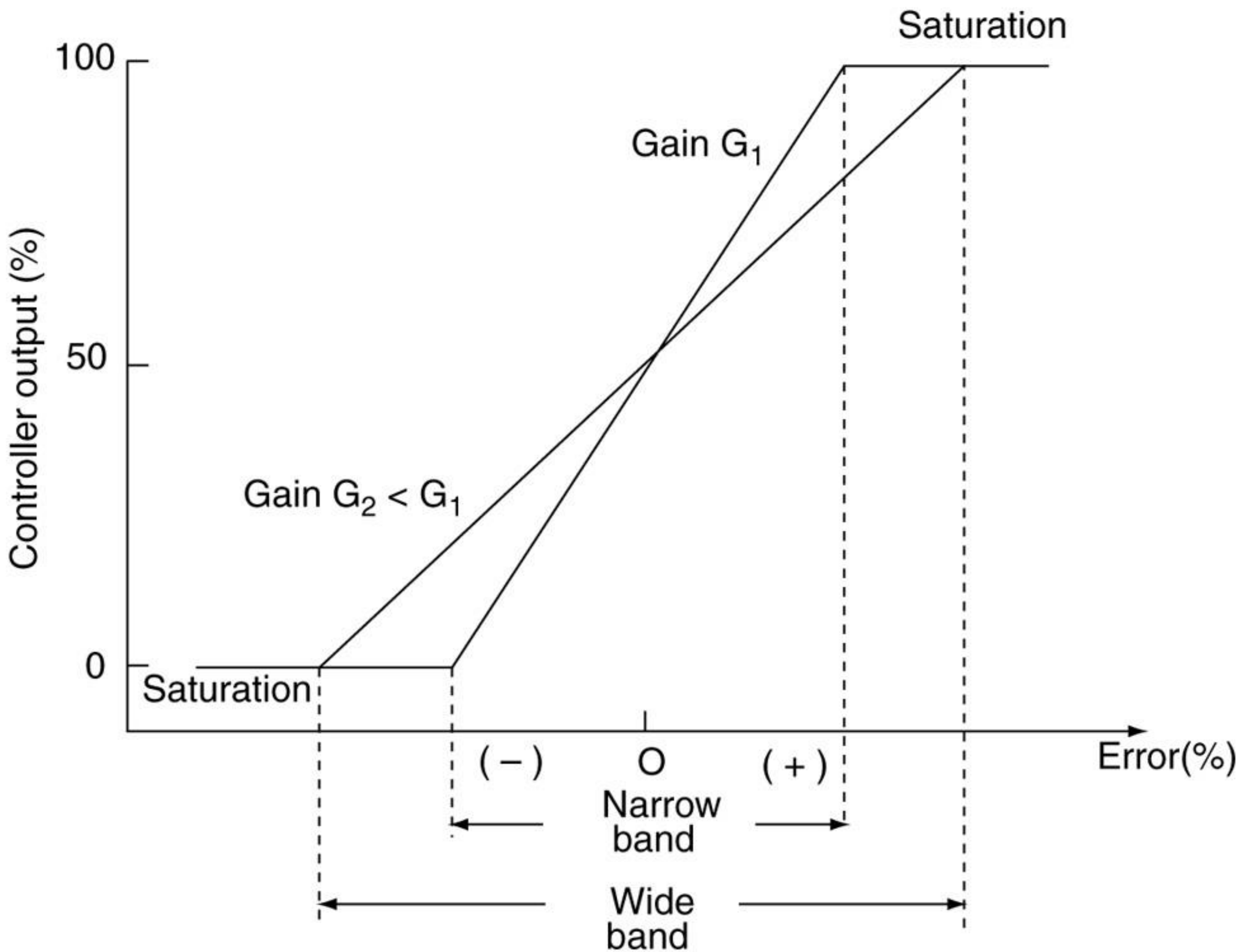
Proportional Band:

In general, the proportional band is defined by the equation

$$PB = \frac{100}{K_P} \tag{9.15}$$

Let us summarize the characteristics of the proportional mode and Equation

1. If the error is zero, the output is a constant equal to p_0.
2. If there is error, for every 1% of error a correction of K_P percent is added to or subtracted from p_0, depending on the reverse or direct action of the controller.
3. There is a band of error about zero of magnitude PB within which the output is not saturated at 0% or 100%.



Direct Acting Proportional Controller

Reverse Acting Proportional Controller

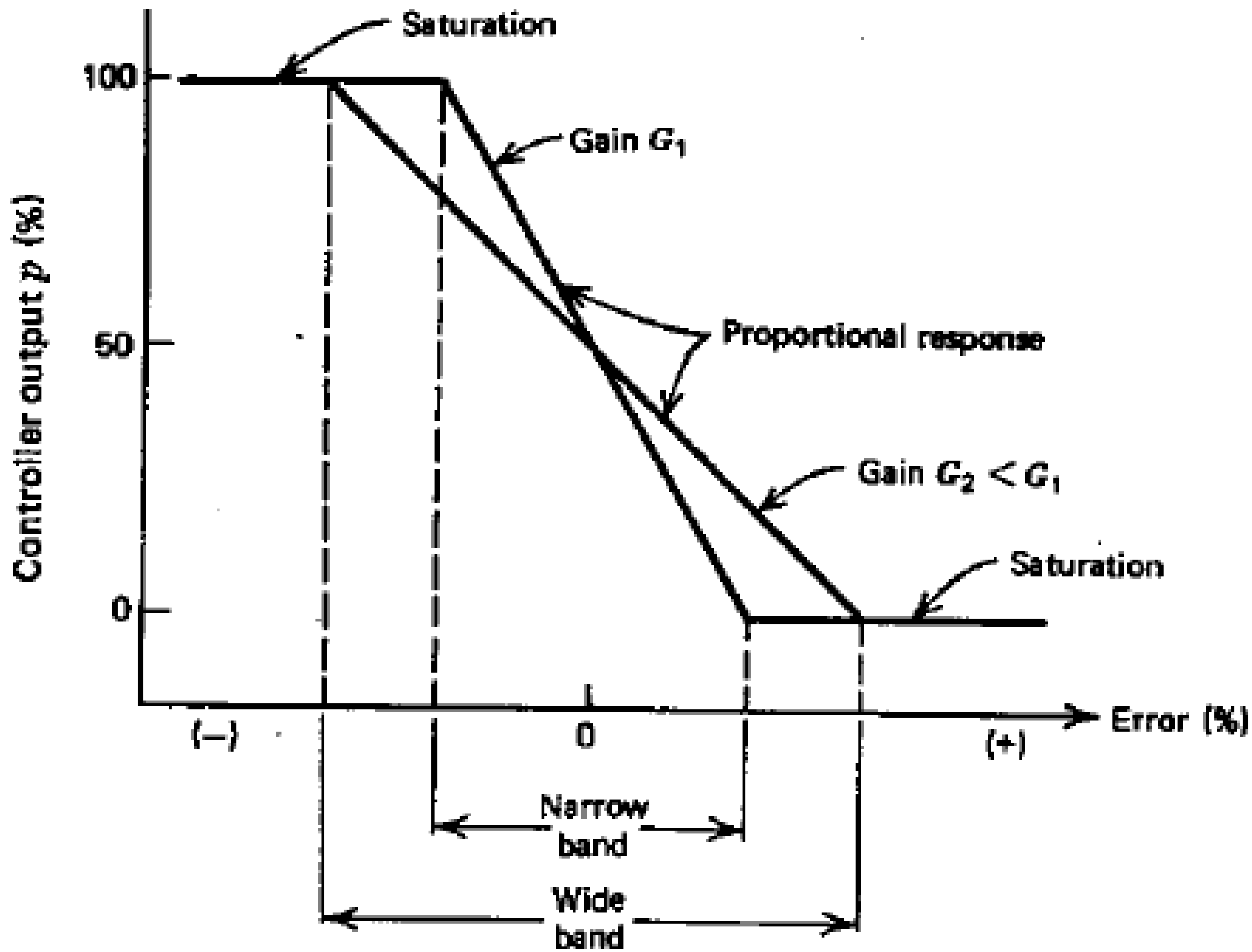
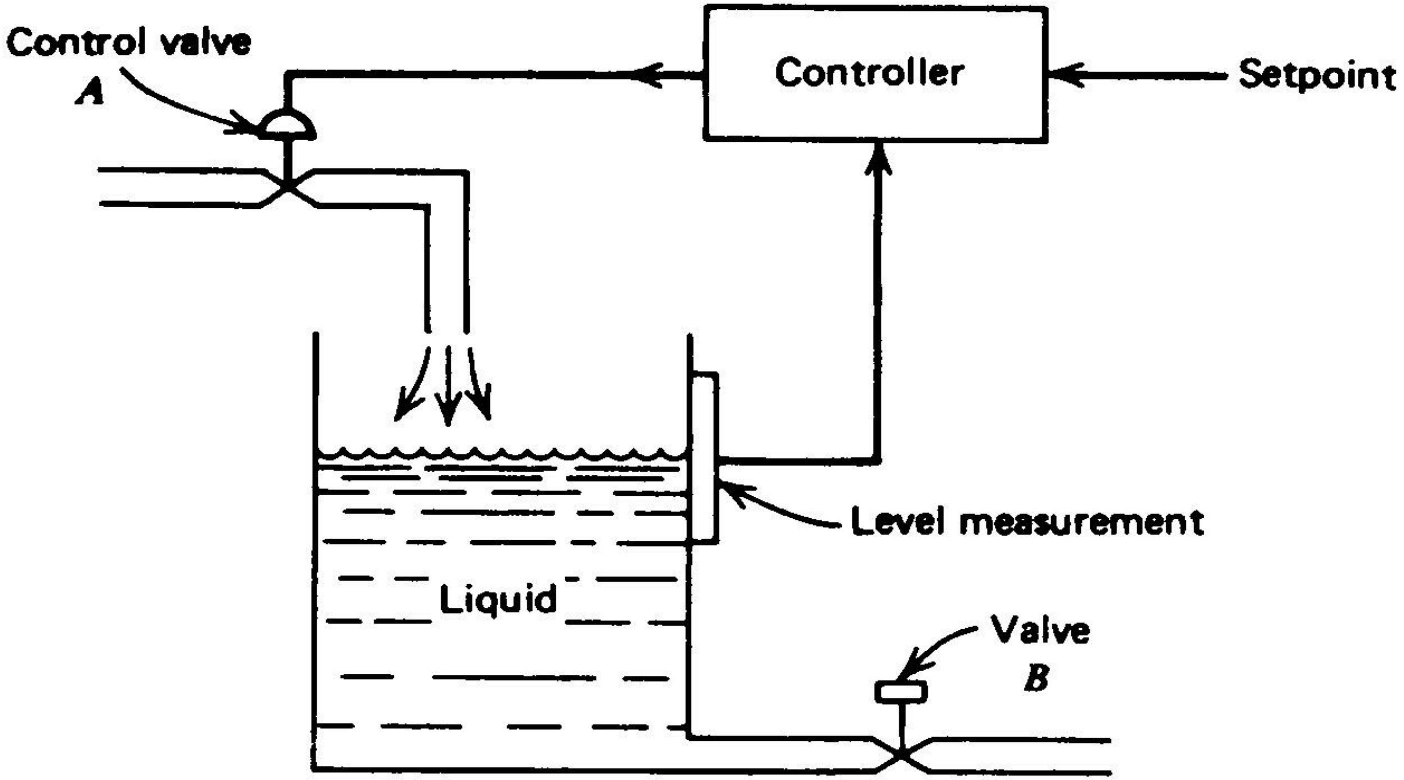


Figure 9.11 The proportional band of a proportional controller depends on the gain, in an inverse fashion.

Offset in a Proportional Controller: Level Control Example

Consider the proportional mode level-control system of Figure 9.13. Valve A is linear with a flow scale factor of 10 m^3/hr per percent controller output. The controller output is nominally 50% with a constant of $K_P = 10\%$ per %. A load change occurs when flow through valve B changes from 500 m^3/hr to 600 m^3/hr. Calculate the new controller output and offset error.



Solution Certainly, valve A must move to a new position of 600 m^3/hr flow or the tank will empty. This can be accomplished by a 60% new controller output because

$$Q_A = \left(10 \frac{m^3/hr}{\%}\right)(60\%) = 600 \ m^3/hr$$

as required. Because this is a proportional controller, we have

$$p = K_P e_p + p_0 \tag{9.14}$$

with the nominal condition $p_0 = 50\%$. Thus

$$e_p = \frac{p - p_0}{K_P} = \frac{60 - 50}{10} \%$$

$$e_p = 1\%$$

so that a 1% offset error occurred because of the load change.

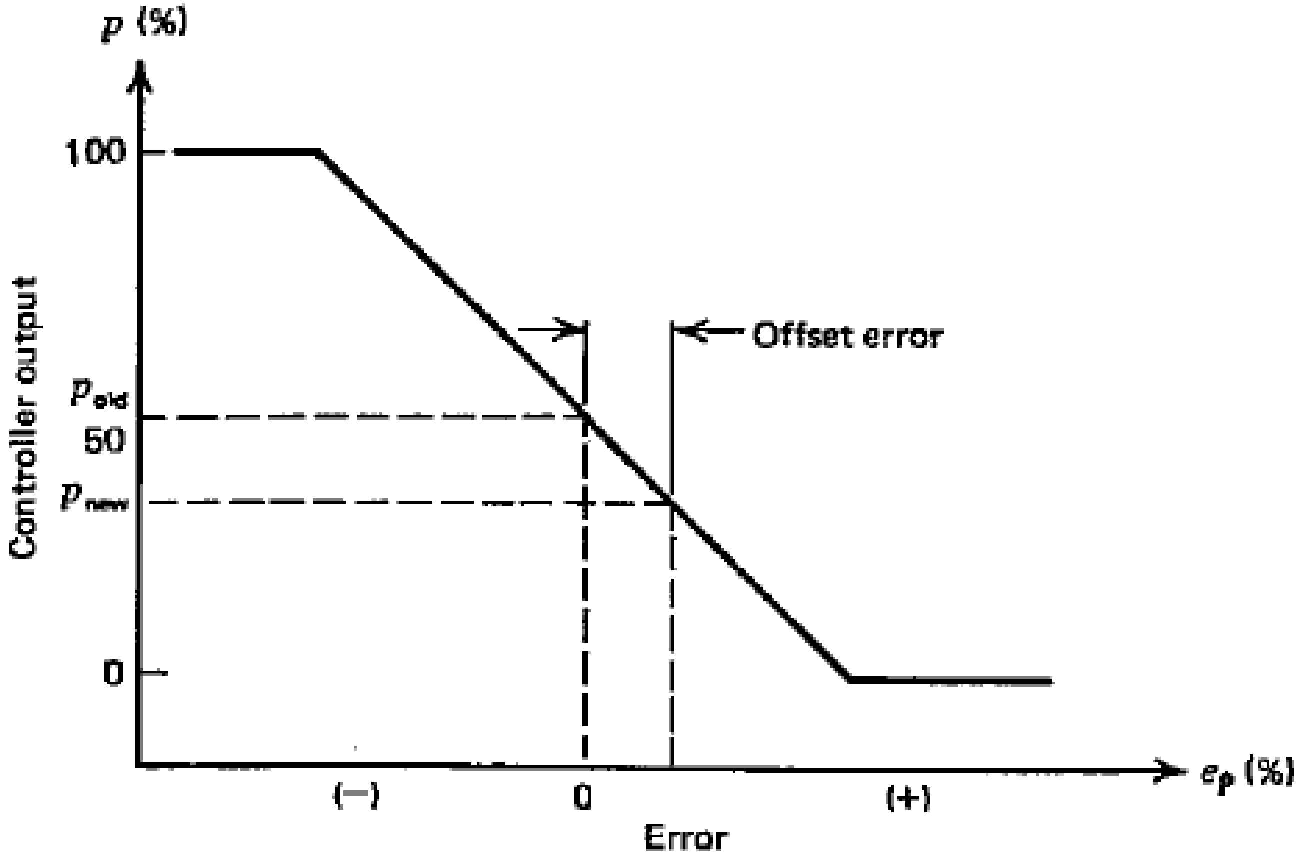


Figure 9.12 An offset error must occur if a proportional controller requires a new nominal controller output following a load change.

If a transient error occurs the system responds by changing the controller output in Correspondence with the transient to effect a return to zero error;

However if a permanent load change occurs that requires a permanent change in controller output to produce the zero error state;

Application of Proportional Controller:

Application

The offset error limits use of the proportional mode to only a few cases, particularly those where a manual reset of the operating point is possible to eliminate offset. Proportional control generally is used in processes where large load changes are unlikely or with moderate to small process lag times. Thus, if the process lag time is small, the proportional band can be made very small (large K_P), which reduces offset error. Figure 9.11 shows that if K_P is made very large, the *PB* becomes very small and the proportional mode acts just like an ON/OFF mode. Remember that the ON/OFF mode exhibited oscillations about the setpoint. From these statements it is clear that for high gain the proportional mode causes oscillations of the error.

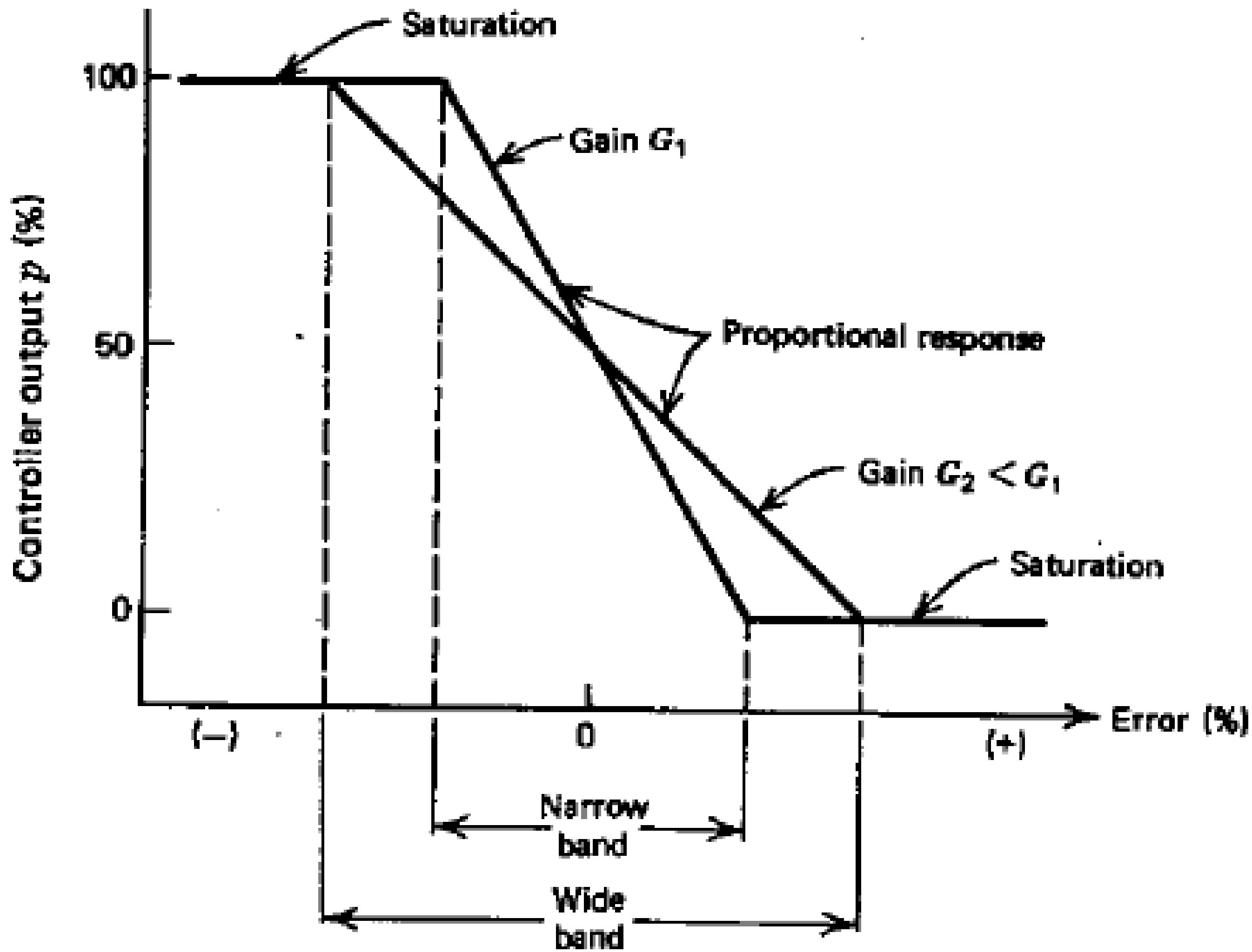


Figure 9.11 The proportional band of a proportional controller depends on the gain, in an inverse fashion.

Integral Controller Mode:

This mode represents a natural extension of the principle of floating control in the limit of infinitesimal changes in the rate of controller output with infinitesimal changes in error. Instead of single speed or even multiple speeds, we have a continuous change in speeds depending on error. This mode is often referred to as *reset action*. Analytically, we can write

$$\frac{dp}{dt} = K_I e_p \tag{9.16}$$

where

$\frac{dp}{dt}$ = rate of controller output change (%/s)

K_I = constant relating the rate to the error ((%/s)/%)

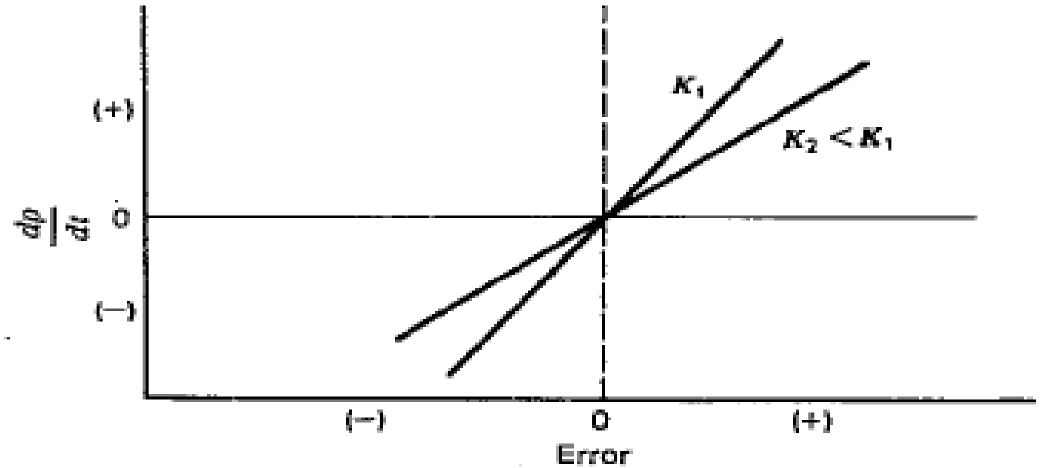
In some cases the inverse of K_I, called the integral time $T_I = 1/K_I$, expressed in seconds or minutes, is used to describe the integral mode.

If we integrate Equation (9.16), we can find the actual controller output at any time as

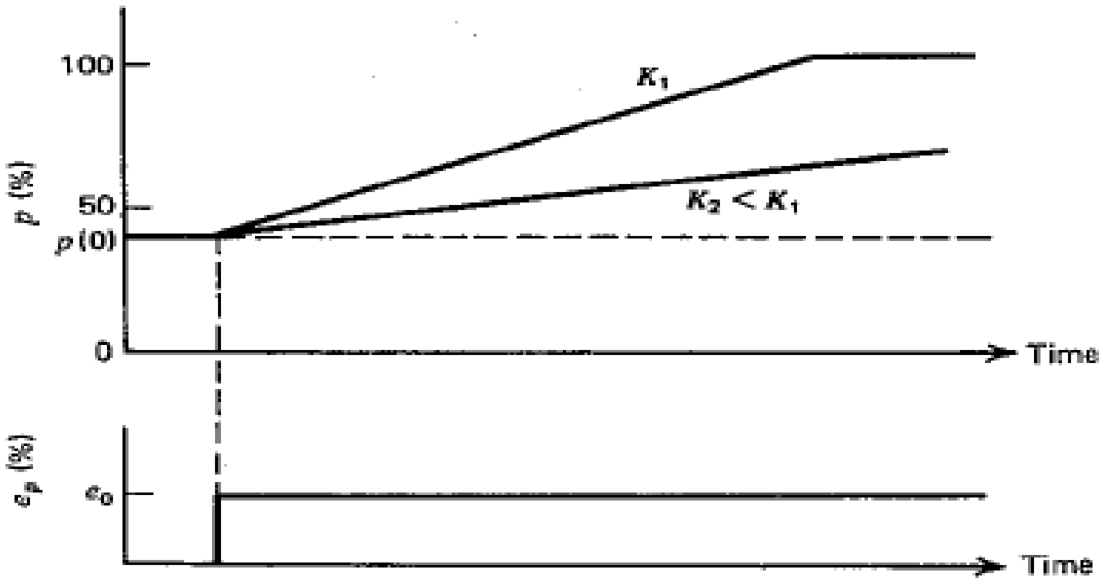
$$p(t) = K_I \int_0^t e_p(t)dt + p(0) \tag{9.17}$$

where

$p(0)$ = the controller output at $t = 0$



a) The rate of output change depends on gain and error



b) Illustration of integral mode response to a constant error

Figure 9.14 Integral controller mode action.

Let us summarize the characteristics of the integral mode and Equation

1. If the error is zero, the output stays fixed at a value equal to what it was when the error went to zero.
2. If the error is not zero, the output will begin to increase or decrease at a rate of K_I percent/second for every 1% of error.

Area accumulation

From calculus we learn that an integral determines the area of the function being integrated. Thus, Equation (9.17) can be interpreted as providing a controller output equal to the net area under the *error-time* curve multiplied by K_I. We often say that the integral term *accumulates* error as a function of time. Thus, for every 1% − s of accumulated error-time area, the output will be K_I percent.

Derivative Controller Mode:

The last *pure* mode of controller operation provides that the controller output depends on the rate of change of *error*. This mode also is known as *rate* or *anticipatory* control. The mode *cannot* be used alone because when the error is *zero or constant*, the controller has no output. The analytic expression is

$$p = K_D \frac{de_p}{dt} \tag{9.18}$$

where

K_D = derivative gain constant (% − s/%)

$\frac{de_p}{dt}$ = rate of change of error (%/s)

The derivative gain constant also is called the rate or derivative time and is commonly expressed in minutes. The characteristics of this device can be noted from the graph of Figure 9.16, which shows controller output for the rate of change of error. This shows that, for a given rate of change of error, there is a unique value of controller output. The time plot of error and controller response further shows the behavior of this mode, as shown in Figure 9.17. The extent of controller output depends on the rate at which this error is changed and *not* on the value of the error.

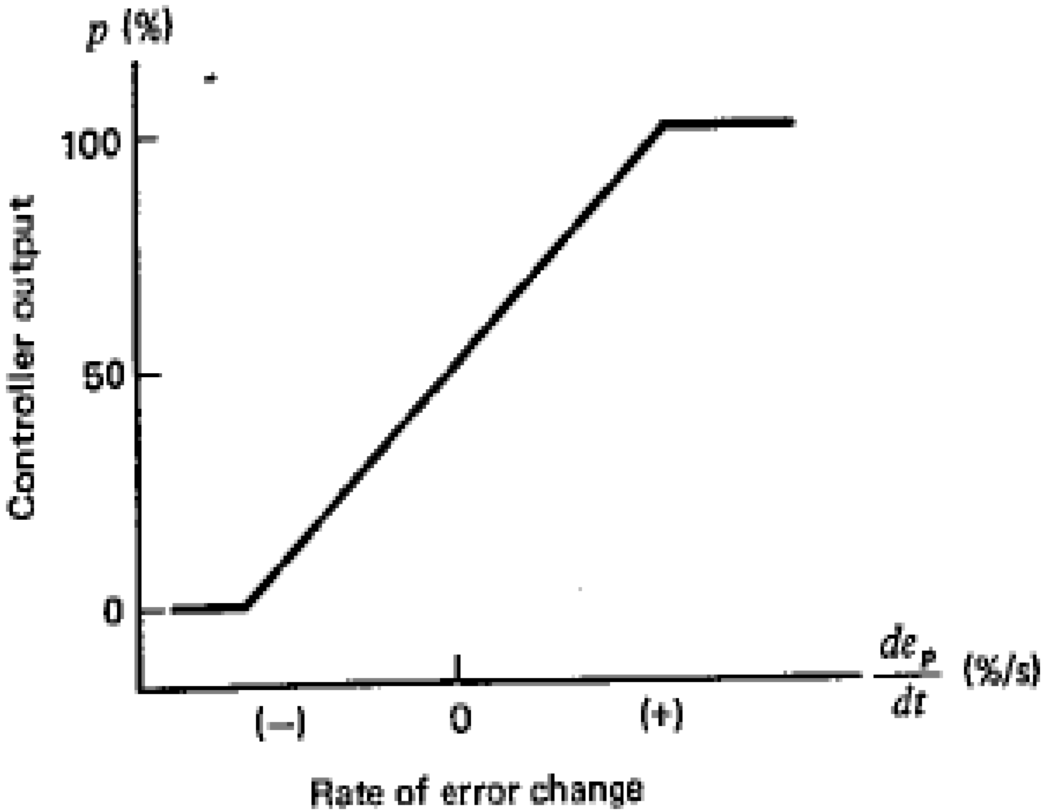
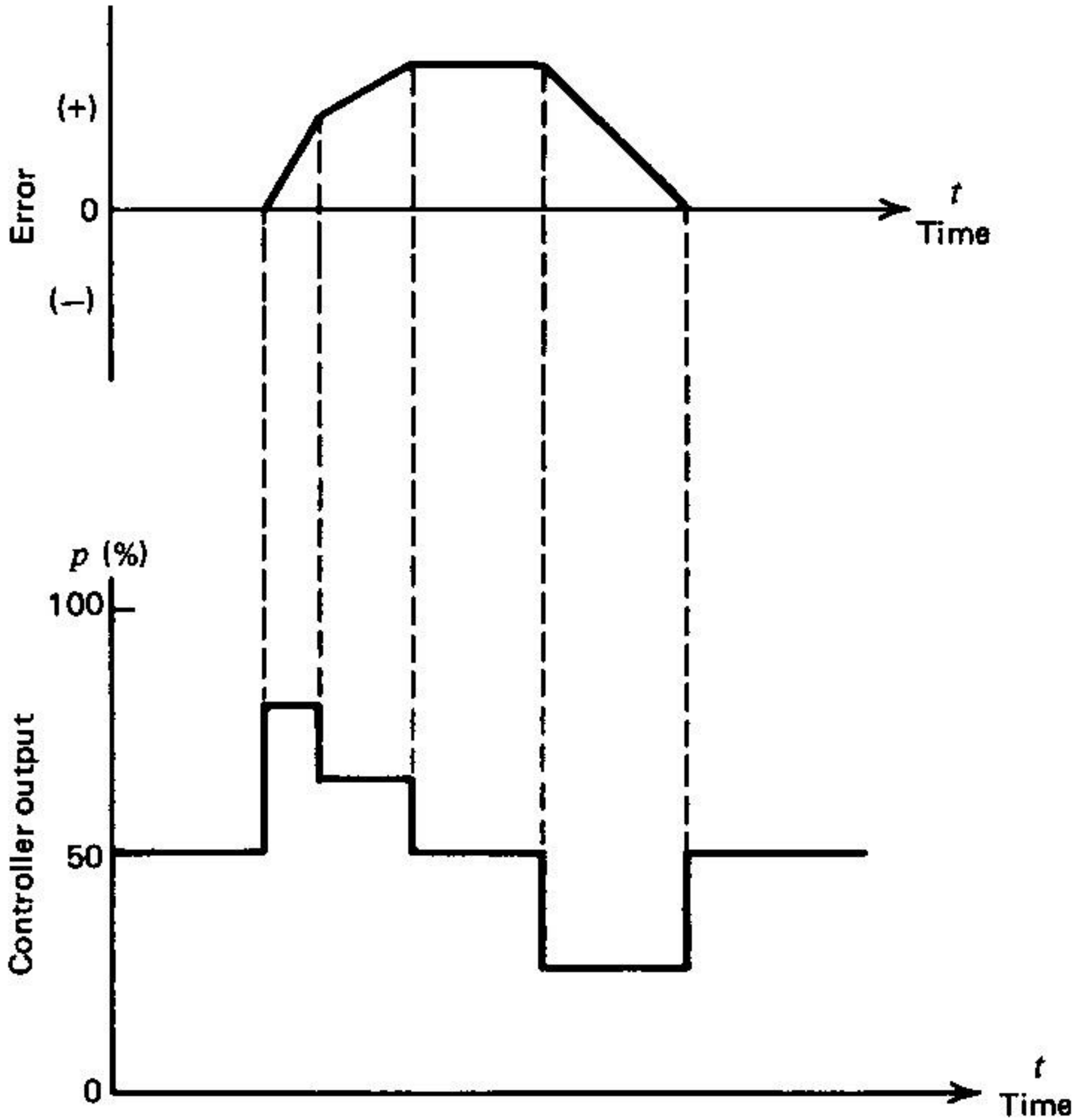
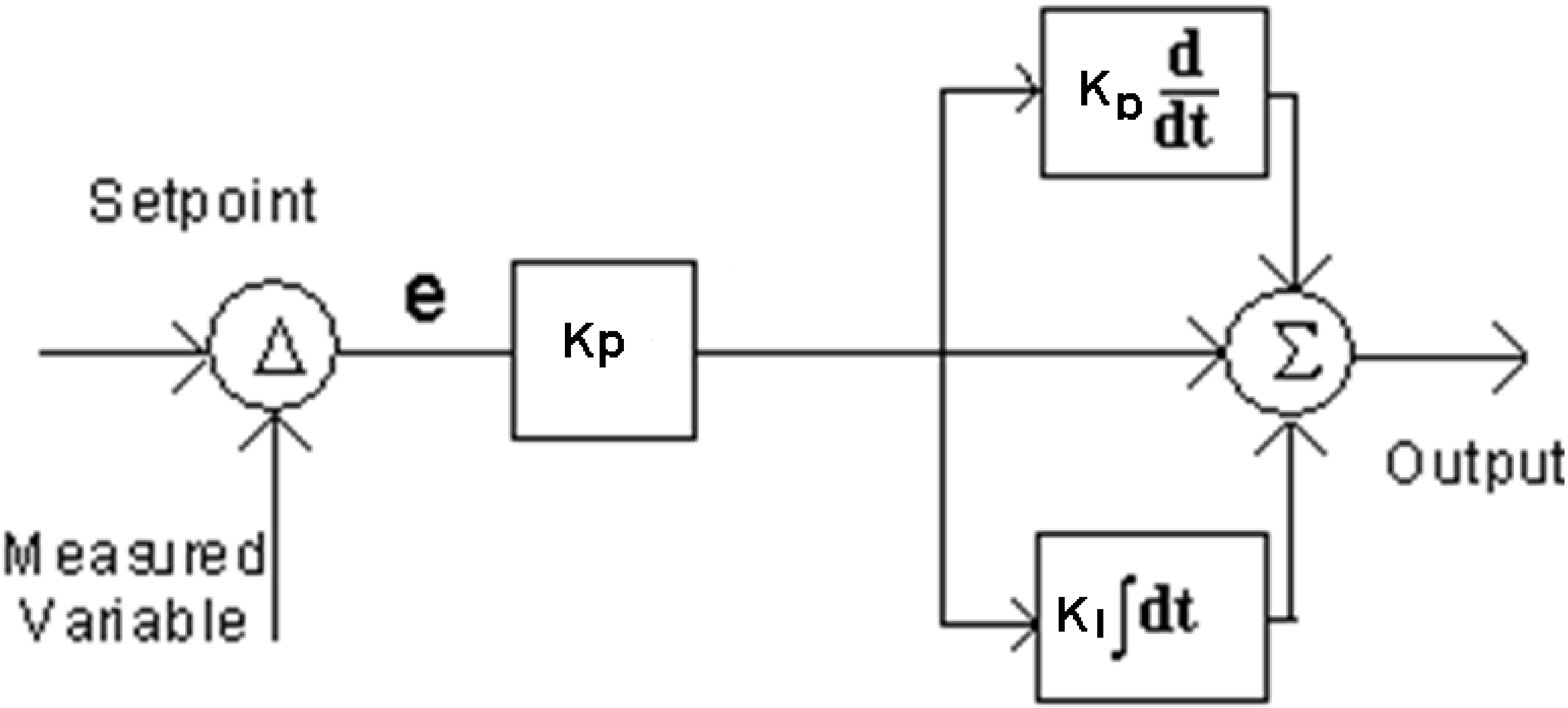


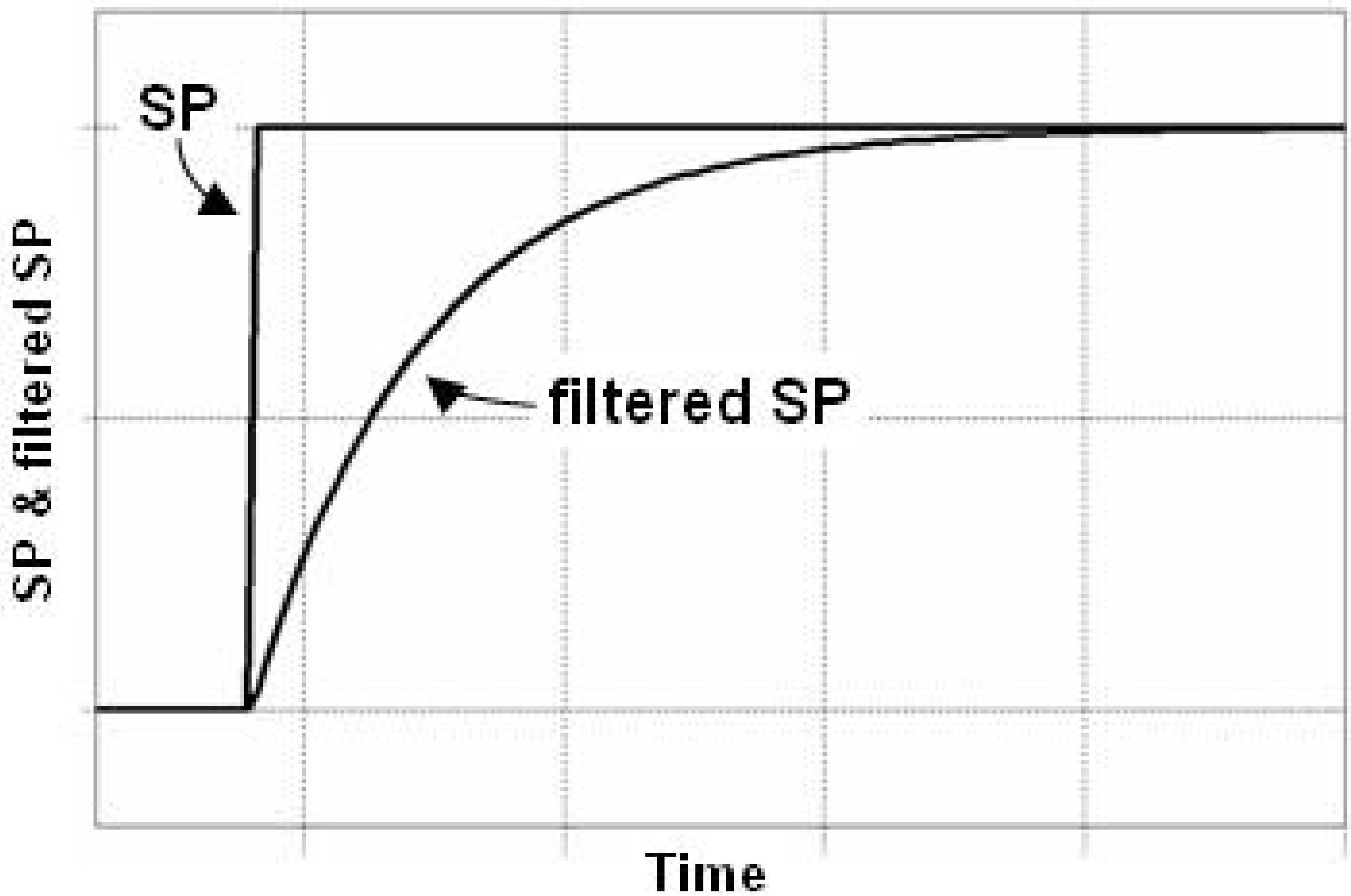
Figure 9.16 Derivative mode of controller action where an output of 50% has been assumed for the zero derivative state.


(+)
Error
0
(–)
t
Time
p (%)
100
Controller output
50
0
t
Time

Composite Controller Modes:

Non-Interactive (Parallel):

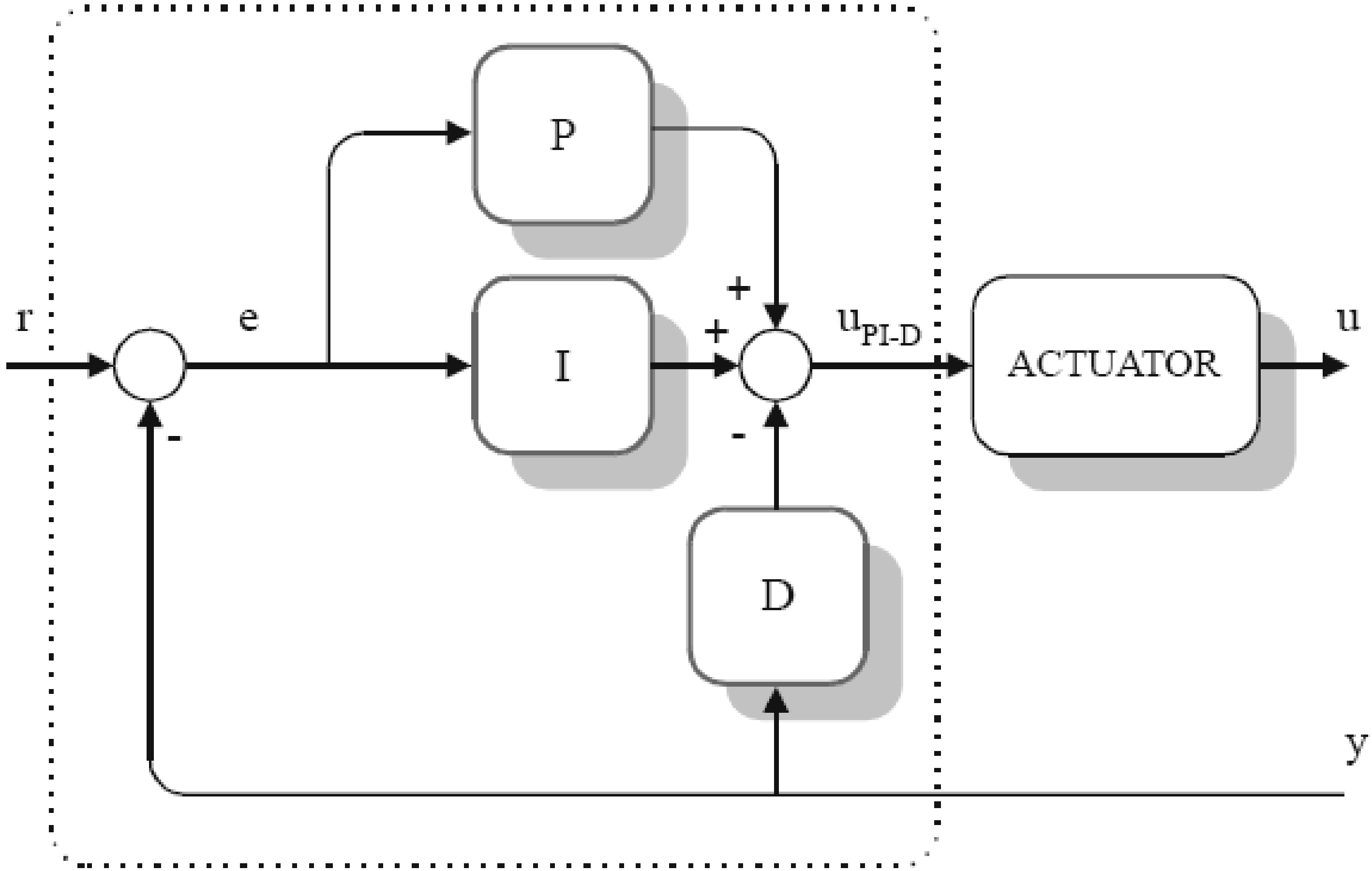




A set point filter takes a step change in SP, and as shown below, forwards a smooth transition signal to the controller.

Composite Controller Modes:

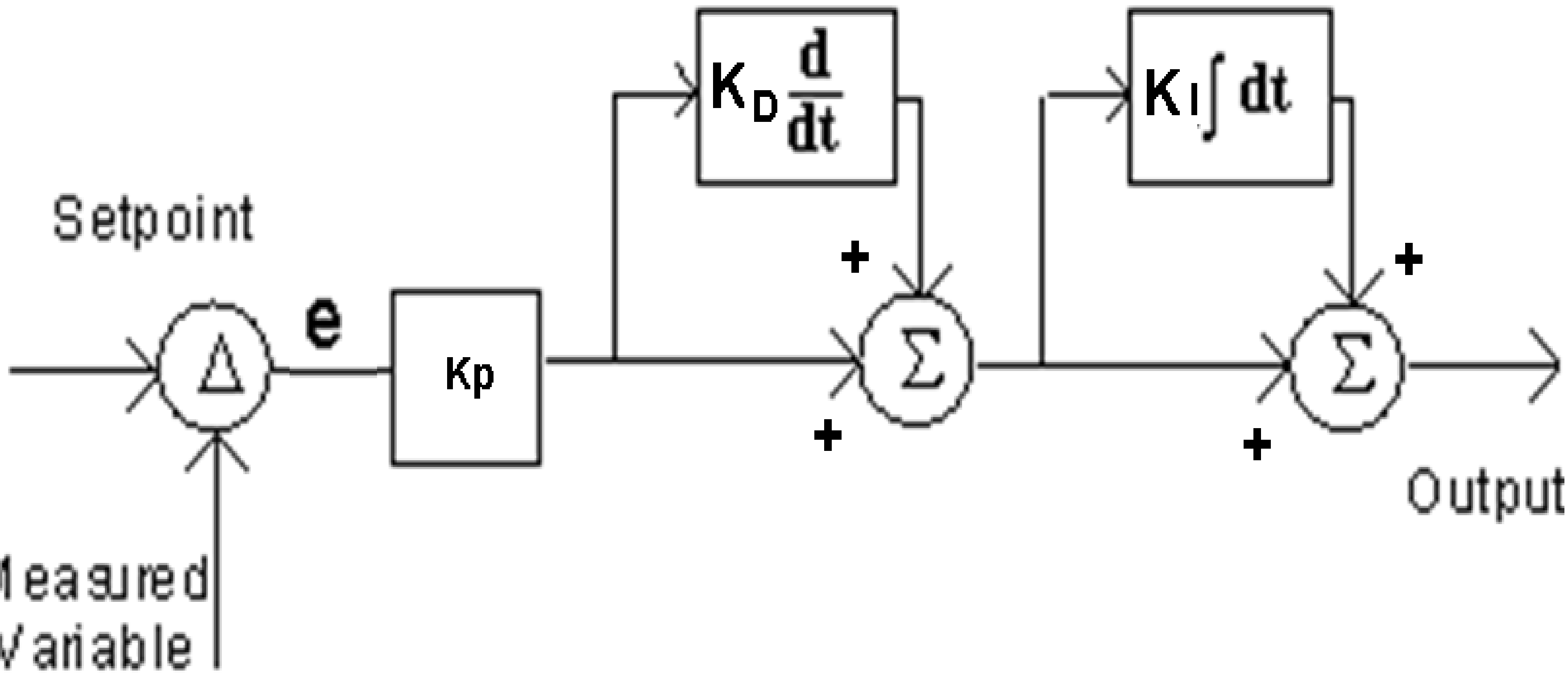
Non-Interactive (Parallel) derivative of Output



Because of possible discontinuity (step change) in reference signal that are transferred into error signal we use this configuration

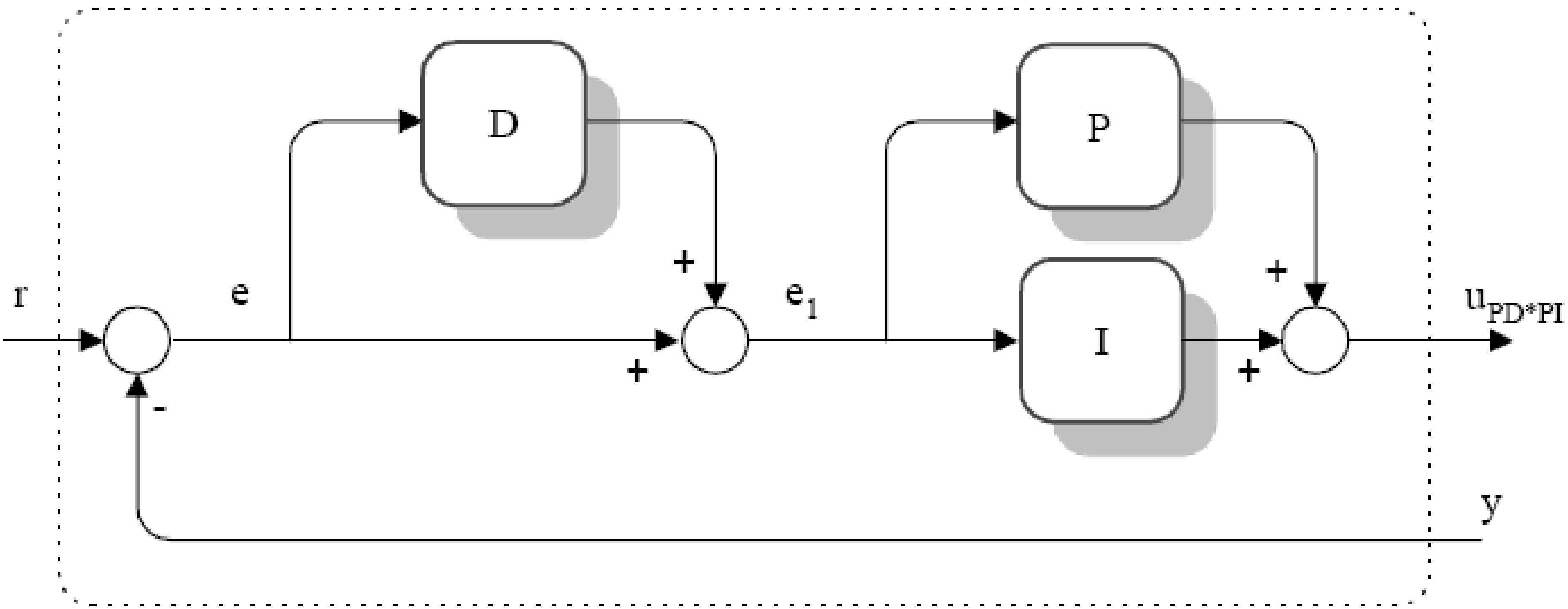
Composite Controller Modes:

Interactive (series):

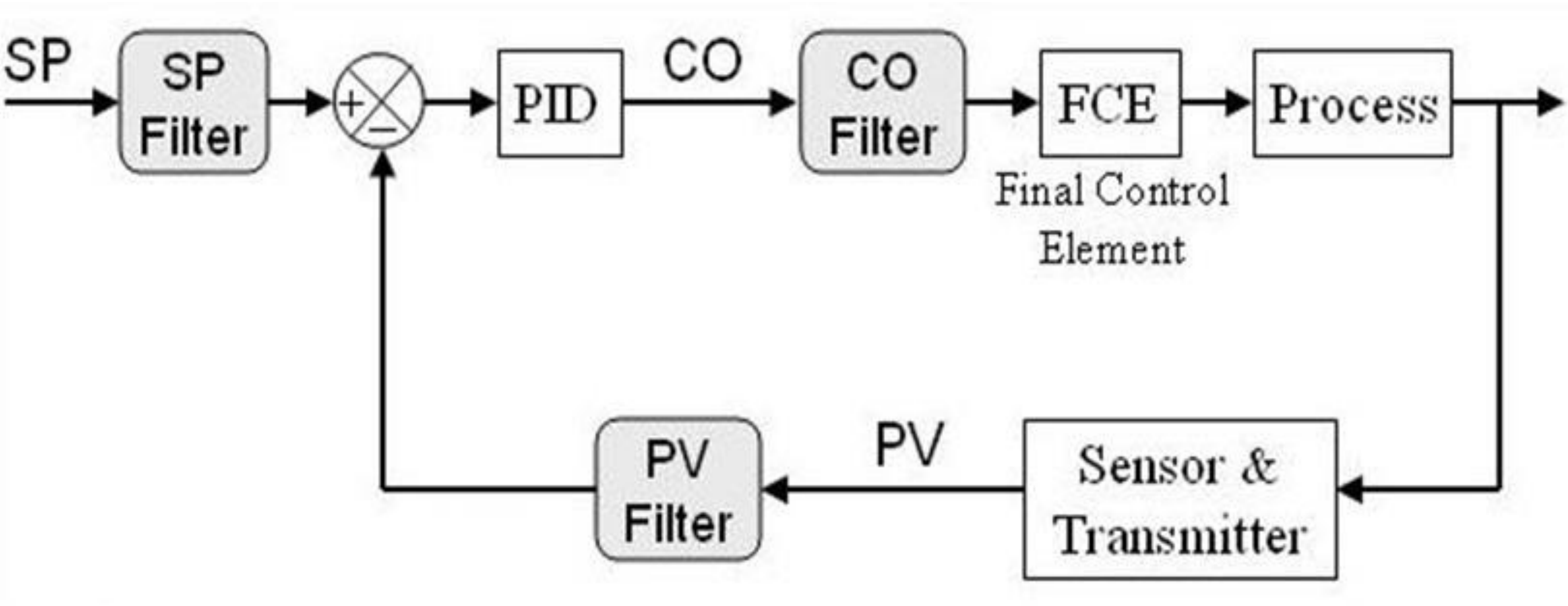


Composite Controller Modes:

Interactive (series):



Composite Controller Modes:



External Filters in Control

Composite Controller Modes:

PI Controller :

This is a control mode that results from a combination of the proportional mode and the integral mode. The analytic expression for this control process is found from a series combination of Equations (9.14) and (9.17)

$$p = K_P e_p + K_P K_I \int_0^t e_p dt + p_I(0) \tag{9.19}$$

where $p_I(0)$ = integral term value at $t = 0$ (initial value).

Let us summarize the characteristics of the PI mode and Equation (9.19).

1. When the error is zero, the controller output is fixed at the value that the integral term had when the error went to zero. This output is given by $p_I(0)$ in Equation (9.19) simply because we chose to define the time at which observation starts as $t = 0$.

2. If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated value [initially $p_I(0)$], depending on the sign of the error and the direct or reverse action.

The integral term cannot become negative. Thus, it will saturate at zero if the error and action try to drive the area to a net negative value.

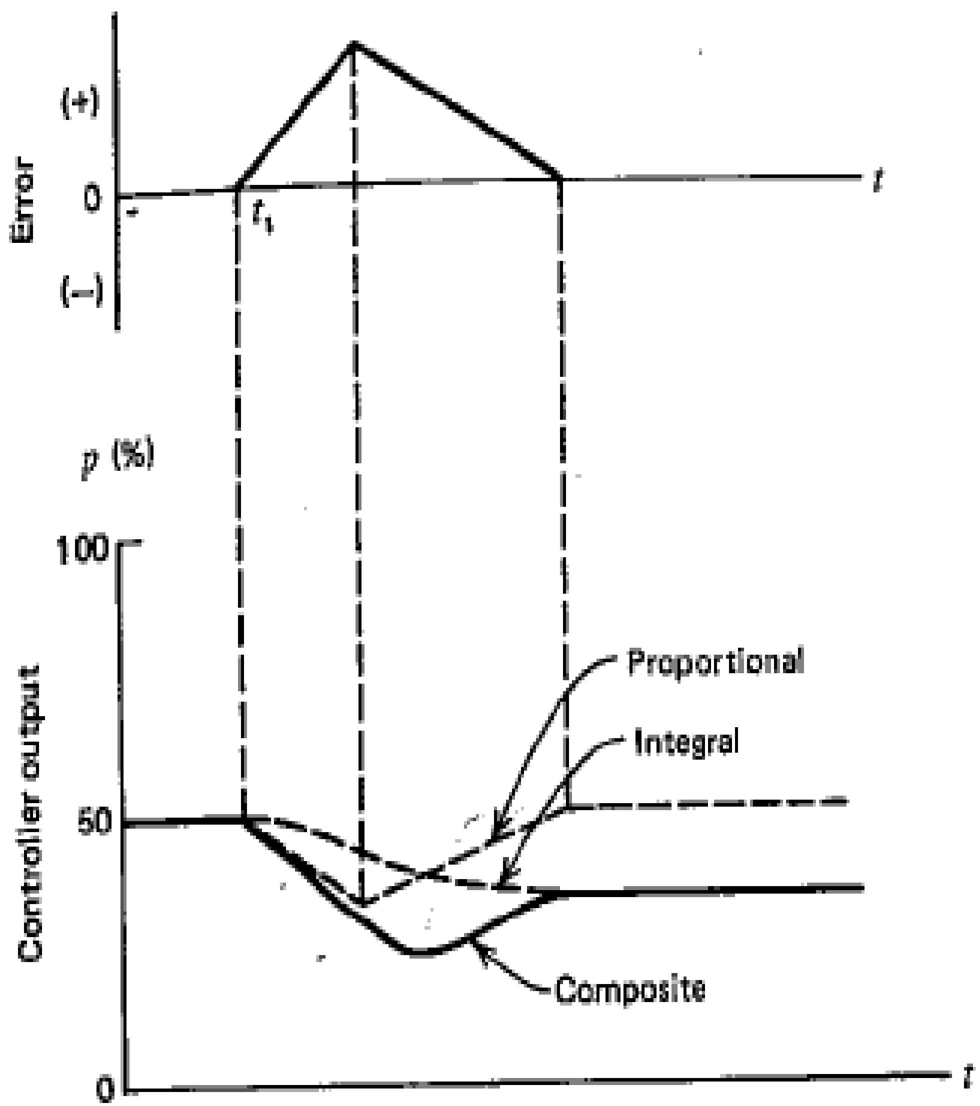


Figure 9.18 Proportional-integral (PI) action showing the reset action of the integral contribution (reverse action).

PD Controller :

A second combination of control modes has many industrial applications. It involves the serial (cascaded) use of the proportional and derivative modes. The analytic expression for this mode is found from a combination of Equations (9.14) and (9.18)

$$p = K_P e_p + K_P K_D \frac{de_p}{dt} + p_0 \qquad (9.20)$$

where the terms are all defined in terms given by previous equations.

It is clear that this system cannot eliminate the offset of proportional controllers. It can, however, handle fast process load changes as long as the *load change offset error* is acceptable. An example of the operation of this mode for a hypothetical load change is shown in Figure 9.21. Note the effect of derivative action in moving the controller output in relation to the error rate change.

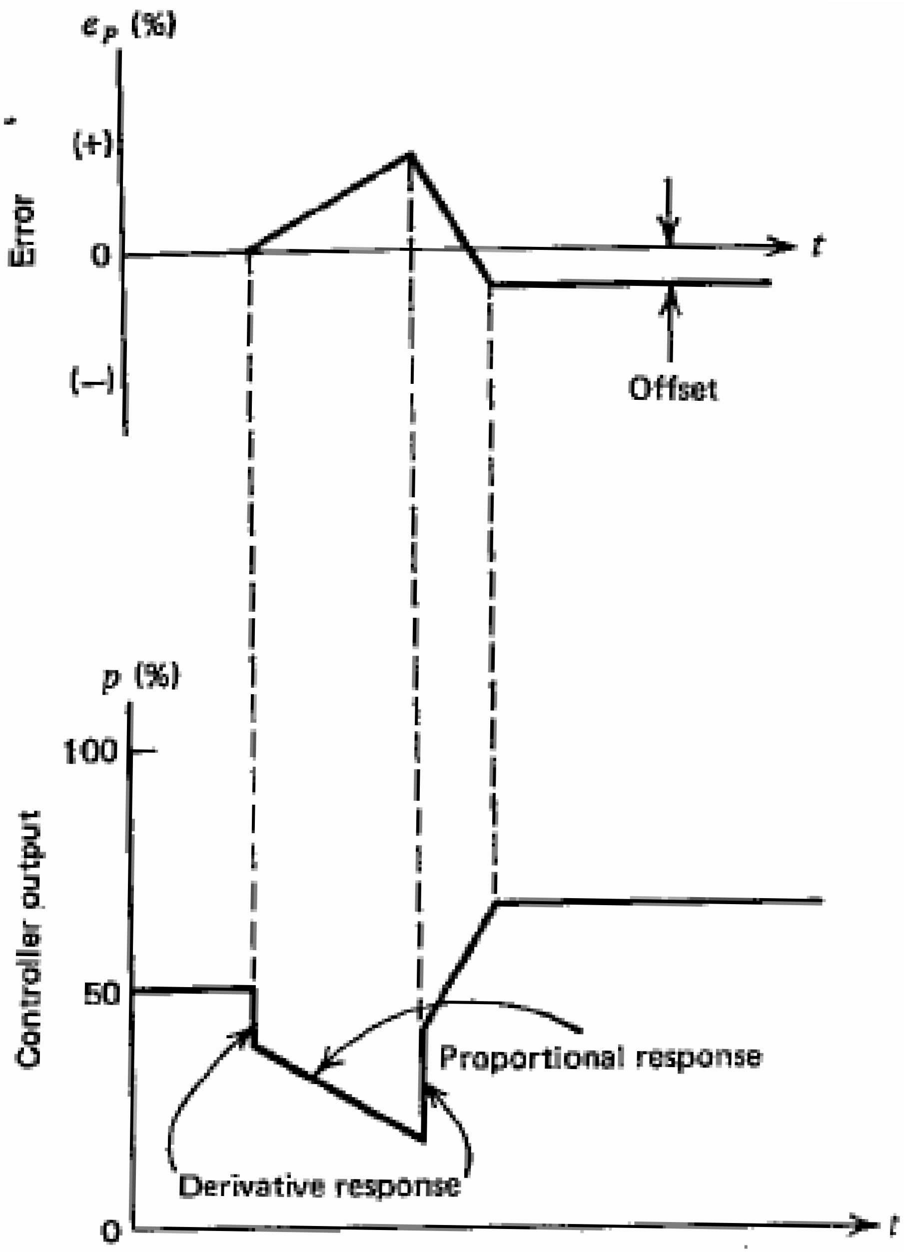


Figure 9.21 Proportional-derivative (PD) action showing the offset error from the proportional mode (reverse action).

PID Controller :

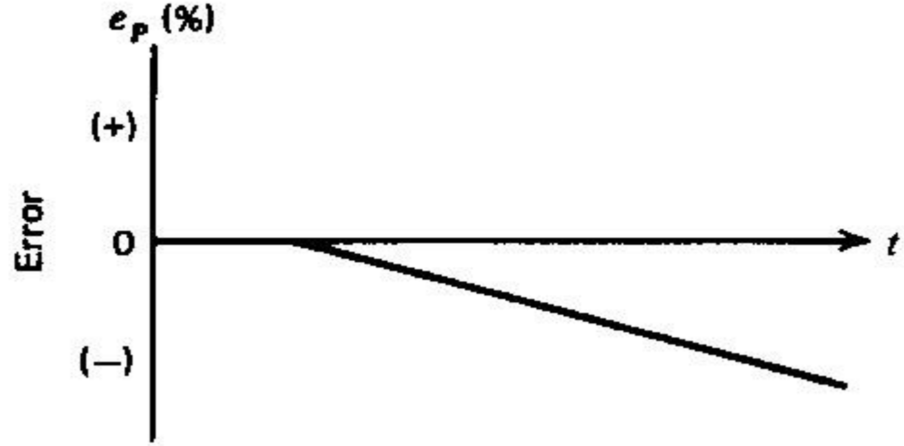
9.6.3 Three-Mode Controller (PID)

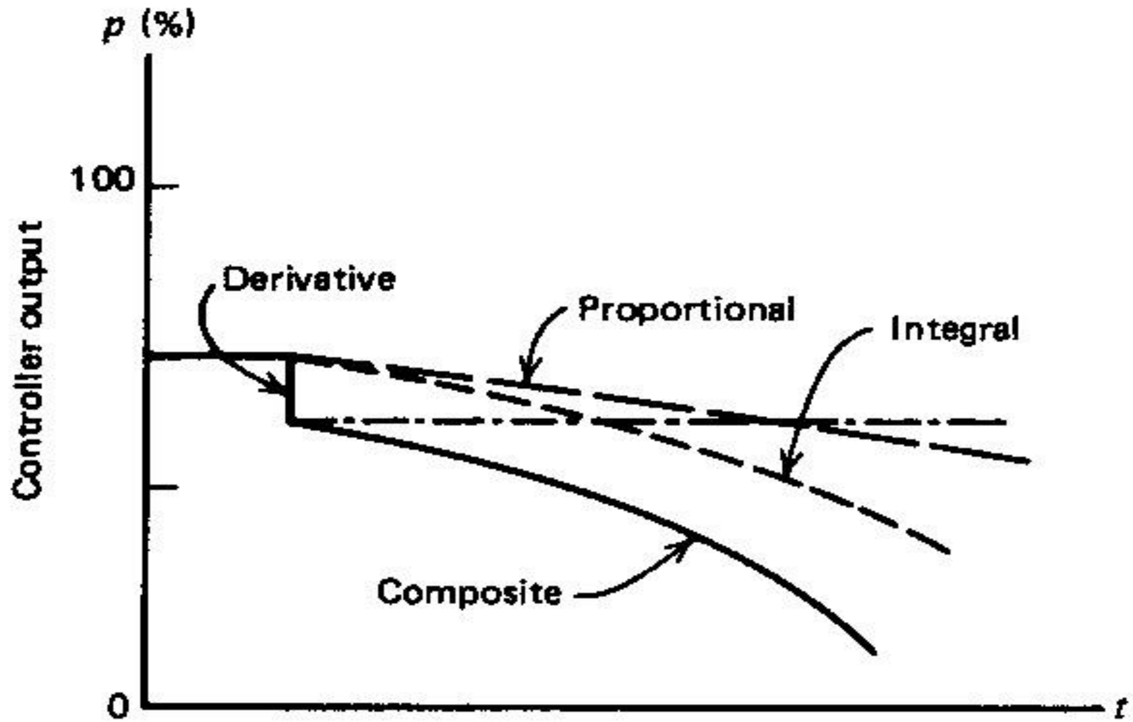
One of the most powerful but complex controller mode operations combines the proportional, integral, and derivative modes. This system can be used for virtually *any* process condition. The analytic expression is

$$p = K_P e_p + K_P K_I \int_0^t e_p dt + K_P K_D \frac{de_p}{dt} + p_I(0) \qquad (9.21)$$

where all terms have been defined earlier.

This mode eliminates the offset of the proportional mode and still provides fast response. In Figure 9.23, the response of the three-mode system to an error is shown.


e_p (%)
(+)
Error
0
(−)
t


p (%)
100
Controller output
Derivative
Proportional
Integral
Composite
0
t

THANK YOU