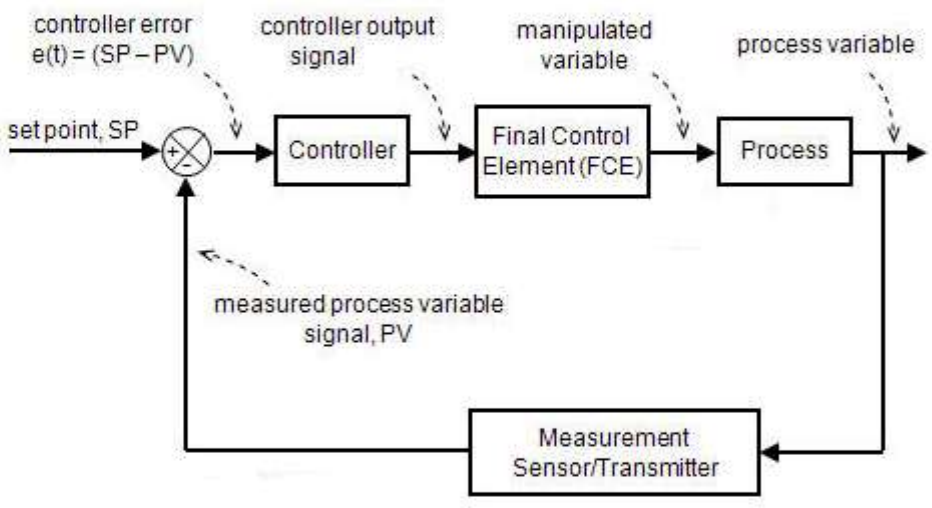
Chapter 3 Process Control Actions

3.1 Process control system: Block diagram, function of each block.
3.2 Discontinuous control actions- two position or ON-OFF: Operation, differential gap
3.3 Continuous control actions-proportional, integral and derivative: operation, output Equations, corresponding transfer function, Response graph.
3.4 Composite controllers - PI, PD, PID controllers : operation, output equations, Response graph, comparison, application
3.5 Electronic op-amp based PI, PD, PID controllers: circuit diagram, equations.

1. Block diagram of process control system and explanation

Block Diagram of Process control system



Function of each block:

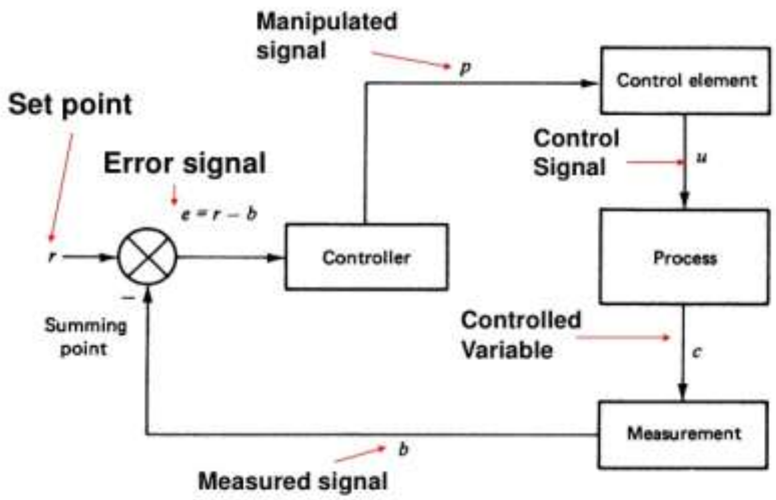
Controller: Controller requires an input which is the difference between the controlled variable and the reference value or the set point of the variable. This difference is called error. Control actions are the term used to represent the relationship between the controller output and error. Evaluation of controller consists of determining the action required to drive the controlled variable to the set point value. The controller output is the commanding signal given to the final control element (FCE) to reduce the error.

Final control element: It is the device that exerts a direct influence on the process. ie it provides those required changes in the controlled variable to bring it to the set point. This element accepts an input from the controller, which is then transformed into some proportional operation performed on the process. Commonly used FSE is control valve.

Process: It is often called as plant. It consists of single variable or multi variables which are to be controlled. Control element output is given to process which changes the process variable.

Error detector: It receives two inputs, set point and controlled variable and error obtained is given to controller.

OR



2. Classification of controllers

1. Discontinuous controller- example is ON-OFF controller
2. Continuous controller –Proportional, Integral and Derivative controller
3. Composite controller- PI,PD and PID

3. On- Off Controller

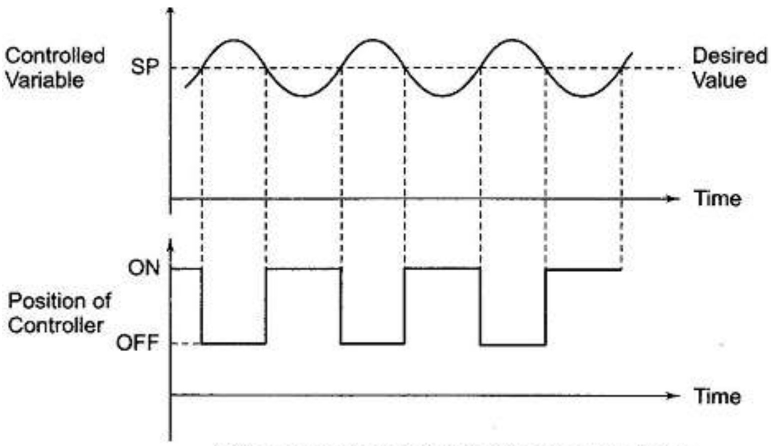
It has only two fixed positions such as on (1) and off (0). The output signal P remains either 0% or 100% depending upon whether the error is negative or positive. So the equation of On-Off controller is:

P = 100% (on) for positive error

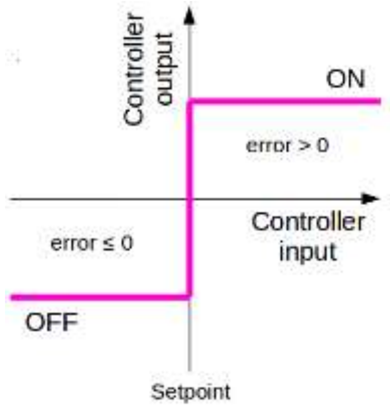
P = 0% (off) for negative error .

Consider a practical example of temperature control system with Set Point "x". When the temperature is more than "x" the on - off controller will be off and when it is less than "x" ,on - off controller will be on.

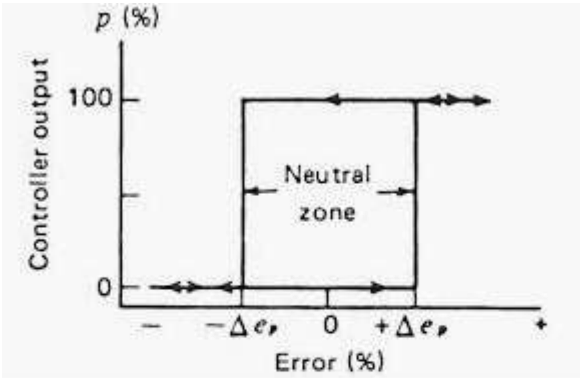
Example:- Relays, Thermostat



Characteristics of an ON–OFF Control Action



- <u>Neutral Zone (NZ) or Differential Gap</u> :
  It is defined as the range of error in On Off controller in which the controller output remains constant. It is the range of error through which the signal moves before the switching action takes place. It is designed to avoid frequent chattering of the controller.



NZ = 2ΔEp

4. **Proportional controller**

- The controller output is directly proportional to the error. The error is the difference between the setpoint and the process variable.

$$P_{out} - P_o \propto E_P$$

$$P_{out} - P_o = K_P\, E_P$$

$$\boldsymbol{P_{out} = K_P\, E_P + P_o}$$

P_{out}= Controller output
K_P = proportional constant

E_P = Error percentage
P_o= Controller output when error is zero

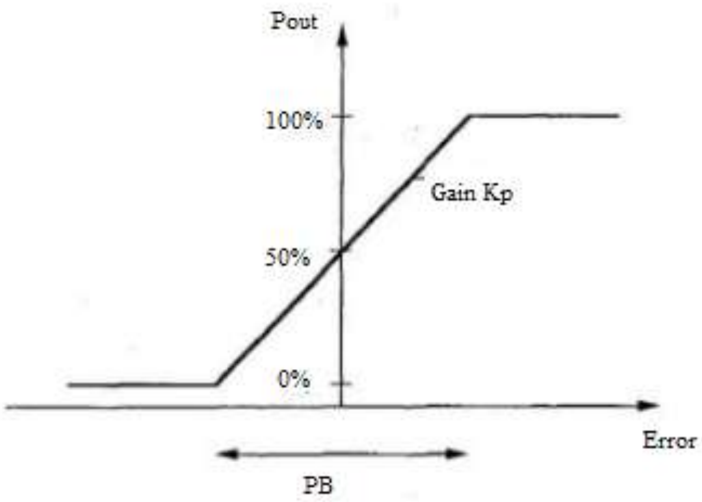
- Here, one to one correspondence exists between the controller output and error.

Transfer function:

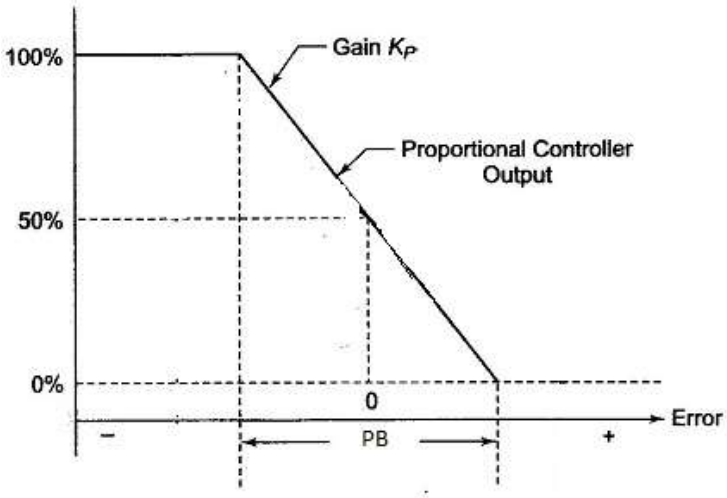
Taking Laplace transform of equation $P_{out} = K_P\, E_P + P_o$,

$P_{out}(s) = K_P\, E_p(s) + P_o(s)$ Therefore, $TF = \frac{P_{out}(s) - P_o(s)}{E_p(s)} = K_P$

Characteristics: (direct and reverse actions):



OR

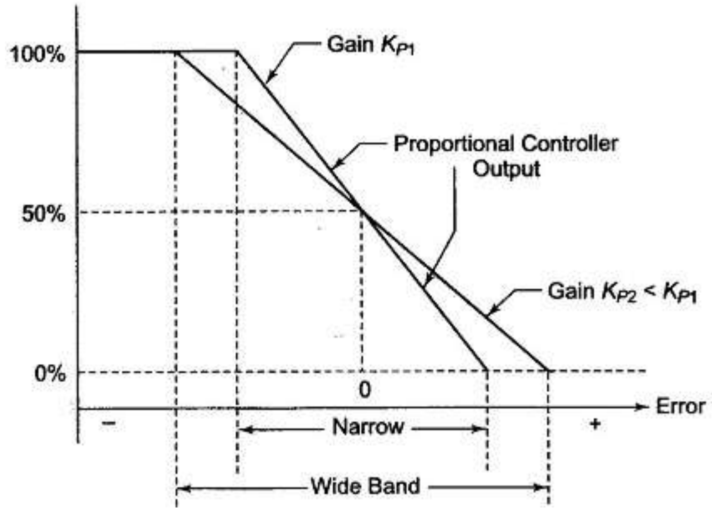


- Proportional Band PB:

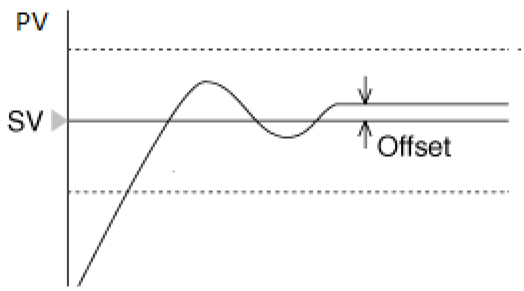
  PB is the range of error for which the controller output changes from 0 % to 100%.

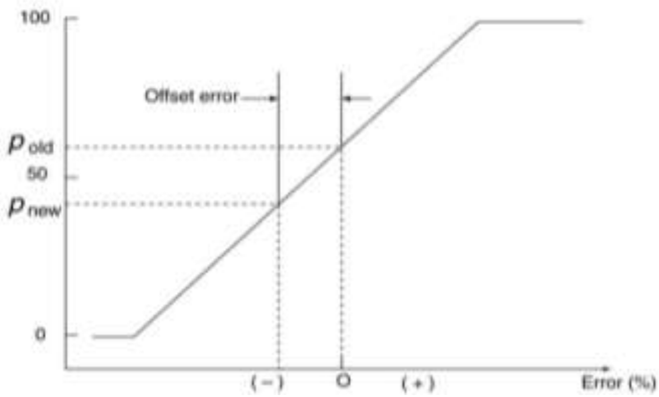
$$PB = \frac{100}{\boldsymbol{K_P}}$$

Proportional controller with two different PB and $\boldsymbol{K_P}$ **:**



- **Offset:**
  It is a permanent residual error in proportional controller which is inherent in nature; it is due to the one to one correspondence existing between the controller output and error. It occurs because the controller cannot adapt to changing external conditions or loads i.e. here, the zero-error output is a fixed value. When a load change requires a new controller output, proportional controller cannot provide that and instead it gives a fixed error from the set point. This fixed error is the offset.Since it is the steady state error, it has to be reduced to improve the performance of the controller.





Methods to eliminate offset:

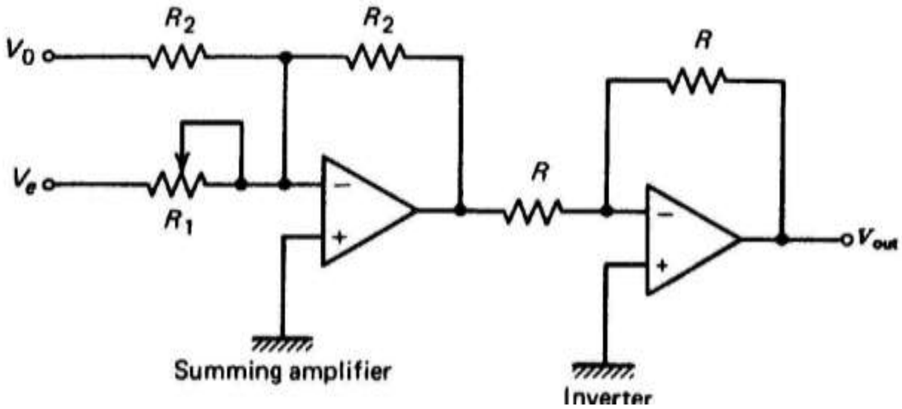
- Manual resetting
- By increasing $\boldsymbol{K_P}$ (But this will decrease PB which in turn makes the system behave like ON-OFF controller)

- Automatic resetting by using Integral controller

  Advantages of P controller:
  - Linear response

  Disadvantages of P controller:
  - Offset

Electronic proportional controller:



Output equation:

$$V_{out} = G_P\, V_e + V_o \qquad \text{where } G_P = \frac{R_2}{R_1}$$

5. **Integral controller (I) (or Reset controller)**

Here, the rate of change of controller output is proportional to the error.

$$\frac{dP_{out}}{dt} \propto E_p$$

$$\frac{dP_{out}}{dt} = K_I\, E_p$$

Taking integral,

$$\boldsymbol{P_{out} = K_I \int_0^t E_p dt + P_0} \quad (P_0 \text{ is the controller output when time t=0})$$

Transfer function:

Taking Laplace transform of equation $\frac{dP_{out}}{dt} = K_I\, E_p$,

$$SP_{out}(s) = K_I\, E_p(s) \qquad \text{Therefore,} \qquad TF = \frac{P_{out}(s)}{E_p(s)} = \frac{K_I}{S}$$

Therefore, it adds pole at origin.

- Integral control is the control mode where the controller output is proportional to the integral of the error with respect to time, i.e. controller output ∝ integral of error with time.

- Integral determines the area of the function being integrated. Therefore it gives the size and magnitude of the error which is the function being integrated.
- When the error occurs, the controller begins to increase or decrease its output at a rate that depends upon the size of the error and the gain based on the equation $\frac{dP_{out}}{dt} = K_I\ E_p$. If the error is zero, the controller output is not changed. If the error is positive, controller output begins to ramp up at a rate determined by the gain.
- Automatic reset or integral action corrects for any offset between set point and process variable automatically. Therefore it is also called Reset controller.
- Integral action is provided by summing the error over time (which is the cumulative addition or integral action), multiplying that by a gain and adding the result to the present controller output. If the error becomes positive or negative, the integral action will begin to accumulate and makes changes to the controller output.
- This controller action is slow and has less stability due to oscillations induced by the integral overshoot in the response. It looks into the past history of errors due to the integral actions.

How does integral action eliminate offset?

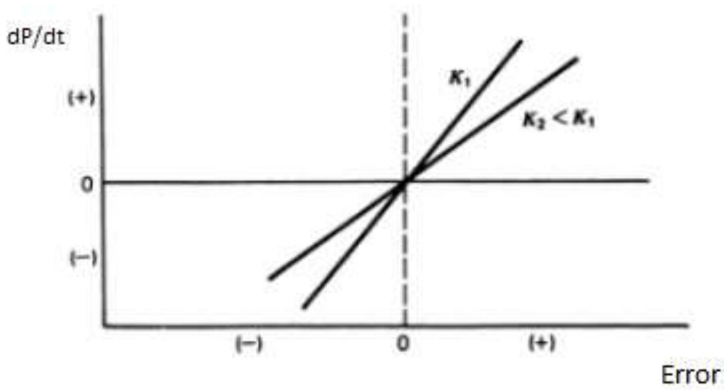
- Offset occurs because the proportional controller cannot adapt to changing external conditions or loads i.e. here, the zero-error output is a fixed value. Integral eliminates this problem by allowing the controller to adapt to changing external conditions by changing the zero-error output. Integral provides a reset of the zero error output after a load change. Thus Integral redefines the output requirements at the set point until the process variable and set point are equal.

OR

- When a load change requires a new controller output, proportional controller cannot provide that and instead it gives a fixed error from the set point. This fixed error is the offset. Integral provides the required new output thereby allowing the error to be zero after a load change. It provides reset of the zero-error output after the load change. Thus integral controller eliminates offset.

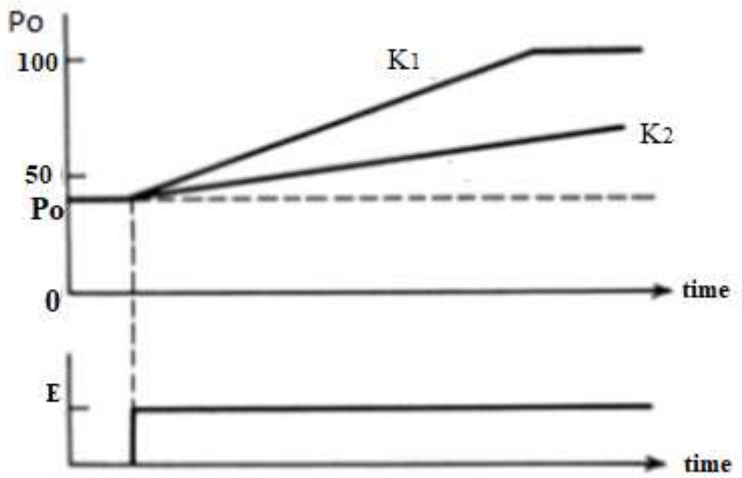
Integral action response:

Two systems with gain K_2 & K_1 $(where\ K_2 < K_1)$ are considered here. The rate of change of controller output is proportional to the error which is shown below:



Integral controller output for a constant error:

Here, controller output begins to ramp up at a rate determined by the gain. Two systems with gain K_2 & K_1 $(where\ K_2 < K_1)$ are considered here. In the case of gain K_1, the output finally saturates at 100% and no further action can occur. (For example, control valve is fully open). The graph is given below:



Advantages:

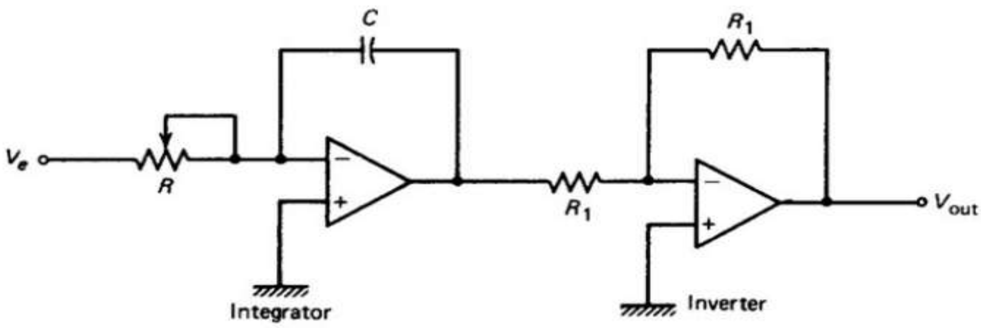
1. Eliminates offset

Disadvantages:

1. Slow response
2. Less stability

Electronic Integral controller:

$$V_{out} = (\frac{1}{RC}) \int_0^t V_e dt + V_0$$



6. **Derivative controller (D)**

Here, the controller output is directly proportional to the rate of change of error signal. Therefore it is also called **rate controller**.
The equation for D controller is:

$$P_{out} = K_D \frac{dE_p}{dt}$$

K_D is the derivative gain constant which is the time constant.
It shows that the controller output will be zero if i) error E_p is zero ii) if error is constant. Therefore D controller is not used alone.

Transfer function:

Taking Laplace transform of equation $P_{out} = K_D \frac{dE_p}{dt}$,

$$P_{out}(s) = K_D\, S\, E_p(s) \qquad \text{Therefore,} \qquad TF = \frac{P_{out}(s)}{E_p(s)} = K_D\, S$$

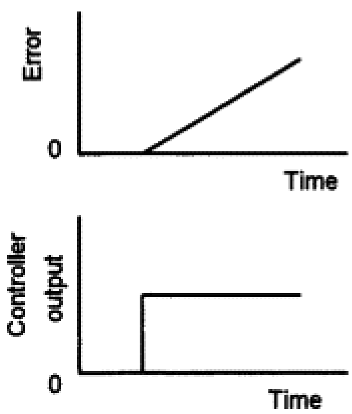
Therefore, it adds zero at origin of S plane.

Anticipatory controller:
It is also called anticipatory controller because:-
If a variable changes suddenly, its rate of change is fast. Since the change in output from derivative controller depends on rate of change of error signal, it gives a large amount of correction to a rapidly changing error signal while the error is still small. Thus it behaves as if anticipating the process error before it becomes too large and takes corrective action in advance. This tends to increase the stability of the system.

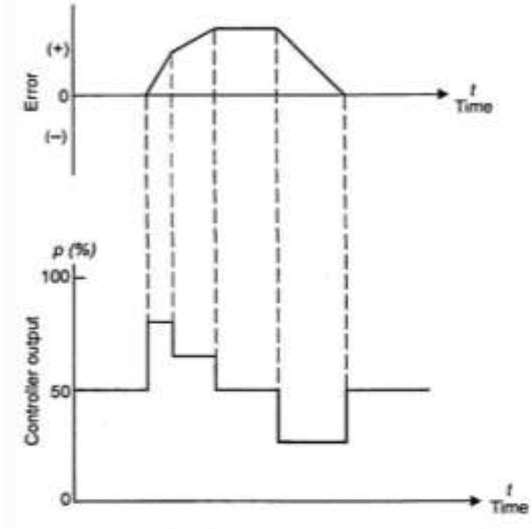
Advantages:
1. Fast
2. Better stability
3. No offset
4. Useful for slow systems or systems with large inertia or capacitance

Disadvantages:
1. Cannot eliminate offset
2. No output for zero or constant error
3. Cannot be used alone
4. Amplifies noise

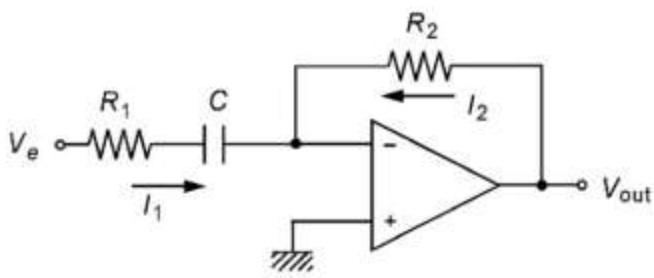
Response:
When the error changes rapidly, with positive slope, the controller output changes suddenly and if the rate of change of error is constant, controller output remains at a constant value. If the error is zero, the controller output is also zero. It is shown below.



In the second example of error, it is assumed that the controller output for no error is 50%. When the error changes rapidly, with positive slope, the controller gives a larger output. When the error changes rapidly, with negative slope (error is decreasing), the controller gives a smaller output. When the error is not changing, controller output is 50%. It is shown below.



Electronic Derivative controller:



$$V_{out} = R_2 C \frac{dV_e}{dt}$$

7. **PI controller:**

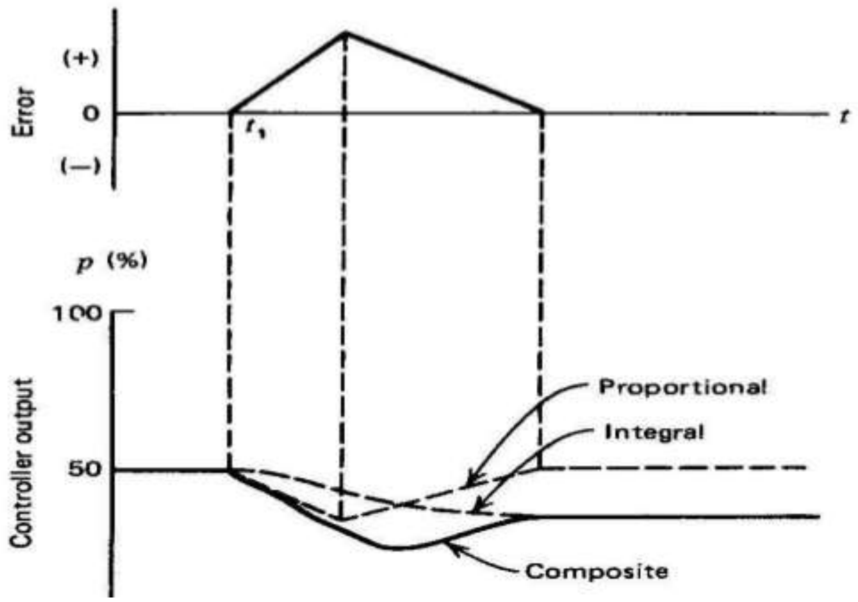
It is the combination of Proportional and Integral controller. The output equation is

$$P_{out} = K_P\, E_P + K_P\, K_I \int_0^t E_p dt + P_0$$ Where P_0 is the controller output when time t=0

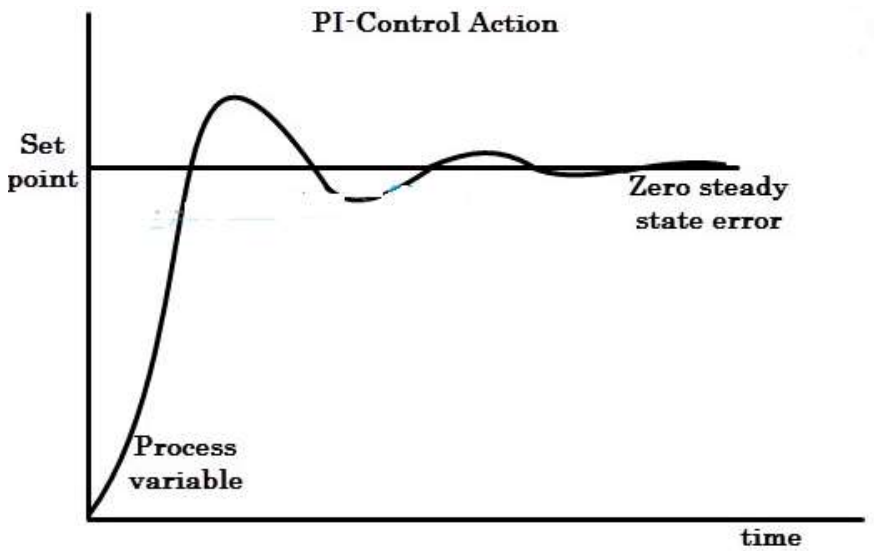
Integral controller is rarely used alone because of its slow response to disturbances. When it is combined with proportional controller, its slow response can be eliminated. Here, one to one correspondence of the proportional controller is available and integral controller eliminates offset.

PI mode ensures that when a deviation takes place, proportional mode reacts immediately to change the controller output since there is not a time integral of deviation. Offset error occurs with a load change but mode provides a new controller output which in turn changes the error to be zero after a load change.

Characteristics:
i) When error=0, controller output is Po (output when t=0)
ii) When error is not zero, the proportional controller gives correction and integral begins to change the accumulated value of the error which is initially P_0



If the error is not zero, the proportional controller gives correction and integral begins to change the accumulated value of the error which is initially P_0

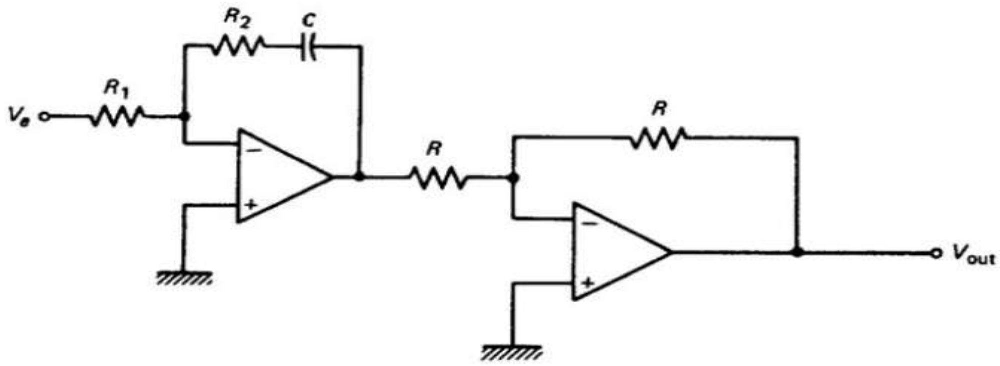


Advantages of PI controller:
Eliminates offset, can be used for systems with large load changes

Electronic PI controller:

$$V_{out} = \frac{R_2}{R_1} V_e + (\frac{R_2}{R_1})(\frac{1}{R_2 C}) \int_0^t V_e dt + V_0$$

$$\frac{R_2}{R_1} = G_P = K_P \qquad \frac{1}{R_2 C} = G_I = K_I$$



8. PD Controller

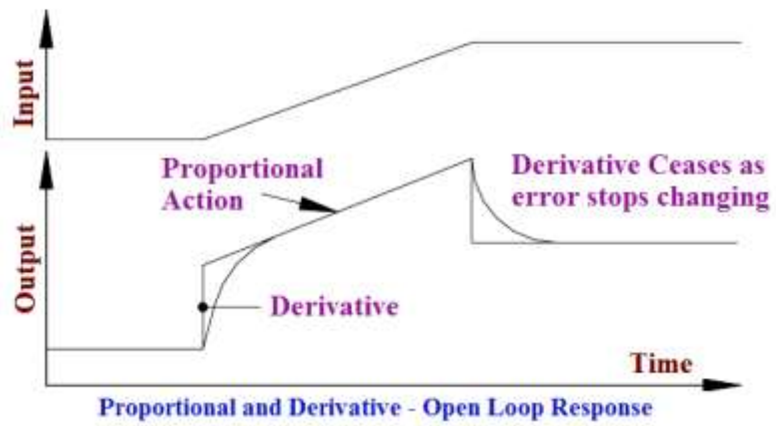
It is the combination of Proportional and Derivative controller. The output equation is

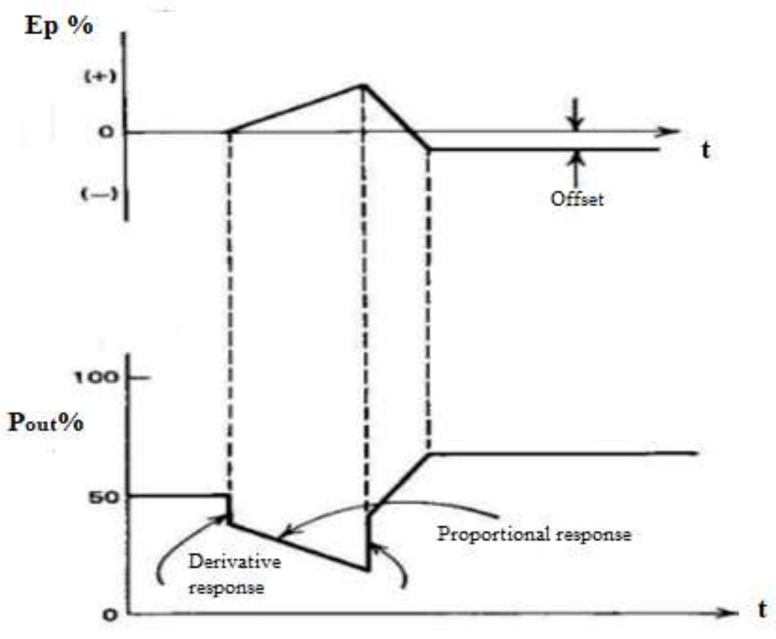
$$P_{out} = K_P E_P + K_P K_D \frac{dE_p}{dt} + P_0$$

Where P_0 is the controller output when error is 0.

It cannot eliminate offset. But it can handle fast process load changes because of derivative action. It improves the speed and stability of the control system response. But it is not suitable for systems with noise problems because derivative action amplifies noise error signals.

Response:





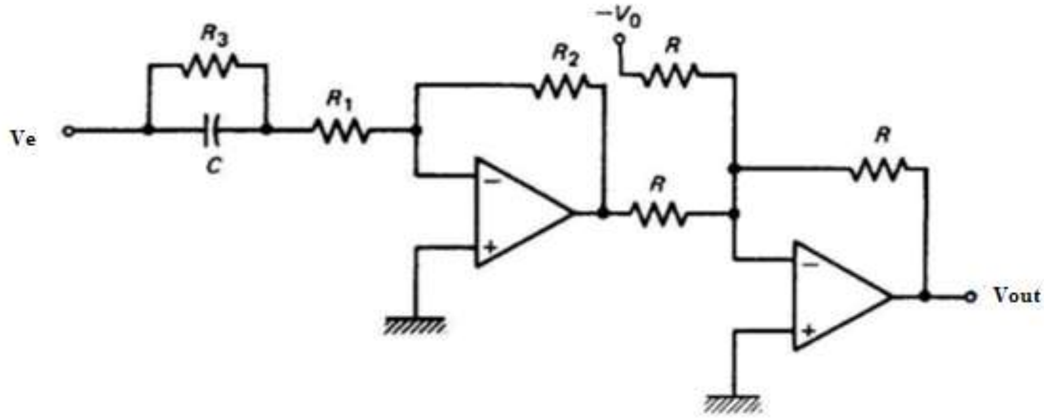
The derivative action moves the controller output in relation to the rate of change of error.

Electronic PD controller:

$$V_{out} = \frac{R_2}{R_1 + R_3} V_e + (\frac{R_2}{R_1 + R_3}) R_3 C \frac{d V_e}{dt} + V_0$$

$$\frac{R_2}{R_1 + R_3} = G_P = K_P$$

$$R_3 C = G_D = K_D$$



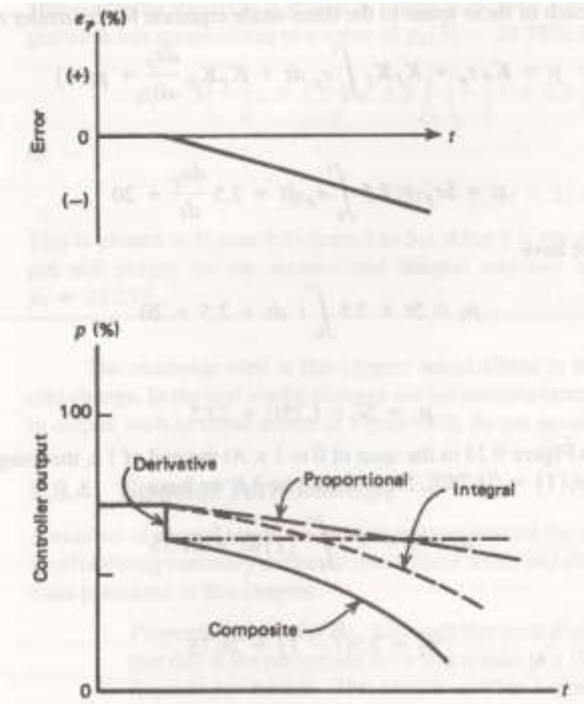
9. PID (Proportional Integral Derivative) control action

PID controller is the combination of proportional-integral-derivative controller.

$$P_{out} = K_p E_p + K_p K_1 \int_0^t E_p dt + K_p K_D \frac{dE_p}{dt} + P_o$$

When an error (the change in measured variable from the set point) is introduced to a PID controller, the controller's response is a combination of the proportional, integral, and derivative actions.
As the error increases, the proportional action of the PID controller produces an output that is proportional to the error signal.
The integral action of the controller produces an output whose rate of change is determined by the magnitude of the error. As the error continues to increase at a steady rate, the integral output continues to increase its rate of change.
The derivative action of the controller produces an output whose magnitude is determined by the rate of change of error.
When combined, these actions produce an output. The output responds immediately to the error with a signal that is proportional to the magnitude of the error.
The proportional action of the controller stabilizes the process. The integral action combined with the proportional action causes the measured variable to return to the set point (reduces the offset).
The derivative action combined with the proportional action reduces the initial overshoot and cyclic period.

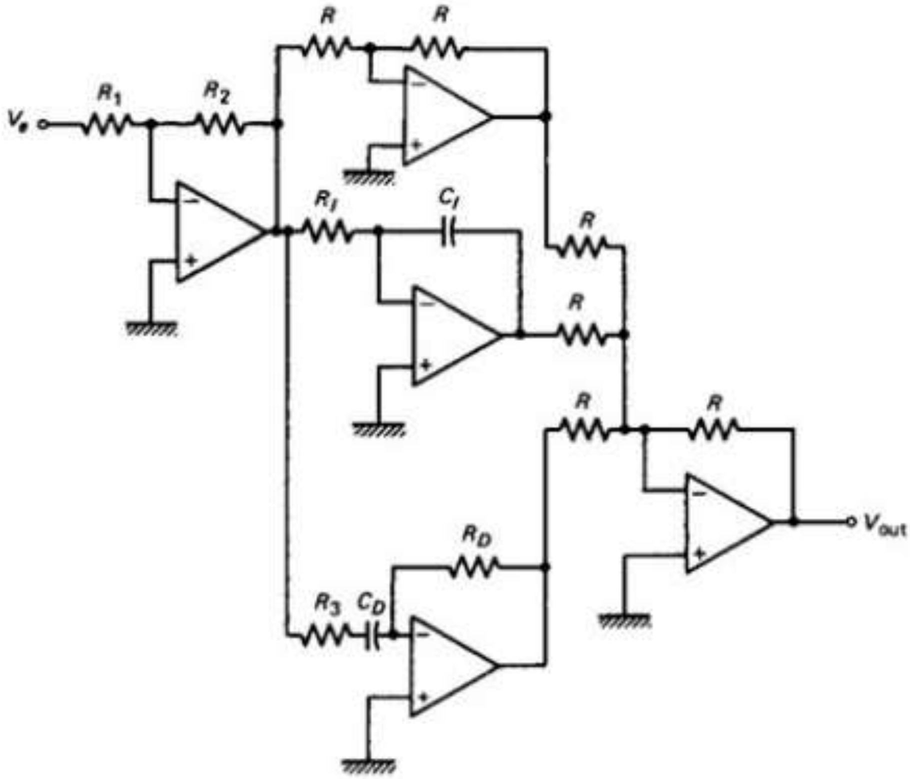
Nature of output response:



Advantages:
1. Offset is reduced.
2. Fast response
3. Produces output depending upon magnitude, duration, and rate of change of error.
4. The PID algorithm is suitable for the large system
5. When there are rapid and large changes in process variables, PID controller is used.

Disadvantages:
1. Complex
2. Tuning of parameters (K_P, K_I, K_D) is difficult.

Electronic PID controller:



$$V_{out} = \frac{R_2}{R_1}\,V_e + (\frac{R_2}{R_1})(\frac{1}{R_1C_1})\int_0^t V_e dt + (\frac{R_2}{R_1})R_DC_D\frac{d\,V_e}{dt} + V(0)$$

$$where,$$

$$\frac{R_2}{R_1} = G_P = K_P, \qquad \frac{1}{R_1C_1} = G_I = K_I, \;\; R_DC_D = G_D = K_D$$

10. Comparison of P, I & D controller:

Sr.No	Proportional control	Integral control	Derivative control
1	Controller output is proportional to error	Rate of change of controller output is proportional to the error	Controller output is proportional to the rate of change of error
2	Offset is present	Absent	Absent
3	Response to the direction of error	Response to the size, time duration and magnitude of error	Response to the rate of change of error
4	Amplifies noise	Eliminates noise	Amplifies noise

5	Moderate response speed	Slow	Fast
6	Moderate period of oscillation	Long period of oscillation	Small period of oscillation
7	Moderate stability	Less stability (due to poles at origin)	High stability (due to zero at origin)
8	Looks into the present error	Looks into the past history of error	Anticipates the error
9	Action has no sense of time	Depends on time	Measured in terms of time
10	No pole or zero is added	Adds pole at origin	Adds zero at origin
11	Equation is $Pout = K_P E_P + P_0$	$Pout = K_I \int_0^t E_P \, dt + P(0)$	$Pout = K_D \dfrac{dE_P}{dt}$
12	Used in processes with medium process lags	Used in processes with small process lags & small capacitance such as flow & level control system	Used in processes with large process lags & inertia such as temperature control system
13	Response: