Why Different Controller Modes ?

- Delays are inherent to each of factors (like process lag, control lag, dead time) and cannot be avoided.

However, the reaction time can be substantially reduced by maximizing the operation of an instrument in the control loop in two ways:

1. "Select a controller" with operational features that provide the kind of control action needed for a particular process.
2. "Properly tune" the controller to optimize the regulation of the process.

Selecting a Controller

Controllers are designed to operate by using different control modes. Each of these modes has specific characteristics that provide different types of control action. These control modes are:

1] Discontinuous Controller mode

a) On-off or Two-position mode.

b) Multiple Position mode.

2] Continuous Controller mode

a) Proportional mode

b) Integral mode

c) Derivative mode.

Controller Modes

- Normally, a controller generates a control s/g to final control element, based on a measured deviation of controlled variable from setpoint.
- It is natural to ask how the Controller responds to the deviation.
- In a thermo-statically controlled temperature system used in the home, the controller response is simple. If the temperature drops below the thermostat setpoint, a bimetallic relay turns on a heater.
- Consider the case of temperature control in fig(1). Here, no simple ON/OFF decision can be made, thus, if a deviation from liquid temperature (T_L) setpoint occurs, What should the Controller do?
- Should it open the valve a little or a lot?
- Should it open the valve fast or slowly?

These Questions are answered by specifying the "mode" of the controller operation.

- Choice of controller mode involves not only process characteristics but cost analysis, product rate, and other industrial factors.

Two-Position Mode / ON-OFF Control

- In some types of process applications, the controlled variable changes very slowly.
- On-off controller mode is often used for slow acting operations.
- This kind of action controls a final control element that has only two conditions, fully on or fully off.
- The controller cannot move the final control element to any intermediate position between the two extremes.

In general, we can write.

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

- This relation shows that when the measured value is less than the setpoint, full controller output results.
- When it is more than the setpoint, the controller O/P is zero.

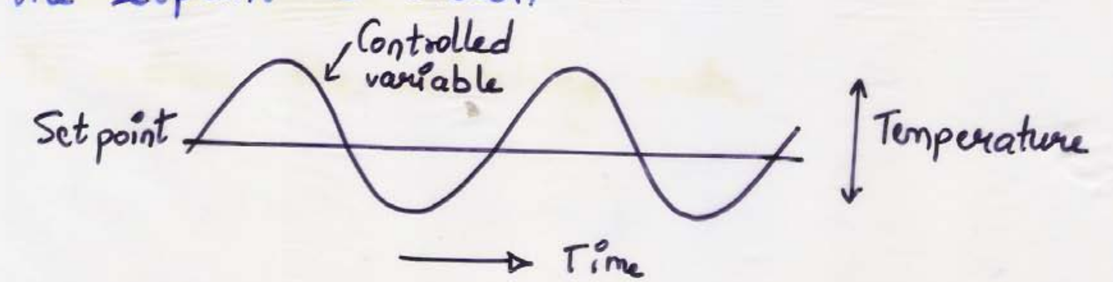
On-off Control

Applications: On-off control mode is best adapted to large scale systems with relatively slow process rates.

- Thus, in example of either a room heating or air-conditioning system, the capacity of the system is very large in terms of air volume, and overall effect of the heater or cooler is relatively slow.
- Another example of such mode is a refrigation unit.

1. The controller compares the temperature (controlled variable) to the setpoint.
2. When the temperature increases above the setpoint, the controller turns a compressor (final control element) fully on.
3. As the temperature lowers below the setpoint, the compressor is turned off.

The controlled variable cycles above and below the setpoint is shown



On-off Mode

- This type of control mode doesn't actually hold the variable at setpoint, but keeps the variable within proximity of setpoint in what is known as a 'dead zone'.

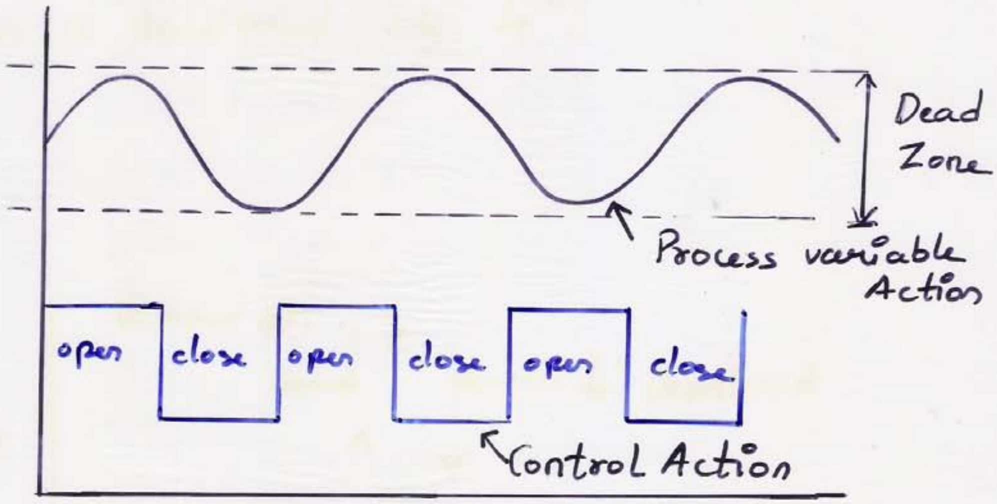
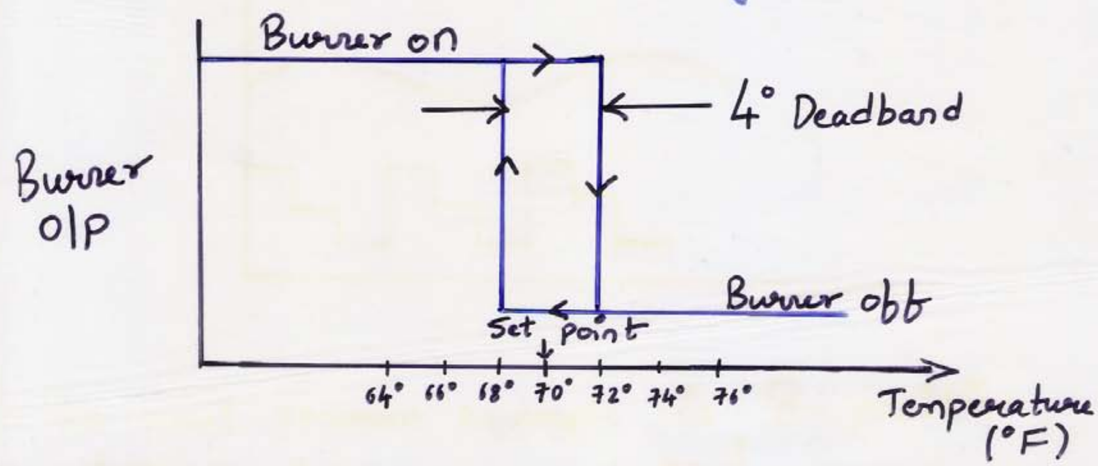


fig Discrete / On-off / Two-position Controller mode.

- One drawback of this system is that the final control element switches on and off can be very high.
- This condition can result in excessive wear to equipment.
- To reduce the switching rate, an On-off differential or hysteresis, is programmed in to the controlled. Also referred to as a 'Deadband'.

On-off Controller mode

- Deadband causes the controller to produce its on and off signals at different values around the setpoint.
- For example, a home heating thermostat may have a deadband of 4°.
- If the temperature setting is 70°, the furnace turns ON at 68° and turns off at 72° as graphically shown below.



Case Study Example:

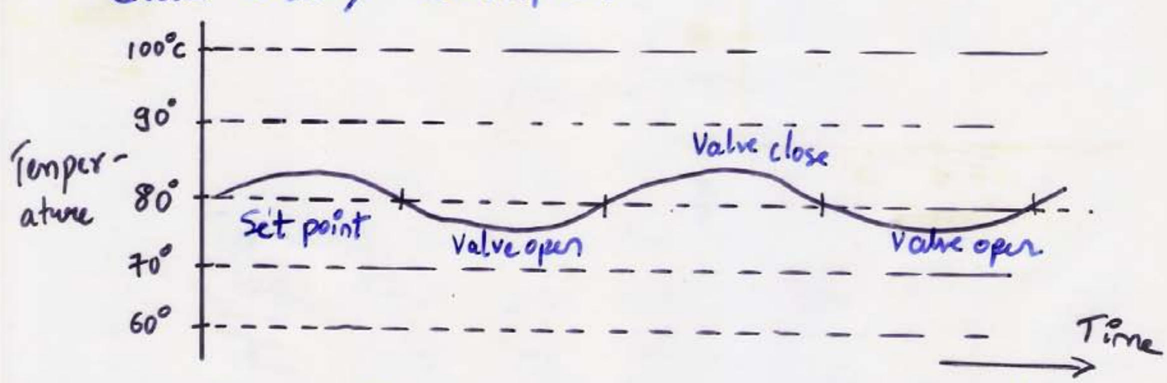


fig: Continuous Record of temperature in On-off Control mode.

Multiposition / Multistep Controller mode

- Multistep controllers are controllers that have atleast one other possible positions in addition to ON and OFF.
- They operate similarly to on-off controllers, but as setpoint is approached, multistep controller takes intermediate steps.
- Therefore, the oscillations around setpoint can be less dramatic in this mode.

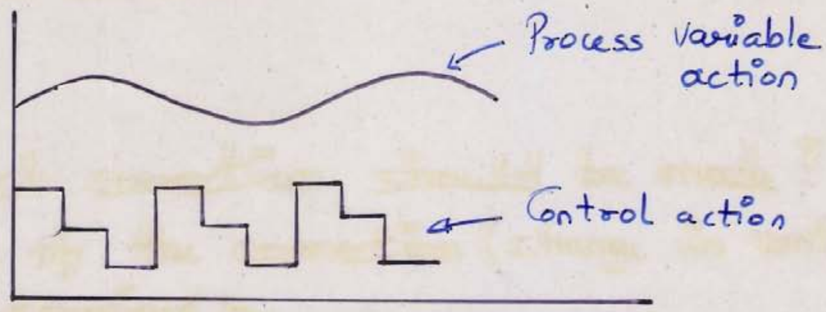
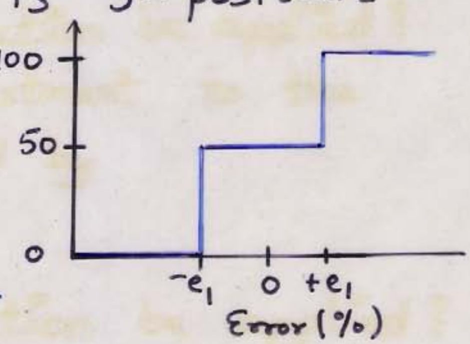


fig: Multi-step Control Profile

- The most common example is 3-position controller where,

Controller o/p :→ $P = \begin{cases} 100 & e_p > e_2 \\ 50 & -e_1 < e_p < e_2 \\ 0 & e_p < -e_1 \end{cases}$



- As long as the error is between e_2 and e_1 of the setpoint, the controller stays at some nominal setting indicated by a controller output of 50%. If error exceeds setpoint by e_1 or more, the o/p is ↑sed by 100%. If it is less than setpoint by $-e_1$ or more, controller o/p is reduced to zero.

Continuous Controller Modes

- In these modes, the o/p changes smoothly in response to error or rate of change of error.
- 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 o/p according to the parameters that have been set in the controller.

It Determines:

How Much correction should be made? The magnitude of the correction (change in controller o/p) is determined by proportional mode of controller.

How Long should the correction be applied? The duration of the adjustment to the controller o/p is determined by 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.

Proportional Mode

- A proportional controller produces an o/p signal with a magnitude ie proportional to the size of error signal it is correcting.
- The o/p of proportional controller moves the final control element to a definite position to attain a desired value of controlled variable.

This mode can be expressed by,

$$\boxed{p = K_p e_p + p_o} \quad ----- (1)$$

where, K_p = Proportional gain between error and controller output

p_o = controller o/p with no error (%)

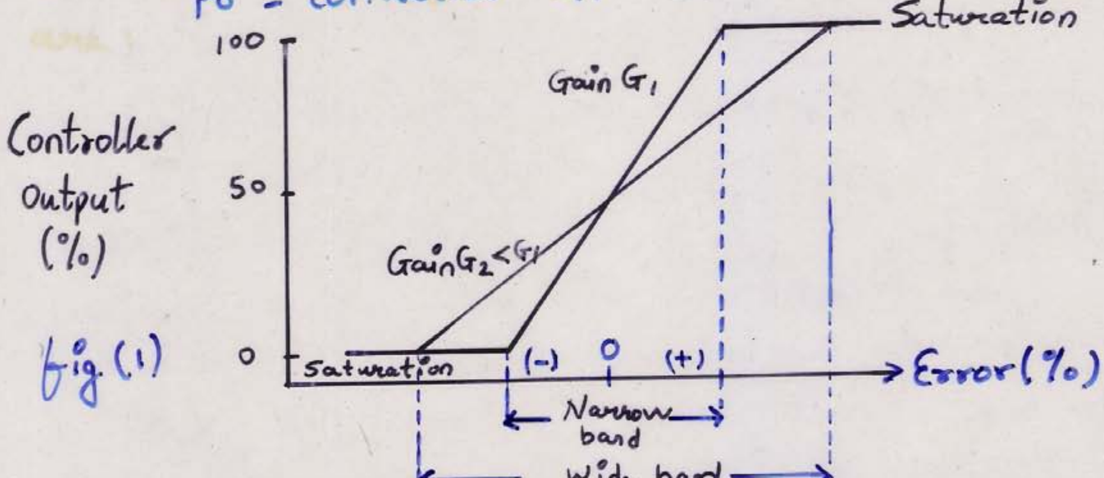


fig. (1)

fig: The Proportional band of a proportional controller depends on the inverse of the gain.

- Range of error to cover the 0% to 100% controller output is called 'proportional band'.

- A plot of proportional mode o/p versus error for equation (1) is shown in fig (1).
- In this case, p_o has been set to 50% and two different gains have been used.

Note that the proportional band is dependent on the gain.

- A high gain means large response to an error, but also a narrow error band within which the o/p is not saturated.

$$\boxed{PB = \frac{100}{K_p}} \quad ; \quad \boxed{p = K_p e_p \pm P_o}$$

Characteristics of proportional mode and eqn(1) are:

1. If the error is zero, the o/p of controller is a constant equal to P_o.
2. If there is error, for every 1% of error, a correction of K_p % is added to or subtracted from P_o, depending on sign of error.
3. There is a band of error about zero of magnitude PB within which the output is not saturated at 0% or 100%

K_p = Proportional Gain

PB = Proportional Band

Offset in Proportional mode:

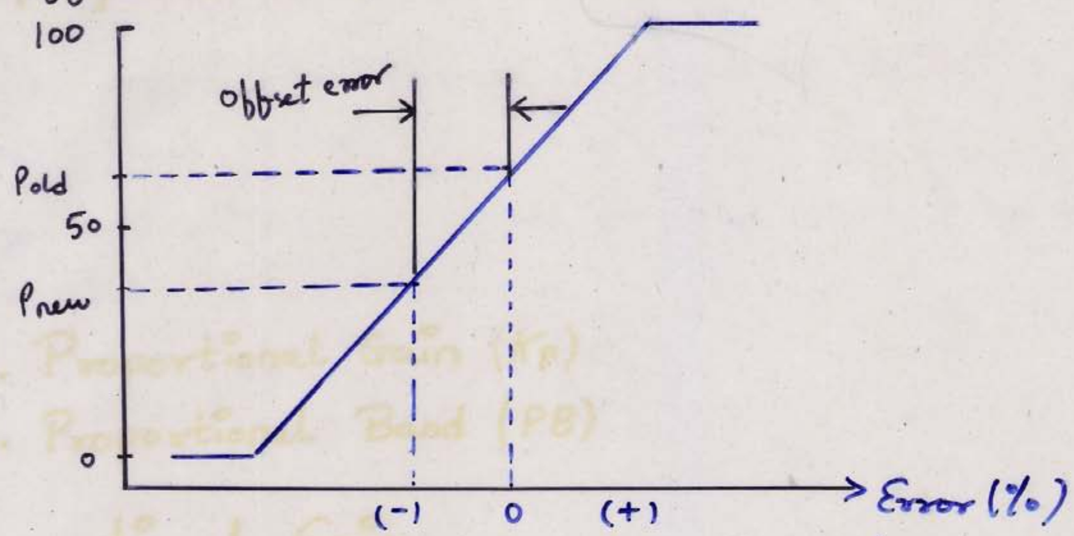


fig: An offset error in Proportional mode.

- An important characteristic of proportional contorl mode is that it produces a permanent residual error in the operating point of the controlled variable when a change in load occurs. This error is referred to as offset.

- It can be minimized by a larger constant, K_p which also reduces the proportional band.

- Proportional action only occurs above and below the set-point within the proportional band.
- The setpoint is located at the mid-point of the range of values in the proportional band.

- Outside the proportional band, the controller functions as if it is the ON-off mode.
- Within the PB, final control element is turned on at an amount that is Anal to (Measured variable - setpoint)

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 (K_P)
  2. Proportional Band (PB)

Proportional Gain

In electronic controllers, proportional action is typically expressed as 'proportional gain'.
Proportional gain (K_P) answers the question:
"What is the % change of the controller o/p relative to the % change in controller i/p?"

$$K_P = \frac{\%\ \text{Output change}}{\%\ \text{Input change}}$$

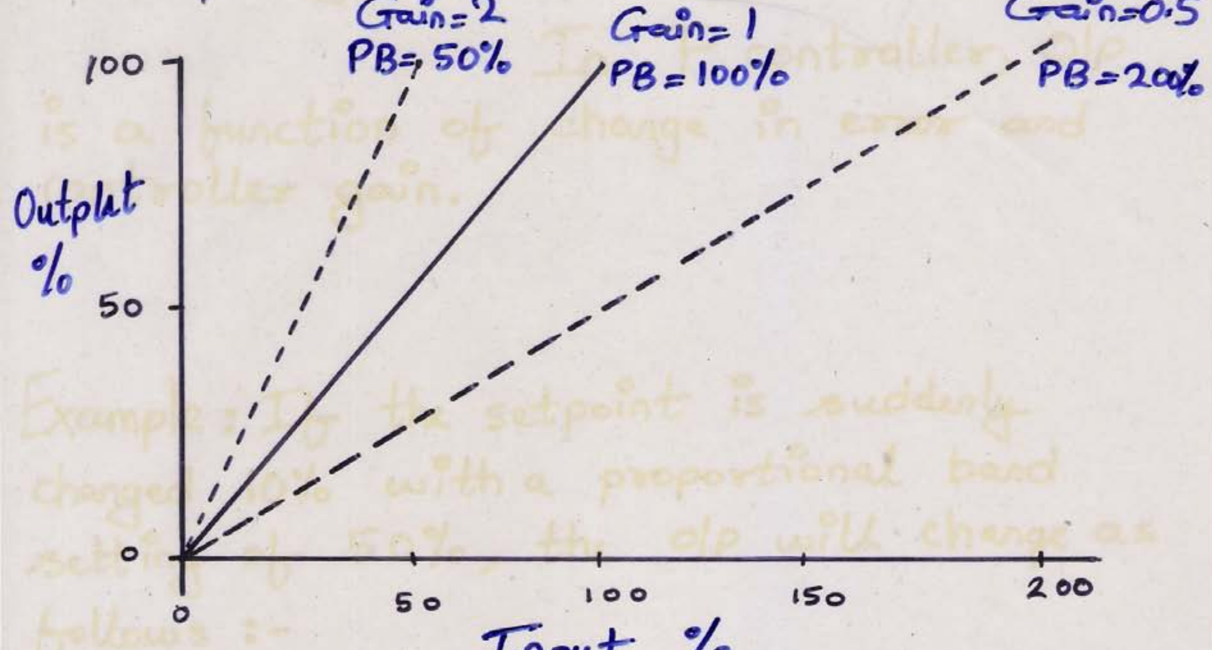
Proportional Band

Proportional band (PB) answer's the question:
"What % of change controller i/p span will cause a 100% change in controller o/p?" OR

$$PB = \frac{\text{Controlled variable \% change}}{\text{Final Control element \% change}} \times 100$$

- PB is defined as % change in the controlled variable that causes the final control element to go through 100% of its range.

Proportional Mode



Relationship between Propartional Gain and Proportional Band.

Limits of Proportional Action

1. Proportional action responds only to a 'change in the magnitude of error.'

2. 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.

PV means Process Variable

Determining the Controller Output

Controller Output: In P controller, O/P is a function of change in error and controller gain.

% O/P change = (% Error change) (Gain)

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

Calculating Controller Output

Δ Controller o/p = % Δ Input × Gain

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

Example: Δ Input = 10% , PB = 50%

So Gain = 100%/50% = 2

$\therefore$ Δ Controller Output = Δ Input × Gain

= 10% × 2

= 20%

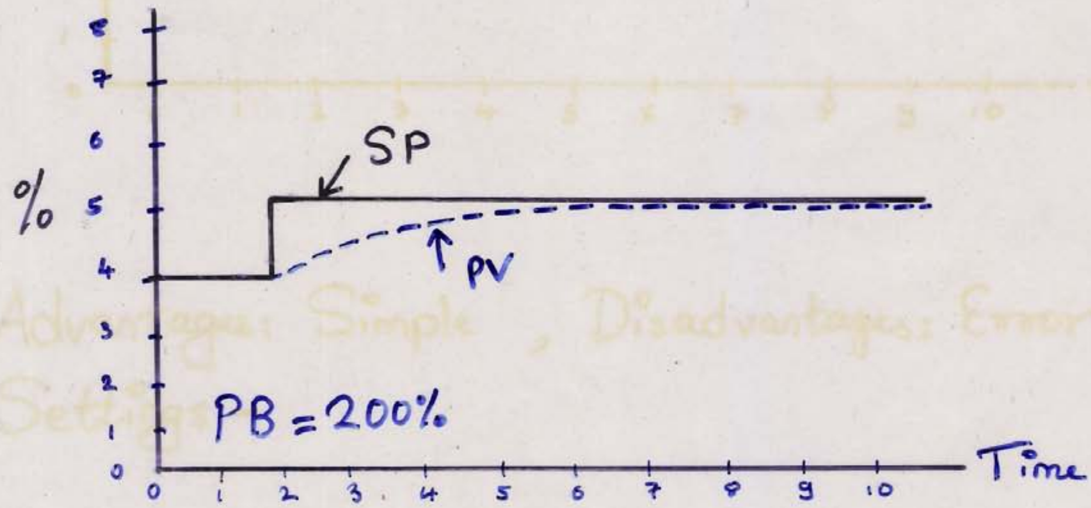
Proportional Action- Closed loop

Closed Loop gain :- Every control loop has a critical or natural frequency. This is the frequency at which cycling may exist.

• If loop gain is too high at this frequency, the PV will cycle around the SP ie the process will become unstable.

Low Gain example:-

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

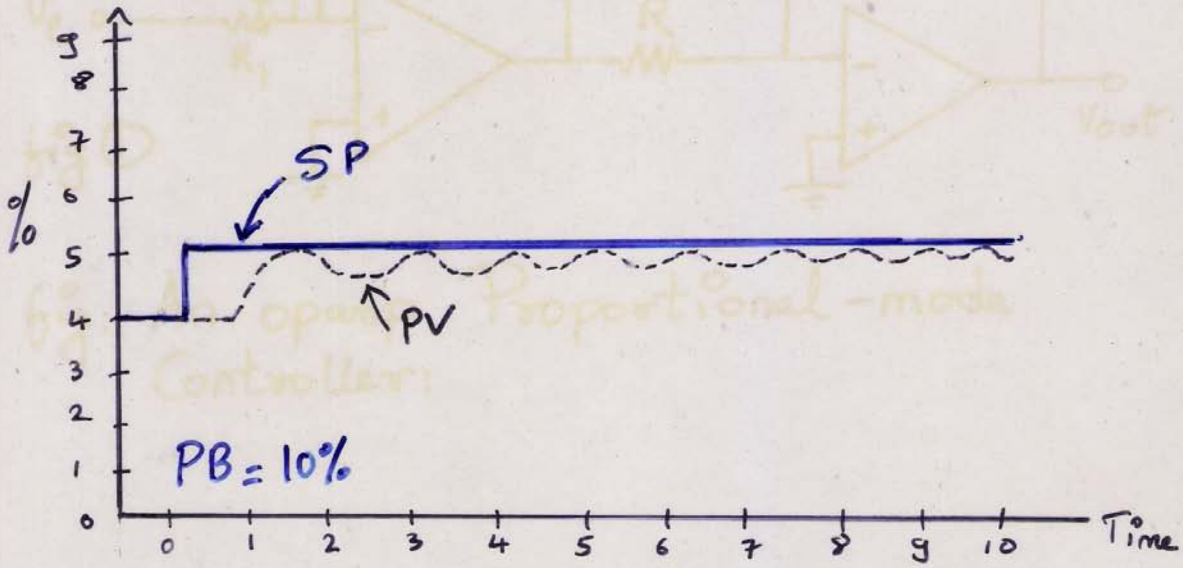


Proportional Control Closed loop
- Low Gain Example.

Proportional Mode Action

High Gain Example:

In this example, the proportional band is small resulting in high gain, which is causing instability.
Notice that the Process variable (PV) is still not on set point (SP).



Proportional Contool Closed loop:- High gain example.

Advantages: Simple , Disadvantages: Error

Settings - PB settings have following effects.

Small PB (%) - Minimize offset
High Gain (%) - Possible Cycling.
Large PB (%) - Large offset
Low Gain (%) - Stable Loop

Electronic Controller

It's a treatment of electronic methods of realizing Controller modes using Opamps as basic element.

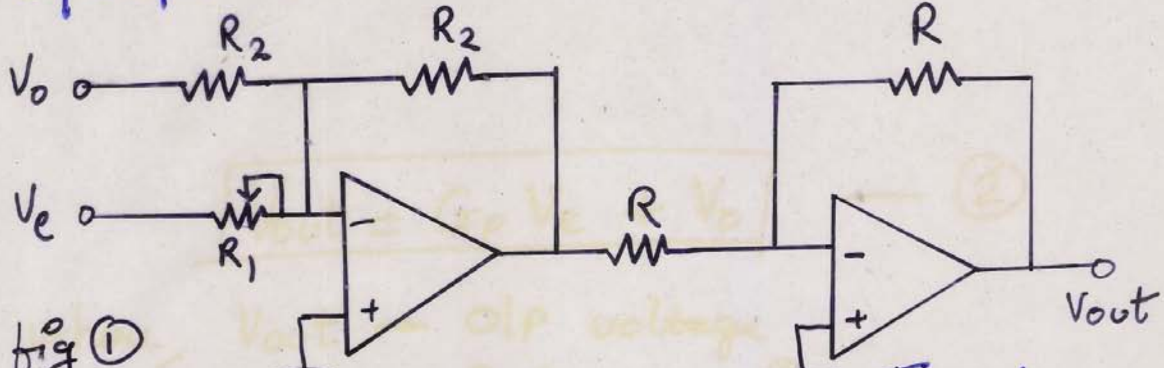


fig ①

fig: An opamp Proportional-mode Controller:

Proportional Mode: $\boxed{p = K_p e_p + p_o}$ — ①

where, $p \rightarrow$ controller o/p 0-100%

$K_p \rightarrow$ Proportional gain

$e_p \rightarrow$ error in % of variable range

$p_o \rightarrow$ Controller o/p with no error

· Implementation of this mode requires a circuit that has a response given by equation ①.

For Proportional mode,

$$p = K_p \cdot e_p + p_o \quad — ①$$

The opamp circuit shown in fig ① shows an electronic Proportional Controller.

In this case, the analog electronic equation for o/p voltage is,

$$\boxed{V_{out} = G_p V_e + V_o} \quad — ②$$

where, $V_{out} \rightarrow$ o/p voltage

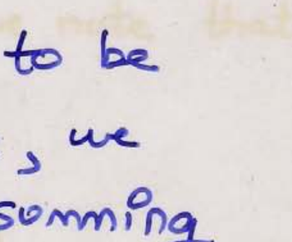
$G_p \rightarrow R_2/R_1$ = gain

$V_e \rightarrow$ error voltage

$V_o \rightarrow$ o/p with zero error.

In this ckt, if we consider both the controller o/p and error to be expressed in terms of voltage, we see equation ① is simply a 'summing amplifier'.

- Here o/p voltage range of ckt, represents a swing of 0% to 100%. Thus, if a final control element needs 0 to 5V, then a zener is added, so that opamp can swing only betn 0 & 5V.



Integral Controller Mode
OR
RESET Controller.

- Offset error of the proportional mode occurs because the controller cannot adapt to changing external conditions - ie. changing loads.

Need of Integral action:-

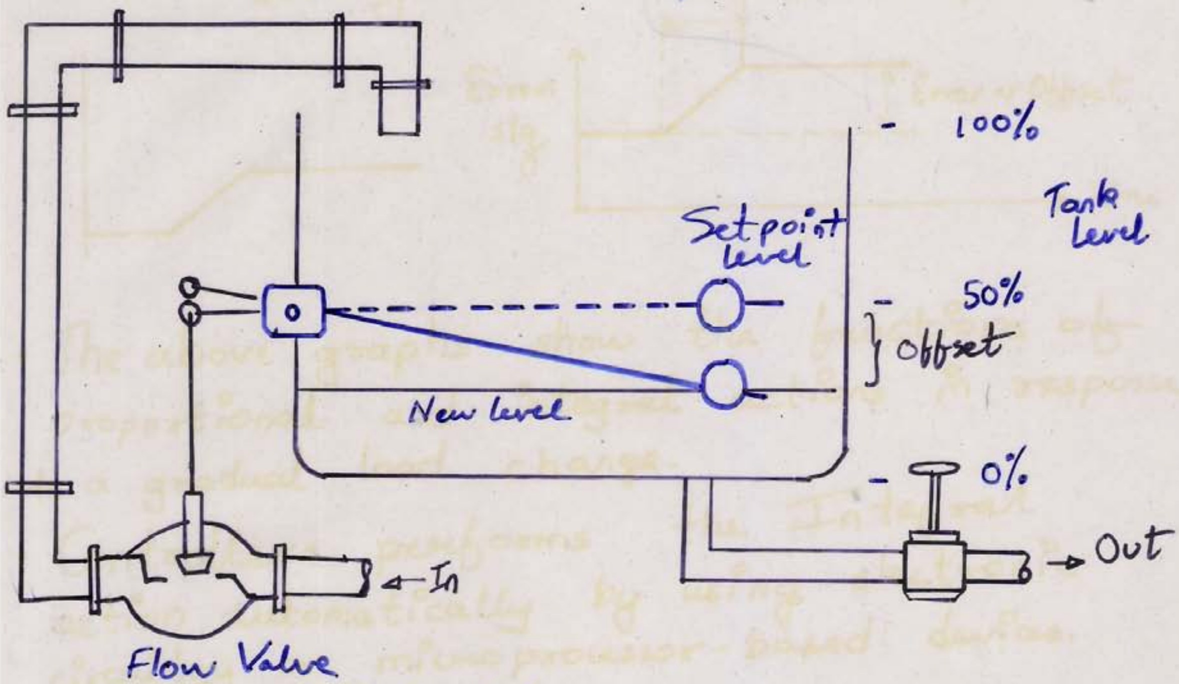
- With proportional mode, the error does not go to zero in time.
- Suppose a system has some error, e_p & the P mode provides a change in controller output, $K_p.e_p$.
- As we watch the error in time, we note that error may reduce, but it does not go to zero; in fact, it may become constant.

Hence, Integral action is needed.

Application:

Integral mode is not used alone, but can be used for systems with small process lags and correspondingly smaller capacities. or where Load varies slowly, but by a large amount.

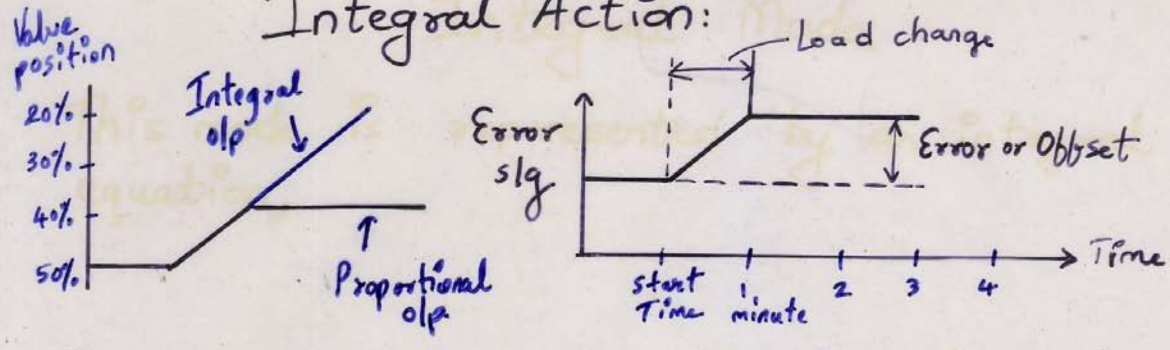
Obbset Example



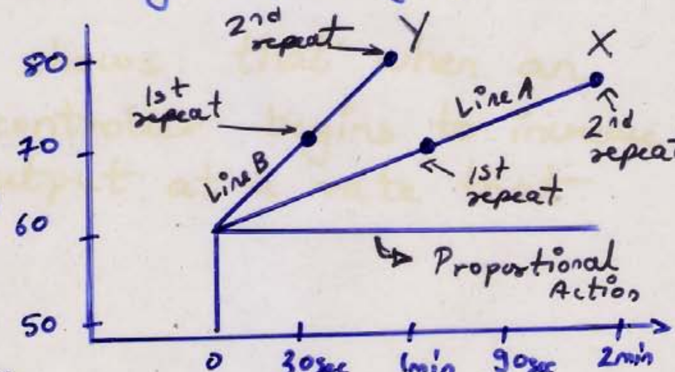
Flow Valve
(Final Control element)

- Offset or error is a constant difference between setpoint (SP) and controlled variable (CV).
- Some systems cannot tolerate obbset. They require that CV return to its original value.
- To eliminate obbset, an integral function is added with the proportional mode to the controller.
- For integral action, controller senses differences between SP and CV.
- As long as an error exists, the integral mode continuously causes the controller to adjust its output until the obbset returns to zero.
- Longer the error exists, greater the Integral Action

Integral Action:



- The above graphs show the functions of proportional and integral actions in response to a gradual load change.
- Controllers perfoorms the Integral action automatically by using electronic circuitry or microprocessor-based devices.
- Integral is also referred to as 'Reset Controller.'
- Term 'reset' is derived from the way in which the integral action periodically adds to the controller's o/P by repeating previous Proportional action.



Reset Action.

- Line A shows reset function repeats 10% ↑se once each minute.
- Line B shows by doubling reset gain on controller, two repeats per minutes occur, causing a 20% change each minute.

Integral Mode

This mode is represented by an integral equation,

$$p(t) = K_I \int_0^t e_p \, dt + p(0) \quad ---(1)$$

where p(0) is the controller o/p when the integral action starts

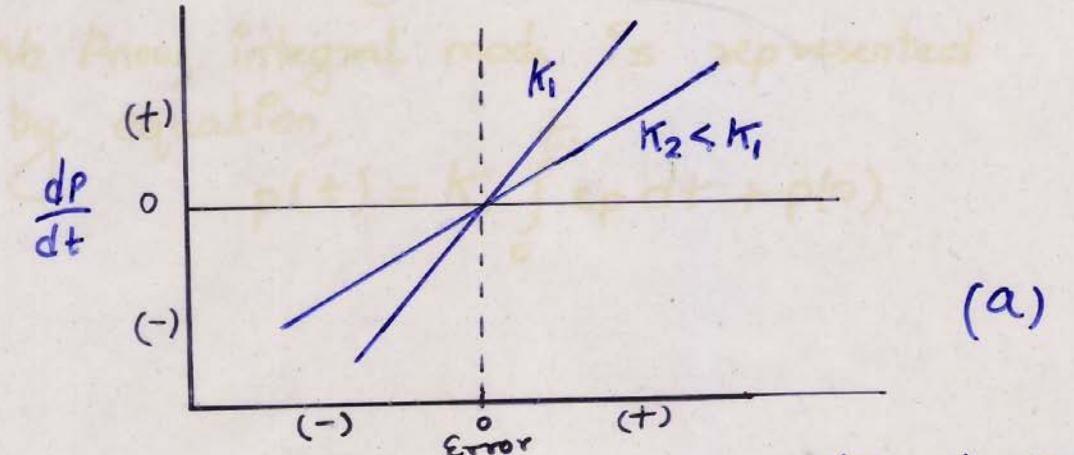
Gain K_I expresses how much controller o/p in % is needed for every %-time accumulation of error.

Another way of thinking of integral action is by taking derivative of equation (1).

ie $$\underbrace{\frac{dp}{dt}}_{\text{Rate at which Controller o/p changes.}} = K_I e_p \quad ----(2)$$

- This equation (2) shows that when an 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.
- If error is zero, controller o/p is not changed
- If there is a positive error, the controller output begins to ramp up at a rate given by eqn (2).

Integral mode



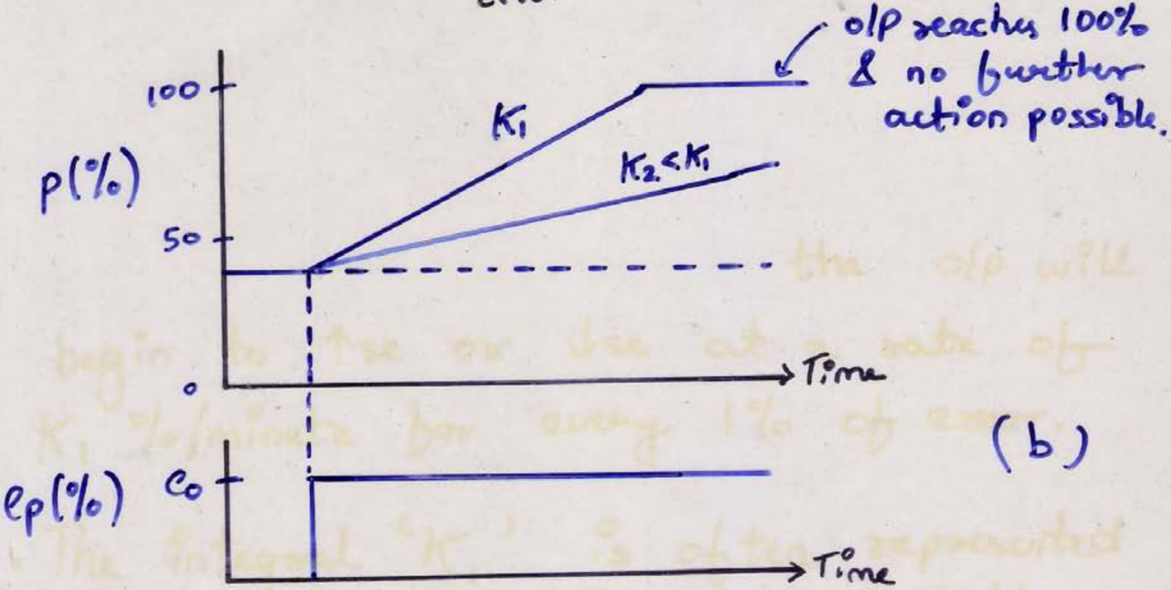


fig Integral mode Controller

Figure (a) shows how the rate of change of controller o/p depends upon the value of error and size of gain.

Figure (b) shows how the actual controller output would look if a constant error occured.

Integral Mode

We know, integral mode is represented by equation,

$$p(t) = K_1 \int_0^t e_p \, dt + p(0) \quad ---(1)$$

Summary of Characteristics of integral mode. and equation (1).

1. If the error is zero, the o/p stays fixed at a value equal to what it was when the error went to zero.
2. If the error is not zero, the o/p will begin to ↑se or ↓se at a rate of K_1 %/minute for every 1% of error.

• The integral 'K_1' is often represented by the inverse, which is called the integral time, or the 'reset action' ie $T_1 = 1/K_1$.

This is often expressed in minutes instead of seconds because this unit is more typical of many industrial process speeds.

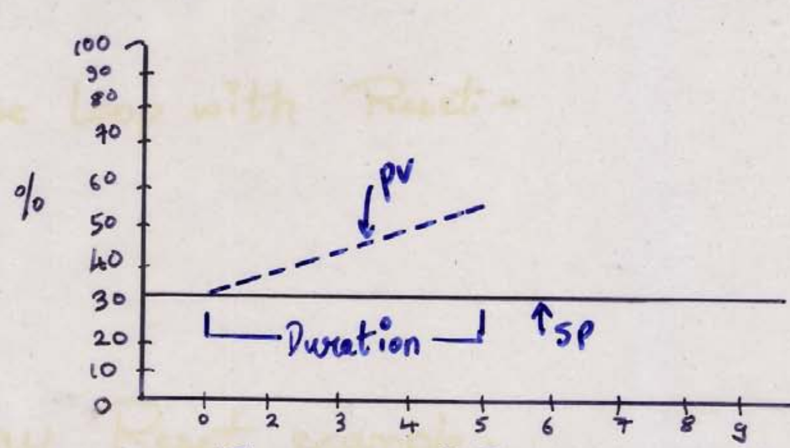
Integral Mode

Integral Action

Duration of Error and Integral mode :

Another example of error is the duration of the error, ie how long has the error existed?

The controller o/p from Integral or Reset mode is a function of duration of the error.



Integral (Reset Action)

Purpose :

The purpose of integral action is to return the PV to SP.

This is accomplished by repeating the action of proportional mode as long as an errorexists

Note: Integral or reset mode is always used with the proportional mode.

Integral Mode:

Setting : - Integral, or reset action, may be expressed in terms of:

(Reset Rate)
1. Repeats Per Minute : How many times the proportional action is repeated each minute.

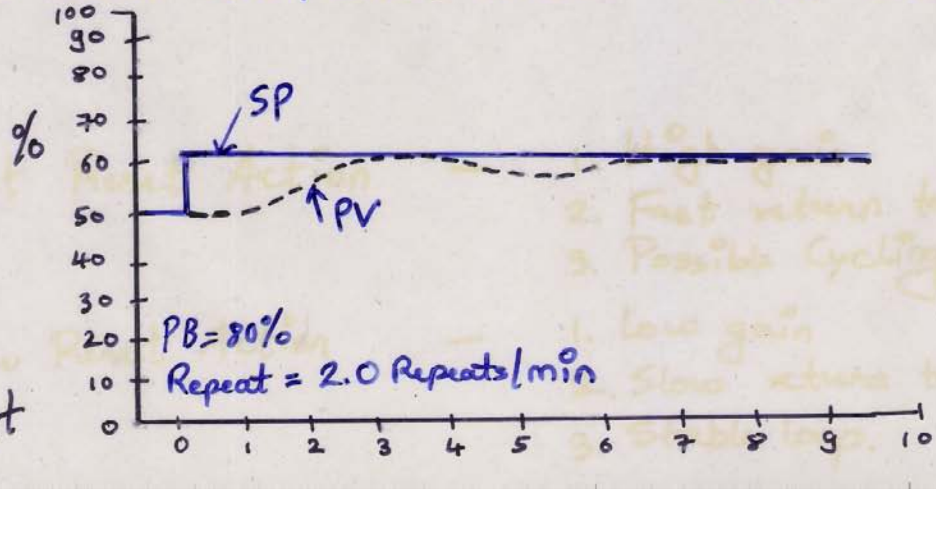
(Reset time)
2. Minutes Per Repeat : How many minutes are required for 1 repeat to occur.

Closed Loop Analysis for Integral mode:

Close 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.

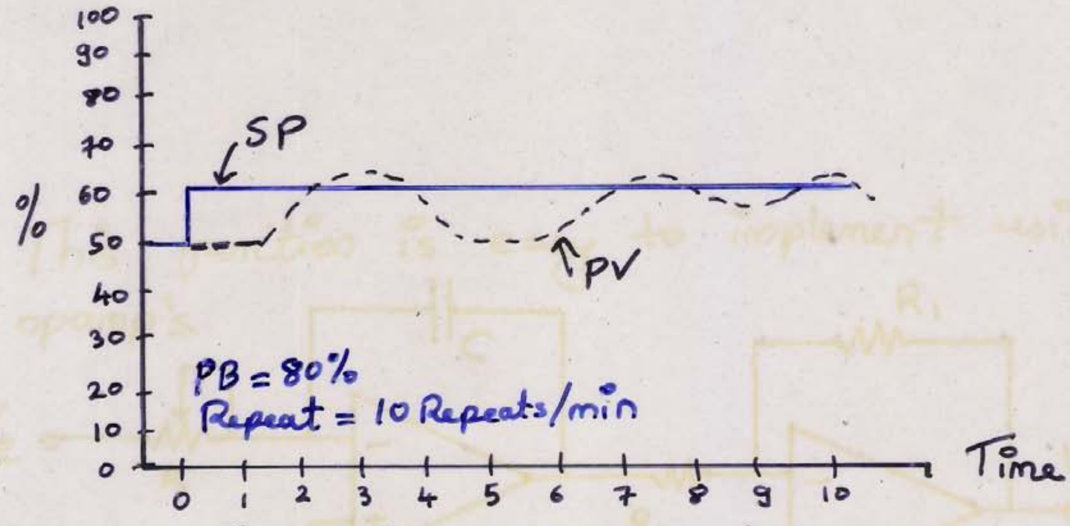
Slow Reset example: In this example, the loop is stable and the process variable (PV) does reach set point (SP) due to reset action

Slow Reset



Integral Mode:

Fast Reset Example: In the example below, reset action is too fast, thus PV is cycling around the SP.



Fast Reset, Closed Loop.

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

Advantages: Eliminates Error
Disadvantages: Reset windup and possible overshoot.

Fast Reset Action — 1. High gain
2. Fast return to setpoint
3. Possible Cycling.

Slow Reset Action — 1. Low gain
2. Slow return to SP
3. Stable loop.

Opamp Integral-mode Controller.

Integral mode is expressed as,

$$p(t) = K_1 \int_0^t e_p(t)\,dt + p_1(0) \quad --- (1)$$

where, $p(t)$ = Controller o/p ; $p_1(0)$ = Controller o/p at $t=0$

K_1 = Integral gain ;

$e_p(t)$ = deviations in % of full-scale variable value.

- This function is easy to implement using opamp's.

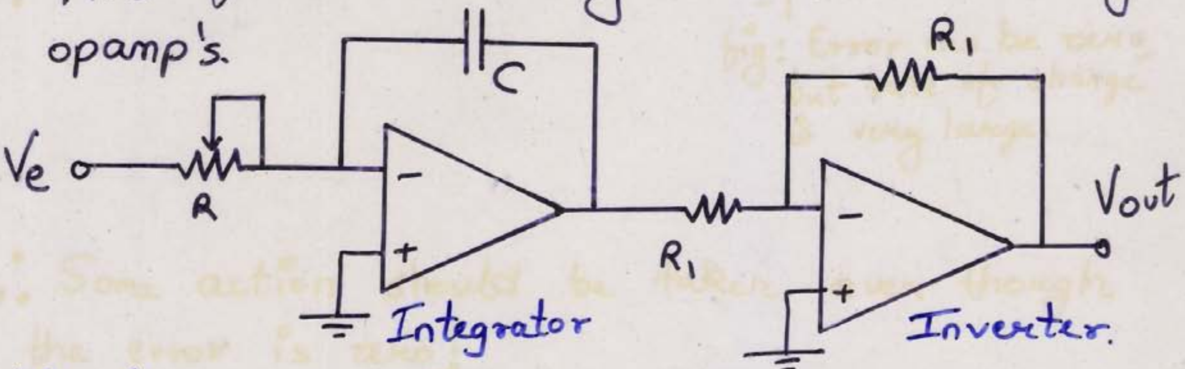


fig. An opamp Integral-mode Controller.

$$\boxed{V_{out} = G_1 \int_0^t V_e\,dt + V_{out}(0)} \quad ---(2)$$

where, V_{out} → o/p voltage

G_1 → $1/RC$ = Integral gain

V_e → Error voltage

$V_{out}(0)$ → Intial o/p voltage.

- The integration time constant ie R and C determines the RATE at which controller o/p ↑ses when error is constant.

Derivative / Rate Controller :-

- Suppose you were in charge of controlling some variable and at some time t_0, your helper yelled out, " The error is zero. What action do you want to take?" Answer: None

- But suppose you have a screen that shows variation of error in time.

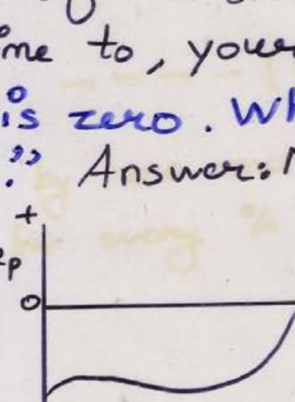


fig: Error can be zero, but rate of change is very large.

- Clearly, here even though the error at t_0 is zero, it is changing in time and will certainly not be zero in following time.

∴ Some action should be taken even though the error is zero!

This scenario describes the nature and need for Derivative action.

- Derivative controller action responds to the rate at which the error is changing that is the derivative of the error.

- Derivative action is not used alone because it provides no o/p when error is constant.

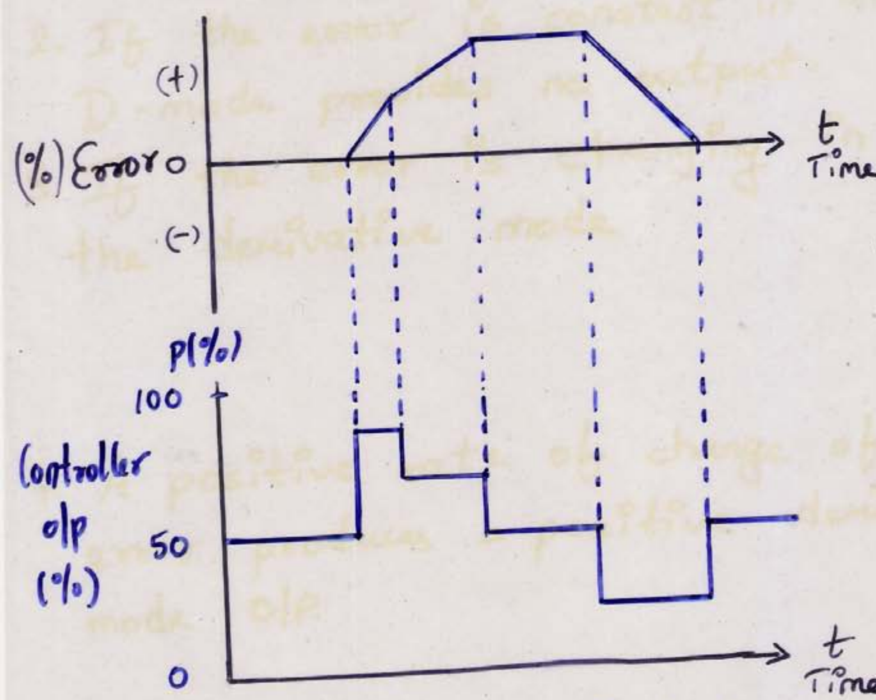
- Derivative controller action is also called 'Rate action' and 'anticipatory control'.

Derivative Mode

Equation for derivative mode is given by,

$$\boxed{p(t) = K_D \frac{de_p}{dt}} \quad ----(1)$$

where, K_D - Gain which tells us by how much % to change controller o/p for every % rate of change of error.



• Here, Controller o/p with no error or rate of change of error is 50%

fig : Derivative mode Controller action changes depending on rate of change of Error.

• When the error changes very rapidly with +ve slope, o/p jumps to large value, & when error is not changing, o/p returns to 50%. Finally, when error is lsing with -ve slope, o/p discontinuosly changes to a lower value.

Derivative Mode:

· It's given by equation,

$$p(t) = K_D \frac{de_p}{dt} \quad --- (1)$$

Characteristics of D-mode & $eq^n(1)$ are:

1. If the error is zero, the mode provides no output.
2. If the error is constant in time, the D-mode provides no output.
3. If the error is changing in time, the derivative mode, contributes an o/p of K_D % for every 1% per second rate of change of error.
4. A positive rate of change of change of error produces a positive derivative mode o/p.

· Derivative mode is usually used with a small gain, because a rapid rate of change of error can cause very large, sudden changes of controller o/p. Such an event can lead to Instability.

Where Derivative Mode is Used?

- 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 o/p.
- To improve response, a large initial change in controller o/p may be applied.
- This action is the role of the Derivative mode.

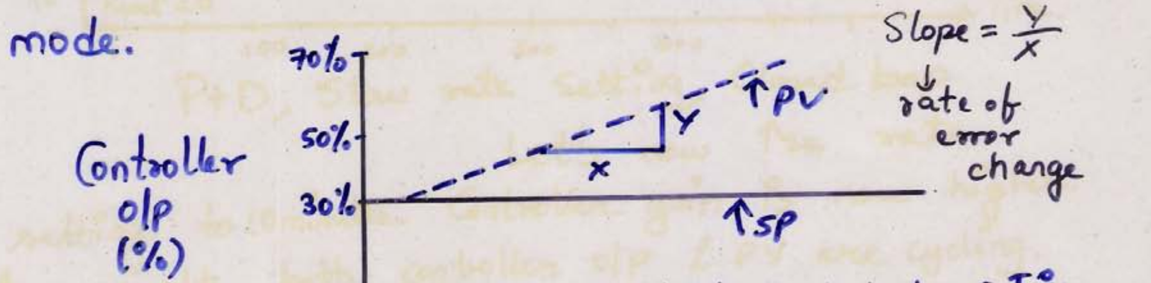


fig: Derivative Action is based on rate of change in Error.

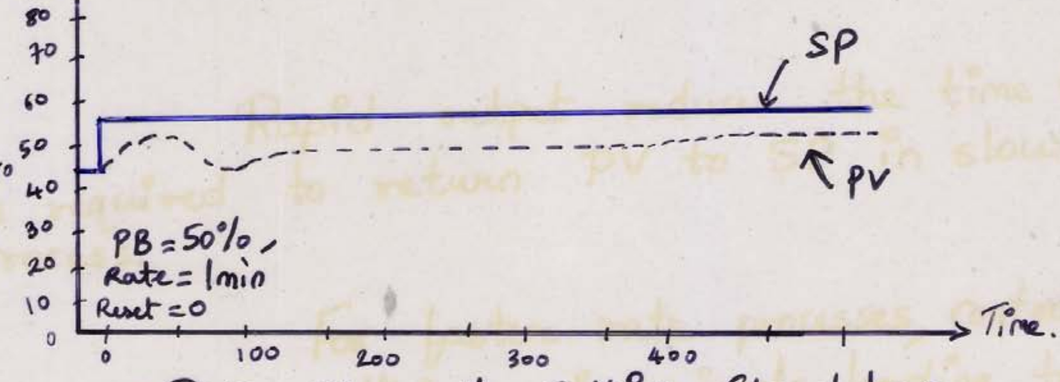
- Derivative action is initiated whenever there is a 'change in rate of change of error' ie (slope of the PV).
- If there is a change in slope of PV, the derivative mode 'immediately' ↑ses the o/p by that amount.

Derivative Action:

Rate Action/Effect:

Here, change in o/p due to rate action is a function of speed (rate) of change of error.

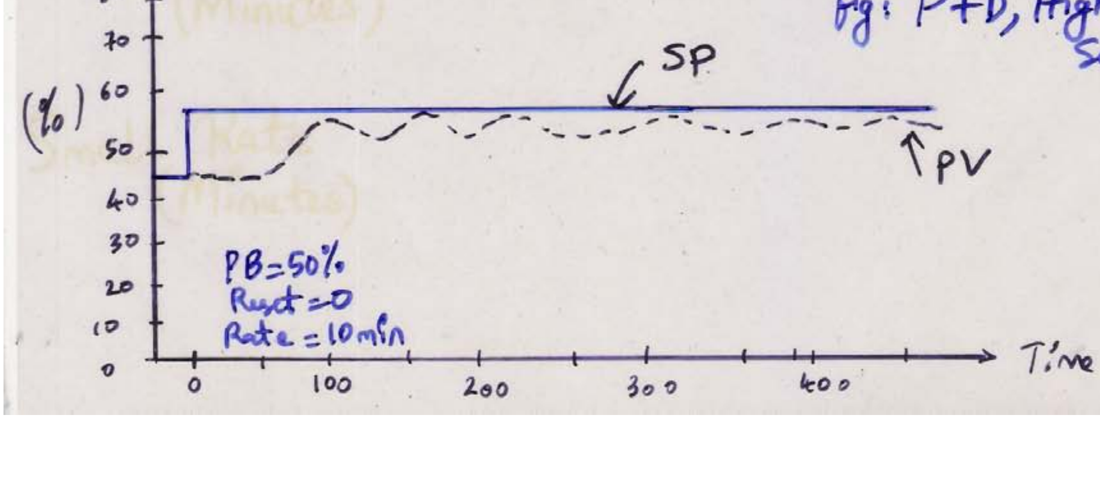
• Addition of Derivative /Rate mode alone will not cause PV to match SP.



P+D, Slow rate Setting, Closed loop

• Effect of Fast Rate: Let's now ↑se rate setting to 10minutes. Controller gain is now higher. As a result, both controller o/p & PV are cycling. Point here is that ↑sing the rate setting will not cause the PV to settle at SP.

fig: P+D, High Rate Setting



Derivative Mode (RATE mode)

Application: In derivative mode, the controller o/p is dependent on the 'Speed of change' of the input or error, the o/p will be very erratic if rate is used on fast process or one with noisy signals.
The controller o/p, as a result of rate, will have the greatest change when the input changes rapidly.

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

Disadvantages: For faster rate processes, controller dramatically amplifies noisy signals leading to cycling.

Settings:

Large Rate (Minutes)
1. High Gain.
2. Large o/p change.
3. Possible cycling.

Small Rate (Minutes)
1. Low Gain
2. Small o/p change.
3. Stable loop

Limitations of Derivative Modes:

- Derivative mode is never used alone, but in combination with proportional or PI mode.
- Derivative action is <u>Unable</u> to remove the offset present in P-mode.
  This offset is a constant. ∴ since there is no rate of change that occurs, D-mode action produced is Zero.
- Derivative control is <u>unsuitable</u> for system that are exposed to <u>noisy</u> environments.
  Noisy signals contain high-frequency components which are amplified by the derivative action. These amplified signals will appears at the controller o/p and may cause unwanted changes by final control element.

- Derivative Control is used in following type of Process applications:

- Those process applications that have <u>Large</u> and <u>Rapid</u> <u>load</u> <u>changes</u> in a slow response system. Derivative mode enables the controller to respond more rapidly and position the Final control element <u>more</u> <u>quickly</u> than is possible with only proportional action.

Opamp Derivative mode Controller

Derivative mode: It is represented by

$$p(t) = K_D \frac{de_p}{dt} \quad --- -(1)$$

where, p = controller o/p in % of full o/p
K_D = derivative time constant.
e_p = error in % of full-scale range.

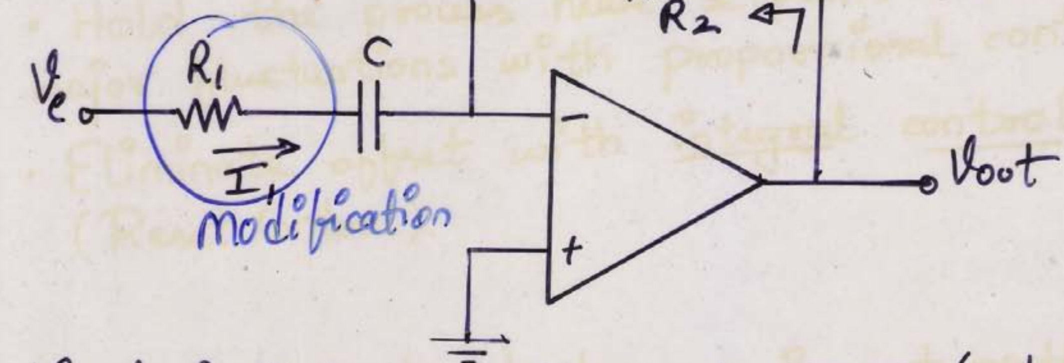


fig A Pratical Derivative-mode opamp Controller

This mode is implemented by opamp circuit shown above, and is given by

$$V_{out} = -RC\frac{dV_e}{dt} \quad --- (2)$$

where I/P voltage has been set equal to the controller error voltage.

- From practical perspective, this ckt cannot be used because it tends to be unstable ie due to its instability (high gain) at high frequencies where derivative action is very large.

$$V_{out} + R_1 C\, dV_{out}/dt = -\underbrace{R_2 C}_{K_D}\frac{dV_e}{dt} - (3)$$

Composite Controllers

P+I   P+D   P+I+D

Features of Each mode:-

- Achieve rapid response to major disturbances with derivative control. (Rate Control)
- Hold the process near setpoint without major fluctuations with proportional control.
- Eliminate offset with integral control. (Reset Control).

Not every process requires a full PID controller.

- If a small offset has no impact on the process, then P control alone may be sufficient.
- PI control is used where no offset can be tolerated, where noise (temporary error readings that do not reflect 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 & where dead time is an issue, customers can use full PID Controller.

Composite Controller Mode

1. Proportional - Integral Controller (PI)

This mode can be expressed by,

$$p = K_p e_p + K_p K_I \int_0^t e_p \, dt + p_I(0) \quad ---(1)$$

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

Here, proportional mode offset problem is eliminated by Integral control mode.

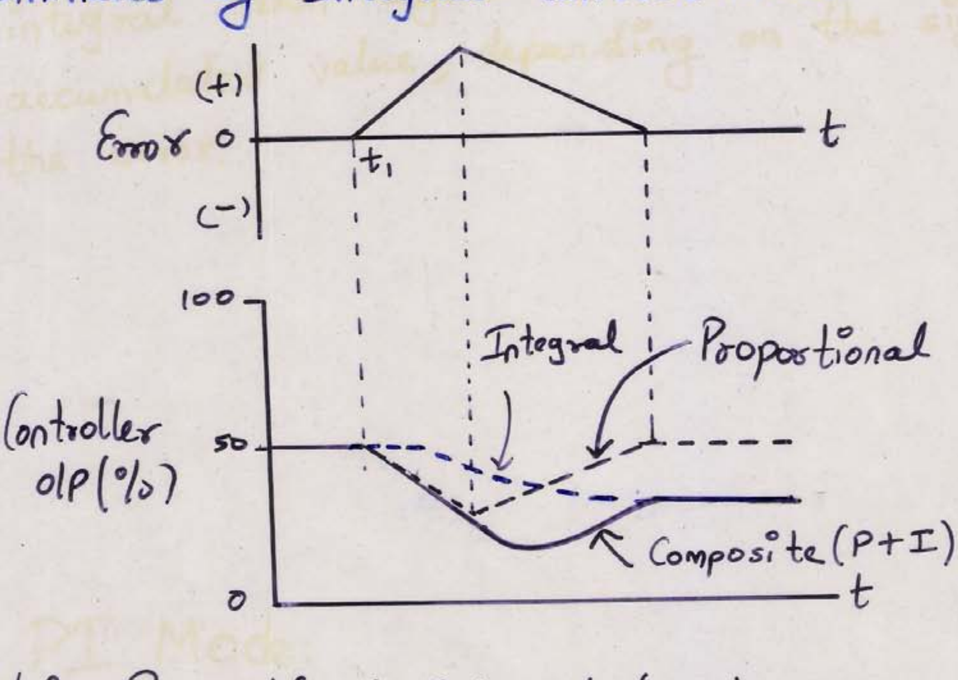


fig: Proportional- integral (PI) action showing the reset action of integral contribution

This example is for reverse action (where an ↑se in CV causes a ↓se in controller o/p)

PI Controller Mode

Characteristics of PI mode and eqⁿ(1) are

- When the error is zero, the contoller o/p is fixed at the value that the integral term had when the error went to zero.
- If the error is not zero, the proportional term contributes a correction, and the integral term begins to ↑se or ↓se the accumulated value, depending on the sign of the error.

Applications:-

- This composite PI mode eliminates the offset problem of proportional controllers.
- It follows that mode can be used in systems with frequent or large load changes.

PI Mode:

Function: To eliminate offset.

Application:

For large and slow set point or load changes.

Opamp Proportional- Derivative (PD) Controller

- A powerful combination of controller mode is PD mode. This combination is implemented using a circuit similar to that shown in fig below.

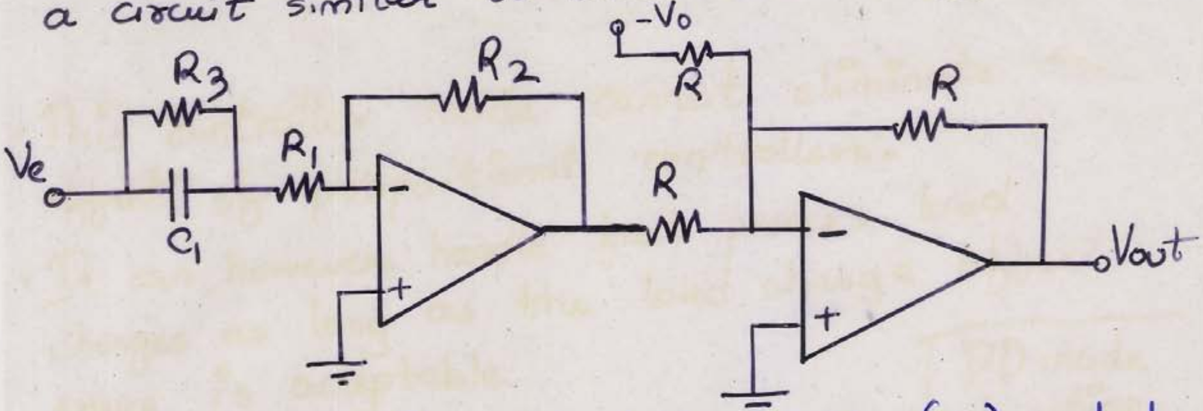


fig: An opamp Proportional-Derivative (PD) control mode controller

PD mode: $p = K_P e_p + K_P K_D \frac{de_p}{dt} + p_0$ ---(1)

From above circuit of opamp using PD mode, equation becomes,

$$V_{out} = \left(\frac{R_2}{R_1+R_3}\right) V_e + \left(\frac{R_2}{R_1+R_3}\right) R_3 C \frac{dV_e}{dt} + V_o \quad \text{--(2)}$$

where, proportional gain $G_P = R_2/(R_1+R_3)$
and derivative gain $G_D = R_3 C$

PD mode Application:

- For sudden set point or quick load changes in a slow response system.

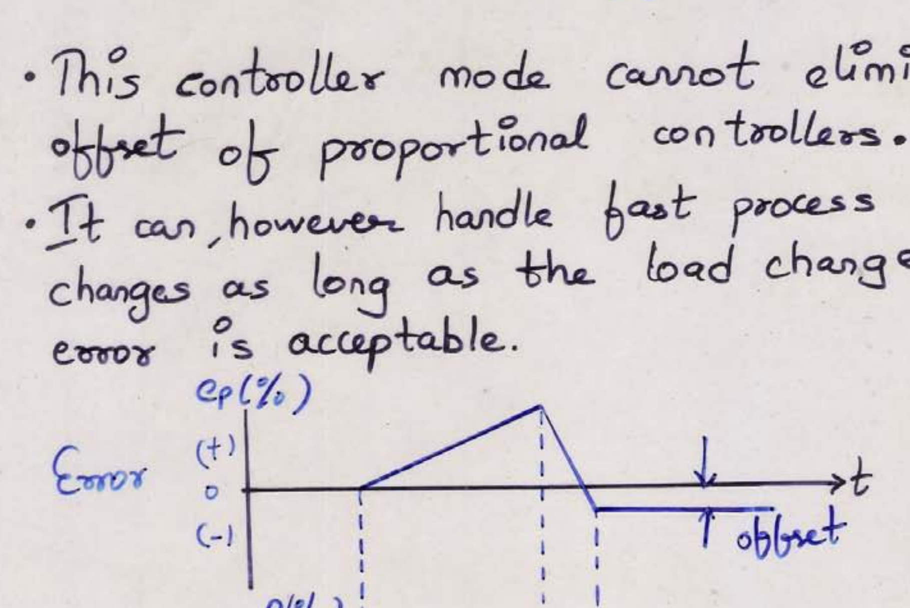
Proportional- Derivative Control mode (PD)

• This mode can be expressed as,

$$p = K_P e_p + K_P K_D \frac{de_p}{dt} + p_o \quad ----(1)$$

• This controller mode 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.



PD mode function
↓
To speed up response & minimize overshoot

fig: PD action showing the offset error from Proportional mode. (Reverse action example)

• An example of operation of this mode for a hypothetical load change is shown in figure. Note the effect of derivative action in moving the controller o/p in relation to the error rate change.

Opamp Proportional- Integral Controller

- A simple combination of P and I provides P-I controller action.

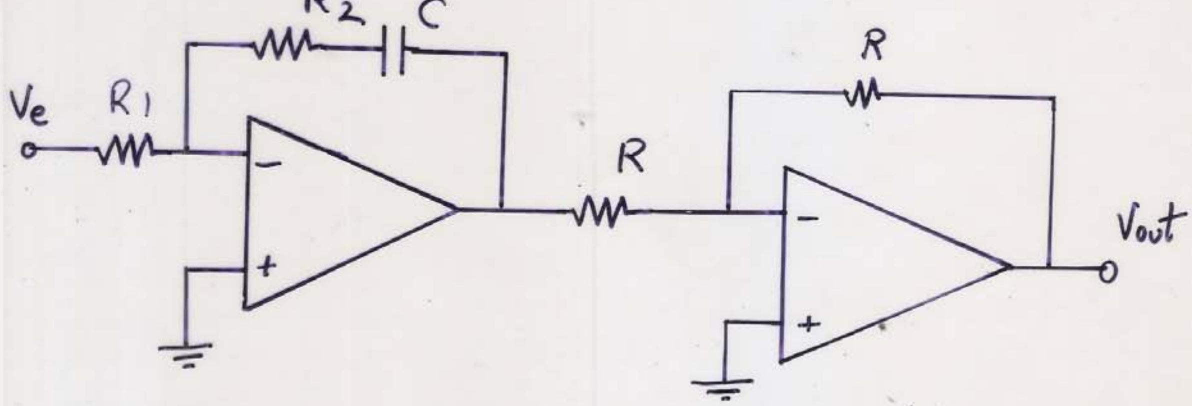


fig: An opamp proportional-integral (PI) mode Controller.

PI mode is given by

$$p = K_p e_p + K_p K_I \int_0^t e_p dt + p_1(0) \quad ---(1)$$

From opamp-circuit analysis for PI mode,

$$V_{out} = \left(\frac{R_2}{R_1}\right) V_e + \left(\frac{R_2}{R_1}\right) \frac{1}{R_2 C} \int_0^t V_e dt + V_{out}(0) \quad ---(2)$$

The adjustments of this controller are the 'proportional band' through $G_P = \frac{R_2}{R_1}$ and the 'integration gain' through $G_I = \frac{1}{R_2 C}$

PID Controller Mode

- 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 conditions. The analytic expression is,

$$p = K_p e_p + K_p K_I \int_0^t e_p dt + K_p K_D \frac{de_p}{dt} + p_I(0) \quad \text{-----(1)}$$

- This mode eliminates the offset of the proportional mode and still provides fast response.

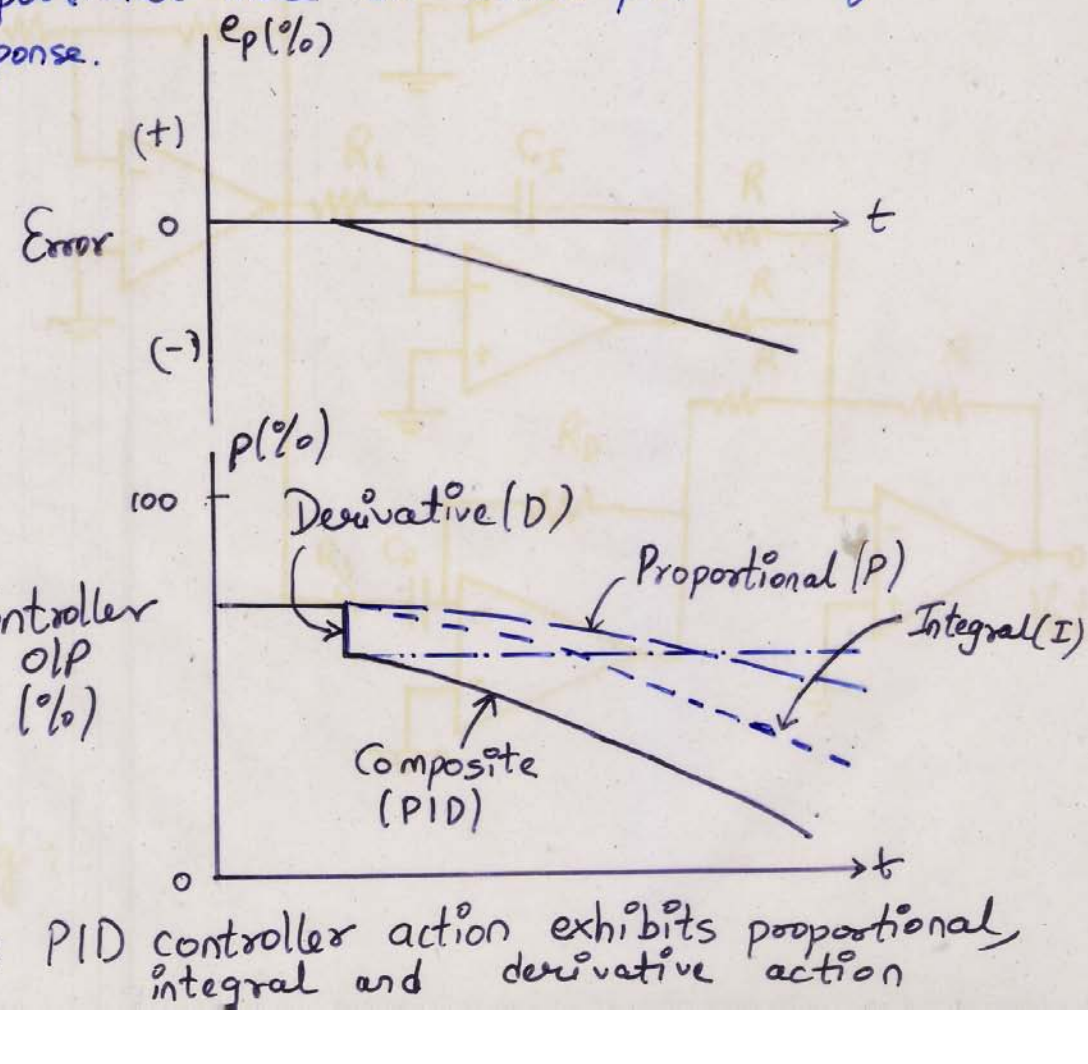


fig: PID controller action exhibits proportional, integral and derivative action

PID Controller with Opamps

PID mode: $p = K_p e_p + K_p K_I \int_0^t e_p dt + K_p K_D \frac{de_p}{dt} + p_I(0)$ ---(1)

where, p = controller o/p, K_p - proportional gain
e_p = Process error, K_I - integral gain
K_D = derivative gain, $p_I(0)$ - initial controller integral o/p

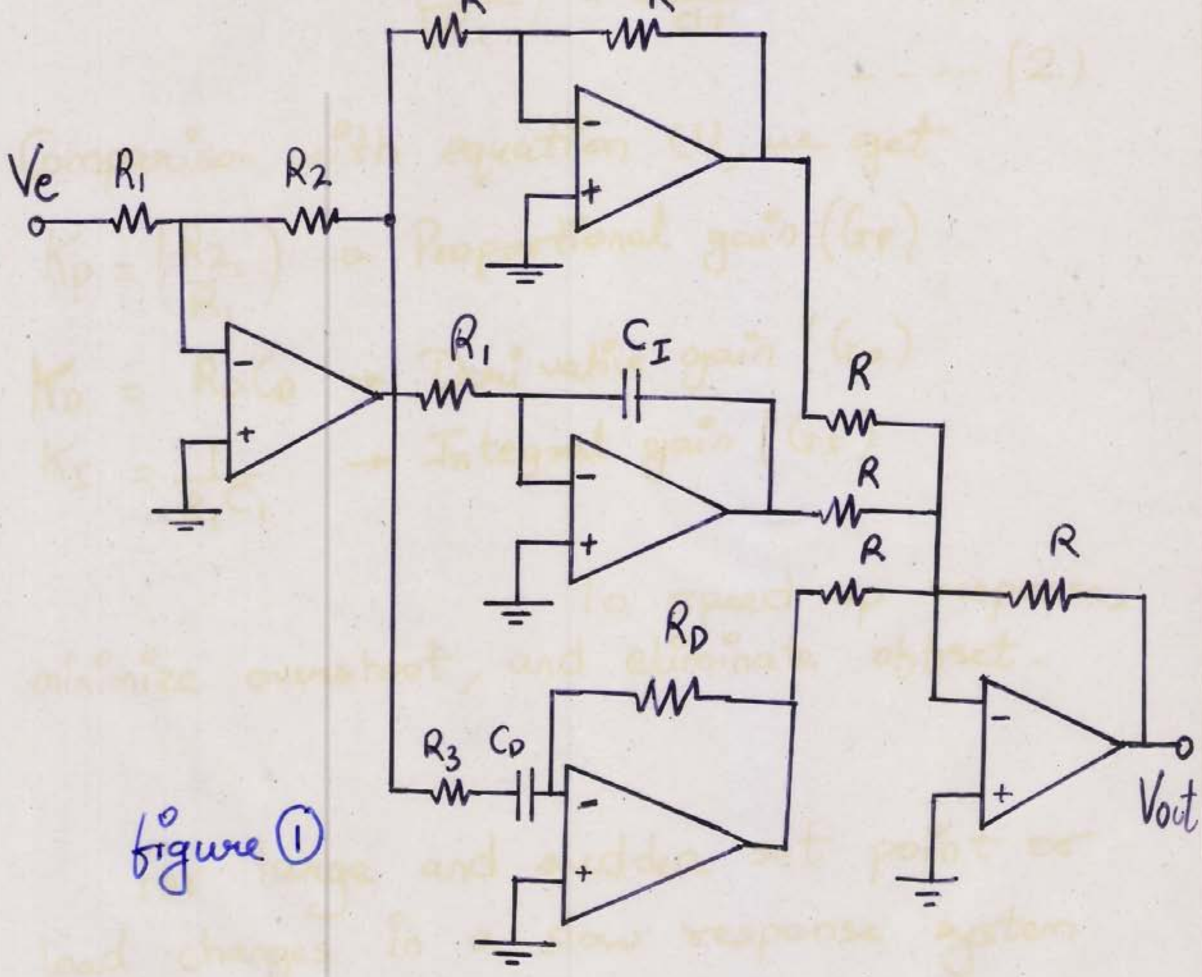


figure ①

fig: Direct implementation of a three-mode PID Controller with opamp.

PID Controller with Opamps

Analysis of figure (1) in previous slide, shows that o/p is

$$-V_{out} = \left(\frac{R_2}{R_1}\right) V_e + \left(\frac{R_2}{R_1}\right)\frac{1}{R_1 C_1}\int V_e\,dt + \left(\frac{R_2}{R_1}\right) R_D C_D \frac{dV_e}{dt} + V_{out}(0) \quad \text{---- (2)}$$

Comparison with equation (1), we get

$K_P = \left(\frac{R_2}{R_1}\right) \rightarrow$ Proportional gain (G_P)

$K_D = R_D C_D \rightarrow$ Derivative gain (G_D)

$K_I = \frac{1}{R_1 C_1} \rightarrow$ Integral gain (G_I)

PID mode Function:- To speed up response, minimize overshoot, and eliminate offset.

PID mode Applications:-

For large and sudden set point or load changes in a slow response system

Proportional, Integral and Derivative Mode Summary

Mode Combination	Function	Applications
Proportional (P)	To provide gain	For small set point or small load change
Proportional + Integral (PI)	To eliminate offset	For large, and slow set point or load changes.
Proportional + Derivative (PD)	To speed up response & minimize overshoot	For sudden set point or quick load changes in a slow response system.
Proportional-Integral-Derivative (PID)	To speed op response, minimize overshoot and eliminate offset	For large and sudden set point or load changes in a slow response system