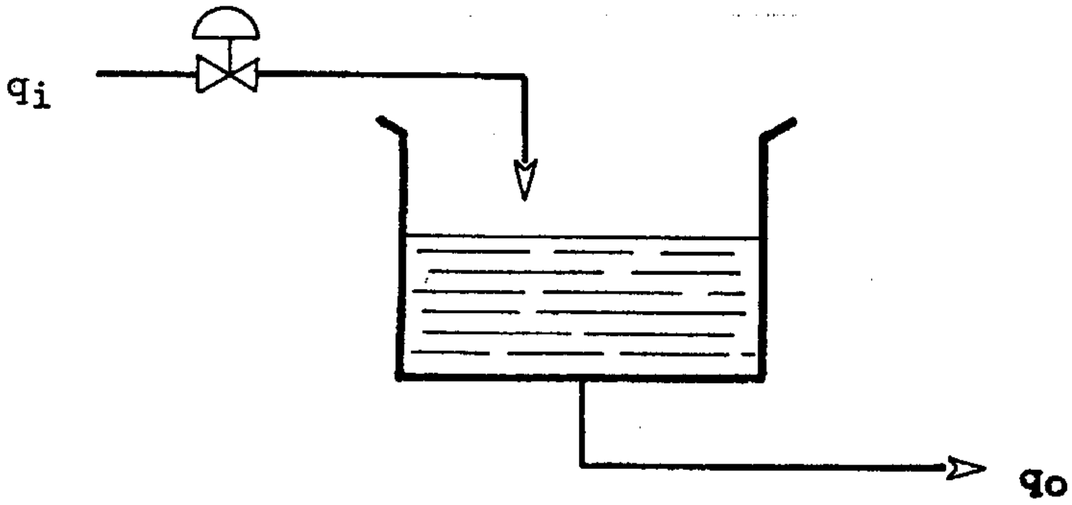
CHAPTER 2: ELECTRONIC CONTROL

MODULE 1: CONTROL CONCEPTS

Introduction

Consider the level control of an open tank with a variable demand outflow and variable inflow regulation, possible by control valve throttling.



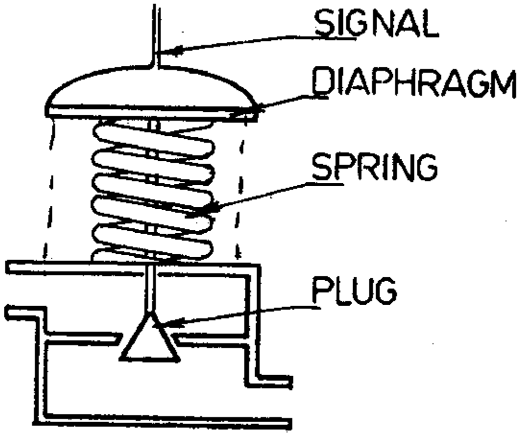
The level will only remain constant when the inflow (q_i) just equals the outflow (q_o). If the demand increases, the level will begin to drop until the inflow has been increased sufficiently to stabilize the system ($q_i = q_o$).

Control Valves

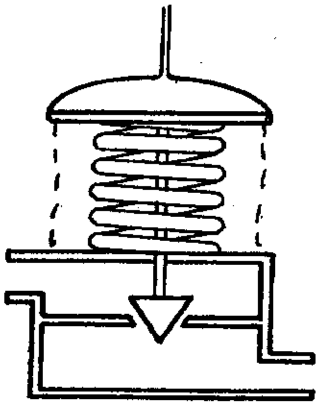
Throughout this course the pneumatic actuator control valve will be considered as the final device in the control loop. These valves operate on a spring opposed diaphragm principle. The diaphragm presents an area for the applied signal pressure to act on. A substantial driving force (F = P x A) can be obtained from a low pressure pneumatic signal by the selection of a larger area diaphragm.

The control valve may be selected not only as the regulating device in a control loop but also to ensure that the process will be left in a non hazardous state following a complete loss of instrument air. If the tank in the previous sketch must not overflow, then the valve selected for inflow regulation should fail closed (following loss of instrument air).

Such a valve can be referred to as an air to open style. Increasing the pneumatic signal applied to the valve actuator will open the valve more, decreasing the signal will allow the spring to drive the valve more closed. The following simplified sketches show both an air to open and an air to close valve.

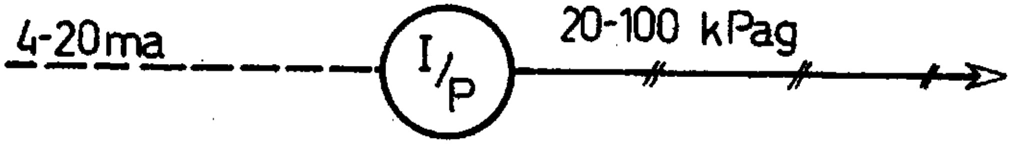


FAIL CLOSED (A/O)

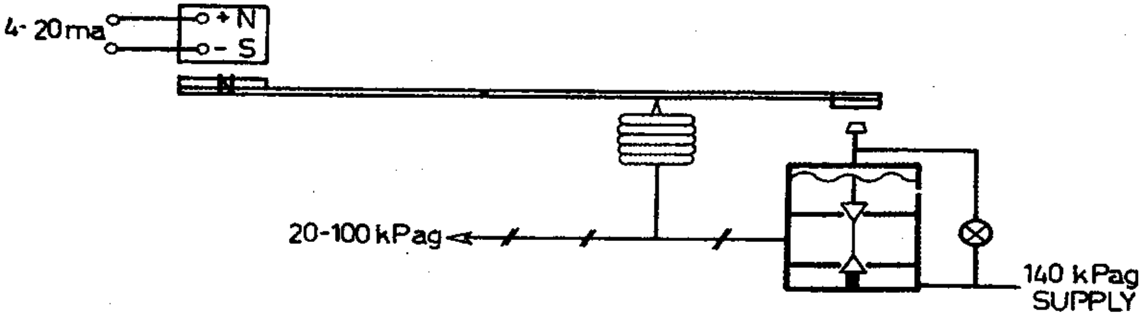


FAIL OPEN (A/C)

I/P Transducer



The current signal developed by a controller must be applied to the final actuator to effect the process. In many cases the final device is a pneumatically actuated valve. A transducer is required to convert the current signal to an equivalent pneumatic signal.



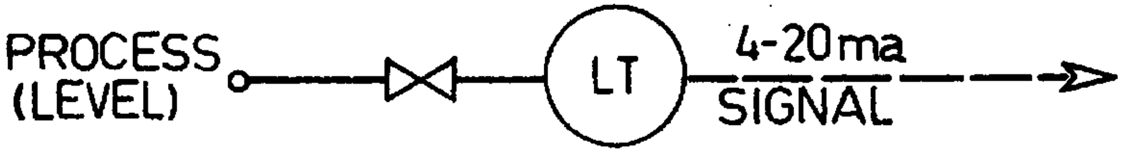
- The current signal is applied to a small coil which acts as an electric magnet deflecting a force bar proportional to the current magnitude.
- This motion can be used to position a flapper wrt a nozzle to alter the nozzle back pressure.
- The nozzle back pressure is amplified by a pneumatic relay and applied simultaneously to the output and a feedback bellows.
- The feedback bellows ensures that there will be a linear relationship between the 4 - 20 mA signal applied and the 20 - 100 kPag pneumatic signal produced.

Electronic Transmitter

A transmitter is required for measuring tank level and developing a signal that can be displayed remotely for level indication, alarm monitoring, or control.

An electronic transmitter produces a 4 - 20 mA (now accepted as industry standard) or a 10 - 50 mA signal representative of process variation. If the transmitter was suitably calibrated the signal would vary linearly from 4 - 20 mA as the tank level changes from 0 - 100%. The transmitter is just the control loop data link with the process.

The electronic signal calculations can be determined by direct ratio.
The 4-20 mA signal span is 16 mA with a live zero value of 4 mA.



The current signals can be determined by converting the percent process measurement to a decimal value, multiply by 16 (span), and add 4 (live zero).

Example:

Determine the 4-20 mA signal which corresponds to a level of 120 cm WC in a 0 - 200 cm WC level system.

$$\textbf{Percent Process} = \frac{120}{200} \text{x} 100 = 60\%$$

$$\textbf{Decimal Equivalent} = \frac{60}{100} = .6$$

$$\textbf{4-20 mA Signal} = \left((.6) \text{ x } 16\right) + 4 = 13.6 \text{ ma}$$

Notice that a quick approximate check can be made by knowing that a 25% process change results in a 4 mA signal change

Consequently, process values of 0, 25, 50, 75 and 100%. Are represented by current signals of 4, 8, 12, 16 and 20 mA.

Example

Determine the 4 - 20 mA transmitter signal if the temperature is 250°C when the calibrated range is 150 - 400°C.

Process Span = 400 -150 = 250 °C

Change In Measurement = 250 - 150 = 100°C

$$\textbf{Percent Process} = \frac{100}{250} \text{ x } 100 = 10.04 \text{ ma}$$

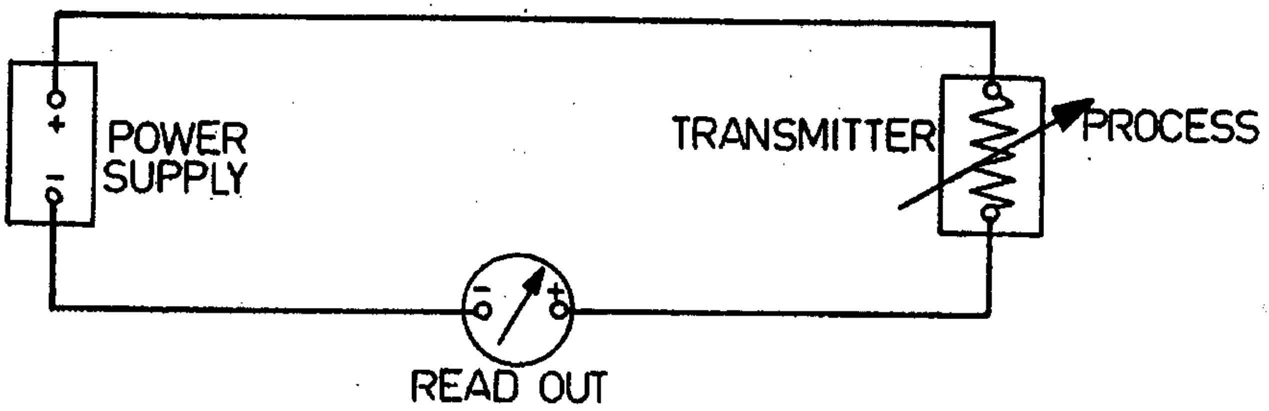
$$\textbf{4-20 mA Signal} = \left(\left(\frac{40}{100}\right)16\right) + 4 = 10.4 \text{ ma}$$

With a properly calibrated electronic transmitter, the 4 - 20 mA signal will vary in an analog fashion as the process changes so that by monitoring the current signal value, the process value will be known.

Transmitter Operation

Most electronic transmitters consist of some form of motion detector, oscillator, rectifier and amplifier which will convert the measured change in the process to a recognizable change in the current signal.

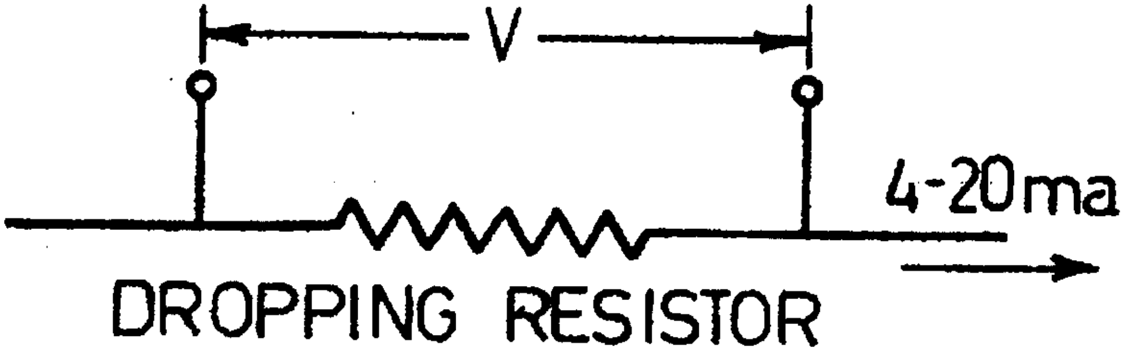
The transmitter can be thought of as just a variable resistor in a constant voltage circuit which is varied by the changing process.



If the transmitter resistance decreases, the current signal will increase and vice versa. It is important to note that the current flowing anywhere in this loop at some particular time will be the same current magnitude within the 4-20 mA range.

Current Alarm

The measurement signal from the transmitter can be continually monitored to provide an alarm indication if an abnormal process condition should occur.



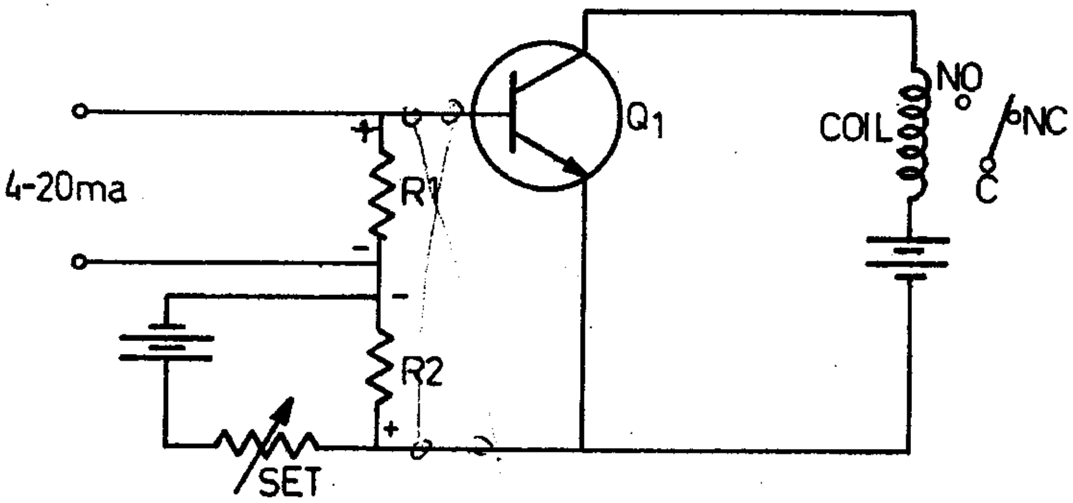
The current alarm is a voltage input device that would require a particular dropping resistor in the current loop.

Example

A dropping resistor of 62.5 Ω would provide a voltage of 0.25 - 1.25 VDC when placed in a 4 - 20 mA loop.

$$R = \frac{E}{I} = \frac{1.25\text{V}}{.02\text{AMPS}} = 62.5\text{W}$$

The alarm unit would involve a comparator type circuit to compare the measurement to the alarm set point.



If the measurement potential across R_1 is greater than the set potential across R_2, then Q_1 will be forward biased allowing current to flow through the relay coil. The relay contacts will change status and alarm lamps, horns, etc. can be activated.

Electronic Controller

The transmitted signal of 4 - 20 mA can also be monitored by an electronic controller which is a voltage input device. A dropping resistor is placed in the current loop to develop the required input voltage signal.

Example

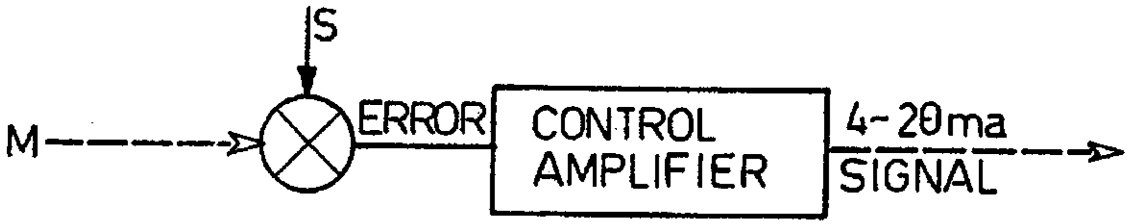
A 250 Ω dropping resistor will develop 1 - 5 VDC with a 4 - 20 mA signal.

The measurement signal can be compared to the set point (desired operating point) to determine the process error sign and magnitude.

Error = Set Point - Measurement

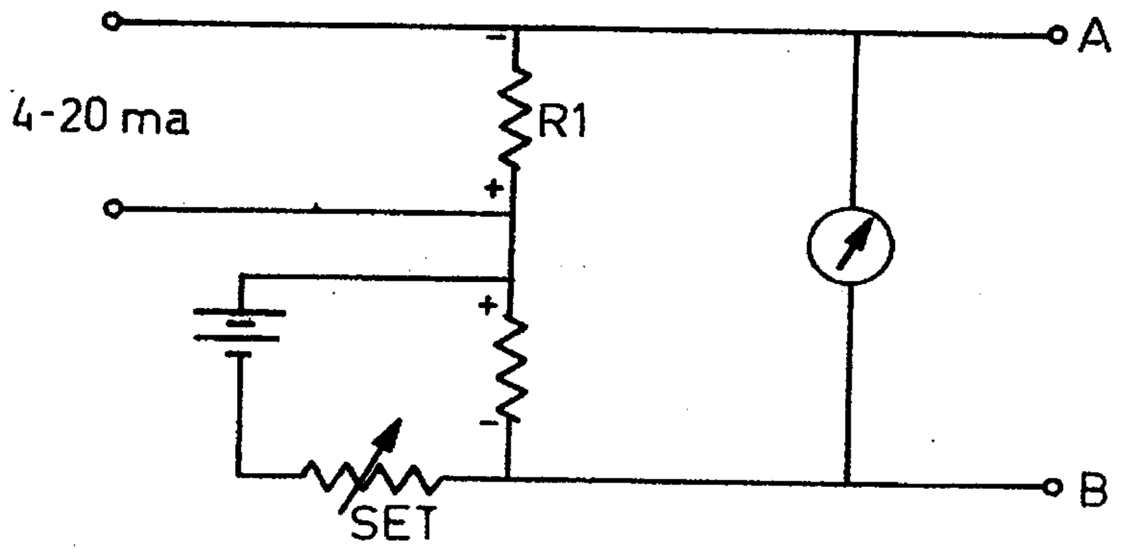
$E = S - M$

This error can now be suitably amplified by the controller to produce a corrective control signal of 4 - 20 mA.



A simple comparator circuit can be used by the electronic controller to determine the magnitude and direction of the process error.

Comparator Circuit



If the measurement signal develops a smaller voltage drop across R_1 than the set voltage across R_2, then point A will be positive with respect to B. Should the measurement signal develop a larger voltage drop across R_1 than the set voltage across R_2, then point A will be negative with respect to B.

This changing magnitude and polarity can be used to drive the control amplifier to develop the 4 - 20 mA control signal.

The direction that a controller must respond to a given error is called the control action.

- If the controller responds to the process rising above the set point by increasing the control signal then the controller is said to have *direct action.*
- An *increase* in measurement will result in an *increase* in control signal with direct action. This can be shown as (increasing, increasing) or (↑↑).

- Should a controller respond to an increase in measurement above the set point by decreasing the control signal, then the controller is said to have *reverse action.*
- *An increase* in measurement will result in a *decrease* in control signal with reverse action. This can be shown as (increasing, decreasing) or (↑↓).

If the controller for a given application could respond proportional to the error, a more stable control of the process would be possible than with on/off control. A system under on/off control will drive the valve from one extreme to the other resulting in process cycling. With proportional control the valve can be throttled slightly as the process varies about the set point.

The controller gain can be calculated by comparing the percentage change in control signal to the percentage change in measurement.

$$\text{Gain} = \frac{\%\ \Delta\ \text{Output}}{\%\ \Delta\ \text{Input}}$$

The proportional band value is reciprocally related to the gain as follows:

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

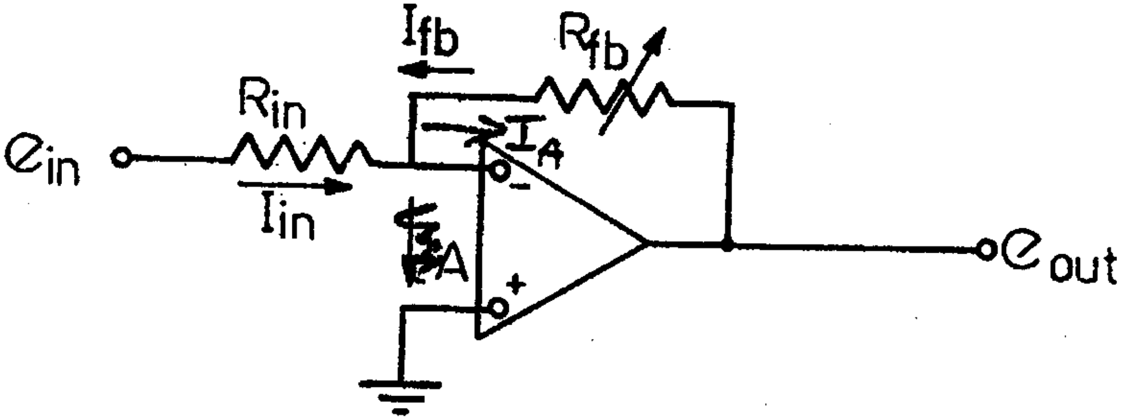
Percent Proportional Band (%PB) is defined as that percent of scale change by the measurement about the set point which will change the control signal through 100%

$$\%\text{PB} = \frac{\%\ \Delta\ \text{Output}}{\%\ \Delta\ \text{Input}} \text{ x } 100$$

The controller gain can be varied to effect the total control loop gain to provide as close a control as possible while ensuring process stability.

The error signal from the comparator can be amplified by a variable gain amplifier to develop the required control signal.

Variable Gain Amplifier



Assume that a high gain amplifier is available as sketched. The inverting model is selected for simplicity.

By Kirchhoff's current law:

$$I_{IN} + I_{fb} = I_A$$

The amplifier is designed to have a very high input impedance so that I_A can be considered as zero for all practical purposes.

$$I_{IN} + I_{fb} = 0$$

$$I_{IN} = - I_{fb}$$

Substituting by Ohm's law:

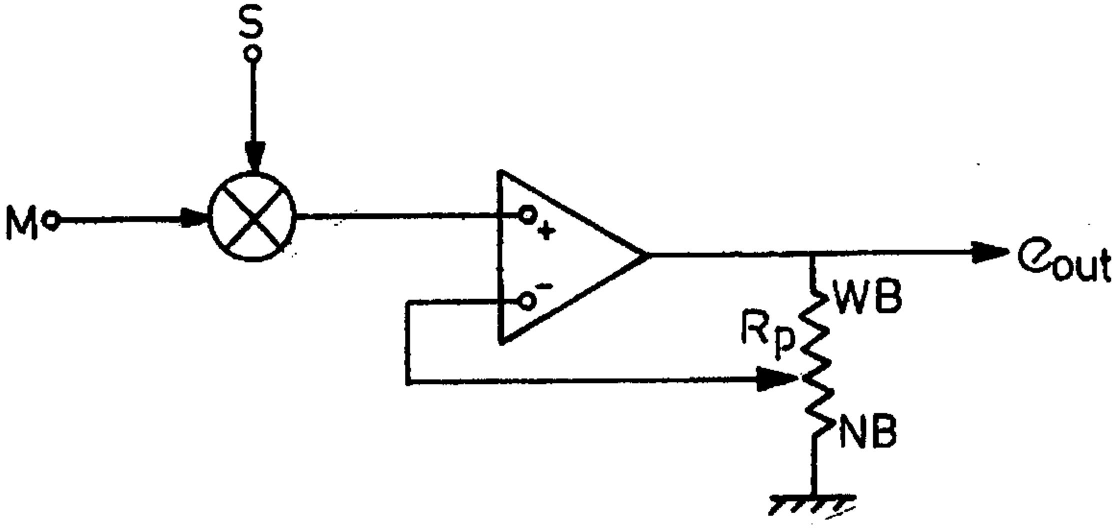
$$\frac{e_{IN}}{R_{IN}} = - \frac{e_{OUT}}{R_{fb}}$$

$$e_{OUT} = - e_{IN}\left(\frac{R_{fb}}{R_{IN}}\right)$$

The output voltage can be changed for a given input signal by changing the value of R_{fb}. The gain of this amplifier is simply the ratio of R_{fb}/R_{in}. From this development, all that is required is the fact that the gain of an amplifier can be changed by adjusting a resistance value.

Simplified Electronic Proportional Controller

A reverse action controller will be used for the example model in this lesson. The error signal from the comparator is applied to the non inverting terminal of the OP-AMP. If the process is greater than the setpoint, then the output signal will decrease. Consider the signal (e_{OUT}) being utilized to position the final device which in turn should change the value of the measurement signal.



- If the measurement equals the set point, the error will be zero. Internal biasing is supplied to the amplifier so that a mid scale output will be developed when the error is zero. A perfectly aligned, straight proportional controller will develop a 12 mA signal when the measurement is at the set point.

- Consider the measurement dropping below the set point, then a more positive input will be applied to the amplifier. The amplifier output will rise, increasing the voltage drop across R_p), a fraction of this voltage is fed back to the inverting terminal of the amplifier. The output signal will stabilize when sufficient potential is applied as feed back so that the difference across the inverting and non inverting terminals is zero volts.

- If the contact on R_p is placed to a lower position, less feedback voltage is applied to the amplifier and e_{OUT} would have to rise more before stabilizing. A larger change in output for a particular input is recognized as a higher gain or narrower proportional band setting. By changing the contact position of R_p, the proportional band is varied to achieve suitable process recovery from a transient disturbance.

Offset and Reset

Consider a level system operating under straight proportional control with a control valve on the inflow. For every distinct level position in the tank there will be one corresponding valve position. (% error x gain = % Δ output.)

Assume that the level was initially at the set point with inflow matching outflow. If a demand increase should occur so that outflow exceeds inflow, then the tank level will begin to drop away from the set point producing an error.

The more error developed, the more the inflow will be increased by the controller signal. Eventually the valve will be positioned enough so that inflow matches outflow and the level will stabilize.

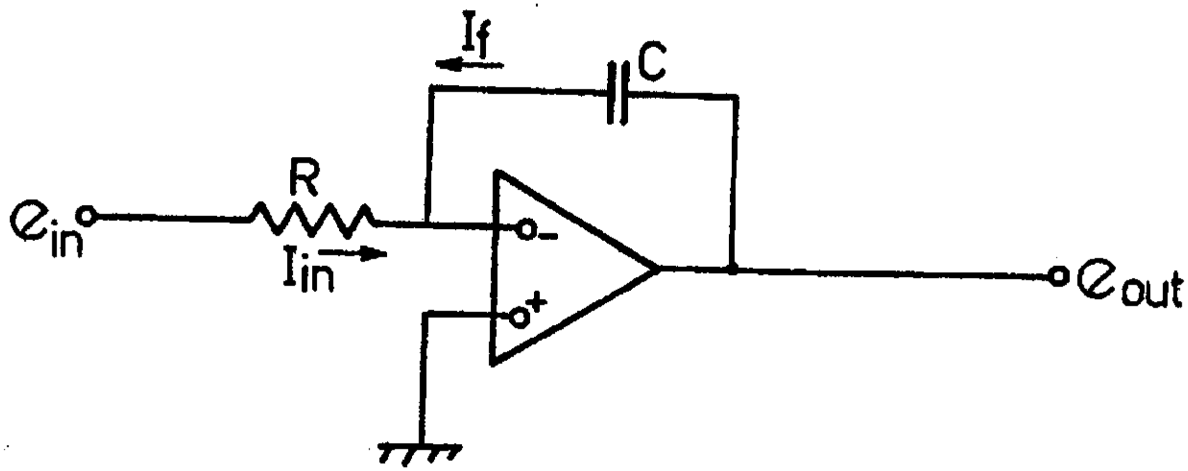
This error required to restore equilibrium is called *offset,* and in most control systems is the limiting factor of straight proportional control,

Offset is the stable deviation of a process, under straight proportional control, away from the set point following a process supply or demand disturbance.

If the valve in this system could be positioned further than the proportional response requires, then the process can be restored to the set point. (opening inflow valve more will cause the level to rise.).

Reset or integral mode is required to eliminate offset by integrating or summing the process error involved. Reset responds until the error is reduced to zero by driving the manipulated variable to that value required to achieve stabilization at the set point. In order to achieve integral mode (or reset mode) the error signal could be applied as the input signal to an integrating Amplifier.

Integral Function Amplifier



As before, allow that $I_{in} = -I_{fb}$.
Recall that charge equals capacitance times voltage:

$$Q = CV$$

Considering the change in charge for a particular capacitor results in:

$$Q = I\,t$$

The charge resulting from a particular current flow is a function of time:

so that

$$\Delta Q = I_{fb}\Delta t$$

$$I_{fb}\Delta t = C\Delta V$$

$$I_{fb} = \frac{C\Delta V}{\Delta t} = \frac{C\Delta e_{OUT}}{\Delta t}$$

$$I_{in} = -I_{fb}$$

$$\frac{e_{IN}}{R} = -C\,\frac{\Delta e_{OUT}}{\Delta t}$$

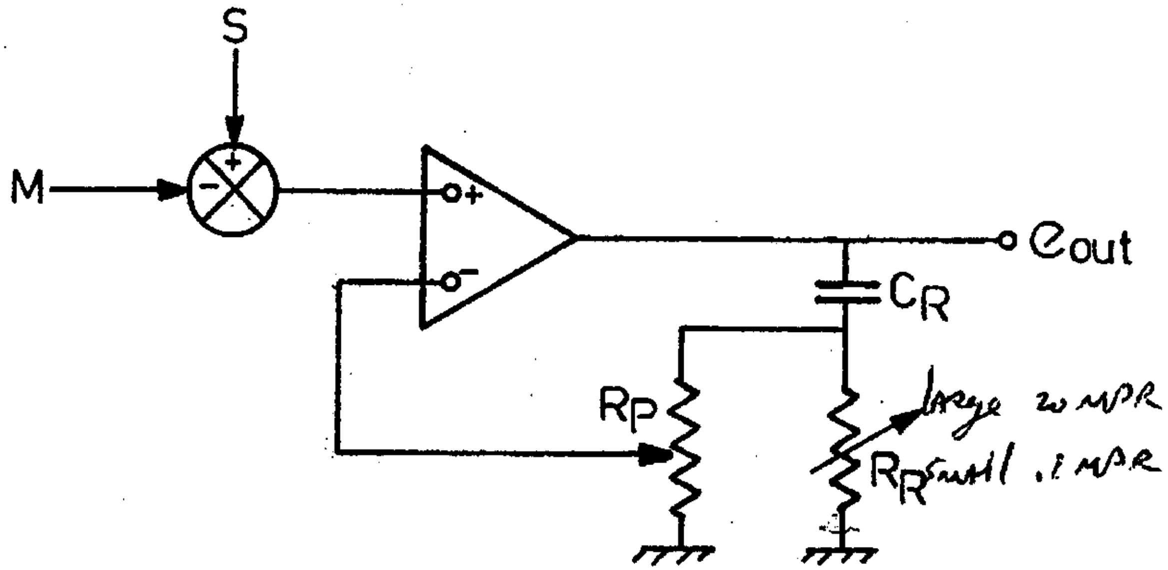
$$\Delta e_{OUT} = \frac{e_{IN}}{-RC}\Delta t$$

Integrating both sides results in the output voltage being an integral function of the input.

$$e_{OUT} = -\frac{1}{RC}\int_{0}^{t} e_{IN}\,dt$$

The output signal will be a summation function of the input signal (error). From this development, all that is required is to recognize that an integral function can be achieved using an RC network with an OP AMP.

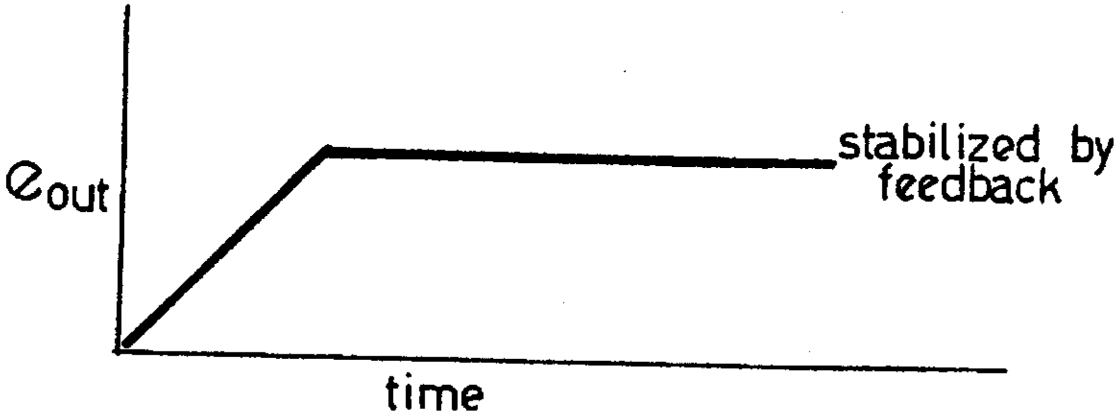
Simplified Electronic PI Controller



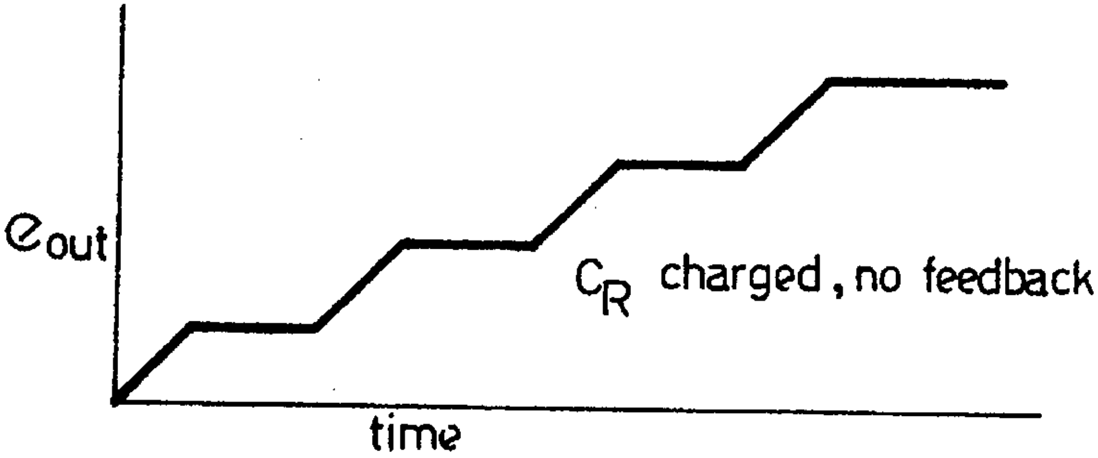
Reverse action is used for this proportional plus reset (or integral) controller model.

- **Consider the measurement dropping below the set point, then a more positive signal is produced by the comparator and applied to the non inverting terminal of the operational amplifier.**
- **The output signal of the amplifier will begin to increase causing capacitor C_R to charge.**
- **Feedback voltage will be applied to the inverting terminal only while C_p is charging, developing a voltage drop across R_R and R_p. Once C_R is charged, there will be no current flow and consequently no voltage drop across R_R and R_p. The feedback potential will drop to ground value or feedback is removed once C_R is charged.**
- **As C_R begins to charge due to the rise in the output signal, a fraction of the voltage across R_p will be applied back to the inverting terminal to stabilize the amplifier and hold the output at one particular magnitude. (Note that this is proportional response.) As soon as the amplifier stabilizes the output signal stops changing, and C_p will become charged depending on the time constant R_R C_R.**

- **Once C_R is charged, the voltage across R_p will disappear and the R_p contact is reduced to ground potential.**
- **There is no voltage applied to the inverting terminal but the error signal is still applied to the non inverting terminal causing the output signal to rise again.**
- **The complete cycle will be repeated causing the signal to level out again at some larger magnitude.**
- **The reset action will step the output in the direction of the original proportional response until the measurement is forced back to the set point.**



- **If the measurement is forced back to the set point, then the error will be zero and the amplifier will hold the new output until an error appears.**
- **Consider the OP-AMP driving the output until the difference across the inverting and non inverting terminals is zero volts and then holding the output signal steady at this last value.**



If R_p is set very large, then the charge time for C_R will approach infinity and the response will approximate straight proportional control. Reset mode can be considered shut off when R_R is very large.

Reset time is the time in minutes required for reset to duplicate the original proportional response to a process disturbance. This is the number of minutes necessary to repeat the proportional response or the Minutes Per Repeat (MPR). Reset rate is just the reciprocal of MPR-and-has the units Repeat Per Minute (RPM).

$$\text{MPR} = \frac{1}{\text{RPM}}$$

- **Use of reset time or reset rate on the instrument dial is up to the discretion of the manufacturer and has lead to some interesting results in circumstances like initial start-ups.**
- **The reset effect can accidentally be set to maximum rather than being eliminated. Take the time to ensure that the reset mode adjustment is in MPR or RPM and then adjust accordingly.**
- **Reset action is minimized with a very low reset rate (0 RPM) or a very large reset time (60 MPR).**

Example

A pressure controller is bench checked with the set point at 100 kPag on a scale of 0-150 kPag. The % PB is set to 40%, and the action is direct. Reset is set at 0.75 RPM. Determine the initial control signals due to proportional response and state what the signal will be at 1 minute and 2 minutes after the pressure is suddenly raised to 110 kPag.

Assume that the control signal was initially stable at 8 mA. Plot a graph of control signal (4-20 mA) vs time (minute) for three minutes after the perturbation was applied.

Solution

Initial signal = 8 mA

$$\%\text{PB} = 40\%, \qquad \text{Gain} = \frac{100}{\%\text{PB}} = \frac{100}{40} = 2.5$$

$$\text{Gain} = \frac{\%\ \Delta\text{Output}}{\%\ \Delta\text{Input}}$$

$$\textbf{\%}\Delta\ \textbf{Input} = \frac{110-100}{150}\ \text{x}\ 100 = \frac{10}{150}\text{x}100 = 6.7\%$$

%Δ Output = Gain x %Δ Input

%Δ Output = (2.5) (6.7) = 16.75 %

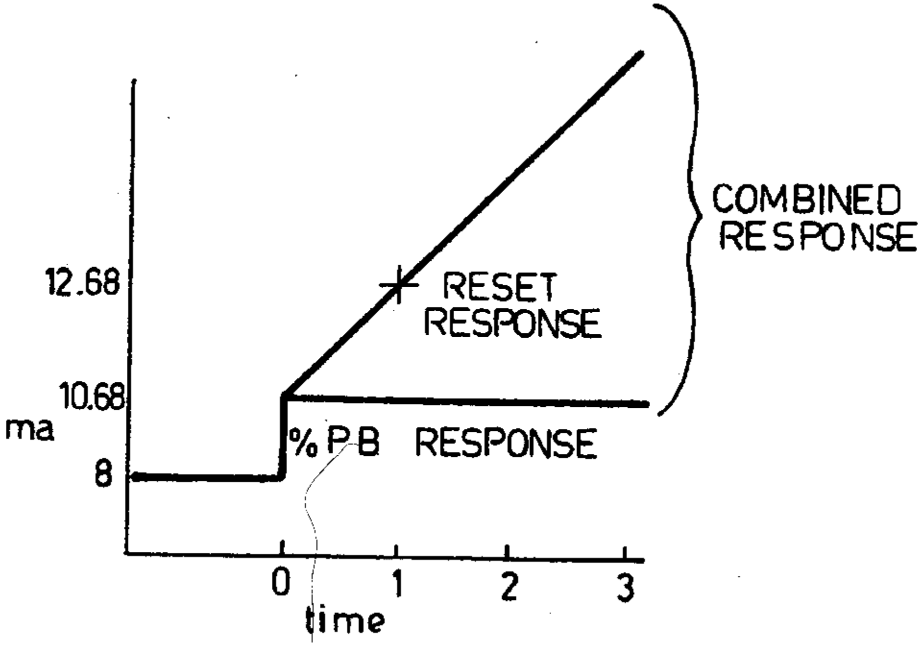
$$\textbf{mA Signal change} = \frac{16.75}{100}\text{x}16 = 2.68\ \text{ma}$$

The control signal will rise 2.68 mA due to proportional response. This is the magnitude of 1 repeat.

1 Repeat = 2.68 mA
.75 Repeat = (.75) (2.68) = 2 mA

The reset rate of .75 RPM will raise the signal 2 mA each minute.

Immediate signal will be:	**8 + 2.68 = 10.68 mA**
Signal in 1 minute:	**10.68 + 2 = 12.68 mA**
Signal in 2 minutes:	**12.68 + 2 = 14.68 mA**
Signal in 3 minutes:	**14.68 + 2 = 16.68 mA**



Reset Wind Up

Pneumatic or electronic controllers with reset mode can occasionally integrate the control signal right off the signal range if a sustained deviation is imposed upon the controller or if the reset rate is too fast for the process.

Assume a demand change has resulted in the measurement dropping below the set point for some time. The reset action will integrate this error and continually raise (or lower, depending on the deviation) the control signal until it is well above the 100% signal value (20 mA). Assume the control signal is raised to 26 mA, the valve can only be positioned to 100% open or closed status so that the extra signal is meaningless. The amount of signal above 100% or below 0% will not change the valve position. This condition is known as reset wind-up.

As the process rises, the valve is held open by the wind-up signal. If the error is still negative, reset will continue to ramp the output (until the error is zero). The measurement must cross the set point before the output can begin to change within the signal range.

The steady state control signal will predominantly be the integral term. The error must change signs (process cross the set point) before the controller can integrate the signal back down to a suitable control value. The result of this wind-up action will be a cycling process similar to on/off control. The solution to this problem in most cases is to ensure that the reset rate is adjusted properly for a given application.

The idea of wind-up is more easily demonstrated by considering how a computer would provide proportional plus reset action. Consider the following simplified portion of a program.

```
PROGRAM                                        COMMENTS
    Sum = 0.................................   initialize summing location
100 Read T .................................   read process temperature
    E1= SP - T .............................   calculate current error
    Sum = Sum + E1..........................   integrate or sum error
    $SIG = K*(E1 + \frac{Sum}{R})$..........   R = Reset time, K = Gain
    Output SIG .............................   apply control signal to DAC
    Service other loops
    Go To 100 ..............................   read process temperature
```

Assume that the loop is executed once each second and the error (E1), sum value (Sum), and % signal (SIG) is recalculated once each second. If a particular error, say 5% exists and the process is slow to respond, then every second the sum will be incremented by 5%. Imagine the consequences of this constant 5% error being summed every second for three or four minutes. (Allow k = 1, R = 1 for simplicity.) The control signal will be well above 100% and the loop can be said to be wound up.

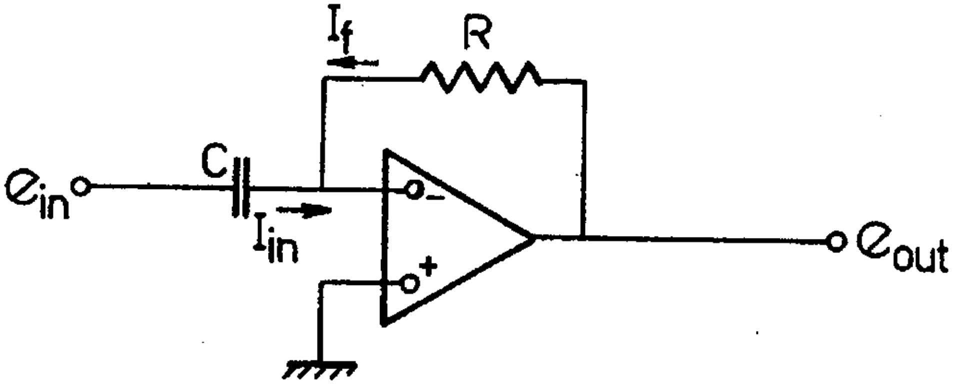
Leading instrument manufacturers provide an optional anti-wind-up feature for control applications in which reset wind-up could occur. The output of a derivative amplifier is fed as the input to the reset amplifier so that as the error begins to change derivative will respond, and begin to remove the wind-up effect before the process crosses the set point. Another solution used is to apply external feedback to the reset mode so that the integration is a function of the process response and not the control signal change.

Derivative Mode

- **If the controller can sense how rapidly a deviation is occurring, a control response can be made to attempt to stabilize the process.**
- **The faster the process is changing, the larger the control signal change would be in an attempt to stop the process variation.**
- **Such a control response is called derivative or rate response and would tend to minimize deviation and maximize stability if properly employed.**
- **Derivative time is the time in minutes that the control signal will be advanced by derivative over straight Proportional response while the error is changing.**
- **A derivative time of two minutes would cause the control signal to be advanced by two minutes.**
- **The control signal right now would be that magnitude that proportional alone would cause two minutes from now while the same rate of error change is applied.**
- **The error signal can be applied as the input to a derivative amplifier and the output signal developed will be proportional to the rate of change in the error.**

Derivative Function Amplifier

Again allow that $I_{IN} = -I_{fb}$ and that $\Delta Q = C\Delta e_{IN}$



$$\Delta Q = I_{IN}\,\Delta t = C\Delta e_{IN}$$

$$I_{IN} = \frac{C\Delta e_{in}}{\Delta t}$$

$$I_{fb} = \frac{e_{OUT}}{R}$$

$$I_{IN} = -I_{fb}$$

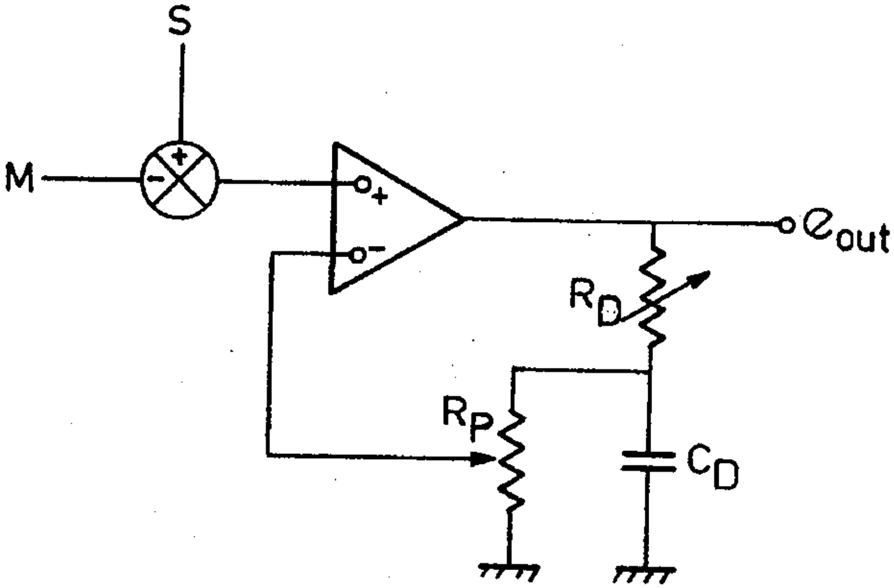
$$\frac{C\Delta e_{IN}}{\Delta t} = \frac{-e_{OUT}}{R}$$

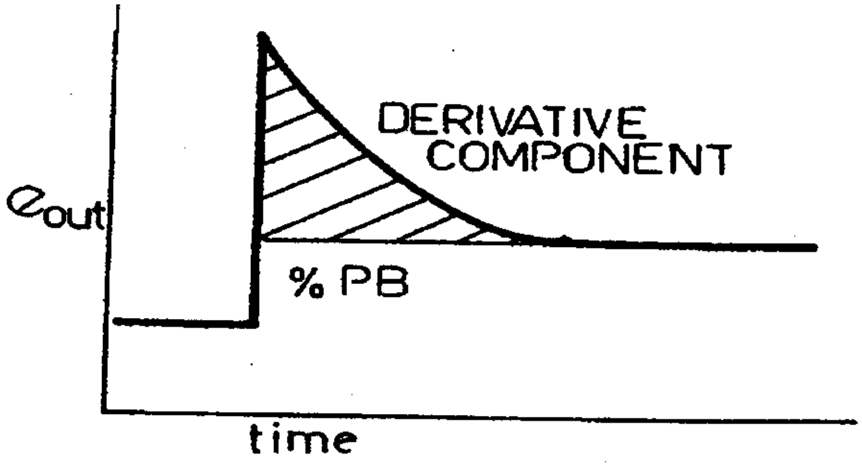
$$e_{OUT} = -RC\,\frac{\Delta e_{IN}}{\Delta t}$$

$$e_{OUT} = -RC\,\frac{de_{in}}{dt}$$

The output voltage is a derivative function of the input signal. All that is required from this development is to know that a derivative function is possible using an OP-AMP with an RC feedback network.

Simplified Electronic PD Controller





- **Note that full proportional feedback will be obtained after C_D is charged (opposite of the reset network.) Again reverse action is used for the working model. If the measurement drops below the set point, the amplifier output will begin to rise and C_D will charge providing feedback potential to the inverting terminal. If R_D is very small then C_D will charge quickly and feedback will depend only on the R_p setting (straight proportional control). This would be a derivative time of zero minutes.**
- **If a larger value is selected for R_D, it will delay the charge time of C_D; temporarily interrupting the amplifier feedback. As a result, the amplifier output will rise to a larger magnitude signal than would be expected with straight proportional control. As C_D charges the feedback potential is increased until the output is returned to the straight proportional level.**
- **The final actuator should be stroked more to give a larger change in process until C_D is charged and normal proportional control is restored. The larger input to the process should have a braking effect on the deviation and tend to hold the process closer to the set point. In the steady state the derivative component will disappear (error is no longer changing) so that control response will revert to straight proportional.**
- **Offset will still be a problem with proportional plus derivative control.**

Example

A proportional plus derivative controller is subjected to a positive ramp of 10%/min for three minutes and then held steady at the new position. The initial control signal was stable at 12 mA. The PB = 100% with a derivative time of 1 minute. Control action is reverse. Sketch a graph of control response (4-20 mA) vs time (minutes). Show ideal and practical control response curves.

Solution

A 10% error change/min for 3 minutes = 30% total change.

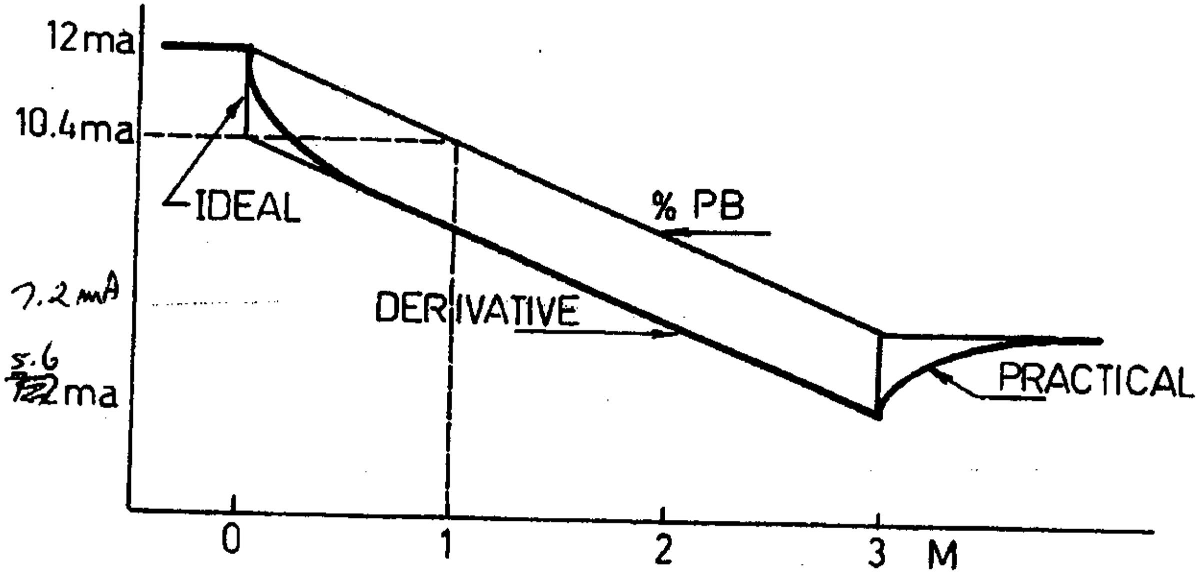
Controller Gain = 1, since PB = 100%

Control signal must decrease 30% over 3 minutes

Δ Signal = .3 x 16 = 4.8 mA decrease

∴ Proportional response will cause the control. signal to drop from 12 mA to 7.2 mA in three minutes.

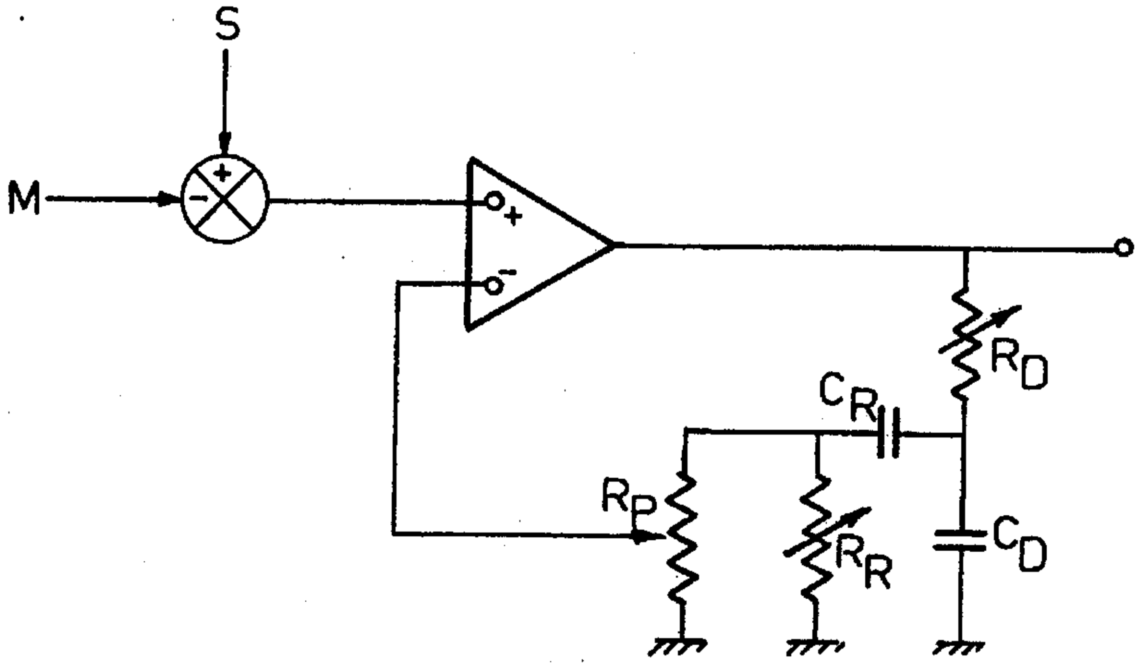
- **The derivative time is 1 minute so that superimposed on the proportional curve will be the derivative response.**
- **Derivative will cause the signal to be now what proportional would cause 1 minute from now while the error is changing the proportional curve will be shifted down by an additional 10% (1.6 mA).**



Simplified PID Electronic Controller

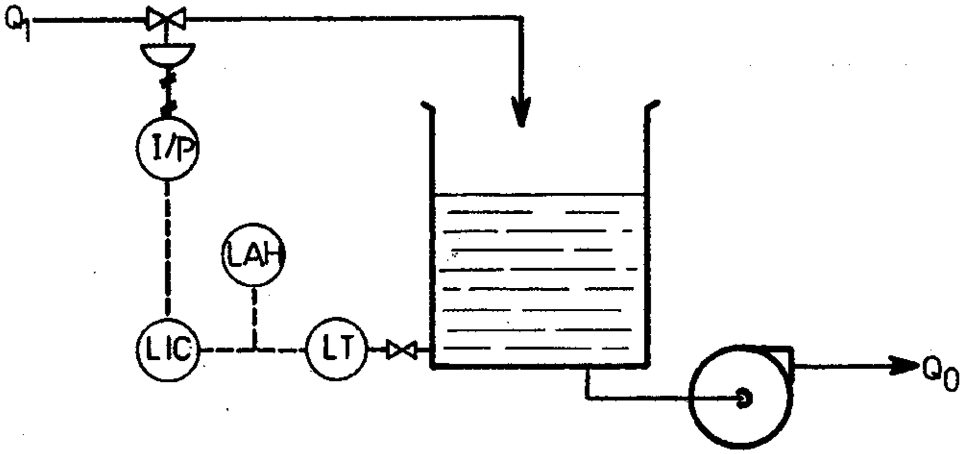
All three modes can be combined to provide maximum stability, minimum deviation controlled response with the elimination of offset.

- **Suitable process response to a transient disturbance can be achieved by varying R_p contact (% PB), R_R (Reset time) and R_D (Derivative time).**
- **If proportional only control is required, set R_D to zero resistance to provide zero minutes derivative time and set R_R to maximum resistance to provide 0 RPM.**
- **The R_p contact can then be varied to achieve the quarter decay process recovery curve. R_R can then be set to remove offset while maintaining stable control.**
- **Finally R_D can be adjusted to minimize deviations and cycling to provide optimum three mode control.**



The Complete System

The controller output will now form a separate current loop so that the I/P transducer will operate as a function of the control signal. The spring opposed diaphragm actuator will drive the control valve as the 4-20 mA signal is transduced to 20-100 kPag and applied to the diaphragm casing. The complete electronic level control system can be represented by the following sketches.



LT	-	Level Transmitter
LAH	-	Level Alarm High (Current Alarm)
LIC	-	Level Indicating Controller
I/P	-	Current to Pneumatic Transducer
Q_1	-	Inflow
Q_o	-	Outflow

- A level decrease will produce a corresponding decrease in the 4-20 mA signal from the level transmitter.
- The valve in use is an air to open style so that the controller action must be reverse
- The decrease in measurement below the set point will cause the reverse action controller to raise the 4-20 mA signal proportional to the error.
- The increase in the 4-20 mA control signal applied to the I/P transducer will increase the corresponding 20-100 kPag signal applied to the valve.
- The valve will now be stroked more open to increase the inflow to the tank and try to restore the level to the set point.

The Electronic Control Loop

Assignment

1. What 4-20 mA transmitter signal will be developed if the level is 80 cm WC when the calibrated range is 0-120 cm WC? (Answer 14.67 mA)
2. A controller has a proportional band of 40% and a process upset causes the transmitter signal to change 2 mA. What change in control signal will result? (Answer 5 mA)
3. A current alarm is connected to a 4-20 mA loop (level) across a 125 ohm dropping resistor, what voltage signal level would correspond to a 85% high level condition? (Answer 2.2 volts)
4. The proportional response to a process disturbance changed the control signal from 12 to 10.5 mA. Over the next two minutes reset mode drives the signal to 9.75 mA. If the % PB is 30% find the reset time in MPR. (Answer 4 MPR)
5. Explain the purpose of a comparator in a control system. Sketch a simple DC circuit which would function as a comparator.
6. Sketch a simplified electronic controller based on an OP-AMP with an RC feedback network to provide proportional plus reset action. Discuss the operation.
7. Repeat question 6. for a proportional plus derivative device.
8. Explain what reset wind-up is and why it will occur. How does the wind-up condition affect the overall loop control?
9. Explain the difference between reset rate and reset time.
10. Sketch an electronic control loop used on a hot bleed/ cold service water heat exchanger. The objective is to control the temperature of the hot bleed as it leaves the HX. The temperature is sensed by an RTD and the valve on the service water is an air to close style. Discuss one cycle of operation, stating controller action.