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ONLINE COURSE WARE

SUBJECT NAME: PROCESS CONTROL SYSTEM

SUBJECT CODE: FT 704 B

CREDIT:

Module I

Lecture 1:

Introduction to Control System:

Introduction to Elementary control concept

A control system is a system, which provides the desired response by controlling the output. The following figure shows the simple block diagram of a control system.

Figure1.1

Here, the control system is represented by a single block. Since, the output is controlled by varying input, the control system got this name. We will vary this input with some mechanism. In the next section on open loop and closed loop control systems, we will study in detail about the blocks inside the control system and how to vary this input in order to get the desired response.

Examples − Traffic lights control system, washing machine

Traffic lights control system is an example of control system. Here, a sequence of input signal is applied to this control system and the output is one of the three lights that will be on for some duration of time. During this time, the other two lights will be off. Based on the traffic study at a particular junction, the on and off times of the lights can be determined. Accordingly, the input signal controls the output. So, the traffic lights control system operates on time basis.

Classification of Control Systems

Based on some parameters, we can classify the control systems into the following ways.

Continuous time and Discrete-time Control Systems

- Control Systems can be classified as continuous time control systems and discrete time control systems based on the **type of the signal** used.
- In **continuous time** control systems, all the signals are continuous in time. But, in **discrete time** control systems, there exists one or more discrete time signals.

SISO and MIMO Control Systems

- Control Systems can be classified as SISO control systems and MIMO control systems based on the **number of inputs and outputs** present.
- **SISO** (Single Input and Single Output) control systems have one input and one output. Whereas, **MIMO** (Multiple Inputs and Multiple Outputs) control systems have more than one input and more than one output.

<u>Lecture 2 :</u>

Open and closed loop system:

Control Systems can be classified as open loop control systems and closed loop control systems based on the **feedback path**.

In **open loop control systems**, output is not fed-back to the input. So, the control action is independent of the desired output.

The following figure shows the block diagram of the open loop control system.

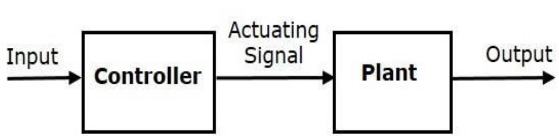


Figure1.2

Here, an input is applied to a controller and it produces an actuating signal or controlling signal. This signal is given as an input to a plant or process which is to be controlled. So, the plant produces an output, which is controlled. The traffic lights control system which we discussed earlier is an example of an open loop control system.

In **closed loop control systems**, output is fed back to the input. So, the control action is dependent on the desired output.

The following figure shows the block diagram of negative feedback closed loop control system.

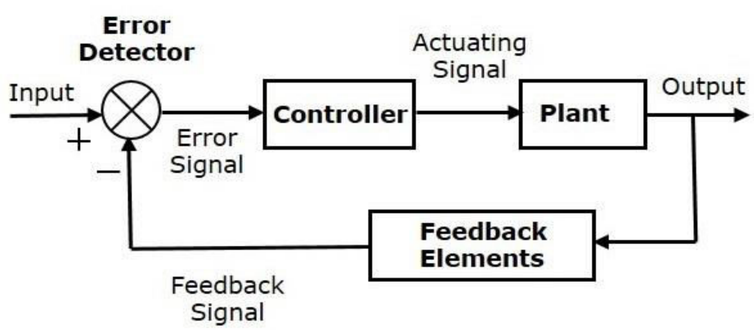


Figure1.3

The error detector produces an error signal, which is the difference between the input and the feedback signal. This feedback signal is obtained from the block (feedback elements) by considering the output of the overall system as an input to this block. Instead of the direct input, the error signal is applied as an input to a controller.

So, the controller produces an actuating signal which controls the plant. In this combination, the output of the control system is adjusted automatically till we get the desired response. Hence, the closed loop control systems are also called the automatic control systems. Traffic lights control system having sensor at the input is an example of a closed loop control system.

The differences between the open loop and the closed loop control systems are mentioned in the following table.

Open Loop Control Systems	**Closed Loop Control Systems**
Control action is independent of the desired output.	Control action is dependent of the desired output.
Feedback path is not present.	Feedback path is present.
These are also called as **non-feedback control systems**.	These are also called as **feedback control systems**.
Easy to design.	Difficult to design.
These are economical.	These are costlier.
Inaccurate.	Accurate.

<u>Lecture 3:</u>

Transfer function of open loop and closed loop control systems:

Mathematical Model:

The control systems can be represented with a set of mathematical equations known as **mathematical model**. These models are useful for analysis and design of control systems. Analysis of control system means finding the output when we know the input and mathematical model. Design of control system means finding the mathematical model when we know the input and the output.

The following mathematical models are mostly used.

- Differential equation model
- Transfer function model
- State space model

Let us discuss the first two models in this chapter.

Differential Equation Model

Differential equation model is a time domain mathematical model of control systems. Follow these steps for differential equation model.

- Apply basic laws to the given control system.
- Get the differential equation in terms of input and output by eliminating the intermediate variable(s).

Example

Consider the following electrical system as shown in the following figure. This circuit consists of resistor, inductor and capacitor. All these electrical elements are connected in **series**. The input voltage applied to this circuit is *vi*

and the voltage across the capacitor is the output voltage *vo*

.

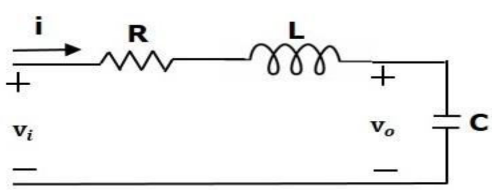


Figure1.4

Mesh equation for this circuit is

$$v_i = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t} + v_o$$

Substitute, the current passing through capacitor $i = c\frac{\mathrm{d}v_o}{\mathrm{d}t}$ in the above equation.

$$\Rightarrow\ v_i = RC\frac{\mathrm{d}v_o}{\mathrm{d}t} + LC\frac{\mathrm{d}^2v_o}{\mathrm{d}t^2} + v_o$$

$$\Rightarrow \frac{\mathrm{d}^2v_o}{\mathrm{d}t^2} + \left(\frac{R}{L}\right)\frac{\mathrm{d}v_o}{\mathrm{d}t} + \left(\frac{1}{LC}\right)v_o = \left(\frac{1}{LC}\right)v_i$$

The above equation is a second order **differential equation**.

Transfer Function Model of open loop system:

Transfer function model is an s-domain mathematical model of control systems. The **Transfer function** of a Linear Time Invariant (LTI) system is defined as the ratio of Laplace transform of output and Laplace transform of input by assuming all the initial conditions are zero.

If $x(t)$and $y(t)$ are the input and output of an LTI system, then the corresponding Laplace transforms are $X(s)$ and $Y(s)$Therefore, the transfer function of LTI system is equal to the ratio of $Y(s)$and $X(s)$.

i.e.TransferFunction $=Y(s)/X(s)$

The transfer function model of an LTI system is shown in the following figure.

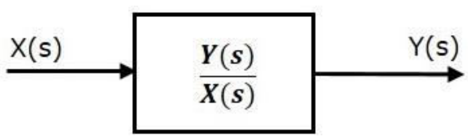


Figure1.5

Here, we represented an LTI system with a block having transfer function inside it. And this block has an input $X(s)$ & output $Y(s)$

Example

Previously, we got the differential equation of an electrical system as

$$\frac{d^2v_o}{dt^2}+\left(\frac{R}{L}\right)\frac{dv_o}{dt}+\left(\frac{1}{LC}\right)v_o=\left(\frac{1}{LC}\right)v_i$$

Apply Laplace transform on both sides.

$$s^2V_o(s)+\left(\frac{sR}{L}\right)V_o(s)+\left(\frac{1}{LC}\right)V_o(s)=\left(\frac{1}{LC}\right)V_i(s)$$

$$\Rightarrow\left\{s^2+\left(\frac{R}{L}\right)s+\frac{1}{LC}\right\}V_o(s)=\left(\frac{1}{LC}\right)V_i(s)$$

$$\Rightarrow\frac{V_o(s)}{V_i(s)}=\frac{\frac{1}{LC}}{s^2+\left(\frac{R}{L}\right)s+\frac{1}{LC}}$$

$vo(s)$ is the Laplace transform of the output voltage vo.

The above equation is a **transfer function** of the second order electrical system. The transfer function model of this system is shown below.

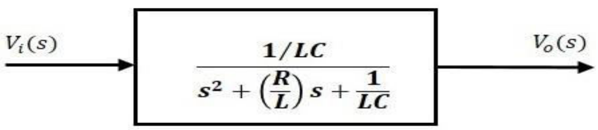


Figure1.6

Here, we show a second order electrical system with a block having the transfer function inside it. And this block has an input $Vi(s)$ & an output $Vo(s)$.

Transfer Function Model of close loop system:

As we discussed in previous chapters, there are two types of **feedback** — positive feedback and negative feedback. The following figure shows negative feedback control system. Here, two blocks having transfer functions $G(s)$ and $H(s)$ form a closed loop.

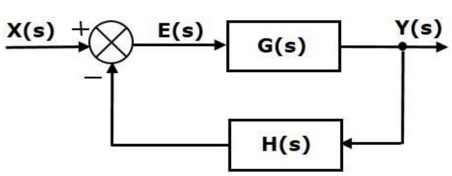


Figure1.7

The output of the summing point is -

$$E(s) = X(s) - H(s)Y(s)$$

The output $Y(s)$ is -

$$Y(s) = E(s)G(s)$$

Substitute $E(s)$ value in the above equation.

$$Y(s) = \{X(s) - H(s)Y(s)\}G(s)\}$$

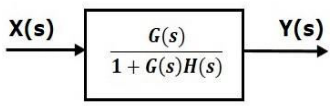
$$Y(s)\,\{1 + G(s)H(s)\} = X(s)G(s)\}$$

$$\Rightarrow \frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)}$$

Therefore, the negative feedback closed loop transfer function is $\frac{G(s)}{1+G(s)H(s)}$

Therefore, the negative feedback closed loop transfer function is $G(s)1+G(s)H(s)$

This means we can represent the negative feedback connection of two blocks with a single block. The transfer function of this single block is the closed loop transfer function of the negative feedback. The equivalent block diagram is shown below.



Similarly, you can represent the positive feedback connection of two blocks with a single block. The transfer function of this single block is the closed loop transfer function of the positive feedback, i.e., $G(s)/(1-G(s)H(s))$.

<u>Lecture 4</u>

<u>Block Diagrams:</u>

Basic Elements of Block Diagram:

The basic elements of a block diagram are a block, the summing point and the take-off point. Let us consider the block diagram of a closed loop control system as shown in the following figure to identify these elements.

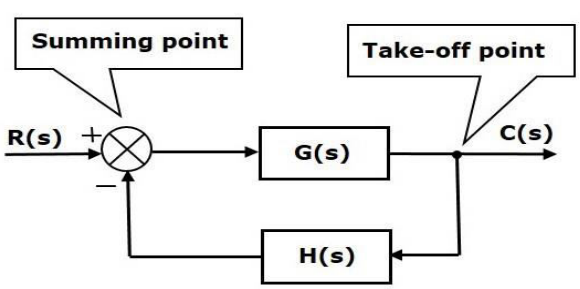


Figure1.8

The above block diagram consists of two blocks having transfer functions G(s) and H(s). It is also having one summing point and one take-off point. Arrows indicate the direction of the flow of signals. Let us now discuss these elements one by one.

Block

The transfer function of a component is represented by a block. Block has single input and single output.

The following figure shows a block having input X(s), output Y(s) and the transfer function G(s).

Transfer Function$(s) = Y(s)/X(s) \Rightarrow Y(s) = G(s)/X(s)$

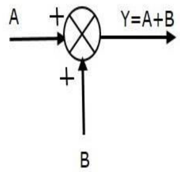
Output of the block is obtained by multiplying transfer function of the block with input.

Summing Point

The summing point is represented with a circle having cross (X) inside it. It has two or more inputs and single output. It produces the algebraic sum of the inputs. It also performs the summation or subtraction or combination of summation and subtraction of the inputs based on the polarity of the inputs. Let us see these three operations one by one.

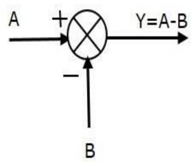
The following figure shows the summing point with two inputs (A, B) and one output (Y). Here, the inputs A and B have a positive sign. So, the summing point produces the output, Y as **sum of A and B.**

i.e.Y = A + B.



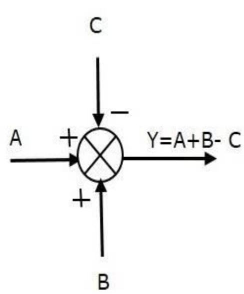
The following figure shows the summing point with two inputs (A, B) and one output (Y). Here, the inputs A and B are having opposite signs, i.e., A is having positive sign and B is having negative sign. So, the summing point produces the output **Y** as the **difference of A and B**.

Y = A + (-B) = A - B.



The following figure shows the summing point with three inputs (A, B, C) and one output (Y). Here, the inputs A and B are having positive signs and C is having a negative sign. So, the summing point produces the output **Y** as

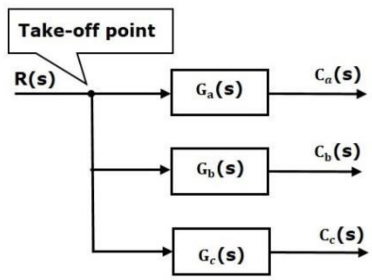
Y = A + B + (−C) = A + B − C.



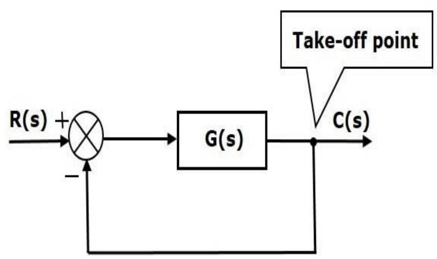
Take-off Point

The take-off point is a point from which the same input signal can be passed through more than one branch. That means with the help of take-off point, we can apply the same input to one or more blocks, summing points.

In the following figure, the take-off point is used to connect the same input, R(s) to two more blocks.



In the following figure, the take-off point is used to connect the output C(s), as one of the inputs to the summing point.



<u>**Lecture 5:**</u>

Block Diagram Representation of Electrical Systems

In this section, let us represent an electrical system with a block diagram. Electrical systems contain mainly three basic elements — **resistor, inductor and capacitor**.

Consider a series of RLC circuit as shown in the following figure. Where, $V_i(t)$ and $V_o(t)$ are the input and output voltages. Let i(t) be the current passing through the circuit. This circuit is in time domain.

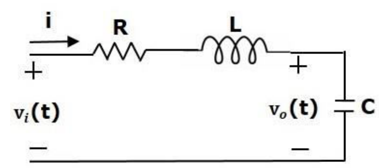


Figure1.9

By applying the Laplace transform to this circuit, will get the circuit in s-domain. The circuit is as shown in the following figure.

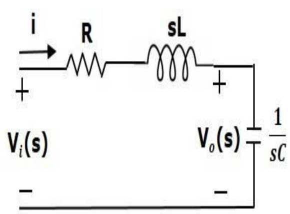


Figure1.10

From the above circuit, we can write

$$I(s) = \frac{V_i(s) - V_o(s)}{R + sL}$$

$$\Rightarrow I(s) = \left\{\frac{1}{R+sL}\right\}\{V_i(s) - V_o(s)\}$$

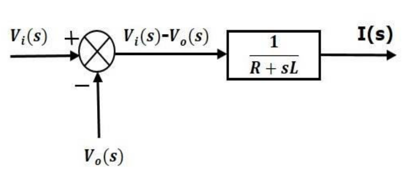
(Equation 1)

$$V_o(s) = \left(\frac{1}{sC}\right) I(s)$$

(Equation 2)

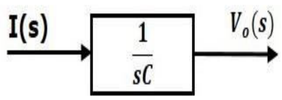
Let us now draw the block diagrams for these two equations individually. And then combine those block diagrams properly in order to get the overall block diagram of series of RLC Circuit (s-domain).

Equation 1 can be implemented with a block having the transfer function, 1/(*R*+*sL)*. The input and output of this block are {*Vi*(*s*)−*Vo*(*s*)} and *I*(*s*). We require a summing point to get



{$Vi(s)−Vo(s)$}. The block diagram of Equation 1 is shown in the following figure.

Equation 2 can be implemented with a block having transfer function, $1/sC$. The input and output of this block are $I(s)$ and $Vo(s)$. The block diagram of Equation 2 is shown in the following figure.



The overall block diagram of the series of RLC Circuit (s-domain) is shown in the following figure.

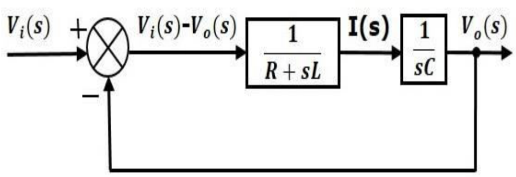


Figure1.11

Similarly, you can draw the **block diagram** of any electrical circuit or system just by following this simple procedure.

- Convert the time domain electrical circuit into an s-domain electrical circuit by applying Laplace transform.
- Write down the equations for the current passing through all series branch elements and voltage across all shunt branches.
- Draw the block diagrams for all the above equations individually.
- Combine all these block diagrams properly in order to get the overall block diagram of the electrical circuit (s-domain).

Block diagram algebra is nothing but the algebra involved with the basic elements of the block diagram. This algebra deals with the pictorial representation of algebraic equations.

<u>Lecture 6:</u>

Basic Connections for Blocks:

There are three basic types of connections between two blocks.

Series Connection

Series connection is also called **cascade connection**. In the following figure, two blocks having transfer functions $G1(s)$ and $G2(s)$ are connected in series.

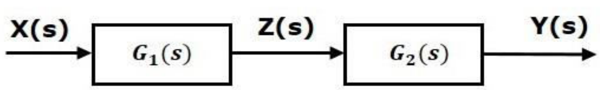


Figure1.12

For this combination, we will get the output $Y(s)$ as

$$Y(s) = G_2(s)Z(s)$$

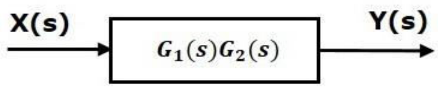
Where, $Z(s) = G_1(s)X(s)$

$$\Rightarrow Y(s) = G_2(s)[G_1(s)X(s)] = G_1(s)G_2(s)X(s)$$

$$\Rightarrow Y(s) = \{G_1(s)G_2(s)\}X(s)$$

Compare this equation with the standard form of the output equation, $Y(s) = G(s)X(s)$. Where, $G(s) = G_1(s)G_2(s)$.

That means we can represent the **series connection** of two blocks with a single block. The transfer function of this single block is the **product of the transfer functions** of those two blocks. The equivalent block diagram is shown below.



Similarly, you can represent series connection of 'n' blocks with a single block. The transfer function of this single block is the product of the transfer functions of all those 'n' blocks.

Parallel Connection

The blocks which are connected in **parallel** will have the **same input**. In the following figure, two blocks having transfer functions $G1(s)$ and $G2(s)$are connected in parallel. The outputs of these two blocks are connected to the summing point.

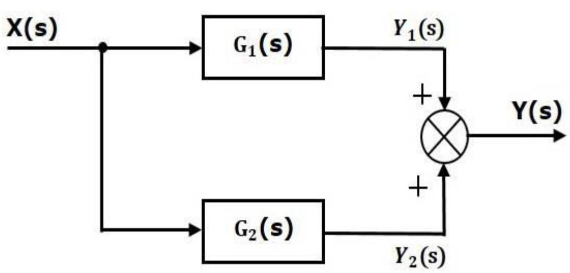


Figure1.13

For this combination, we will get the output $Y(s)$ as

$$Y(s) = Y_1(s) + Y_2(s)$$

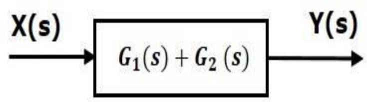
Where, $Y_1(s) = G_1(s)X(s)$ and $Y_2(s) = G_2(s)X(s)$

$$\Rightarrow Y(s) = G_1(s)X(s) + G_2(s)X(s) = \{G_1(s) + G_2(s)\}X(s)$$

Compare this equation with the standard form of the output equation, $Y(s) = G(s)X(s)$.

Where, $G(s) = G_1(s) + G_2(s)$.

That means we can represent the **parallel connection** of two blocks with a single block. The transfer function of this single block is the **sum of the transfer functions** of those two blocks. The equivalent block diagram is shown below.



Similarly, you can represent parallel connection of 'n' blocks with a single block. The transfer function of this single block is the algebraic sum of the transfer functions of all those 'n' blocks.

Feedback Connection

As we discussed in previous chapters, there are two types of **feedback** — positive feedback and negative feedback. The following figure shows negative feedback control system. Here, two blocks having transfer functions $G(s)$ and $H(s)$ form a closed loop.

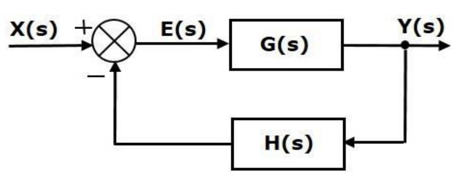


Figure1.14

The output of the summing point is -

$$E(s) = X(s) - H(s)Y(s)$$

The output $Y(s)$ is -

$$Y(s) = E(s)G(s)$$

Substitute $E(s)$ value in the above equation.

$$Y(s) = \{X(s) - H(s)Y(s)\}G(s)\}$$

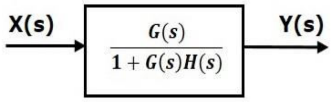
$$Y(s)\left\{1 + G(s)H(s)\right\} = X(s)G(s)\}$$

$$\Rightarrow \frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)}$$

Therefore, the negative feedback closed loop transfer function is $\frac{G(s)}{1+G(s)H(s)}$

Therefore, the negative feedback closed loop transfer function is $G(s)1+G(s)H(s)$

This means we can represent the negative feedback connection of two blocks with a single block. The transfer function of this single block is the closed loop transfer function of the negative feedback. The equivalent block diagram is shown below.



Similarly, you can represent the positive feedback connection of two blocks with a single block. The transfer function of this single block is the closed loop transfer function of the positive feedback, i.e., $G(s)/(1-G(s)H(s))$.

Lecture 7:

Simplification of a control system using block diagram reduction:

Block Diagram Algebra for Summing Points:

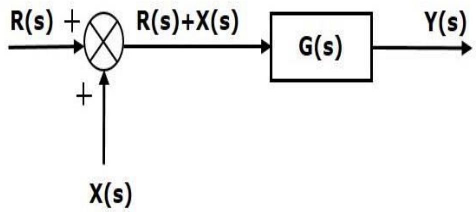
There are two possibilities of shifting summing points with respect to blocks −

- Shifting summing point after the block
- Shifting summing point before the block

Let us now see what kind of arrangements need to be done in the above two cases one by one.

Shifting Summing Point after the Block

Consider the block diagram shown in the following figure. Here, the summing point is present before the block.



Summing point has two inputs $R(s)$ and $X(s)$. The output of it is $\{R(s)+X(s)\}$.

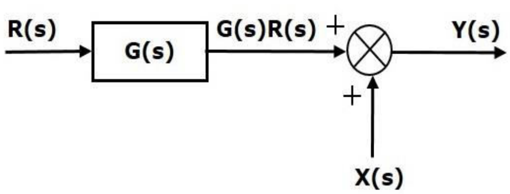
So, the input to the block $G(s)$ is $\{R(s)+X(s)\}$ and the output of it is –

$$Y(s)=G(s)\{R(s)+X(s)\}$$

$$\Rightarrow Y(s)=G(s)R(s)+G(s)X(s)$$

(Equation 1)

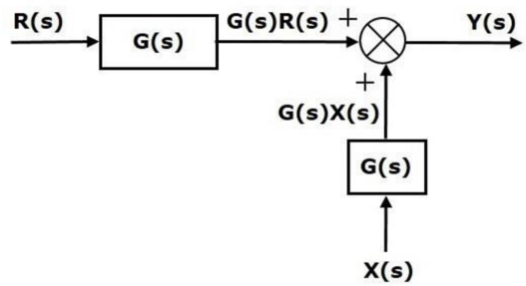
Now, shift the summing point after the block. This block diagram is shown in the following figure.



Output of the block $G(s)$ is $G(s)R(s)$.

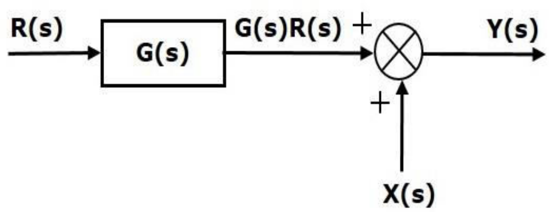
The output of the summing point is $Y(s)=G(s)R(s)+X(s)$ **(Equation 2)**

Compare Equation 1 and Equation 2.The first term '$G(s)R(s)$ 'is same in both the equations. But, there is difference in the second term. In order to get the second term also same, we require one more block $G(s)$. It is having the input $X(s)$ and the output of this block is given as input to summing point instead of $X(s)$. This block diagram is shown in the following figure.



Shifting Summing Point Before the Block

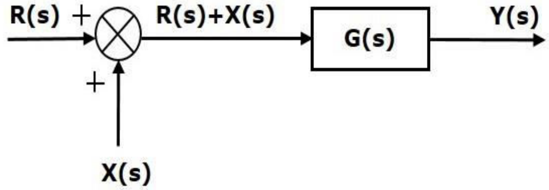
Consider the block diagram shown in the following figure. Here, the summing point is present after the block.



Output of this block diagram is -

$Y(s) = G(s)\,R(s) + X(s)$ **(Equation 3)**

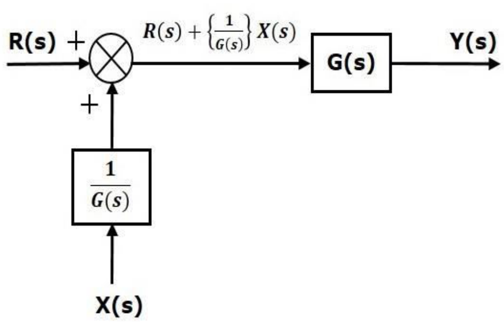
Now, shift the summing point before the block. This block diagram is shown in the following figure.



Output of this block diagram is -

$Y(S)=G(s)R(s)+G(s)X(s)$ **(Equation 4)**

Compare Equation 3 and Equation 4,The first term '$G(s)R(s)'$ is same in both equations. But, there is difference in the second term. In order to get the second term also same, we require one more block $1G(s)$. It is having the input $X(s)$ and the output of this block is given as input to summing point instead of $X(s)$. This block diagram is shown in the following figure.



Block Diagram Algebra for Take-off Points

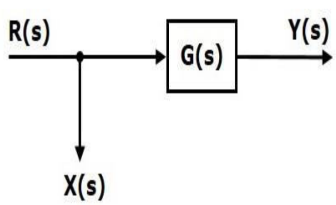
There are two possibilities of shifting the take-off points with respect to blocks −

- Shifting take-off point after the block
- Shifting take-off point before the block

Let us now see what kind of arrangements is to be done in the above two cases, one by one.

Shifting Take-off Point after the Block

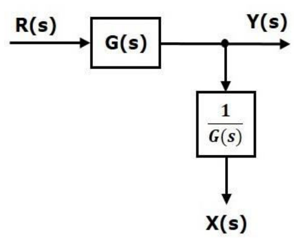
Consider the block diagram shown in the following figure. In this case, the take-off point is present before the block.



Here, $X(s)=R(s)$

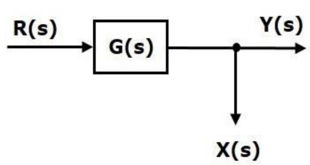
and $Y(s)=G(s)R(s)$

When you shift the take-off point after the block, the output $Y(s)$ will be same. But, there is difference in $X(s)$ value. So, in order to get the same $X(s)$ value, we require one more block $1G(s)$. It is having the input $Y(s)$ and the output is $X(s)$. This block diagram is shown in the following figure.



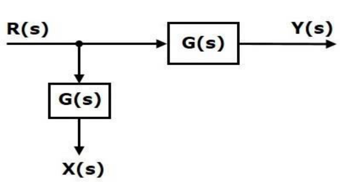
Shifting Take-off Point before the Block

Consider the block diagram shown in the following figure. Here, the take-off point is present after the block.



Here, $X(s) = Y(s) = G(s)\, R(s)$

When you shift the take-off point before the block, the output $Y(s)$ will be same. But, there is difference in $X(s)$ value. So, in order to get same $X(s)$ value, we require one more block $G(s)$. It is having the input $R(s)$ and the output is $X(s)$. This block diagram is shown in the following figure.



<u>Lecture 8:</u>

Block Diagram Reduction Rules:

Follow these rules for simplifying (reducing) the block diagram, which is having many blocks, summing points and take-off points.

- **Rule 1** − Check for the blocks connected in series and simplify.
- **Rule 2** − Check for the blocks connected in parallel and simplify.
- **Rule 3** − Check for the blocks connected in feedback loop and simplify.
- **Rule 4** − If there is difficulty with take-off point while simplifying, shift it towards right.
- **Rule 5** − If there is difficulty with summing point while simplifying, shift it towards left.
- **Rule 6** − Repeat the above steps till you get the simplified form, i.e., single block.

Note − The transfer function present in this single block is the transfer function of the overall block diagram.

Example

Consider the block diagram shown in the following figure. Let us simplify (reduce) this block diagram using the block diagram reduction rules.

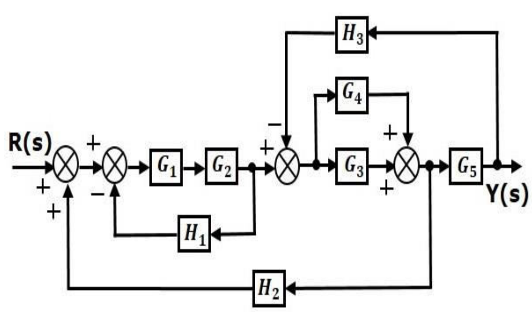
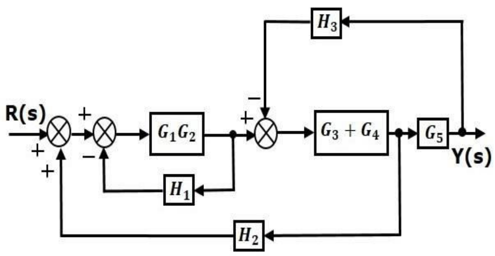
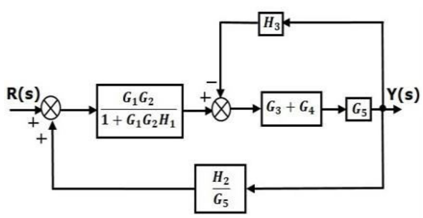


Figure1.14

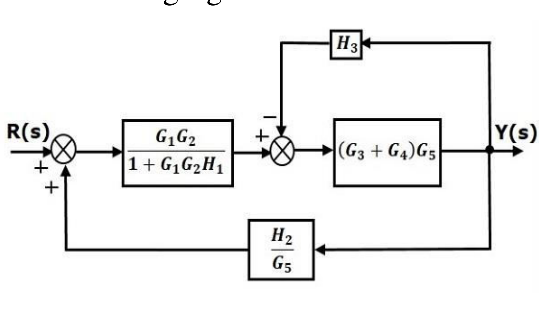
Step 1 − Use Rule 1 for blocks *G*1and *G*2. Use Rule 2 for blocks *G*3 and *G*4. The modified block diagram is shown in the following figure.



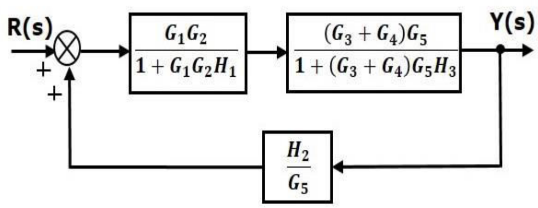
Step 2 − Use Rule 3 for blocks *G*1*G*2 and *H*1. Use Rule 4 for shifting take-off point after the block *G*5. The modified block diagram is shown in the following figure.



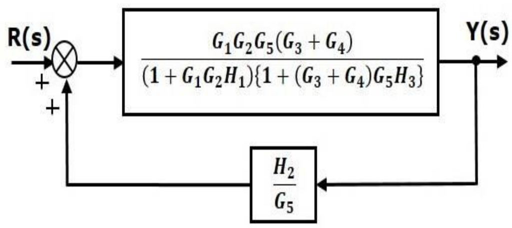
Step 3 − Use Rule 1 for blocks (*G*3+*G*4) and *G*5 . The modified block diagram is shown in the following figure.



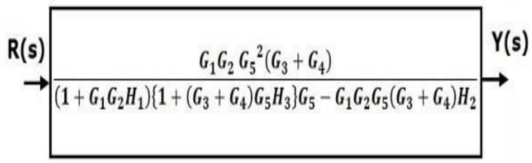
Step 4 − Use Rule 3 for blocks (*G*3+*G*4) *G5* and *H*3. The modified block diagram is shown in the following figure.



Step 5 − Use Rule 1 for blocks connected in series. The modified block diagram is shown in the following figure.



Step 6 − Use Rule 3 for blocks connected in feedback loop. The modified block diagram is shown in the following figure. This is the simplified block diagram.



Therefore, the transfer function of the system is

$$\frac{Y(s)}{R(s)} = \frac{G_1 G_2 G_5^2 (G_3 + G_4)}{(1 + G_1 G_2 H_1)\{1 + (G_3 + G_4) G_5 H_3\} G_5 - G_1 G_2 G_5 (G_3 + G_4) H_2}$$

Note − Follow these steps in order to calculate the transfer function of the block diagram having multiple inputs.

- **Step 1** − Find the transfer function of block diagram by considering one input at a time and make the remaining inputs as zero.
- **Step 2** − Repeat step 1 for remaining inputs.
- **Step 3** − Get the overall transfer function by adding all those transfer functions.

The block diagram reduction process takes more time for complicated systems. Because, we have to draw the (partially simplified) block diagram after each step. So, to overcome this drawback, use signal flow graphs (representation).

Module II

Lecture 9

2.1 Introduction:

Process: It is an unit where the physical or chemical change or both occurs among a numbers of raw materials under certain environmental condition and one or more final products at desired quality & quantity are obtained.

Process Control: It is the technique by which one or more process variables in a process maintained at their desired values in order to get product at better quality and linear cost with better safety operation of plant.

2.2 Servo and Regulatory Control

The objective of any control system is one of the following:

Regulatory Control: Elimination of Disturbances
Servo Control: Making the controlled variable follow the changes in set point

2.2.1 Regulatory Control

In regulatory control, the deviation of the output from the setpoint is minimized by adjusting the input to the system(controlling variable). A regulatory control system will normally have a fixed reference or set point. The set point can change, but the changes are not be very frequent. Set point remains constant for relatively large period of time.

2.2.2 Servo Control

Another commonly used type of control system, which has a slightly different objective From regulatory control, is called a servo control. In this case, the objective is to force some parameter to vary in a specific manner. Instead of regulating a variable value to a set point, the servo control forces the controlled variable value to follow variation of the reference value.For example, in an industrial robot arm like the one shown in figure , servomechanisms force the robot arm to follow a path from point A to point B.

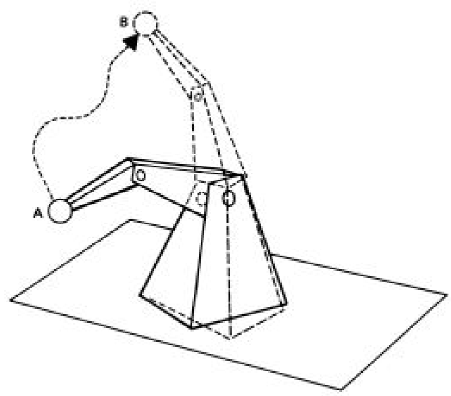
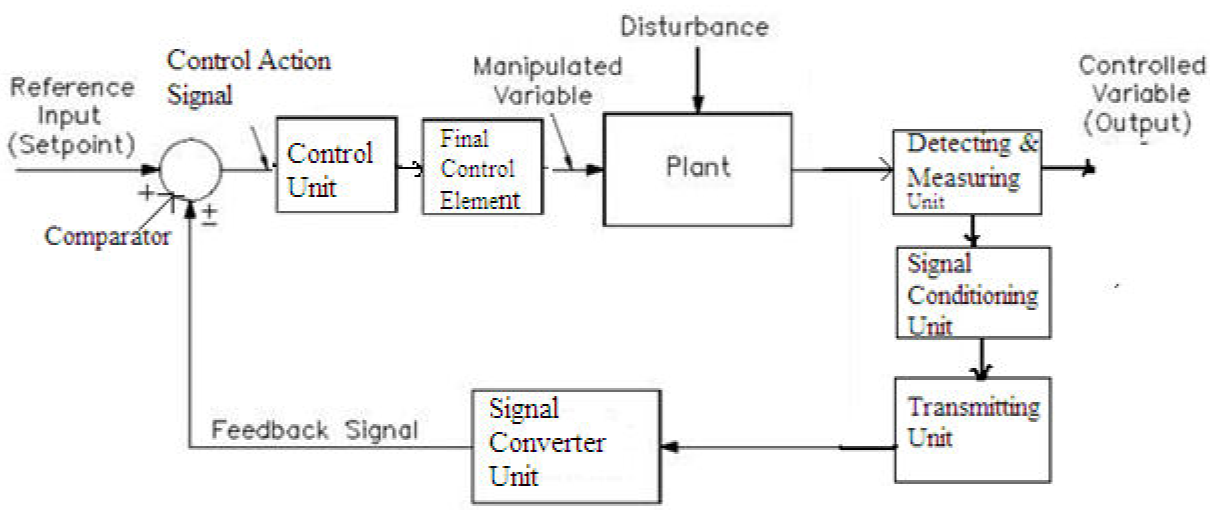


Figure:2.1

2.3 Basic Block Diagram of Process Control



Basic block diagram of any feedback control loop is-

So a basic feedback control loop consists of the following blocks-

2. Feedback unit: Feedback unit consists of

a) Detecting & Measuring Unit

b) Signal Conditioning Unit

c) Transmitting Unit

a) Detecting & Measuring Unit: Clearly, to control a variable in a process, we must have information about the variable itself. Such information is found by measuring the variable.
In general, a measurement refers to the conversion of the variable into some corresponding analog of the variable, such as a pneumatic pressure, an electrical voltage or current, or a digitally encoded signal. A sensor is a device that performs the initial measurement and energy conversion of a variable into analogous digital, electrical, or pneumatic information.

b) Signal Conditioning Unit: Further transformation or signal conditioning may be required to complete the measurement function. The result of the measurement is a representation of the variable value in some form required by the other elements in the process-control operation.

c) Transmitting Unit: This unit converts the output of the signal conditioning unit into a signal which can be transmitted to a remote controller or display unit without any distortion.

2. Signal Converter Unit: It is optional & required if signal conversion is necessary.

3. Controller Unit: Controller unit consists of

a) Comparator

b) Control unit

a) Comparator: Comparator compares the measured value with the reference value and accordingly generates error signal.

b) Control unit: The purpose of control unit is to examine the error and determine what action, if any, should be taken.

4. Final Control Element: A final control element is defined as a mechanical device that manipulates controlling variable to get the controlled variable at desired value.

Lecture 10:

2.4 Characteristic parameters of a process:

Process Equation, Process Quantity, Process Potential, Process Resistance, Process Capacitance, Process Lag, Self Regulation

Process Equation:

A process-control loop regulates some dynamic variable in a process. The controlled variable generally depends on many other parameters in the process .One of these other parameters is to be selected as controlling parameter. Process equation is the equation that defines the controlled variable is the function of which other parameters of the process.

Process Load:

From the process equation, or knowledge of and experience with the process, it is possible to identify a set of values for the process parameters that results in the controlled variable having the set point value. This set of parameters is called the nominal set. The term process load refers to this set of all parameters, excluding the controlled variable. When all parameters have their nominal values, we speak of the nominal load on the system. The required controlling variable value under these conditions is the nominal value of that parameter. If the set point is changed, the control parameter is altered to cause the variable to adopt this new operating point. The load is still nominal, however, because the other parameters are assumed to be unchanged. Suppose one of the parameters changes from nominal, causing a corresponding shift in the controlled variable. We then say that a process load change has occurred.

Transient: Another type of change involves a temporary variation of one of the load parameters. After the excursion, the parameter returns to its nominal value. This variation is called a transient. A transient causes variations of the controlled variable, and the control system must make equally transient changes of the controlling variable

Process Lag:

At some point in time, a process-load change or transient causes a change in the controlled variable. The process-control loop responds to ensure that, some finite time later, the variable returns to the setpoint value. Part of this time is consumed by the process itself and is called the process lag.

Self-Regulation:

A significant characteristic of some processes is the tendency to adopt a specific value of the controlled variable for nominal load with no control operations. The control operations may be significantly affected by such self-regulation.

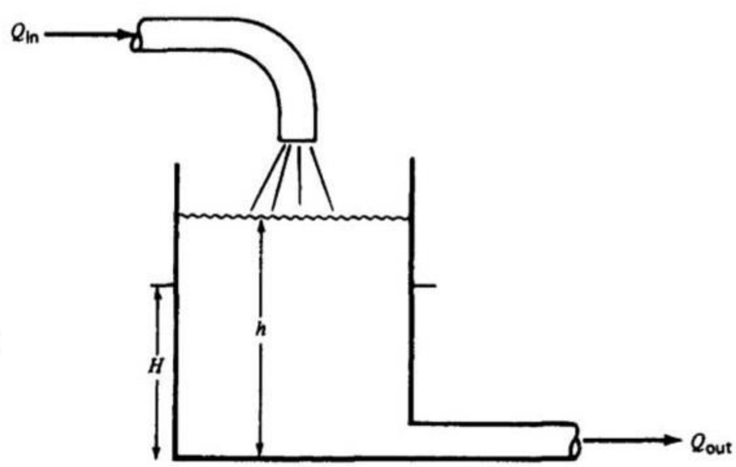


Figure: 2.2

The tank consists of an input pipeline where from water falls at a particular rate and it also has a output pipeline through which water is flowing at a particular flow rate. If the inflow rate just matches the outlet rate,then the liquid in the tank is fixed at some nominal level. If the inflow rate increases slightly, the level rises and at a certain level again level gets fixed as inflow rate again becomes equal to the outflow rate(As the water level height increases)

Others parameters are Process Quantity, Process Potential, Process Resistance, Process Capacitance

Lecture 11:

Role of controllers in process industry:

Process control systems make sure industrial processes are carried out efficiently, consistently and with as little variation as possible. They're installed in industrial settings to:

- help maintain throughput, quality, yield and energy efficiency
- make sure working practices are carried out safely and profitably

Systems measure, monitor and control manufacturing processes and activities. They identify and correct any abnormalities or variations from specified values, either manually or automatically. The aim is to make sure that production is consistent and that as little energy is wasted as possible.

Lower level controls can't handle complex situations like equipment faults. These have to be dealt with either manually, by an operator, or by other controls at a higher level of the hierarchy.

Benefits of an efficient process control system

Your business could benefit from a well-designed control system in many ways, including:

- energy savings - energy wastage is reduced when your plant and machinery are efficiently operated
- improved safety - control systems automatically warn you of any abnormalities which minimises the risk of accidents

- consistent product quality - variations in product quality are kept to a minimum and reduce your wastage
- lower manufacturing costs - detecting faults early means throughput, yield and quality are maintained
- improved environmental performance - systems can give an early warning of a rise in emissions

2.5 Modes of Control Action:

Controllers can be divided in –

i) Discontinuous Mode

ii) Continuous Mode

2.5.1 Discontinuous Mode of Controller:

ON/OFF/ Two position/Bang-Bang Controller:

The most common discontinuous controller mode is the ON/OFF controller.

The analytic equation can be written as

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

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 output is zero.

Neutral Zone: In virtually any practical implementation of the two-position controller, there is an overlap as increases through zero or decreases through zero. In this span, no change in controller output occurs. This is best shown in figure, which plots controller output versus error of a two-position controller. We see that until an increasing error changes by above zero, the controller output will not change state. In decreasing, it must fall below zero before the controller changes to the 0% rating. The range , which is referred to as the neutral zone or differential gap, is often purposely designed above a certain minimum quantity to prevent excessive cycling.

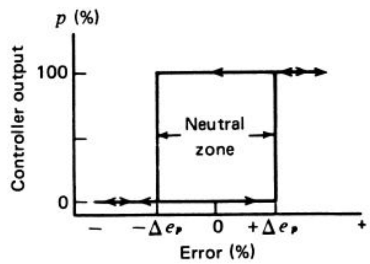


Figure: 2.3

<u>Multiposition Mode:</u>

To reduce the cycling behavior of the Two-position control mode, several intermediate settings of the controller output is introduced. This discontinuous control mode is used in an attempt also to reduce overshoot and undershoot of the two-position mode. This mode is represented by

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

Three position Controller can be represented by

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

Floating-Control Mode:

In floating control, the specific output of the controller is not uniquely determined by the error. If the error is zero, the output does not change but remains (floats) at whatever setting it was when the error went to zero.

Lecture 12:

Time Proportional Control:

In this control action the output of the controller is either 100%(ON) or 0% (OFF) like ON-OFF controller but the ON time or OFF time differs according to the error.

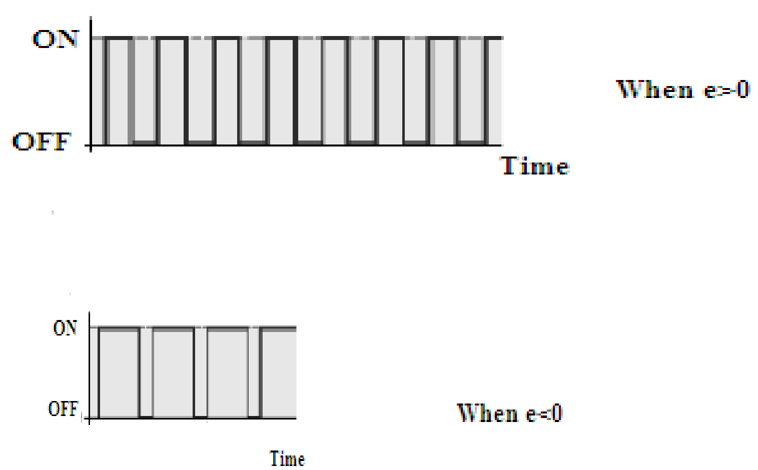


Figure2.4

2.5.2 Continuous Mode of Controller:

Proportional Control Mode:

In the proportional mode a smooth & linear relationship exists between the controller output and the error. Thus, over some range of errors about the setpoint, each value of error has a unique value of controller output in one-to-one correspondence. The range of error to cover the 0% to 100% controller output is called the proportional band, because the one-to-one correspondence exists only for errors in this range. This mode can be expressed by

$$p = K_P e_p + p_0$$

K_P = proportional gain between error and controller output (% per %)

P_0 = controller output with no error (%)

Proportional Band (PB): The range of error to cover the 0% to 100% controller output is called the proportional band. The proportional band is defined by the equation

PB =100/K_P

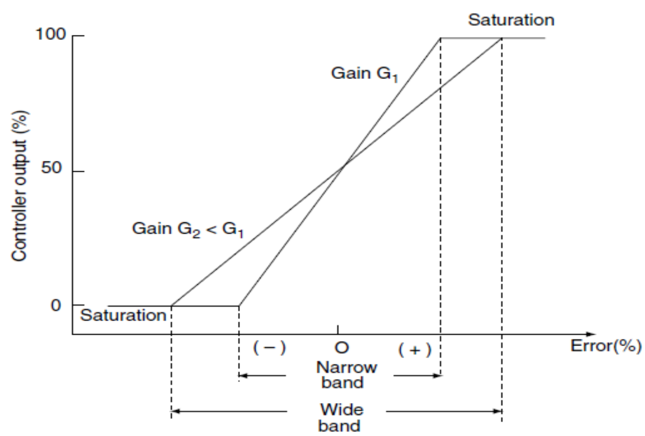


Figure: 2.5

Offset: An important characteristic & disadvantage of the proportional control 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, which also reduces the proportional band.

Application: Proportional control generally is used in processes where large load changes are unlikely or with moderate to small process lag times.

<u>Lecture 13:</u>

<u>Integral-Control Mode:</u>

The integral mode eliminates offset error by allowing the controller to adapt to changing external conditions by changing the zero-error output. Therefore, this mode is represented by an integral equation

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

Or, $$p(t) = K_I \int_0^t e_P \, dt + p(0)$$

Where, $p(0)$ is the controller output when the integral action starts. The gain expresses how much controller output in percent is needed for every percent-time accumulation of error.

Therefore, Integral action is provided by summing the error over time, multiplying that sum by a gain, and adding the result to the present controller output. If the error becomes positive or negative for an extended period of time, the integral action will begin to accumulate and make changes to the controller output.

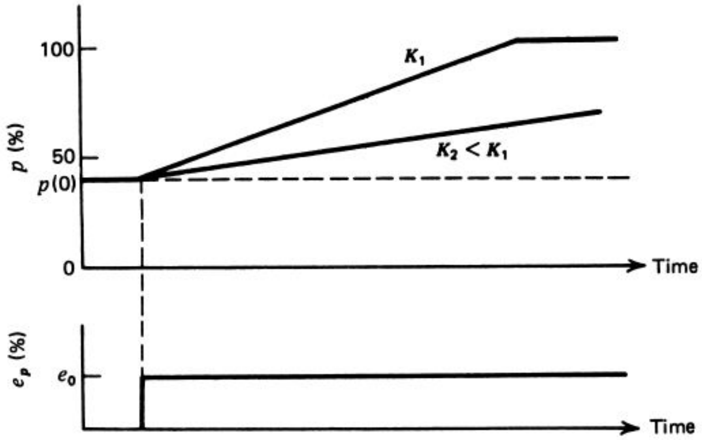


Figure:2.6

Integral time or Reset Time: The integral gain, is often represented by the inverse, which is called the integral time,or the reset time.

Integral Saturation: Integral Windup occurs when the integral controller reaches its limit and no more affecting the controlled system. In this case, the integral term continues accumulating and increasing the controller output.

Lecture 14

Derivative-Control Mode:

Derivation controller action responds to the rate at which the error is changing ,that is, the derivative of the error.This mode is represented by the expression

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

K_D = Derivative gain(how much percent to change the controller output for every percent-per-second rate of change of error)

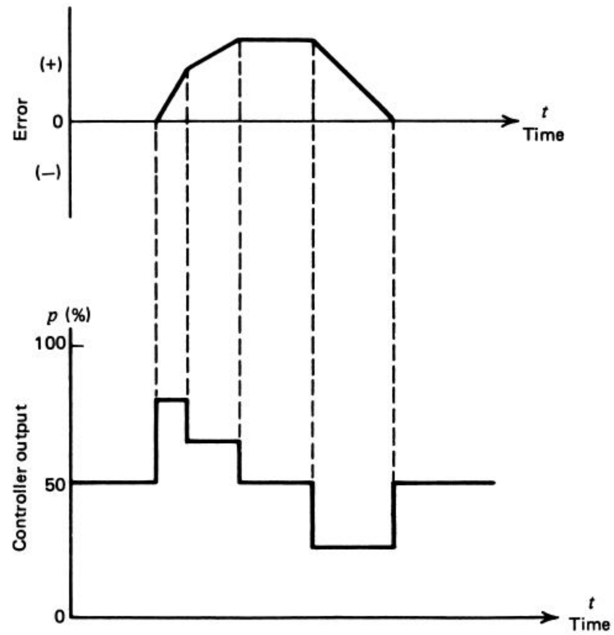


Figure:2.7

Derivative action is not used alone because it provides no output when the error is constant,which is not desirable. A small change in error will affect largely on controller's output. The high derivative gain will result in heavy overshoots and overall system's stability.

Derivative controller action is also called **rate action and anticipatory control.**

2.6 Composite Control Modes

It is possible to combine several basic modes to get advantages of each mode. Which is known as composite mode of controller.In some cases, an added advantage is that the modes tend to eliminate some limitations they individually possess. Commonly used Composite modes are-

Proportional-Integral Control (PI):

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

Where, $P_I(0)$ = integral term value when control action starts

$$p = K_P e_p + K_P K_I \int_0^t e_p \, dt + p_I(0)$$

The main advantage of this composite control mode is that the one-to-one correspondence of the proportional mode is available and the integral mode eliminates the inherent offset.

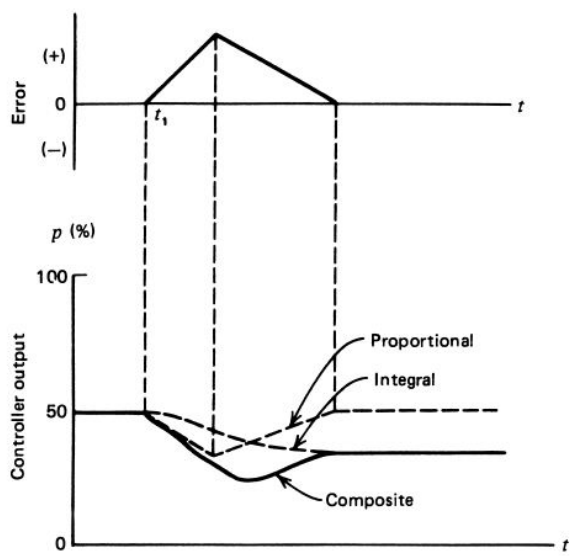


Figure:2.8

When the error is zero, the controller output 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 increase or decrease the accumulated value depending on the sign of the error and the direct or reverse action.

Lecture 15:

Proportional-Derivative Control Mode (PD):

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

$$p = K_P e_p + K_P K_D \frac{de_p}{dt} + p_0$$

This mode cannot eliminate the offset of proportional controllers. It can handle fast process load changes as long as the load change offset error is acceptable.

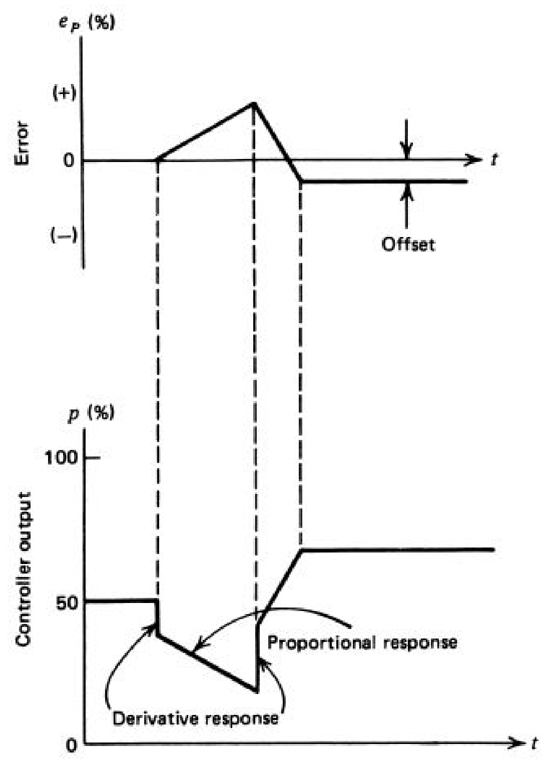


Figure:2.9

Three-Mode Controller (PID):

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

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

This mode eliminates the offset error of the proportional mode and still provides fast response.It comprises of all the advantages of all three modes as well as eliminates the disadvantages.

Lecture 16:

2.7 Electronic Controllers

In Electronic controller op amps are used as the primary circuit element. Discrete electronic components also are used to implement this function, but the basic principles are best illustrated using op amp circuits.

2.7.1 Error Detector

The detection of an error signal is accomplished in electronic controllers by taking the difference between voltages. One voltage is generated by the process signal current passed through a resistor. The second voltage represents the set point. This is usually generated by

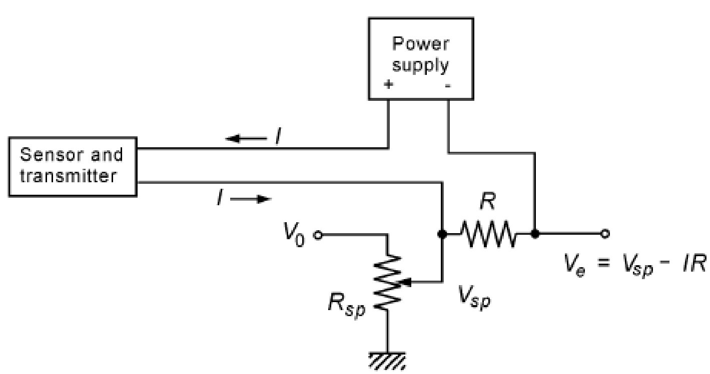


Figure:2.10

The current output from the sensor is used to produce a voltage, IR, across the resistor, R. This is placed in series opposition to the set point voltage(VSP), tapped from a variable resistor connected to a constant positive source . The result is an error voltage,which is then used in the process controller to calculate controller output.

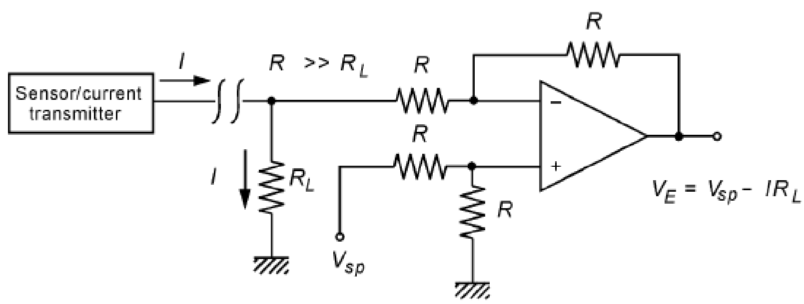


Figure:2.11

2.7.2 ON-OFF Controller:

A two-position controller can be implemented in different way. A method using op amp implementation of ON/OFF control with adjustable neutral zone is given in figure.

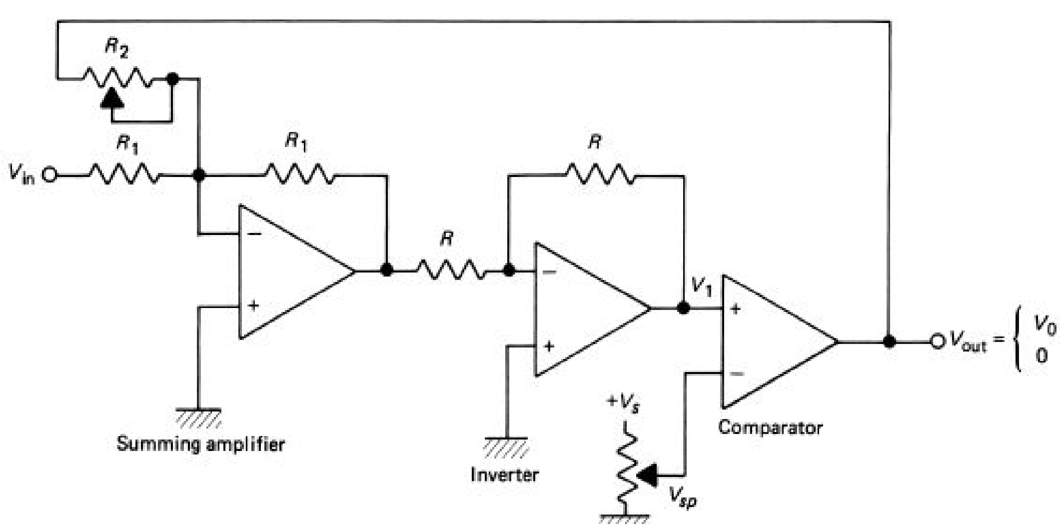


Figure:2.12

For this circuit, we assume that if the controller input voltage, in, reaches a value, then the comparator output should go to the ON state, which is defined as some voltage,VH . When the input voltage falls below a value VL, the comparator output should switch to the OFF state, which is defined as 0 V. The comparator output switches states when the voltage on its input,V1, is equal to the setpoint value,VSP . Analysis of this circuit shows that the high (ON) switch voltage is

VH = Vsp

and the low (OFF) switching voltage is

$$V_L = V_{sp} - \frac{R_1}{R_2} V_0$$

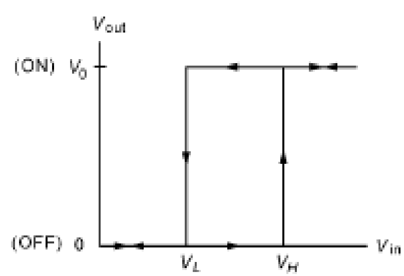


Figure:2.13

Lecture 17

2.7.3 Proportional Mode:

Implementation of this mode requires a circuit that has a response given by

$$p = K_P e_p + p_0$$

Where

P0 = controller output with no error

ep = error in percent of variable range

KP = proportional gain

Aanalog electronic equation for the output voltage is

Vout = GPVe + V0

Where, Vout = output voltage

Ve = error voltage

GP = R2/R1 = gain

V0 = output with zero error

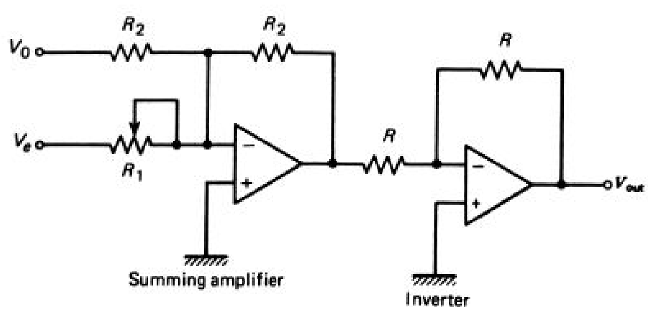


Figure:2.14

Problem: A controller is scaled so that 0–10 V corresponds to a 0–100% output. If and full-scale error range is 10 V, find the values of and to support a 20% proportional band about a 50% zero-error controller output.

R2 = 10 k_ V0 R1

The value of V0 is 50% of 10 V, or 5 V, to provide the zero-error controller output.

To design for a 20% proportional band means that a change of error of 20% must cause the controller output to vary 100%. Thus, from Vout = GPVe + V0

we note that when the error has changed 20% of 10 V, or 2 V, we must have full controller output change. Thus,

$$G_P = \frac{\Delta V_{\text{out}}}{\Delta V_e} = \frac{10}{2}$$
$$G_P = 5$$

so that if $R_2 = 10\ \text{k}\Omega$, then

$$R_1 = R_2/G_P = \mathbf{2\ k\Omega}$$

<u>Lecture 18</u>

<u>2.7.4 Integral Mode:</u>

The integral mode is represented by the equation

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

P(0) = controller output when control action starts

ep = deviations in percent of full-scale variable value

KI = integration gain (s-1)

p(t) = controller output in percent of full scale

This function is easy to implement when op amps are used as the building blocks.The corresponding equation relating input to output is

$$V_{out} = G_I \int_0^t V_e \, dt + V_{out}(0)$$

where
V_{out} = output voltage
$G_I = 1/RC$ = integration gain
V_e = error voltage
$V_{out}(0)$ = initial output voltage

The values of R and C can be adjusted to obtain the desired integration time. The initial

controller output is the integrator output at t=0 .

Electronic I controller:

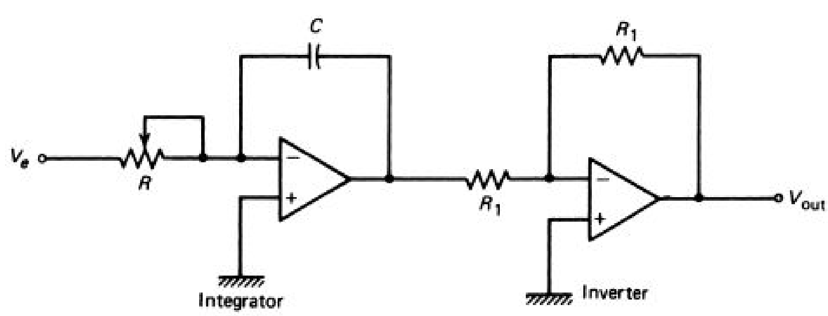


Figure:2.15

Lecture 19:

2.7.5 Derivative Mode:

The derivative mode is never used alone because it cannot provide a controller output when the error is zero. It is implemented with op amps so it can be combined with other modes. The control mode equation of derivative mode-

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

where p = controller output in percent of full output
K_D = derivative time constant (s)
e_p = error in percent of full-scale range

The above equation can be represented by

$$V_{out} = -RC \frac{dV_e}{dt}$$

From a practical perspective, this circuit cannot be used because it tends to be unstable, it may

begin to exhibit spontaneous oscillations in the output voltage. The reason for this instability is the very large gain at high frequencies where the derivative is very large.

In order to make a practical circuit, a modification is provided that essentially "clamps" the gain above some frequency to a constant value. The actual transfer function for this circuit can be shown to be given by

$$V_{out} + R_1 C \frac{dV_{out}}{dt} = -R_2 C \frac{dV_e}{dt}$$

Circuit can be implemented-

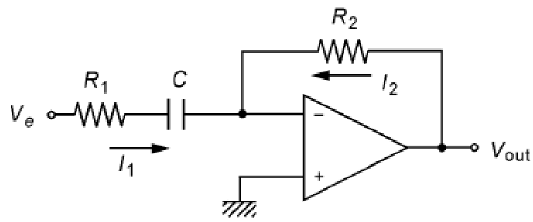


Figure:2.16

2.8 Composite Controller Modes

Composite modes are implemented easily using op amp techniques. Basically, this consists of simply combining the mode circuits introduced in the previous section.

2.8.1 Proportional-Integral Mode:

A simple combination of the proportional and integral circuits provides the proportional-integral mode of controller action.

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

The resulting circuit is shown in figure.

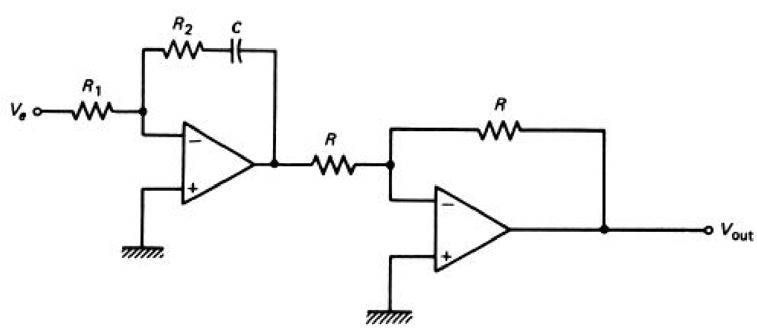


Figure:2.17

Problem: Design a proportional-integral controller with a proportional band of 30% and an integration gain of 0.1%/(%–s). The 4- to 20-mA input converts to a 0.4- to 2-V signal, and the output is to be 0–10 V. Calculate values of , Gp, GI, R2, R1 and C, respectively.

Answer: A proportional band of 30% means that when the input changes by 30% of range, or

0.48 V, the output must change by 100%, or 10 V. This gives a gain of

Gp =R2/R1 =10 V/0.48 = 20.83

A of 0.1%/(% – s) says that a 1% error for 1 s should produce an output change of 0.1%.One

percent of 2.6 V is 0.016 V, and 0.1% of 10 V is 0.01 V, so

GI =1/R2C =0.01/0.016 = 0.625 s-1

Or R2C= 2.6 s

Consider any value of C and find R2 .From the value of GP find value of R1 using the value of R2.

Lecture 20:

2.8.2 Proportional-Derivative Mode:

A powerful combination of controller modes is the proportional and derivative modes. This combination is implemented using the circuit

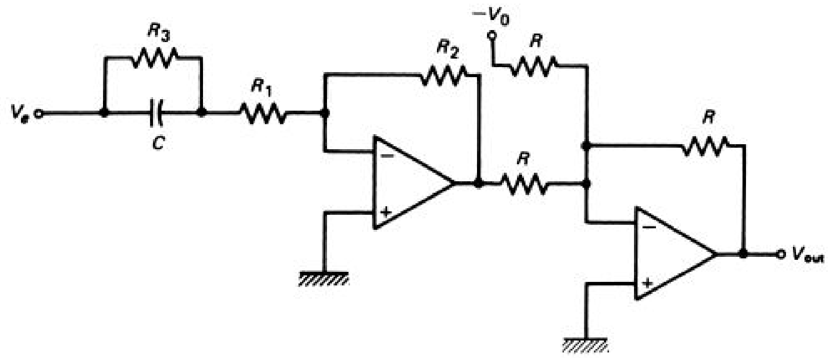


Figure:2.18

$$V_{\text{out}} + \left(\frac{R_1}{R_1 + R_3}\right) R_3 C \frac{dV_{\text{out}}}{dt} = \left(\frac{R_2}{R_1 + R_3}\right) V_e + \left(\frac{R_2}{R_1 + R_3}\right) R_3 C \frac{dV_e}{dt} + V_0$$

The output of the circuit is-

Or,

$$V_{\text{out}} = \left(\frac{R_2}{R_1 + R_3}\right) V_e + \left(\frac{R_2}{R_1 + R_3}\right) R_3 C \frac{dV_e}{dt} + V_0$$

Where, $\left(\frac{R_1}{R_1 + R_3}\right) R_3 C \frac{dV_{\text{out}}}{dt}$ is used to clamp the output.

So, the resulted output relates with the PD controller equation

$$p = K_P e_p + K_P K_D \frac{de_p}{dt} + p_0$$

Problem:A proportional-derivative controller has a 0.4- to 2.0-V input measurement range, a 0 to 5V output, Kp = 5%/% , and KD = 0.08%per (%/min). The period of the fastest expected signal change is 2.5 s. Implement this controller with an op amp circuit.

2.8.3 Proportional-Integral-Derivative Mode:

The ultimate process controller is the one that exhibits proportional, integral, and derivative response to the process-error input. This mode is characterized by the equation

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

This equation can be represented by

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

This can be implemented

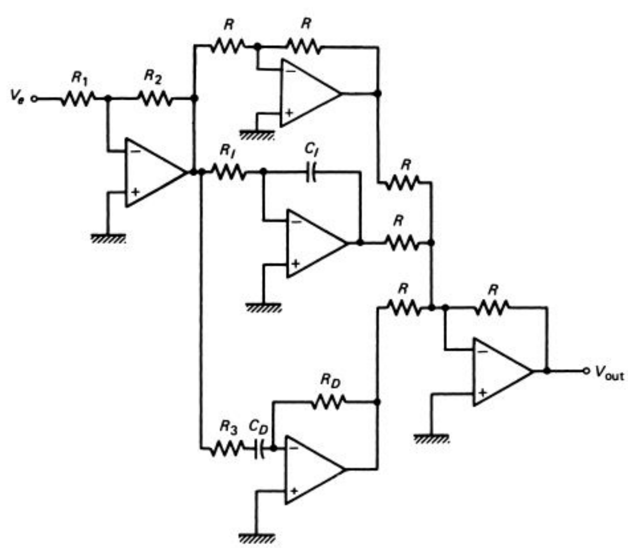


Figure:2.19

Lecture 21:

2.9 Pneumatic Controllers:

The pneumatic controller is based on the nozzle/flapper as the basic mechanism of operation, much as the op amp is used in electronics.

Proportional Controller:

A proportional mode of operation can be achieved with the system shown in figure .If the input pressure increases, then the input bellows forces the flapper to rotate to close off the nozzle. When this happens, the output pressure increases so that the feedback bellows exerts a force to balance that of the input bellows. A balance condition then occurs when torques exerted by each about the pivot are equal, or

$$(p_{out} - p_0)A_2x_2 = (p_{in} - p_{sp})A_1x_1$$

This equation is solved to find the output pressure

$$p_{out} = \frac{x_1}{x_2}\frac{A_1}{A_2}(p_{in} - p_{sp}) + p_0$$

Where,

P = pressure with no error

psp = setpoint pressure

x2 = feedback lever arm (m)

A2 = feedback bellows effective area (m2)

pout = output pressure (Pa)

x1 = level arm of input (m)

A1 = input and setpoint bellows effective area (m2)

pin = input pressure (Pa)

Where, $K_p = \left(\frac{x_1}{x_2}\right)\left(\frac{A_1}{A_2}\right)$

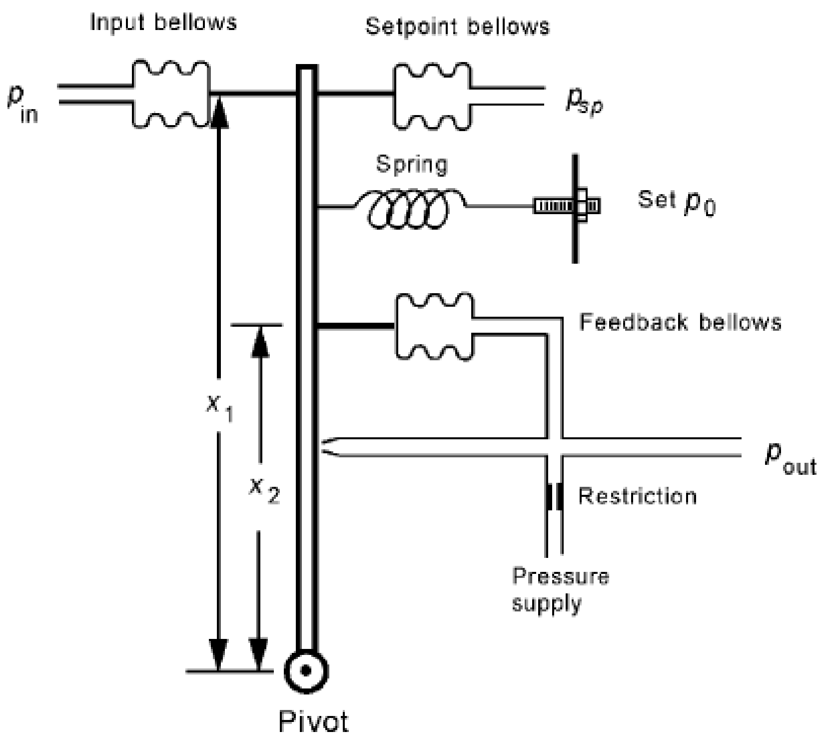


Figure:2.20

Lecture 22:

2.9.2 Proportional-Integral

This control mode is also implemented using pneumatics by the system shown in figure. In this case, an extra bellows with a variable restriction is added to the proportional system. Suppose the input pressure shows a sudden increase. This drives the flapper toward the nozzle, increasing output pressure until the proportional bellows balances the input as in the previous case. The integral bellows is still at the original output pressure, because the restriction prevents pressure changes from being transmitted immediately. As the increased pressure on the output bleeds through the restriction, the integral bellows slowly moves the flapper closer to the nozzle, thereby causing a steady increase in output pressure (as dictated by the integral mode). The variable restriction allows for variation of the leakage rate, and hence the integration time.

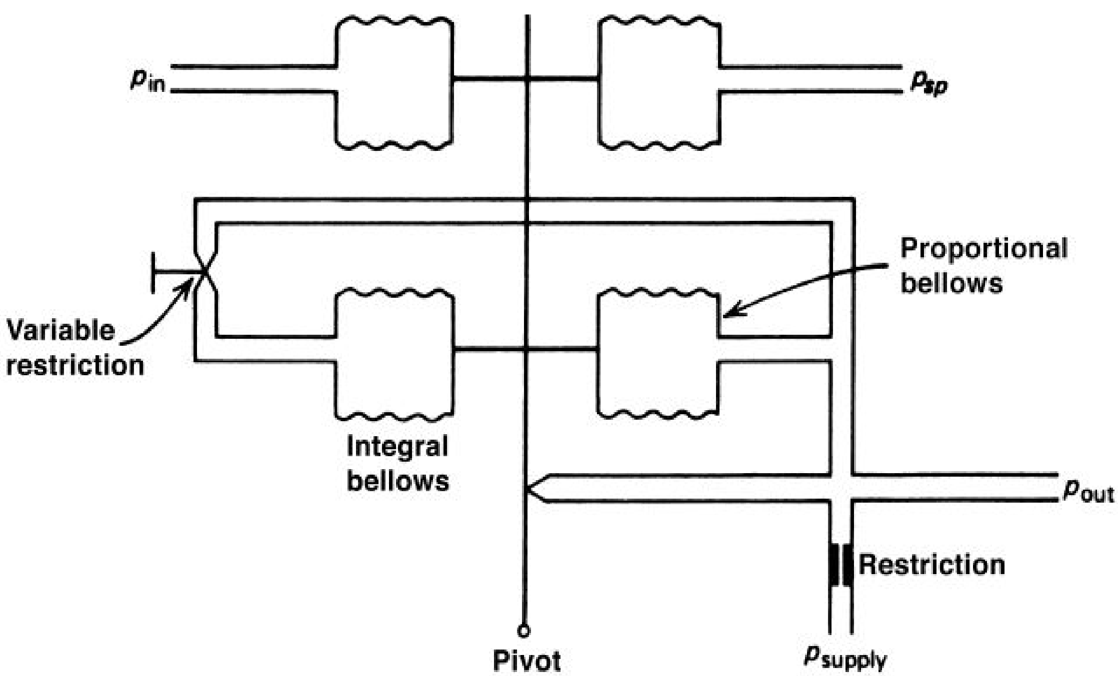


Figure:2.21

2.9.3 Proportional-Derivative

This controller action can be accomplished pneumatically by the method shown in figure. A variable restriction is placed on the line leading to the balance bellows. Thus, as the input pressure increases, the flapper is moved toward the nozzle with no impedance, because the restrictions prevent an immediate response of the balance bellows. Thus, the output pressure rises very fast and then, as the increased pressure leaks into the balance bellows, decreases as the balance bellows moves the flapper back away from the nozzle. Adjustment of the variable restriction allows for changing the derivative time constraint.

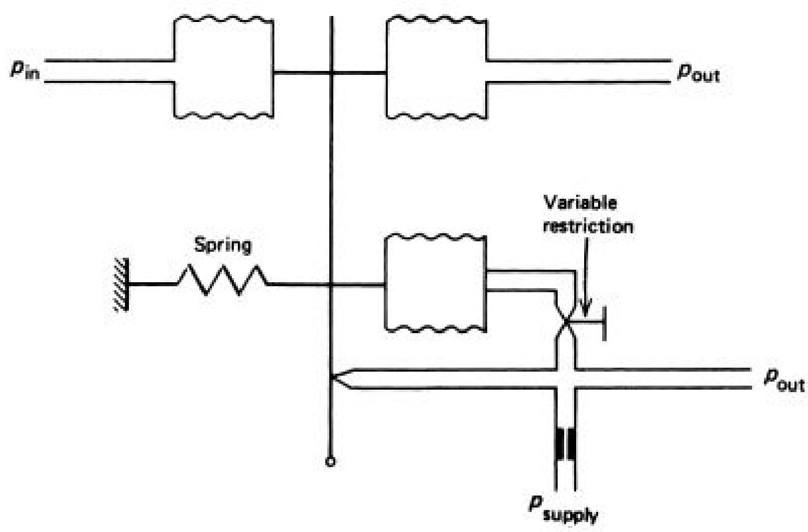


Figure:2.22

Lecture 23

2.9.4 Proportional-Integral-Derivative Controller

The three-mode controller is actually the most common type produced, because it can be used to accomplish any of the previous modes by setting of restrictions. This is simply a combination of the three systems presented. By opening or closing restrictions, the three-mode controller can be used to implement the other composite modes. Proportional gain, reset time, and rate are set by adjustment of bellows separation and restriction size.

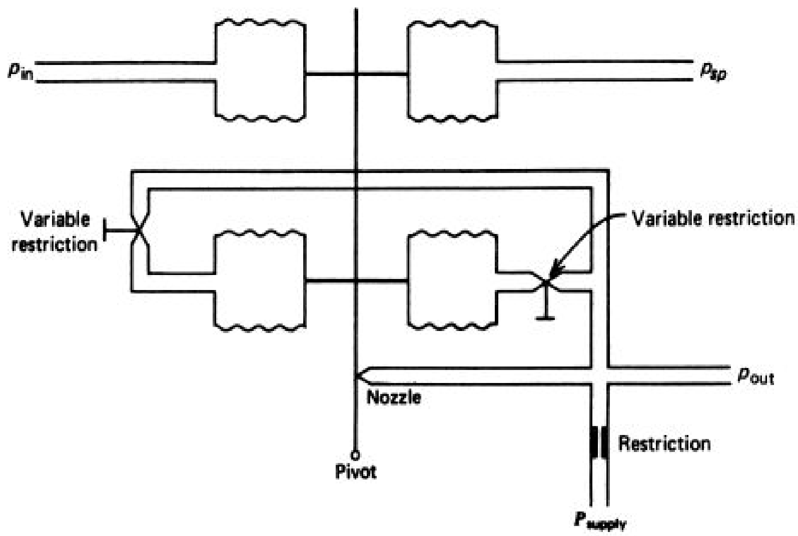


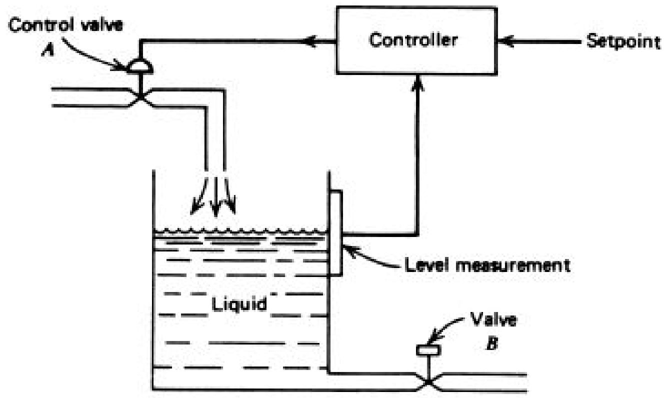
Figure:2.23

Sample Questions:

2. The temperature of water in a tank is controlled by a two-position controller. When heater is off the temperature drops at 2 K per minute. When the heater is on the temperature rises at 4 K per minute. The set point is 323 K and the neutral zone is +4% to -4%of the set point. There is a 0.5-min lag at both the on and off switch points. Find the period of oscillation and plot the water temperature versus time.

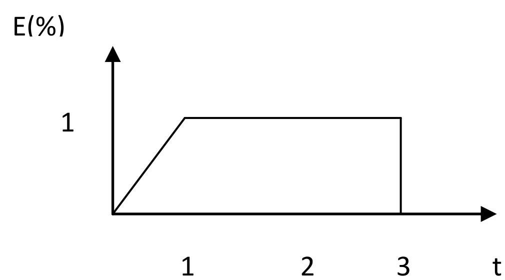
2. Consider the proportional-mode level-control system of figure. Valve *A* is linear, with a flow scale factor of 10 m^3/h per percent controller output. The controller output is nominally

50% with a constant of K_P = 10% per %. A load change occurs when flow through valve *B* changes from 500 m^3/h to 600 m^3/h. Calculate the new controller output and offset error.



3. Atemperature controller controls temperature from 100° to 200°C. Asensor provides an output of 2 to 8 V for this temperature range. The controller output drives a heater with an output of 0 to 5 volts. What circuit gain is needed if the controller of is to be used with a proportional gain of 4%/%?

4. Plot the graph of a PI controller output as a function time. The error to the controller is shown in fig. Kp=5, KI=2.0 s-1, PI(0)=20%. 5



5. What is 'Neutral zone'? In which controller it occurs?

6. Draw the basic block diagram of a process control loop and explain the blocks in it. 5

7. Draw and explain the working principle of Electronic ON-OFF controller

Lecture 24:

3.1 Final Control Element: Actuators

A valve actuator is a device that produces force to open or close the valve utilizing a power source. This source of power can be manual (hand, gear, chain-wheel, lever, etc.) or can be electric, hydraulic or pneumatic. Basic actuators turn valves to either fully opened or fully closed positions. But modern actuators have much more advanced capabilities. They not only act as devices for opening and closing valves, but also provide intermediate position with high degree of accuracy. The valve actuator can be packaged together with logic control and digital communication ability to allow remote operation as well as allowing predictive maintenance data.

Figure. 3.1: Control Valve with Actuators

3.1.1 Type of Actuators:

- Pneumatic Actuators
- Electric Actuators
- Hydraulic Actuators

But Pneumatic and Electric Actuators are most commonly used.

Pneumatic: Pneumatic actuators utilize an air signal from an external control device to create a control action via a solenoid. These are commonly available in two main forms: piston actuators and diaphragm actuators.

Electric:

Electric actuators are motor driven devices that utilize an electrical input signal to generate a motor shaft rotation. This rotation is, in turn, translated by the unit's linkage into a linear motion, which drives the valve stem and plug assembly for flow modulation. In case of electric signal failure, these actuators can be specified to fail in the stem-out, stem-in, or last position. Commonly used motors for electric actuators include steppers and servos.

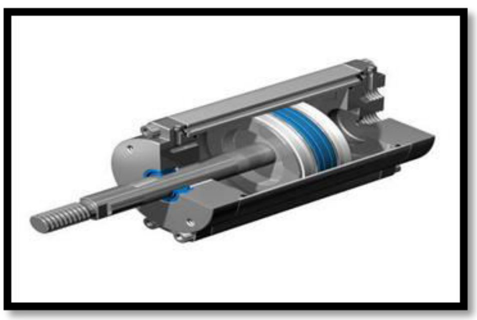


Figure.: 3.2: Pneumatic Actuator

Figure.: 3.3: Electric Actuator

Difference between Pneumatic and Electric Actuators:

The major difference between pneumatic and electronic actuators is the speed of operation.The two technologies are so different that one cannot be a drop-in replacement for the other.Each has inherent advantages and disadvantages.

Advantages of Pneumatic Actuators:

- The biggest advantage of the pneumatic actuators is their failsafe action. By design ofthe compressed spring, the engineer can determine if the valve will fail closed oropen, depending on the safety of the process.

- Provide high force and speed, which are easily adjustable and are independent ofeach other
- Have a delayed response which makes them ideal for being resilient against smallupsets in pressure changes of the source.
- Most economical when the scale of deployment matches the capacity of thecompressor.
- Provide inherent safety and are ideal for hazardous and explosive environment.

Limitations of Pneumatic Actuators:

- Maintenance and operating costs can be high, especially if a serious effort has notbeen made to quantify and minimize the costs. Maintenance costs includereplacement cylinder costs and plugging air-line leakages whereas the operatingcosts include the cost of compressed air, i.e. electricity for the compressor.

Advantages of Electric actuators:

- Provide precise control and positioning in comparison to pneumatic actuators.
- Response time is essentially instantaneous.
- High degree of stability.
- Help adapt machines to flexible processes.
- Low operating cost. Controllers and drivers low voltage circuitry consume power to afar lesser degree.

Limitations of Electric Actuators:

- The primary disadvantage of an electric actuator is that, should a power failure occur,the valve remains in the last position and the fail-safe position cannot be obtainedeasily unless there is a convenient source of stored electrical energy.
- Higher cost than pneumatic actuators.

- The actuator needs to be in an environment that is rendered safe. Generally notrecommended for flammable atmospheres.

Lecture 25

3.2Control Valves

The control action in any control loop system is executed by the final control element. The most common type of final control element used in chemical and other process control is the control valve. A control valve is normally driven by a diaphragm type pneumatic actuator that throttles the flow of the manipulating variable for obtaining the desired control action. A control valve essentially consists of a plug and a stem. The stem can be raised or lowered by air pressure and the plug changes the effective area of an orifice in the flow path. When the air pressure increases, the downward force of the diaphragm moves the stem downward against the spring. So, valve is a mechanical device that controls the flow and pressure of fluid within a system or Process. So basically, it controls flow & pressure.Final control elements are necessary to control the Process variable. Valves are used to control the flow of fluid in process system.

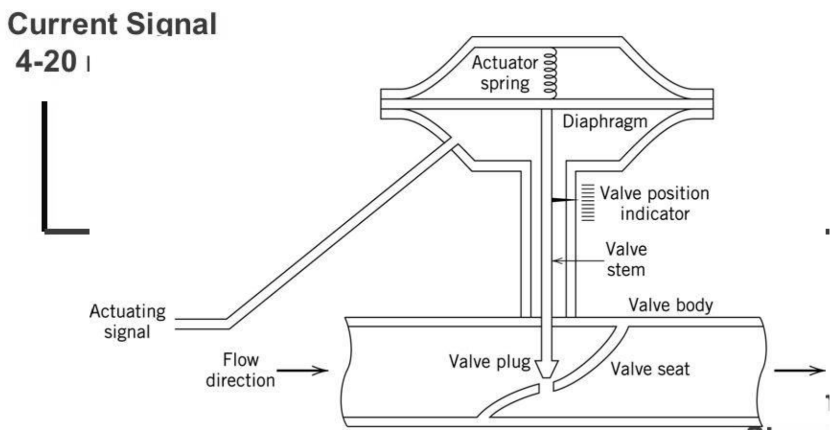


Figure.: 3.4

Different Parts of Control valve

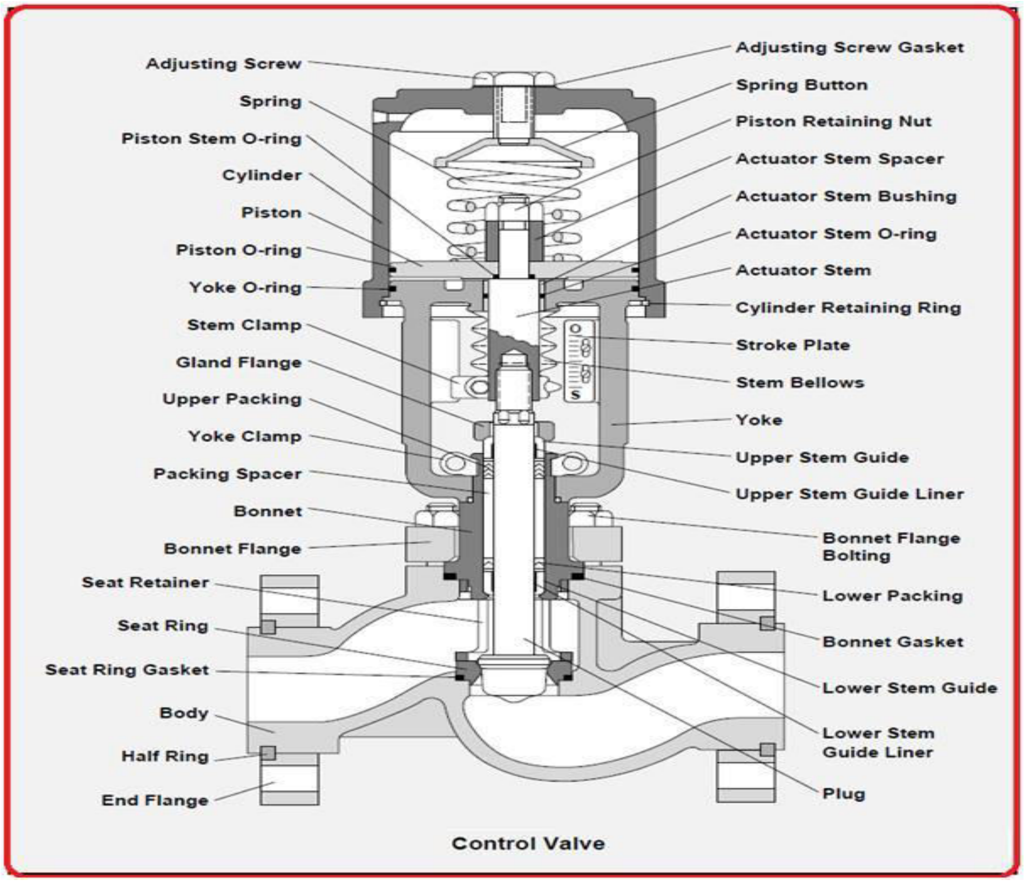


Figure. 3.5: Detailed Diagram Of Control Valve

- **DIAPHRAGM CASE-**Use to enclose the diaphragm to form a pressure chamber, one above the diaphragm and one at the bottom of the diaphragm. The sealing surfaces of the slope away from the diaphragm at the outer edge to insure a pressure tight seal inside the bolt circle at the inner edge.
- **DIAPHRAGM-**A flexible piece of material that flexes in response to the pneumatic signal from the controller. The moulded diaphragm in combination with deep diaphragm case provides a remarkably constant effective area throughout the valve travel.
- **DIAPHRAGM PLATE-**A metal plate that fits the moulded diaphragm and transmit the diaphragm force to the stem.

- **ACTUATOR SPRING-**Opposes the air pressure force on the diaphragm to control the movement of the actuator. It also pushes the actuator to back up to original position when air pressure fails.
- **ACTUATOR STEM-**A metal rod that connects the diaphragm plate to the valve stem.

- **SPRING SEAT-**A piece of metal that holds the actuator spring in position.

- **SPRING ADJUSTER-**A hexagon heads adjuster and is easily accessible to adjust the compression of the actuator spring. Adjusting the tension of the actuator spring will determine the initial movement of the actuator when pneumatic signal is applied.

- **YOKE-**A structure by which the diaphragm case or cylinder assembly is supported rigidly on the bonnet assembly.

- **STEAM CONNECTOR-**Is a split nut threaded to engage the actuator on one end and the valve stem on the other end. The two halves are bolted together to provide a connection that prevents loosening due to torque reactions of valve stem.
- **TRAVEL INDICATOR-**The travel indicator is a stainless steel with its edges cupped downward to add rigidity and also provide a definite position reference.
- **TRAVEL INDICATOR SCALE-**A graduated scale attached to the yoke for indication of valve travel.
- **VALVE STEM-**A rod connected to the actuator stem and extended through the bonnet assembly to permit positioning the valve plug.

- **YOKE LOCK NUT-**Is a rugged lock nut use to fastened the actuator and the valve body. The arrangement of fastening the two parts provide the correct alignment of actuator and body plus adequate strength.
- **PACKING FLANGE-**Use to hold the packing material inside the packing box.
- **PACKING FOLLOWER-**Use to guide and compress the packing material through the bonnet hole.
- **PACKING -** Use to provide seal and prevent leaks through the bonnet hole.To know more about stem packing
- **PACKING BOX-**Enclosed the sealing components where the valve stem enters the bonnet or valve body.
- **BONNET -**The bonnet enclosed the valve plug in the valve body.
- **VALVE PLUG -**A movable part which provides a variable opening in a port.
- **SEAT RING-**Comes in contact with the valve plug to seal the valve tight during close position.
- **VALVE BODY-**A housing for internal parts having inlet and outlet flow connections. The term valve body or even just body, frequently is used in referring to the valve body together with its bonnet assembly and included trim parts. More properly this group of components should be called the valve body assembly.

Lecture 26

3.2.1 Classifications of Control Valves:

Control valves are available in different types and shapes. They can be classified in different ways; based on: (a) action, (b) number of plugs, and (c) flow characteristics.

3.2.2 Valve Characteristics:

The control valve characteristics refers to the relationship between the volumetric flowrate F (Y-axis) through the valve & the valve travel or opening position m (Xaxis), as the valve is opened from its closed position to various degree of opening.

There are three most common control valve characteristics viz Linear, Equal % and Quick-Opening.

a) A control valve is labelled LINEAR if its inherent flow characteristics can be represented by a straight line on a rectangular plot of flowrate F (or % F, or Cv or % Cv) versus % travel m at the ideal condition of constant valve pressure drop.

b) A control valve is said to be EQUAL % if equal increment of valve travel or opening m (or Z) produces equal PERCENT (%) increment in flow F. If this occurs at the ideal condition of constant valve pressure drop , the valve is said to be inherently EQUAL %.

c) The Quick-Opening characteristic control valve has a flat disk instead of a contoured valve plug. Its flow (or Cv) increase rapidly to its maximum flow with minimum initial valve opening.

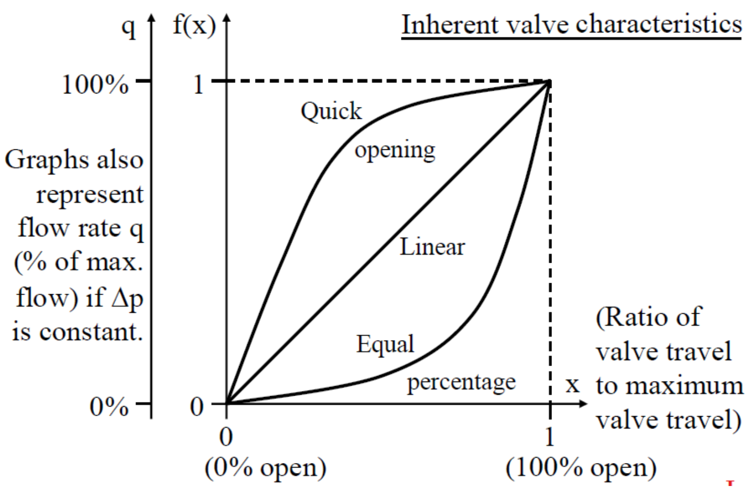


Figure.: 3.6

3.2.3 Valve Size (Capacity):

Valves are sized according to their Cv value. For liquid service, the equation for Cv is:

$$C_v = \text{flow}\sqrt{\frac{\text{specific gravity at flowing temperature}}{\text{pressure drop}}}$$

$$Cv=\sqrt{\left(\frac{S}{\Delta P}\right)}$$

The required flow and pressure drop information used to size a valve is based on the process operations and equipment. Once the Cv value is known, the rated* Cv can be determined from the manufacturer's data books. A general guideline is that valves should be sized so that maximum flow is obtained at about 90% valve open. Valves should be able to provide normal flow condition at around 60% to 70% of the travel. Valve should provide minimum flow when about 10% open. The control valve need not be of the same size as the pipe. It is better to make an error in under sizing a control valve than to oversize it.

As a good engineering practice, the rated Cv of the valve shall be in accordance with following criteria:

If normal flow is specified:

• Calculated Cv – Based on the normal flow
• Selected Cv – Based on 2.4 x normal flow

If maximum flow is specified but is equal to or less than 2.4 x normal flow

• Calculated Cv – based on normal flow
• Selected Cv – based on 2.5 x normal flow

When maximum flow is specified but is greater than 2.4 x normal flow

• Calculated Cv – Based on normal flow
• Selected Cv – Based on 2.1 x maximum flow

Lecture 27

3.2.4 Single Seated Valve

Only one plug is present in the control valve, so it is single seated valve. The advantage of this type of valve is that, it can be fully closed and flow variation from 0 to 100% can be achieved. But looking at its construction, due to the pressure drop across the orifice a large upward force is present in the orifice area, and as a result, the force required moving the valve against this upward thrust is also large. Thus this type of valves is more suitable for small flow rates.

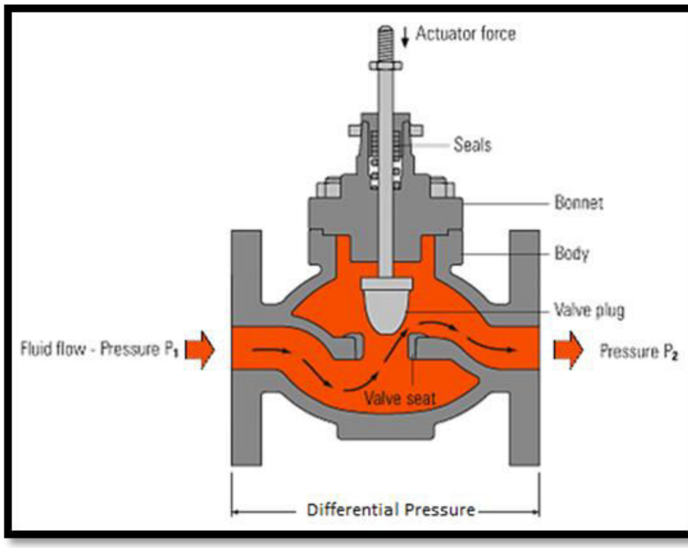
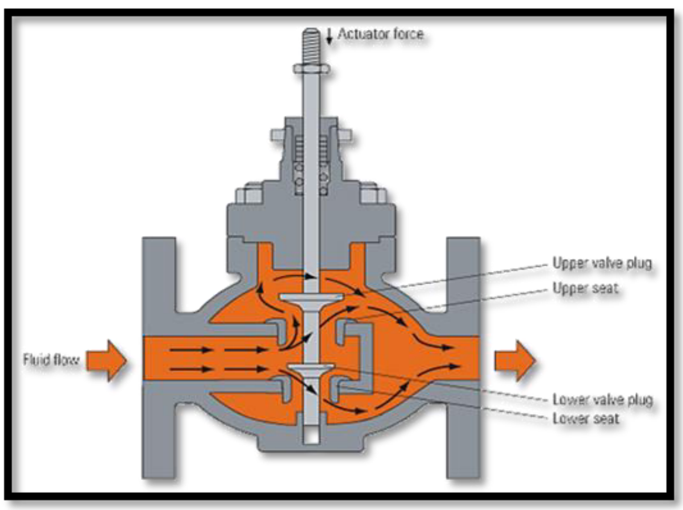


Figure.3.7: Single Seated Valve

3.6.5 Double Seated Valve:



There are two plugs in a double-seated valve; flow moves upward in one orifice area, and downward in the other orifice. The resultant upward or downward thrust is almost zero. As a result, the force required to move a double-seated valve is comparatively much less. But the double-seated valve suffers from one disadvantage. The flow cannot be shut off completely, because of the differential temperature expansion of the stem and the valve seat. If one plug is tightly closed, there is

Figure.3.8: Double Seated Valve

usually a small gap between the other plug and its seat. Thus, single-seated valves are recommended for when the valves are required to be shut off completely. But there are many processes, where the valve used is not expected to operate near shut off position. For this condition, double-seated valves are recommended.

3.2.5 Valve selection:

To decide what type of valve will be used for a given process characteristic;

- Never use a valve that is less than half the pipe size;
- Avoid using the lower 10% and upper 20% of the valve stroke. The valve is much easier to control in the 10 to 80% stroke range.
- There are 5 main parameters to consider when selecting a valve:
  - Cv
  - media compatibility
  - pressure
  - temperature
  - process fitting

Lecture 28

3.2.6 Cavitation:

Cavitation is the formation and collapse of vapor bubbles (cavities) in the liquid flow streams caused by changes in pressure and velocity. There are four primary negative side effects of uncontrolled cavitation in control valves: high noise, excessive vibration, material damage, and deterioration of flow effectiveness. Physical damage to valve trim is usually characterized by a pitted, rough appearance.

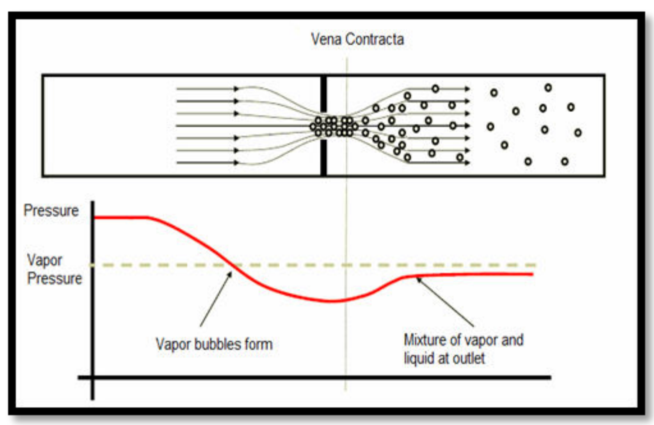


Figure. 3.9: Cavitation Effect

Flashing:

At the point where the fluid's velocity is at its highest, the pressure is at its lowest. Assuming the fluid is incompressible (liquid), if the pressure falls below the liquid's vapor pressure, vapor bubbles form within the valve and collapse into themselves as the pressure increases downstream. This leads to massive shock waves that are noisy and will certainly ruin the equipment.

Requirements for occurrence of flashing:

- The fluid at the inlet must be in all-liquid condition, but some vapor must be present at the valve outlet;
- The fluid at the inlet may be in either a saturated or a subcooled condition; and
- The valve outlet pressure must be either at or below the vapor pressure of the liquid.
- Flashing effects
- Material damage is associated with the formation of sand-blasted surfaces;
- Decreased efficiency - valve ability to convert pressure drop across the valve into mass flowrate is compromised.

Flashing cannot be eliminated in the valve if the downstream pressure is less than the vapor pressure of liquid. However, the damage can be minimized by:

- Hard face trim (using hard facing materials such as Satellite or Tungsten Carbide), more erosion resistant body material.
- Increasing size of the valve, therefore reducing the velocity
- Using angle valve – flow over plug

<u>Noise:</u>

Valve components will tend to vibrate whenever they are subjected to high velocity turbulent flow. Standard control valves will therefore tend to be noisy on high pressure drop applications particularly where flow rates are high, since the low pressure experienced downstream of the seat ring (at the vena contracta) is accompanied by very high velocities reaching as high as the speed of sound. If noise level is less than 100 dBA, the most economical way to reduce noise wouldbe to use some form of path treatment such as insulation, heavier walled pipe, or a silencer. Noise level greater than 100 dBA may create dangerous pipe vibration. Path treatment alone is not likely to be effective, so some form of source treatment (such as labyrinth plugs or multi-step angle valves or using some flow restrictor in series with the valve) is needed.

Lecture 29

3.2.7 Control Valve Accessories:

Control valves alone cannot achieve the purpose, there are many accessories used to work with the control valve to accomplish the task, help to ensure accuracy, There are different types of accessories used for control valves:

1. Valve positioners are devices used to put the valve in the correct position by increasing or decreasing the air load pressure on the actuator. A positioner is a motion-control device designed to actively compare stem position against the control signal, adjusting pressure to the actuator diaphragm or piston until the correct stem position is reached. A properly functioning positioner ensures the control valve will be "well-behaved" and obedient to the command signal.

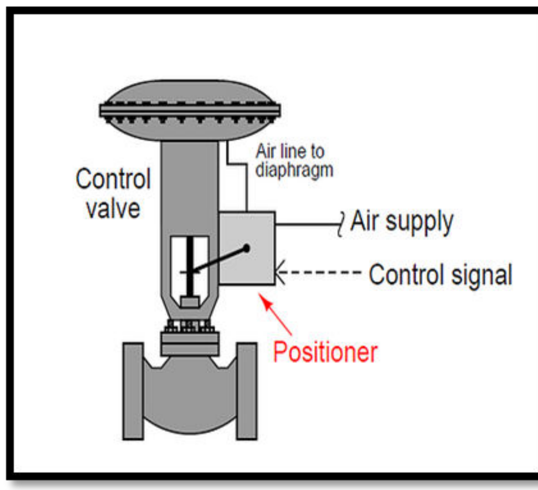


Figure. 3.10: Valve Positioner

2. **Current to pressure converter (I/P)** are device which converts incident current signal into a corresponding standard pressure signal.An I/P converter in common convert a 4-20mA current signal to 3-15 Psi pneumatic signal that a pneumatic positioner can interpret and send to the control valve. The air supply for the I/P converter must be approximately 20 psi so that the converter can control the pressure between 3-15 psi. I/P converters are electrical devices, so plant personnel must choose one that has the appropriate electrical characteristics and certifications for the zone in which it will be installed.

3. **Limit switches** are an indicator, which indicates when a specific position is reached. Limit switches are used most often to indicate the fully open or fully closed position but can be set at intermediate points if desired. A limit switch also can be connected with alarm or indicator light. The switch can be connected to any safety circuits. A non-conducting electromagnetic system triggers when a position is reached to activate internal contact of a circuit. Each switch adjusts individually and can be supplied for either alternating current or direct current systems.

Figure. 3.11: Limit Switch

4. A **volume booster** amplifies the air flow, which is a mechanical relay. Every pneumatic instrumentassociated with the control valve has a limit of flow capacity. For pneumatic actuator, volume booster works

as a relay between a system with low flow volume and one with high flow volume. Volume boosters used on control valves are normally applied with a bypass or gain adjustment to provide stability. The volume booster normally has a built-in deadband where a certain amount of signal change is necessary to activate the volume booster. Figure. 3.12: Volume Booster

5. The position transmitter senses the valve stem position continuously and the position is feed backed to the control system. And the position is compared with the desired position and gives a proper control action by the processor. The position transmitter is an electrical device. There are, however, no contact switches. Instead, a position sensor is used to follow the valve posi amplification circuit, which then provides the transmitter output, the position transmitter produce a signal in range 4-20mA.

Fig. 3.12: Position Transmitter

Air Filter Regulator:

Air Filters are used to remove liquid water and particulate matter from compressed air sources. These are ‘mechanical filters’ and do not remove oil vapours or chemical contaminants in vapour form. Air Filters are characterized by the flow capabilities, the micron size of the filter media and the media type; screen, sintered plastic or metal or other material. Filters will accumulate debris and must be cleaned and the media replaced on a regular basis. The service life of the media is generally based on no more than a 5 psig pressure

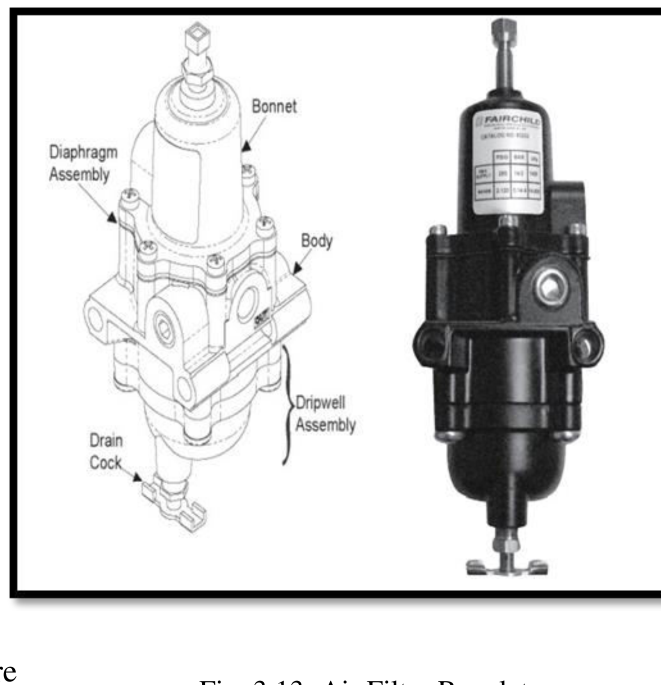
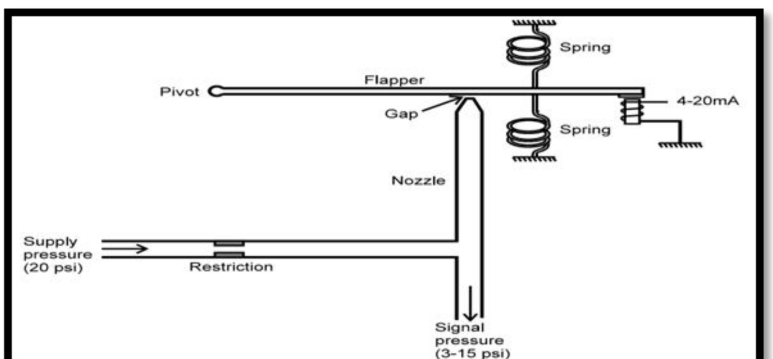


Fig. 3.13: Air Filter Regulator

drop across the device.

I/P Converter:

I/P Transducer accept an electrical input signal and produce a proportional pneumatic output. In this session we are going to discuss about how I/P transducer works. The Flapper of the Flapper-Nozzle instrument is connected to Pivot so that it can move up and down and a magnetic material was attached to other end of flapper and it is kept near the electromagnet.



Principles of a current-to-pressure converter

Figure. 3.14: I/P converter

As the magnet gets activated.the flapper moves towards the electromagnet and the nozzle gets closed to some extent. So the some part of 20 P.S.I supplied will escape through nozzle and remaining pressure will come as output. If the current signal is high, then power of the magnet will increase, then flapper will move closer to the nozzle, so less pressure will escape through nozzle and output pressure increases.

Lecture 30:

3.3 Feed forward control

If a measured disturbance enters a process, the control input can be adjusted to compensate for effect of the disturbance on the output. Perfect compensation would cause the controlled output to show no deviations from its set-point even as a disturbance has entered the process. This compensation to mitigate the transient effect of a measured disturbance on the controlled output is referred to as feed-forward control. A very simple example of feed-forward control is driving a car. Adjusting the hot and cold water knobs for the right temperature water from the shower is an example of feedback control.

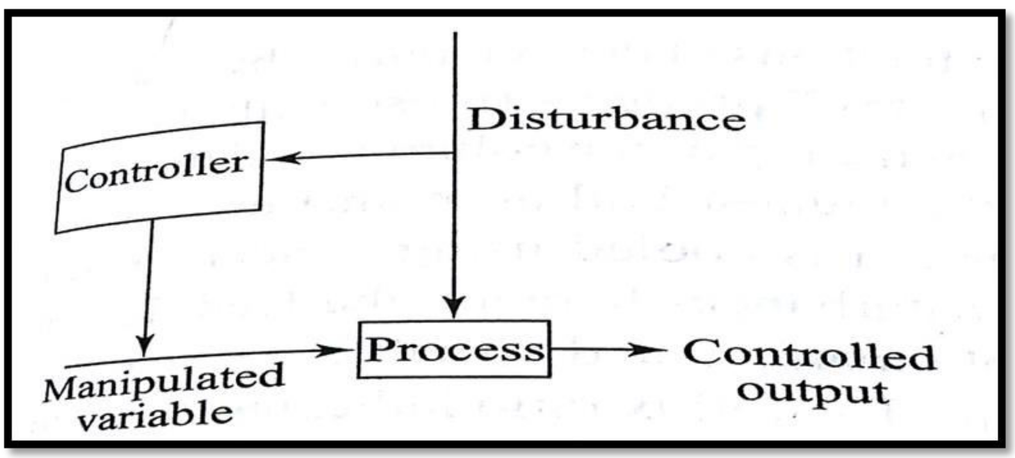
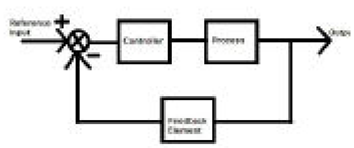


Figure. 3.15: Block diagram of feed forward control

Comparison between feedback and feed forward control system:

Sr. no	Point of Difference	Feedback control system	Feed Forward Control system

Sr. no	Point of Difference	Feedback control system	Feed Forward Control system
1	Definition	Systems in which corrective action is taken after disturbances affect the output	Systems in which corrective action is taken before disturbances affect the output
2	Necessary requirement	Not required	Measurable Disturbance or noise
3	Corrective action	Corrective action taken after the disturbance occurs on the output.	Corrective action taken before the actual disturbance occurs on the output.
4	Block Diagram		
5	Control Variable adjustment	Variables are adjusted depending on errors.	Variables are adjusted based on prior knowledge and predictions.
6	Example	Use of roll sensor as feedback	Use of flow meter as feed forward block in temperature control

Sr. no	Point of Difference	Feedback control system	Feed Forward Control system
		element in ship stabilization system.	systems.

Lecture 31:

3.4 Ratio Control

Ratio control, as the name suggests, is used for maintaining the ratio between two streams. The independent stream is referred to as the wild stream. The ratio controller adjusts the flow of the other stream to keep it in ratio to the wild stream. The wild stream flow measurement is multiplied by theratio set-point to obtain the flow set-point for the manipulated stream. The calculated flowset-point is input to the flow controller on the manipulated stream. Ratio control isimplemented as a feed-forward strategy where two flows are increasedin tandem so that the change in the wild stream is compensated for before it affects the process output.The implementation of ratio control, can be done using three configurations, they are:

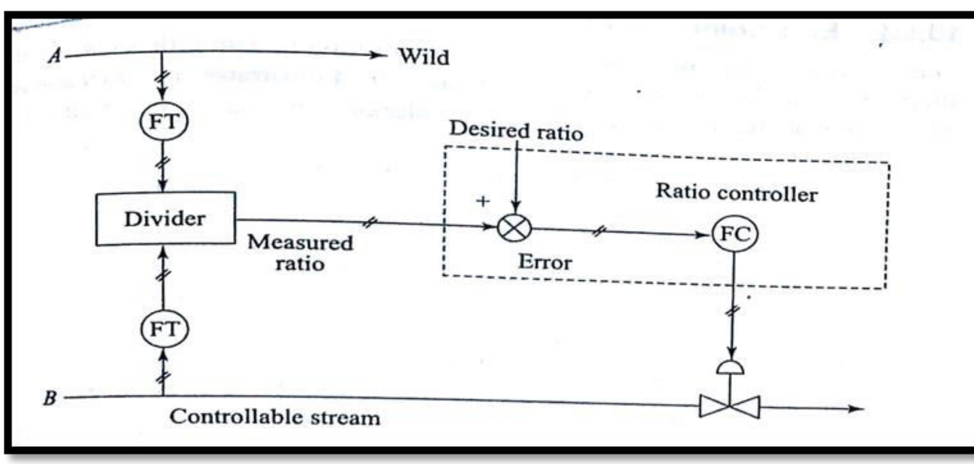
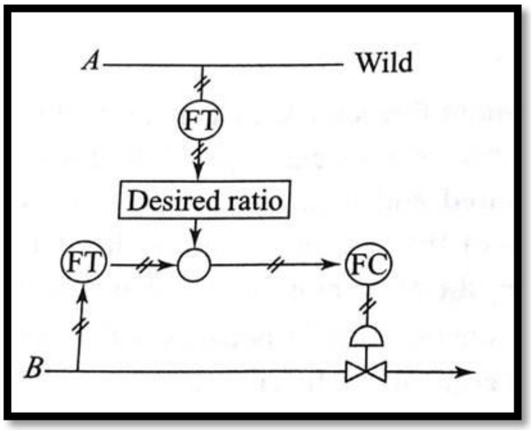


Fig. 3.16: configuration1



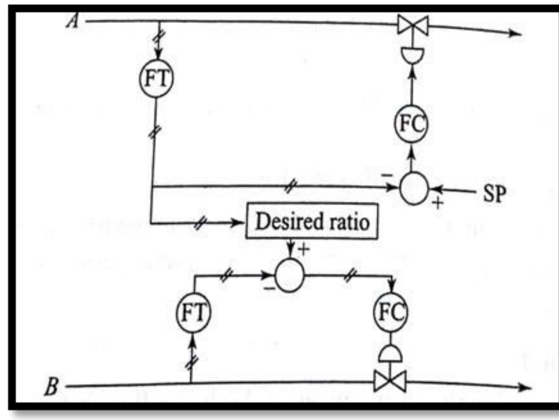


Figure. 3.17: configuration 2 Figure. 3.18: configuration

Applications of ratio control:

Typical applications for ratio control include:

- Blending two or more components. One ingredient may be set for the master production rate; other ingredients are then radioed to this master ingredient.

- Air-fuel ratio control for a combustion process. In a simple air-fuel ratio control system, the fuel flow may be controlled by a temperature or pressure controller. A measure of the fuel flow is then used to determine the set point of the air-flow controller.

- Controlling a product stream to feed rate, as a means of composition control. This is a common control technique for distillation towers.

Lecture 32:

3.5 Cascade Control:

- The primary disadvantage of conventional feedback control is that the corrective action for disturbances does not begin until after the controlled variable deviates from the set point. In other words, the disturbance must be "felt" by the process before the control system responds. Feed forward control offers large improvements over feedback control for processes that have large time constant and/or delay. However, feed forward control requires that the disturbances be measured explicitly and that a model be available to calculate the controller output. Cascade control is an alternative approach that can significantly improve the dynamic response to disturbances by employing a secondary measurement and a secondary feedback controller. The secondary measurement point is located so that it recognizes the upset condition sooner than the controlled variable, but the disturbance is not necessarily measured.

- Cascade control is arguably one of the most useful concepts in chemical process control. The cascade control scheme consists of two control loops, namely the master loop and the slave loop, with the master loop setting the set-point for the slave loop.

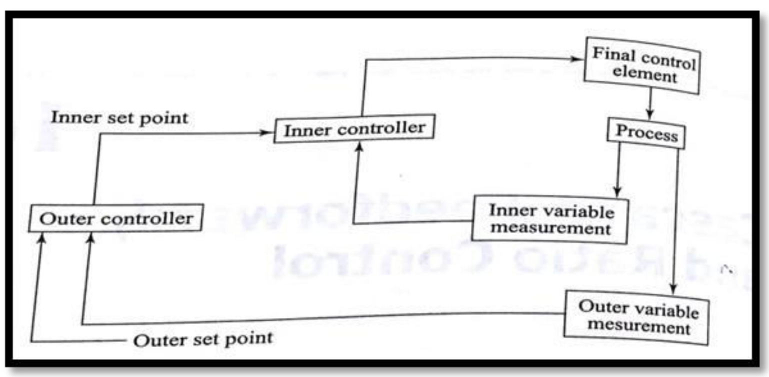


Figure 3.19. : Block diagram Cascade Control

Common example of Cascade Control:

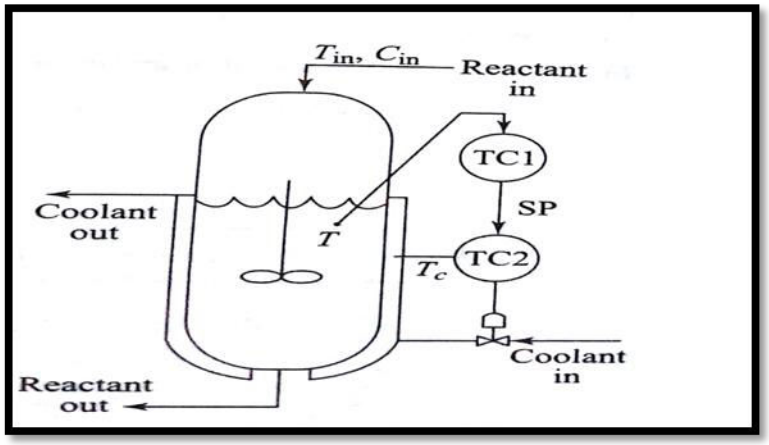


Figure. 3.20: Jacketed CSTR

Lecture 33:

3.6 Multivariable control

Multivariable control system defines a system in which the variable the variable interacts strongly. This kind of system must have more than one input and more than one output. A disturbance in any input causes a change of response from at least one output. This kind of system have as many inputs and outputs as needed to control the process. A system with an equal number of inputs and outputs is said to be **square.** A disturbance in any variable can cause a change in response in any output in its signal path. Depending on the system design, these paths can be direct or indirect.

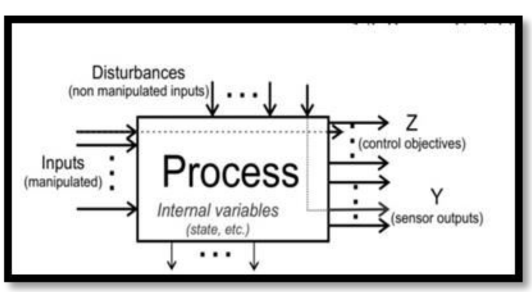
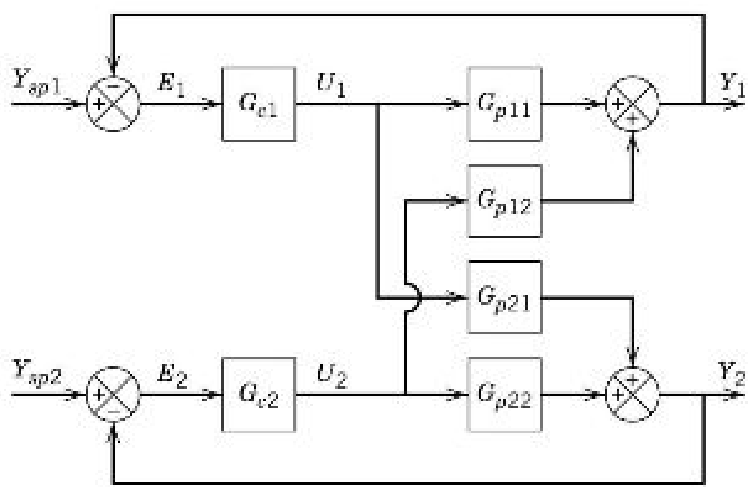


Figure. 3.7: Block Diagram of multivariable control

Each manipulated variable can affect both controlled variable.

Block Diagram for 2x2 Multiloop Control:



Text Books:

1) Control Systems: Engineering, 5th Edition [I. J. Nagrath, M. Gopal]

2) D. Patranabis, Principles of Process Control, TMH , New Delhi, 2nd Ed.

3) D. P. Eckman, Automatic Process control, John Wiley, New York

4) Surekha Bhanot, Process Control Principal & Application , Oxford

5) G. Stephanopoulos, Chemical process Control, PHI

6) C. D. Johnson, Process Control Instrumentation Technology, PHI