Module Number 9

PROCESS CONTROL AND INSTRUMENTATION.

RATIONALE.

The individuals knowledge of process control systems and the use of instrumentation in the paper or board mill will be increased. The operation of such systems, their integral parts and problem solving techniques will be covered

AIMS.

1. To develop understanding in the reason for process control.

2. To understand control methods and modes of control.

3. To understand the design criteria of comparison units sensors and correcting elements.

4. To understand control systems associated with each individual section of the paper or board process including continuos monitoring.

5. To explain common terms used to describe a systems performance,

6. To understand methods used to identify and locate faults.

LEARNING OUTCOMES.

On completion of this module the students should be able to

1. Describe the reasons for process control.

2. Understand control methods.

3. Understand control modes.

4. Understand types of control systems.

5. Understand measurement of parameters by use of a sensor (transducer).

6. Explain comparison units.

7. Understand correcting elements.

8. Explain control systems through out a paper or board mill

9. Explain common terms used to identify a systems performance.

10. Understand methods used to identify and locate process faults.

INDICATIVE CONTENT.

1. Describe the reasons for process control.
   - Maintain optimum performance at all times by manipulation of process variables.
   - ensure process safety is maintained.
   - provide data on process parameters.

2. Understand control methods.
   - feed forward (open loop)
   - feed backward (closed loop)
   - multiple control
   - cascade.
   - derive generalised transfer function of a closed loop system with negative feed back in the form $$\frac{G}{1 + GH}$$

3. Understand control modes.

   - proportional control
   - relate proportional band to gain.
   - demonstrate offset resulting proportional action.
   - investigate the effect of variation in gain.
   - explain proportional integral control.
   - explain proportional, integral and derivative control.

4. Understand types of control.

   to describe typical applications of control systems listed below.

   - on - off.
   - continuous.
   - sequential.
   - process type.
   - servo type

5. Understand measurement of a parameter by use of a sensor.

   explain the following terms as applied to measured systems.

- linearity 1 transfer / function.
- accuracy.
- resolution.
- range.
- sensitivity.
- band width.
- response time.

Investigate the most common sensor applicable to the paper and board industry.
examples:-

- pressure measurement.
- flow measurement.
- level measurement.
- individual instruments applicable to specific areas of a paper or board mill will be covered in section 8.

Understand the need for signal conditioner.

- explain the function of a signal conditioner.
- explain why signal conditioning may involve amplification.
- linearisation.
- filtering.
- modulation and demodulation.
- analogue and digital conversion.
- compensation.

6. Explain comparison units.

- compare automatic and manual control.
- analogue controllers.
- digital controllers
- operational amplifiers.
- programmable logic controllers.

7. Understand correcting elements, actuators used in control systems.

- process control valves
- adjustment screws.
- pressure loading devices.
- electronic motor speed control.
- heat expansion devices.

8. Explain the control systems throughout a paper or board mill.

- pulp mill
- digester control.

- chip refining control.
- stock preparation.
- control systems for virgin fibres.
- control systems for re-cycled fibres.

Approach flow system.

- consistency control.
- thick stock control.
- pressure control.
- flow control.
- thin stock control.
- efflux ratio control.

Forming section.

- tension devices.
- vacuum control systems.

Press section.

- load control.
- temperature control.

Dryer section.

- steam control.
- tension control.

Control loops associated with quality.

- freeness control.
- pH control.
- grammage control.
- moisture control.
- calliper control.
- shade control.
- ash content control.
- cross directional control.

9. Explain common terms used to describe a system performance.

- reliability.
- accuracy.
- repeatability.
- hysteresis.
- lag.
- dead zone.

- drift.
- noise.
- damping.

10. Understand methods used to identify and locate system faults.

- condition monitoring.
- vibration analysis
- interactions of individual control loops.

ACTIVITY BASED IMPLEMENTATION STRATEGY.

The implementation of the paper and boardmaking modules will be :-

1. Lectures by college staff and external industrial specialists.
2. Student activity based learning by use of the departments three laboratories.

All activity will be relevant to the individual modules being taught.

3. The modules will be supported by works visits appropriate to the subject areas being covered.
4. Work based assignments with additional tutorial assistance which will supplement the activity.

ASSESSMENT STRATEGY

The methods to be used to assess student performance will be

1. Timed end of module assessments.

2. Class exercises.

3. Laboratory projects.

4. Work placed assignments.

5. Presentation of assignments.

Introduction

There has been, without doubt, been major developments in the use of instrumentation systems to control Paper and Board mill variables over the last two decades. The benefit for both the producer and customer is plain for all to see.

The instrument systems of the early 1960's have been replaced by sophisticated systems designed by engineers who have a greater understanding of paper and board making.

The purpose of instrumentation systems

There are three basic functions of instrument systems:

1. To maintain optimum performance at all times during the process by the manipulation of process variables.
2. To ensure process safety is maintained at all times.
3. To provide data on the parameters of the process.

The complexity of industrial processes makes it necessary to have automatic control. As the complexity has increased so has the number of process variables, such as level, temperature flow, pH and consistency. It must be evident that as industrial processes develop so also must the use of automatic control. The more the process variables come under automatic control the more the operator becomes master of the plant.

Control is an essential part of any process. The plant must be provided with the capability of being started and stopped and with means where the operation can be adjusted to perform its function as required. Control is necessary not only for the obvious purpose of starting up and shutting down the plant, but also for controlling the conditions at the constant required values. The characteristics of any plant vary for many reasons e.g. wear, build-up of deposits changes in temperature. The process materials can also change in quantity. All of these factors will introduce changes in the operating characteristics of the plant.

The complex functions within a plant require different forms of control systems to keep the controlled variables within acceptable levels.

Requirements of an instrumentation system.

The main requirement is fitness for purpose. For example, a length measurement system might be quoted as having an accuracy of 1 mm. This would mean that all the length values it gives are only guaranteed to this accuracy, e.g. for a measurement which gave a length of 158 mm the actual value could only be guaranteed to be between 157 and 159 mm. If the fitness for purpose criterion for such a measurement system is that the length can be measured to an accuracy of l mm then the system is fit for that purpose.

In order to deliver the required accuracy, the measurement system must have been calibrated to give that accuracy. Calibration is the process of comparing the output of a measurement system against standards of known accuracy. The standards may be other measurement systems which are kept especially for calibration duties or some means of defining standard values. In many companies some instruments and items such as standard resistors are kept in a company standards department and used solely for calibration purposes.

Quality

The British Standard BS5750 (European Standard EN 29001 and International Standard ISO 9001) is the standard, which lays down the standard for a quality system. The term quality is used to mean that a product is one that is fit for its purpose or meets requirements.

The standard definition for quality is that it is the totality of features and characteristics of a product or service that bear on its ability to meet stated or implied needs.

In everyday language, the term quality tends to be used to indicate the best available.

For example, compare a Rolls Royce and a Ford Fiesta, the Rolls may be considered to be the quality car above the Ford. But in the way the term quality is used in engineering, both cars can be quality cars if they both meet the needs of those buying them, i.e. both are fit for the purpose for which they were bought. If either of the cars breaks down regularly or the paint work blisters or some other defects occur then they are not considered quality goods.

In order to have a quality system it is necessary for a company to exercise control over its measurement systems. For example, it is not possible for a company to state that a product meets, say, a particular paper or board grade specification if the measurement system used to measure the grade does not meet the accuracy requirements of that specification. Thus a company in following the standard is expected to provide, control, calibrate and maintain inspection, measuring and test equipment suitable to demonstrate the performance of the product to the specified requirements.

The Standard lays down procedures that have to be followed when selecting, using, calibrating, controlling and maintaining measurement standards and measuring equipment. These include:

- the company has to establish and maintain an effective system for the control and calibration of measurement standards and measuring equipment. This might involve in-company calibration or the use of a suitable calibration service.
- all the personnel involved in the calibrating should have adequate training.
- the calibration system used must be periodically and systematically reviewed to ensure that it continues to be effective.
- all measurements, whether for calibration purposes or measurements of products, must take into account all the errors and uncertainties involved in the measurement process.
- the procedures used for calibration need to be documented.
- a separate calibration record should be kept for each measurement instrument. This record is likely to contain a description of the instrument and its reference number, the calibration date, and the calibration results. How frequently the instrument is to be calibrated and probably details of the calibration procedure to be used, details of any repairs or modifications made to the instrument and any limitations on its use.
- the calibration should be carried out using equipment, which can be traceable back to national standards.

Traceable Standards

The equipment used in the calibration of an instrument in everyday company use is likely to be traceable back to national standards in the following way:

- national standards are used to calibrate standards for calibration centres.
- calibration centre standards are used to calibrate standards for instrument manufacturers.
- standardised instruments from instrument manufacturers are used to provide in-company standards.
- in-company standards are used to calibrate process instruments.

There is a simple traceable chain from the instrument used in a process back to national standards.

The national standards are defined by international agreement and are maintained by national establishments, e.g. the National Physical Laboratory in Great Britain and the National Bureau of Standards in the United States. There are seven such primary standards, and two supplementary ones. The seven are:

1 Mass

The mass standard, the kilogram, is defined as being the mass of an alloy cylinder (90% platinum 10% iridium) of equal height and diameter, held at the International Bureau of Weights and Measures at Sevres in France. Duplicates of this standard are held in other countries.

2 Length

The length standard, the metre, is defined as the length of the path travelled by light in a vacuum during a time interval of duration 1/299 792 458 of a second.

3 Time

The time standard, the second, is defined as a time duration of 9 192 63 1 770 periods of oscillation of the radiation emitted by the caesium 133 atom under precisely defined conditions of resonance.

4 Current

The current standard, the ampere, is defined as that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in a vacuum, would produce between these conductors a force equal to 2 x 1 0^{-7} N per metre of length.

5 Temperature

The Kelvin (K) is defined so that the temperature at which liquid water, water vapour and ice are in equilibrium (known as the triple point) is 273.16 K.

6 Luminous intensity

The candela is defined as the luminous intensity, in a given direction, of a specified source that emits monochromatic radiation of frequency 540 x 1012 Hz and that has a radiant intensity of 1/683 watt per unit steradian (a unit solid angle, see below).

7 Amount of substance

The mole is defined as the amount of a substance, which contains as many elementary entities as there are atoms in 0.012 kg of the carbon 12 isotope.

The two supplementary standards are:

1 Plane angle

The radian is the plane angle between two radii of a circle which cuts off on the circumference an arc with a length equal to the radius (Fig. 1)

2 Solid angle

The steradian is the solid angle of a cone which, having its vertex in the centre of the sphere, cuts off an area of the surface of the sphere equal to the square of the radius.

Primary standards are used to define national standards, not only in the primary quantities but also in other quantities that can be derived from them. For example, a resistance standard of a coil of manganin wire is defined in terms of the primary quantities of length, mass, time and current. Typically, these national standards in turn are used to define reference standards that can be used by national bodies for the calibration of standards, which are held in calibration centres.

Glossary of Terms

ACCURACY	The accuracy of a measuring system is the closeness the readings from the system represent the true values of the quantities being measured. Accuracy is normally stated in terms of error, for example: a rule is said to have an accuracy of 0.5mm. A voltmeter may be expressed as a percentage of full- scale deflection (f.s.d.) error % f.s.d. $\frac{\text{indicated value - true value}}{\text{full scale value}}$
BANDWIDTH	The range of frequencies over which an amplifier can be used as an amplifier. Normally this is taken between two points at which the gain has fallen by 3 dB (0.707 of maximum) i.e. the power gain has fallen by half. In many amplifier circuits the bandwidth is deliberately designed to amplify, or reject, one particular range of frequencies (i.e. in a radio).
CALIBRATION	The process of comparing an instrument with a known standard is known as calibration
CONTINUOUS CONTROL SYSTEM	This is one in which the output changes smoothly and continuously, without any steps as the reference signal is varied.
DEAD ZONE	The dead zone is a zone where no output exists. e.g. How far do you push a switch before the light comes on? How far is a diaphragm depressed before the indicator records the movement?

DEMAND, REFERENCE or SET POINT SIGNAL	The command signal input to an automatic control system. The signal is the input to the error detector and sets the value which is to be the controlled condition (i.e. the output of the control system).
DRIFT	Drift is an undesired change in output over a period of time which is unrelated to the input. Drift is affected by:- Power supply fluctuation Magnetic fields Pneumatic supply variations Instrument movement - tilting Temperature changes Humidity changes Wear Contamination of the sensor Vibration or shock.
ERROR or DEVIATION SIGNAL	The output of the comparison unit; the result of Subtracting the feedback signal from the demand signal.
HYSTERESIS	Hysteresis is a tendency of the output to remain constant when the direction of change of the input has been reversed. Example On opening a valve there is a given setting of the valve stem for each turn. On closing the valve the setting of the valve stern (output) does not correspond to the handle setting (Input). This is a source of error caused by friction. Errors caused by repeatability and hysteresis are included in the accuracy of a system.

LAG	Lag in a system is a delay in output with respect to a change in input e.g. heating a tank of water or chemical. The input such as steam heating a cooker is increased but time (lag) will be taken for the fluid temperature to rise.
LINEARITY	The maximum deviation from a linear relationship between input and output i.e. from a constant sensitivity expressed as a percentage of full scale.
NEGATIVE FEEDBACK	The transmission of a signal from a later to an earlier stage to be subtracted from the demand signal in the comparison unit
NOISE	The term noise is used for the unwanted signals from unrelated electrical circuits, magnetic fields and vibrations that may be picked up by the instrument or its transmission medium.
ON OFF CONTROL	This system is a simpler and cruder alternative to the continuous control system. It is a system in which the output can only be full on or switched off, changing from one state to the other as the error signal changes from positive to negative.
POSITIVE FEEDBACK	This is a signal which is added to the demand signal. The effect of this would be to drive the controlled condition rapidly to either its upper or lower limit. This principle is used in circuits such as oscillators.
POWER AMPLIFICATION	This unit increases the power of a signal so that it is capable of doing some physical work.
PROCESS CONTROL SYSTEM	A system which controls some physical quantity or condition of a manufacturing process (e.g. control the flow of paper stock in a pipeline).
RANGE	The total range of values which an instrument or measuring system is capable of measuring.

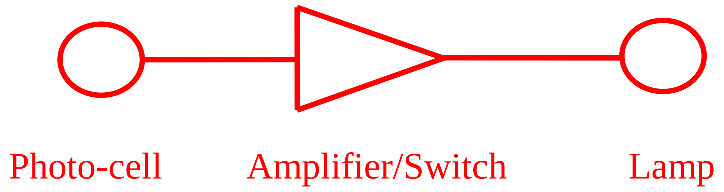
RELIABILITY	Reliability is the probability of an instrument system functioning as, when, where required and for the time required. Normally the higher the reliability, the higher the cost but less need for maintenance and replacement would be expected to offset the initial cost. Ways of increasing reliability are:- Improve quality of equipment by better design and/or tighter specification. Build back up equipment into the system. Improve layout to allow easy inspection. Take precautions which ensure against accidental damage. Reduce breakdowns by regular inspection. Combine instruments that cross reference each other e.g. grammage/moisture. Provide operator training. Careful pre-selection testing and installation by trained personnel is essential.
REPEATABILITY	Repeatability is the closeness of agreement among repeated measurements of the output for the same value of input made under the same operating conditions.
RESOLUTION	The smallest change of input to an instrument, which can be detected with certainty, expressed as a percentage of full scale.
RESPONSE TIME	The time taken for the output of an instrument to rise from 0% to 100% of the final steady state value. Applicable only to underdamped systems.

SENSITIVITY	Static sensitivity is defined as the ratio of the change in output to the corresponding change in input under static or steady state conditions. Static sensitivity K $= \frac{\text{change in output}}{\text{corresponding change in input}}$
SEQUENCE CONTROL or PROGRAMMED CONTROL	This occurs when a component Provides a sequence of predetermined values of reference signal to control a system, as a function of time or of some other variable. The domestic washing machines for example, operate under programmed control.
SERVO CONTROL SYSTEM or SERVO-MECHANISM	This type of system controls the output of a mechanical system such as linear or rotation. The system includes a power amplifier operating a servomotor, which could be hydraulic or electric.
SPAN	The range of input signals corresponding to the designed working range of the, output signal.
TRANSFER FUNCTION	In a mathematical analysis of a system, the equation that represents the relationship between the output and the input of a particular element would be shown in the block diagram.

Control Systems

There are two basic forms of control systems, open loop and closed loop. The difference between these can be illustrated by consideration of two simple control systems.

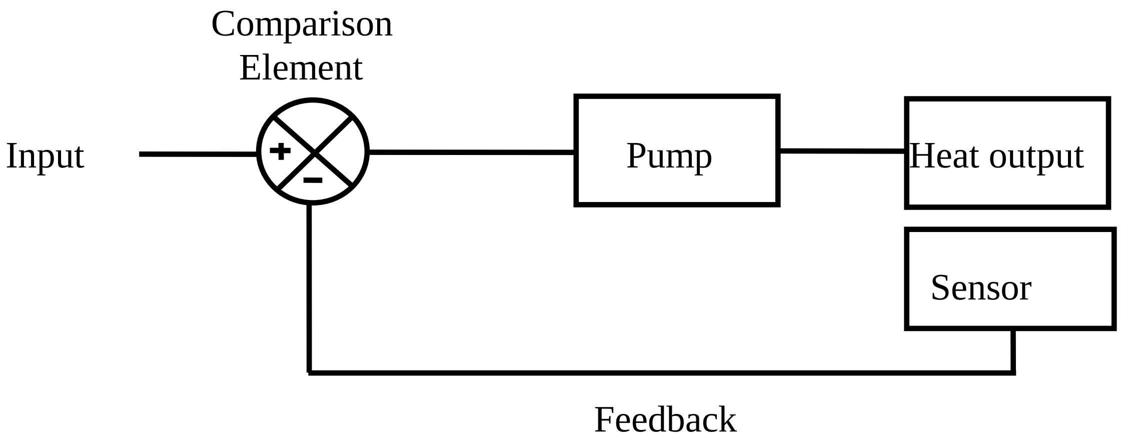
1. Street Light:



The level of light acts upon the sensor until the threshold is reached and the amplifier or switch supplies current to the light.

This is open loop control since there is no feedback of any kind, once the signal to turn the light on is sent then the output is anticipated to be at that value. In such a system there is no way to determine the inaccuracy of the system.

2. Central Heating



In the system above the set point (or desired value) is set by adjustment of the control knob to the desired temperature. This input and the feedback on the room temperature are compared in the comparison unit and an error signal generated. The error signal turns the pump on and off thereby delivering heat to the radiators. The sensor (bi-metalic strip) continually measures the temperature, this information is then the input to the comparison element.

Feedback

A feedback loop is a means whereby a signal related to the actual condition being achieved, is fed back to modify the input signal to the process. All forms of closed loop systems must incorporate feedback. There are two forms of feedback.

The feedback is said to be **negative feedback** when the signal, which is fed back, is used to reduce the difference between the reference value and the actual value of the controlled variable. Negative feedback is denoted by the - symbol within the comparison element (shown above).

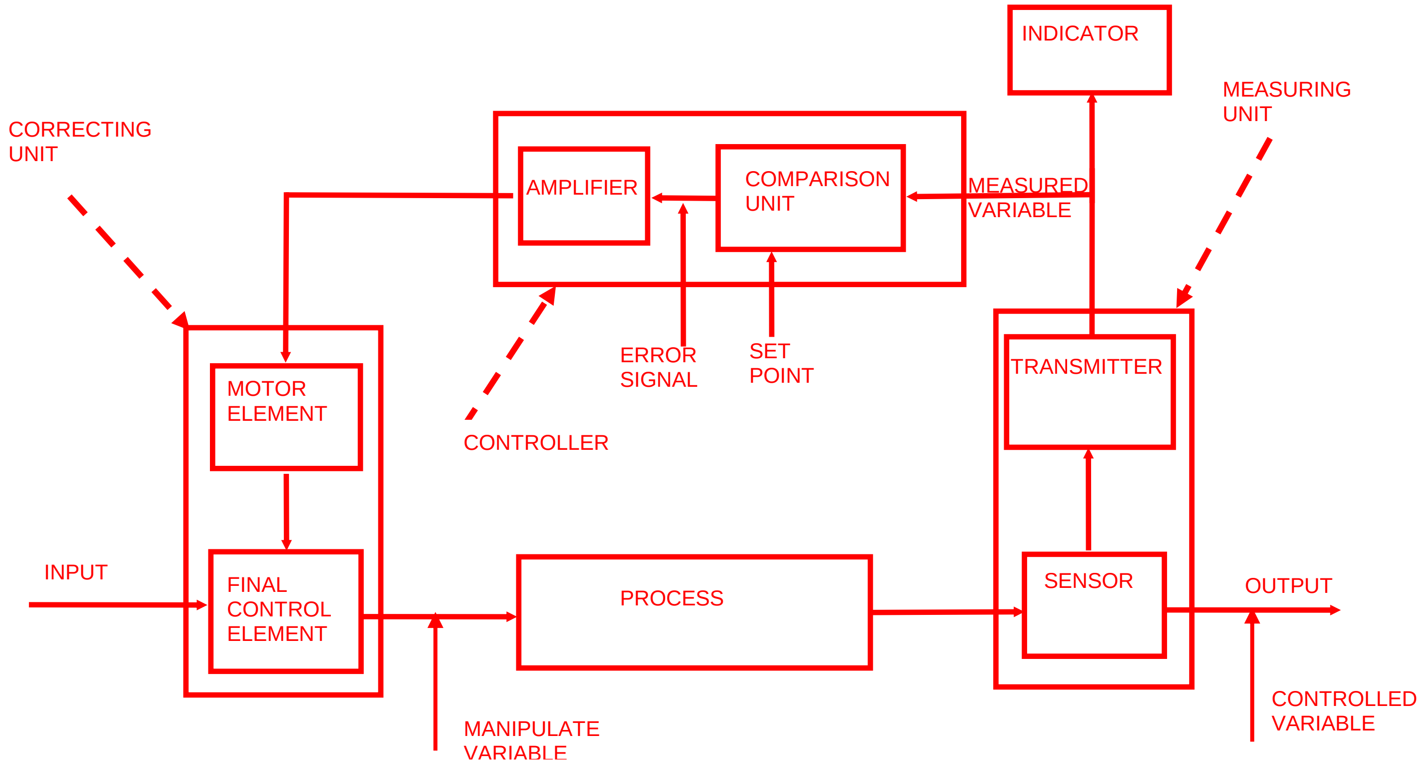
error signal = desired value - feedback signal

Positive feedback occurs when the signal fed back increases the difference between the reference and actual values, i.e.

error signal = desired value + feedback

Positive feedback is denoted by the + symbol within the comparison element.

Elements within a process control system



a. **Input: is the actual process to be controlled e.g. stock flow, level etc.**
b. **Final Control Element: the device that changes the process e.g. valve, motor etc.**
c. **Manipulated variable: the physical quantity that is varied as a result of the actuating signal.**
d. **Process: the physical variable to be controlled.**
e. **Sensor: the device that measures the process.**
f. **Controlled variable: the physical variable under control.**
g. **Transmitter: the part of the measuring unit that provides the measurement signal with enough power to transmit the signal**
h. **Measured variable: the information relating to process condition.**
i. **Indicator: an instrument to display the process variable.**
j. **Comparison unit: the device that receives the measurement signal and the set point (or desired value) signal, compares the two and produces an error signal.**
k. **Set point: The demand set by the operator (or other control system).**
l. **Error signal: the difference between the desired value of the process and the actual value measured.**
m. **Amplifier: a device that provides the error signal with power for transmission to the next stage.**
n. **Motor Element: the muscle that positions the final control element.**

Example

The level of stock in a tank is maintained at a constant level by observing the level of liquid through a gauge glass in the side of the tank and adjustments made to the amount of liquid entering by opening or shutting a control valve. For such a control system what is:

(a) the controlled variable
(b) the reference value
(c) the error signal
(d) the comparison element
(e) the control unit
(f) the process
(g) the measuring device
(h) the correction unit

a. The controlled variable is the level of the liquid in the tank.

b. The reference value is the required level, probably indicated by some mark on the gauge glass.
c. The error signal is the difference between the required level and the actual level indicated through the gauge glass.
d. The comparison element is the workman observing the gauge glass.

e. The operator.

f. The process is the level of water in a container.

g. The measuring device is the gauge glass with the operator.

h. The valve.

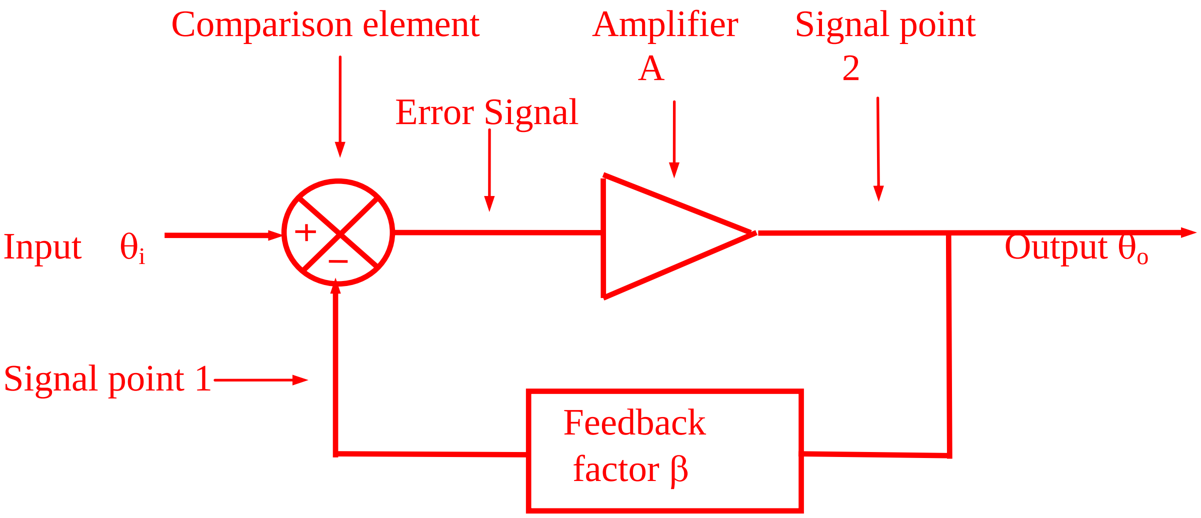
Example

Many electrical resistors have the characteristic that the higher the temperature the lower their resistance. When a current passes through a resistor it becomes warm. A consequence of this is that the resistance decreases. This results in the current increasing. The increased current causes the resistor to become even warmer. A consequence of this is that its resistance decreases even further. This results in an increase in current and so on. Is this an example of negative or positive feedback?

It is positive feedback since the input, the current, is increased by the feedback from the output rather than maintained at a constant value.

Closed Loop transfer function

The term **transfer function** is defined as being the ratio of the output to input for a system. The figure below shows a simple closed loop system.



If θ_i is the input (or reference) value, and θ_o the actual value, (the output), of the system then the transfer function of the entire control system is:

$$\text{transfer function} = \frac{\text{output}}{\text{input}} = \frac{\theta_0}{\theta_i}$$

The feedback signal at point 1 has the transfer function $\beta\theta_o$

The error signal is the difference between the input signal θ_i and the feedback signal $\beta\theta_o$ i.e.
$\theta_i - \beta\theta_o$

The signal at point 2 is equal to the error signal times the gain of the amplifier i.e.
$A(\theta_i - \beta\theta_o)$

The output $\theta_o = A(\theta_i - \beta\theta_o)$

$$\theta_o = A\theta_i - A\beta\theta_o$$

$$\theta_o + A\beta\theta_o = A\theta_i$$

$$\theta_o(1 + A\beta) = A\theta_i$$

$$\theta_o = \frac{A\theta_i}{1 + A\beta}$$

$$\frac{\theta_o}{\theta_i} = \frac{A}{1 + A\beta}$$

Since gain = $\frac{\text{Output}}{\text{Input}}$

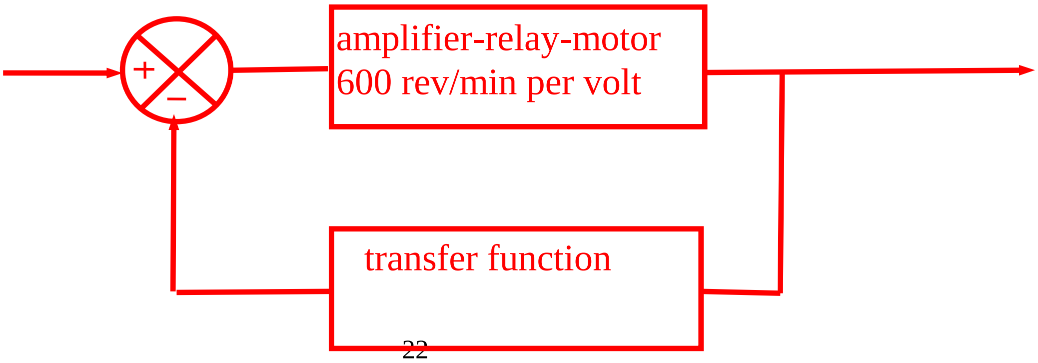
$\therefore$ the transfer function G $= \dfrac{A}{1 + A\beta}$

The above equation is for negative feedback. With positive feedback the denominator of the equation becomes $(1 - A\beta)$.

With the closed-loop system, A is termed the **forward path transfer function** since it is the transfer function relating to the signals moving forward through the system from input to output.

Question

A speed controlled motor driving a dandy roll has an amplifier-relay-motor system with a combined transfer function of 600 rev/min per volt and a feedback loop measurement system with a transfer function of 3 mV per rev/min, as shown below. What is the transfer function of the total system?



3 mV per rev/min

Answer

The system will have negative feedback and so the overall transfer function is given by:

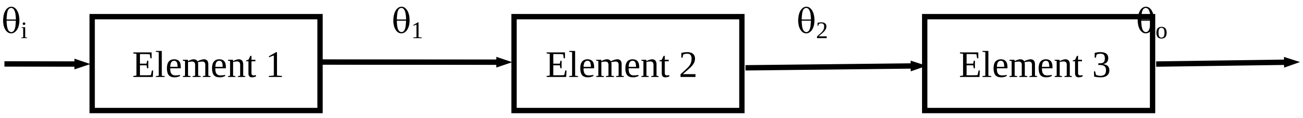
$$\text{transfer function } G = \frac{A}{1 + A\beta}$$

$$= \frac{600}{1 + 600 \times 0.003}$$

$$= 214 \text{ rev/min per volt}$$

Open-loop transfer function

There are many situations where the transfer function is required for a number of elements in series, with no feedback loop. Consider three components in series, as shown below. It is an open-loop system since there is no feedback loop.



For element 1 the transfer function G, is the output θ_1 divided by the input θ_i . Thus

$$G_1 = \frac{\theta_1}{\theta_i}$$

For element 2 the transfer function G, is the output θ_2 divided by the input θ_1. Thus

$$G_2 = \frac{\theta_2}{\theta_1}$$

For element 3 the transfer function G, is the output θ_o divided by the input θ_2 . Thus

$$G_3 = \frac{\theta_o}{\theta_2}$$

The overall transfer function of the system is the output θ_o divided by the input θ_i . This can be written as:

$$G = \frac{\theta_o}{\theta_i} = \frac{\theta_1}{\theta_i} \times \frac{\theta_2}{\theta_1} \times \frac{\theta_o}{\theta_2}$$

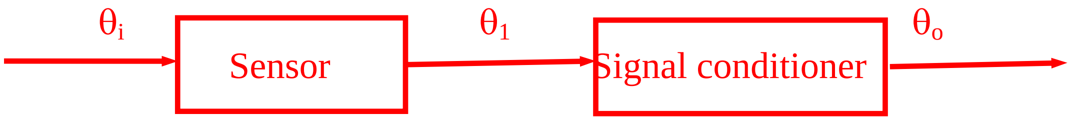
Hence the transfer function for the open loop system above is:

$$G = G_1 \times G_2 \times G_3$$

The overall open-loop transfer function is the product of the transfer functions of the individual elements. This applies however many elements there are connected in series.

Question

A measurement system used with a pressure control system consists of two elements, a sensor and a signal conditioner. If the sensor has a transfer function of 0.1mA/Pa and the signal conditioner a transfer function of 20, what will be the overall transfer function of the measurement system?



The sensor and the signal conditioner are in series so the combined transfer function of the two elements is the product of the transfer functions of the individual elements.

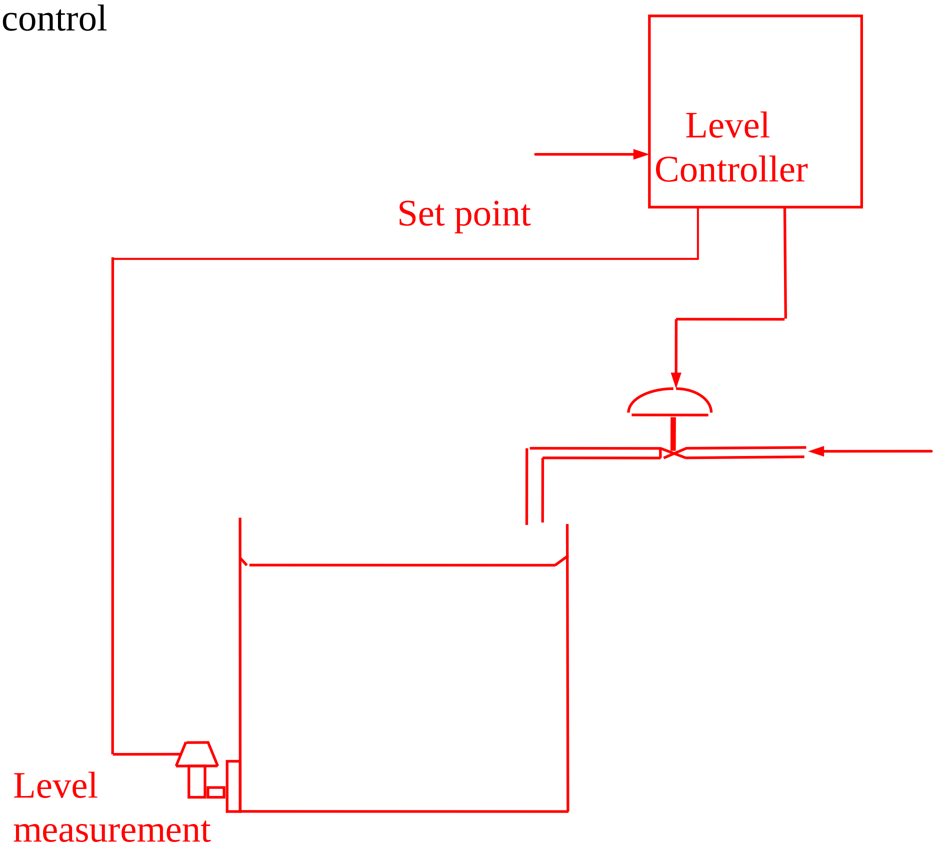
Transfer function = 0. 1 X 20 = 2 mA/Pa

Combination Control Systems

Introduction

The complexity of Industrial processes makes it necessary to have automatic control. As the complexity has increased so has the number of process variables, such as level, temperature flow, pH and consistency. It must be evident that as industrial processes develop so also must the use of automatic control. Automatic control does not replace the operator but rather supplements him. Control is an essential part of any process. The plant must be provided with the capability of being started stopped and with means where the operation can be adjusted to perform its function as required. Control is necessary not only for the obvious purpose of starting up and shutting down the plant, but also for controlling the conditions at the constant required values. The characteristics of any plant vary for many reasons e.g. wear, build-up of deposits changes in temperature. The process materials can also change in quality. All of these factors will introduce changes in the operating characteristics of the plant. Some of the more common multi-variable control systems encountered in the pulp and paper industry which employ two or more measurements or measuring elements in a control loop are: cascade, ratio, autoselector and feedforward.

Single loop control

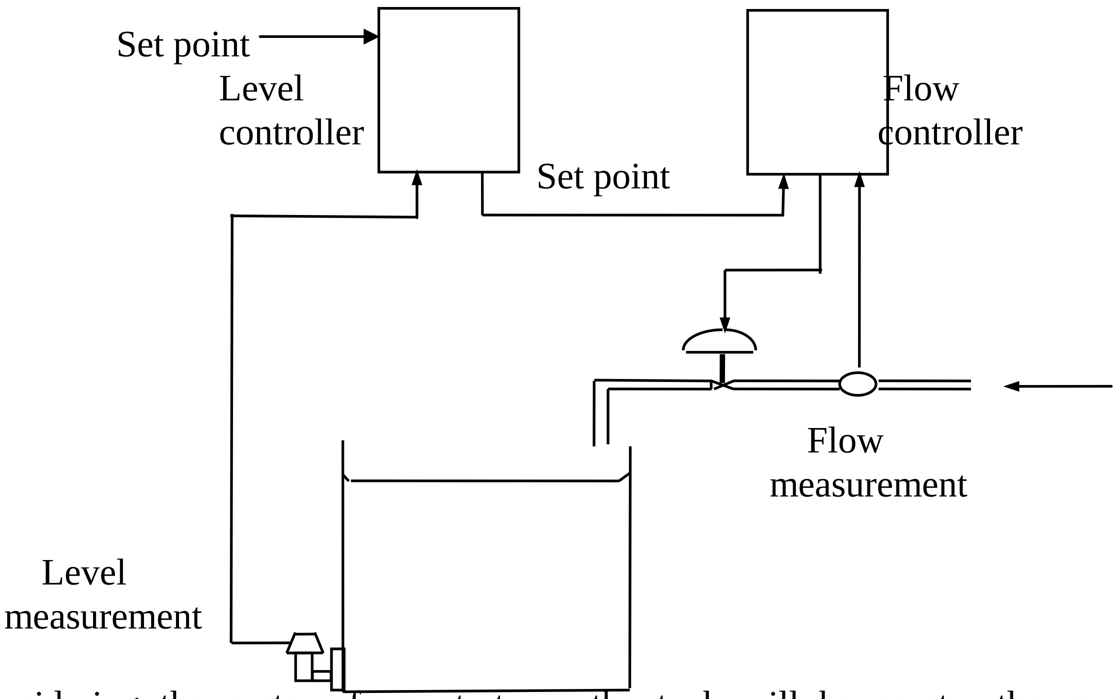


Cascade Control

The objective of a cascade control system is identical to that of a single loop controller, in that its purpose is to maintain a balance between the supply and demand and, thereby, maintain the controlled variable at its required constant value. The need for a slave (or secondary) loop is to reduce time delays in the system therefore stabilising the system and making the operation more accurate.

In cascade control the output of one controller adjusts the set point of another controller. A cascade control system consists of one controller (master or primary) controlling the variable which is to be kept at a constant value and a second controller (slave or secondary) which controls some other variable that can cause fluctuations in the first variable. The master controller positions the set point of the slave and it, in turn, manipulates the control valve. The secondary loop is introduced to reduce the effect of lags, thus stabilising inflow to make the operation more accurate. The secondary controller can be considered as the final control element being positioned by the primary controller in the same way a single controller would position a control valve. The secondary variable is not controlled in the same sense as the primary; it is manipulated just like any, control medium.

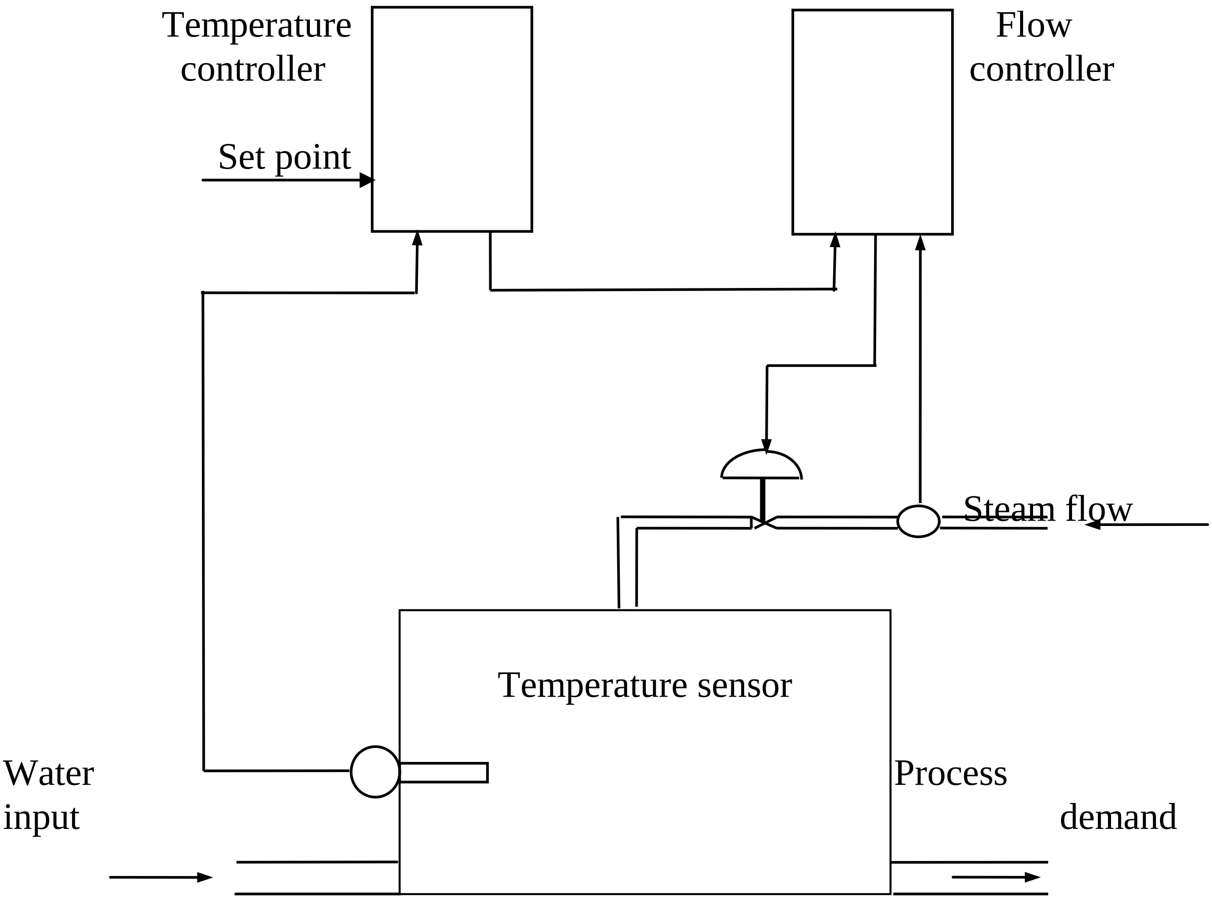
One example of a simple cascade control system is where the output signal of a level controller is used to set the set point of a flow controller on the liquid flowing into a storage tank, as shown below.



Considering the system from start up, the tank will be empty, the master controller will therefore indicate low and will send a high set point to the slave controller. The set point of the slave controller will be at a high level and will demand that the flow into the tank be high.

As the level increases so the output from the master controller will reduce, lowering the set point of the slave controller and thereby reducing the flow into the tank.

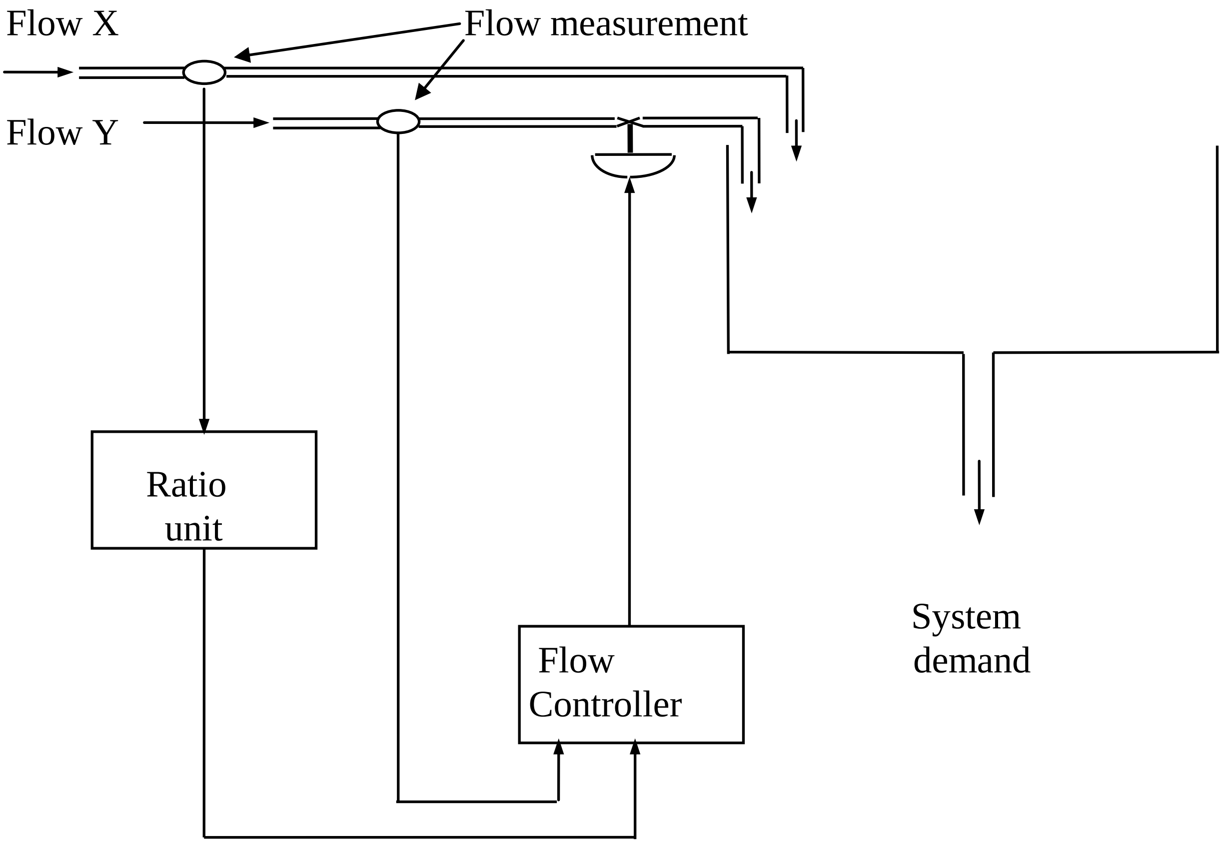
A second example is the use of the output signal from a heat exchanger temperature controller to set the set point of a steam flow controller to the heat exchanger.



Cascade control is used to improve control of processes, which normally involve upsets and long time constants with which single three-mode controllers cannot cope satisfactorily.

Ratio Control

When it is required to maintain one measurement variable, known as the secondary or controlled variable, in a pre-set ratio to another variable, referred to as the primary or uncontrolled variable, ratio control is used. A simple flow ratio control loop is shown below.



In the figure above the system is designed to control secondary flow Y in pre-set ratio to primary flow X (note flow X is uncontrolled). Flow transmitter X senses the primary flow. The ratio unit sets the output in the range of 0% to 100% output of the flow transmitter by a manually set value (possibly computer set):

(Flow output X) x (Pre-set value) = Output of ratio unit

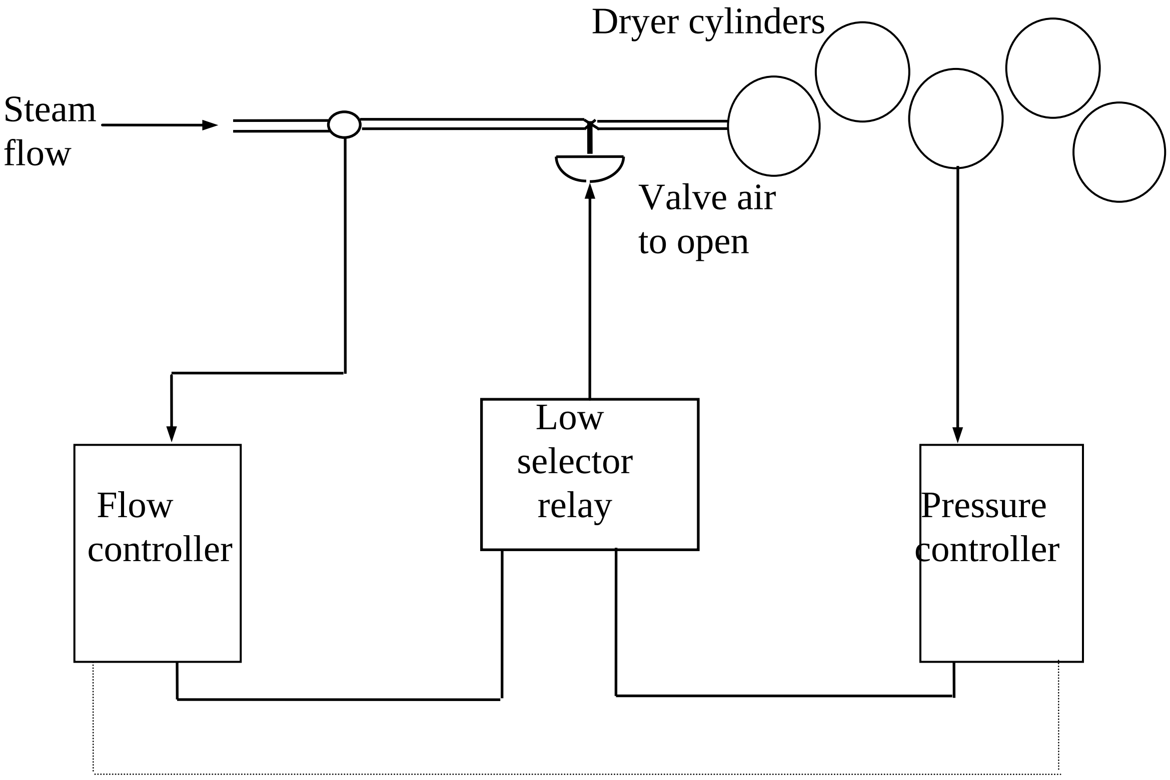
This output then becomes the set point of the controller regulating controlled flow Y. At balance, flow Y equals the set point of the controller, such that:

Flow Y = (Flow X) x (Ratio value)   or   Ratio factor = Flow Y/Flow X.

Continuous stock blending control systems used so extensively in today's paper mills utilise this principle of control.

Auto-selector Control

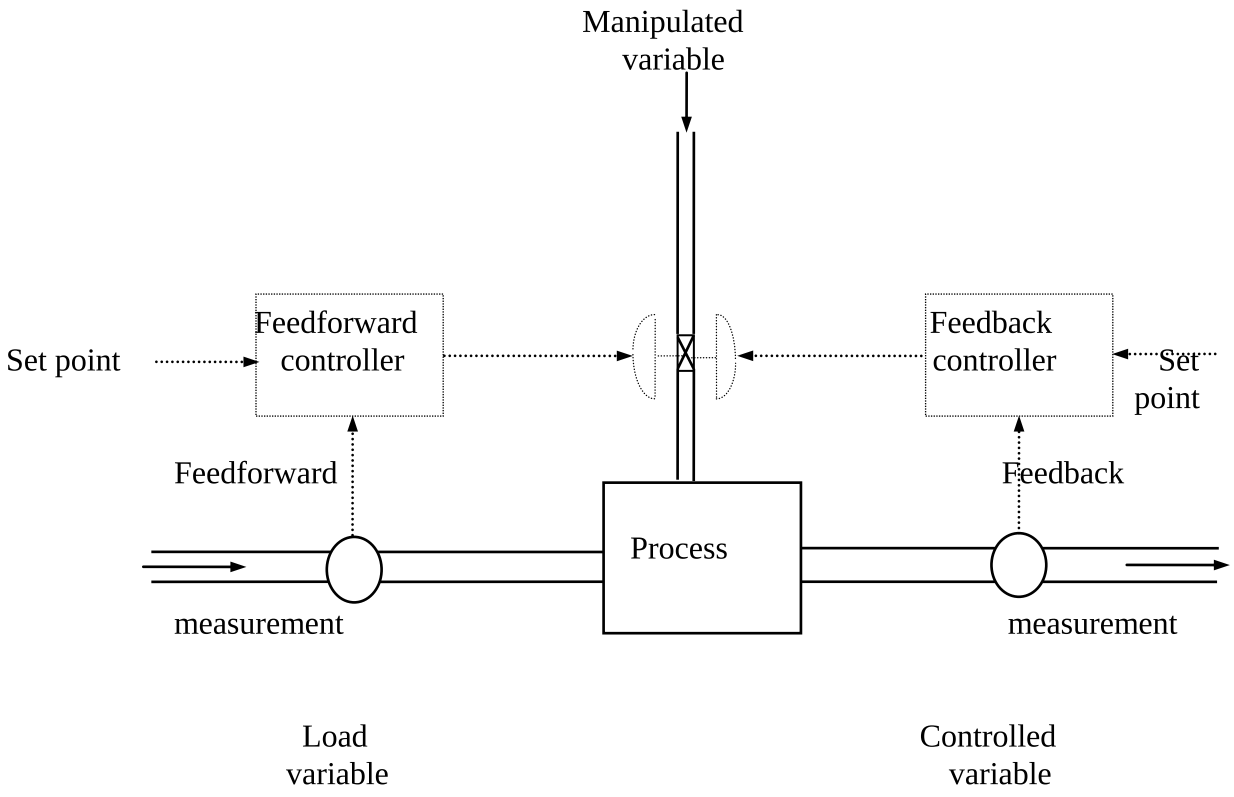
Auto-selector control systems are used when a single final valve is to be manipulated to prevent any one of several process variables, from exceeding a pre-set limit. For instance, it may be desirable to operate a drying process at a certain pressure but there is a more important or overriding limit on the amount of steam that can be used without upsetting the operation of the source of steam as shown below.



To meet these requirements a pressure controller, with set point at the desired pressure, is used on the dryer and a flow controller, with set point at acceptable flow rates, is used on the steam flow. The outputs of both controllers are sent to a selector relay. This relay will allow the output signal from the pressure controller to be transmitted to control as long as the steam flow is below the safe set point of the steam flow controller. As the steam flow approaches the set point of the steam flow controller, the selector transfers the valve-actuating signal from the pressure controller to the flow controller and will maintain this control until the steam flow drops safely below the set point and the selector relay transfers control back to the pressure controller.

Feedforward Control

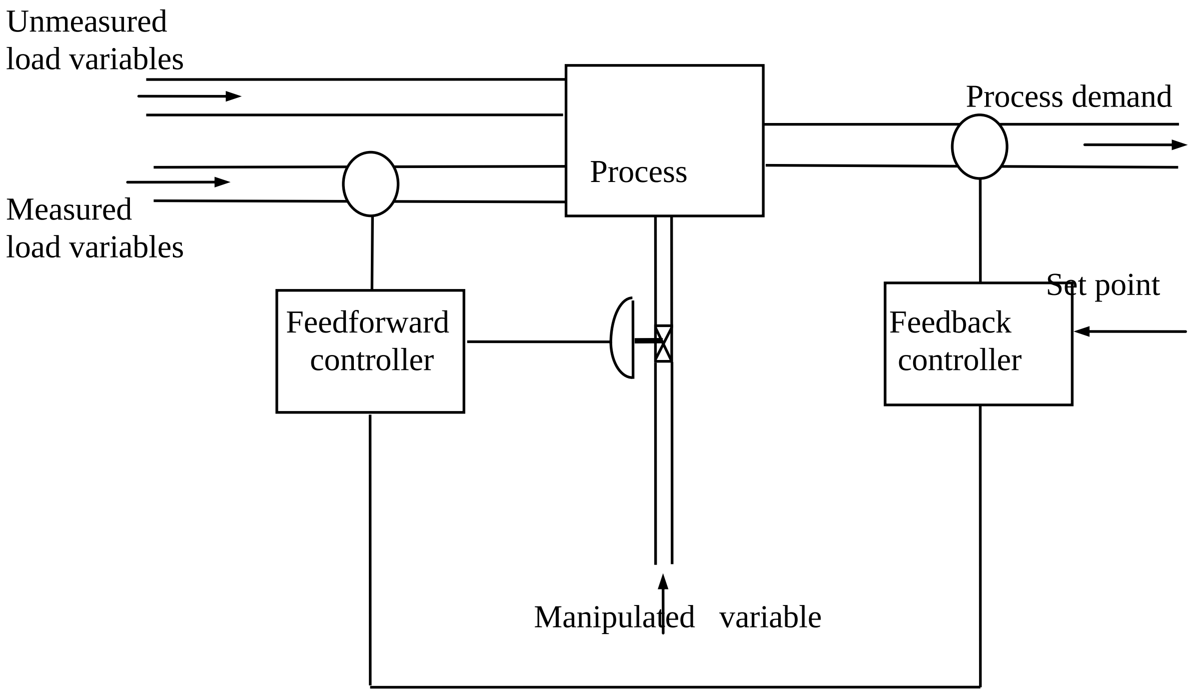
Feedforward control relies on the principle of predicting the amount of required corrective action in input change to a process and when the correction should occur. It is used to improve control of processes which have long time delays such as found in bleach plants, evaporators and paper machines. Under these conditions, the feedback controller suffers from the disadvantage that it is working from a process signal, which does not represent the true condition of the process.



The figure above compares a typical feedforward control loop with a typical feedback loop. With feedback, load changes are detected only after they have affected the controlled variable. Thus, correction is developed later than the load change with the possibility that it could occur when none is needed if the load changes had since been eliminated.

Compensation must also be made for these latter disturbances. This can be accomplished by using a feedback loop to trim the feedforward control loop based on a measurement of the controlled variable as shown below.

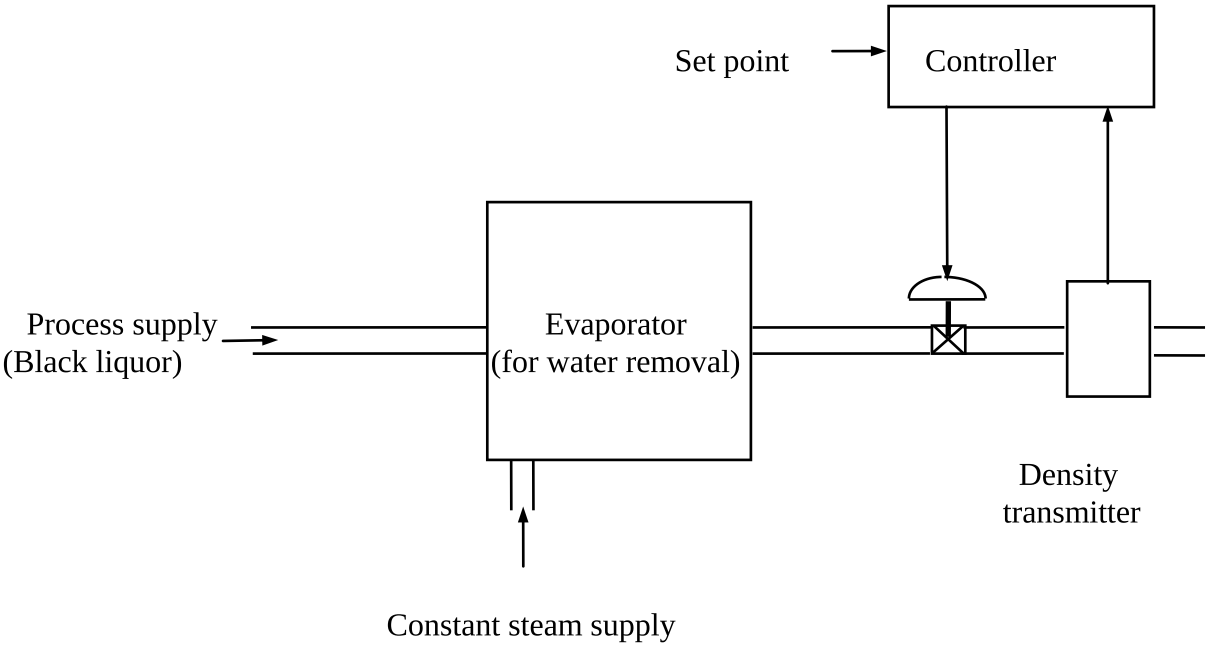
The solution of utilising the advantage of both feedforward and feedback control provides the immediate control system response for major load changes unobtainable with feedback control alone and the ability to provide for long-term drifting of the controlled variable caused by minor unmeasured process load changes.



In the figure above major measured load changes are shown being fed to the feedforward controller whose output is changing the manipulated variable to maintain the controlled variable at the set point. The minor load changes are, however, acting on the process to cause changes in the controlled variable that the feedforward controller is not capable of handling. The controlled variable is fed to the feedback controller which will, in cascade arrangement, cause the feedforward set point to change, thereby compensating for minor deviations in the controlled variable.

Chemical (Kraft) Process

Consider the density control system below

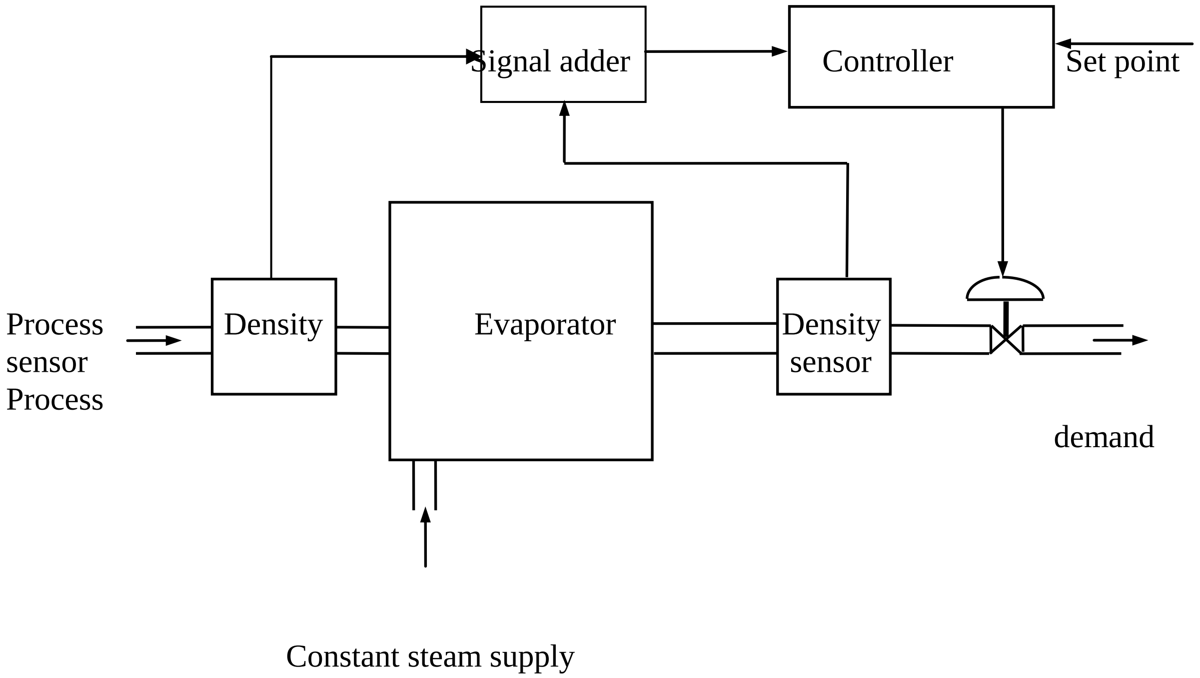


The density of the output is control led by varying the rate at which fluid passes through the evaporator. This single loop is good enough while the feed density remains constant. If the feed density varies it will take some time for the change to reach the density transmitter to the input but this again relies on all other variables, such as steam, remaining constant.

Note:

The density transmitter is used to measure the concentration of the liquor.

Consider the same system but with a second density transmitter added as shown below.



If two density transmitters are used a signal loop is picked up early in the process and fed forward to the control loop. The signal added produces a signal, which is proportional to the sum of the signals from the density transmitters.

The feedforward control loop accepts the process load change as its input and corrects the manipulated variable immediately to prevent the effect of the load change from reaching the controlled variable. Theoretically, feedforward control is capable of perfect control in that the controlled variable never needs deviate from the set point. The feedback controller, on the other hand, cannot function until the controlled variable has in fact deviated from the set point i.e. when there is an error. Thus, perfect control is not theoretically feasible with a feedback controller.

In any process, there are a number of kinds of load changes possible. Some can be measured and used for feedforward control. Others are unknown or measurements for them do not exist but they do affect the controlled variable even if only in a minor way.

System Response

Mechanical systems have three basic elements:

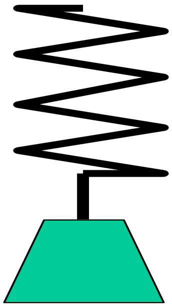
i) Mass which possesses inertia (the ability to resist change).
ii) Springs which possess stiffness.
iii) Dampers which possess resistance.

A system, which contains a spring, mass and no damping, behaves in a predictable way. In the system below a mass is suspended by a spring, if the undamped spring and mass is set into oscillation, two conditions will apply:

i) The acceleration is proportional to the displacement and
ii) The acceleration is always directed towards the equilibrium position.

When these two conditions apply, the oscillation is said to be simple harmonic motion (shm). The vertical oscillation of the mass is of sinusoidal form, with amplitude equal to the initial displacement. In practice there is always some form of damping and the oscillations die away.

In the figure below, if the mass is pulled down then released, oscillation will occur. The graph of displacement against time shows us that the period between oscillations stays the same but the amplitude becomes smaller.

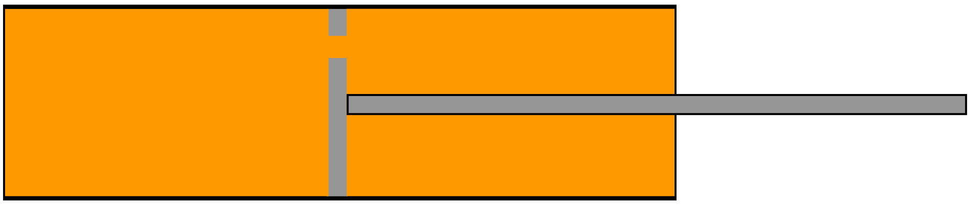


Undamped natural frequency of oscillation $f_n = \frac{1}{2\pi}\sqrt{\frac{\lambda}{m}}$

Where:
λ = the spring rate in Newton per metre
m = mass in kilograms

Damping

The free vibrations of' physical systems all die away with time. All systems possess damping; in fact it is often introduced deliberately. If control systems and instruments did not have damping it would be impossible to get any readings. Therefore, the motion of instruments (and systems) is deliberately damped so the pointer (or system) reaches a steady value in a reasonable time. One type of damping commonly used is the dashpot as illustrated below:

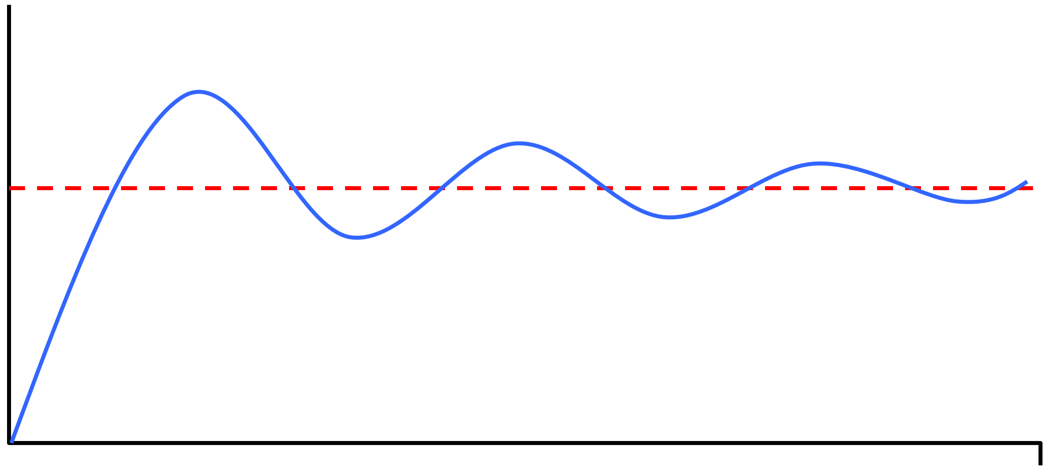


By adjusting the size of the hole (or viscosity of the fluid) different amounts of damping can be introduced. In this type of system the force required to push (or pull) the piston is directly dependent upon the speed at which the piston moves. This type of damping is called VISCOUS DAMPING. It is the type of friction experienced when a car moves through air, a disc moves in a magnetic field, etc.

There are three definite degrees of damping; we will consider each of these in turn.

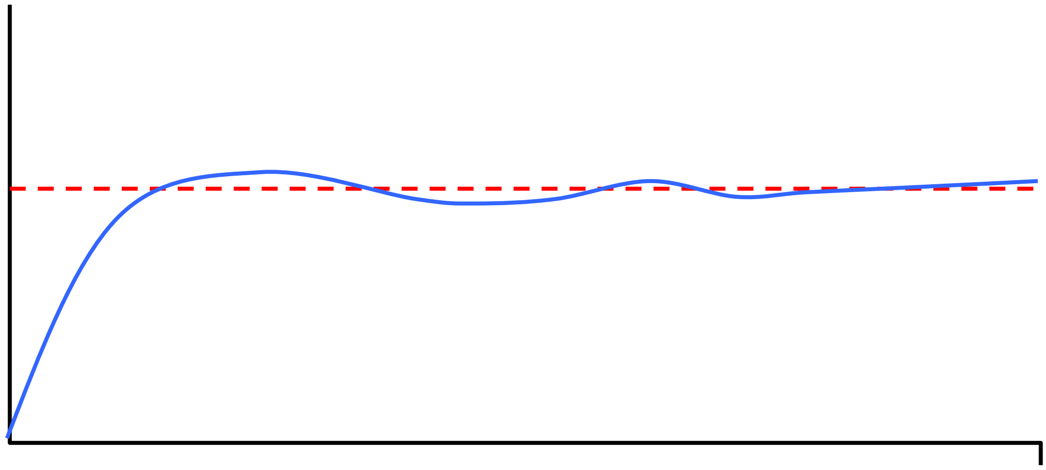
Under damped transient

If there is insufficient viscous damping, the system will drive the output as quickly as possible towards the desired position, and due to the inertia of the system, it will overshoot the desired position. This will cause the error signal to change polarity thus driving the output in the opposite direction so as to nullify the error. This will be repeated until the system reaches the steady state condition.



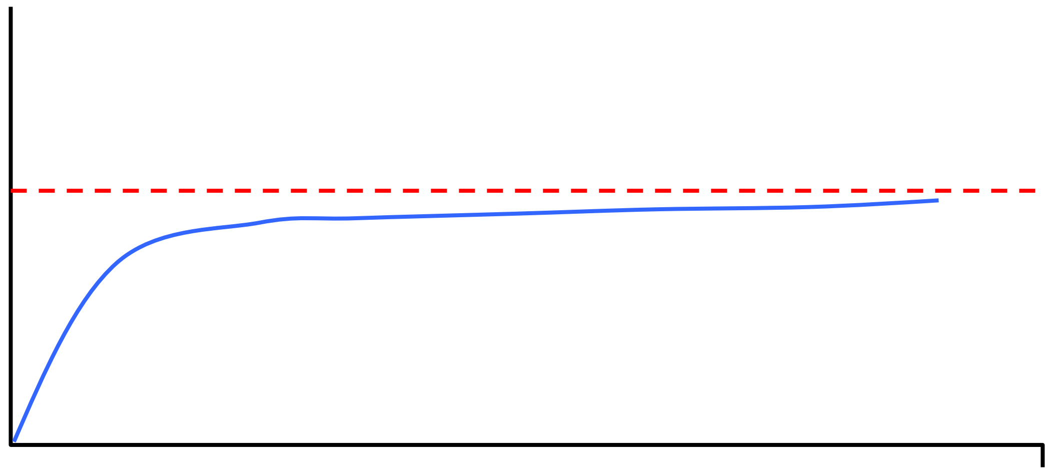
Critically damped transient

By increasing the viscous damping of the system, the oscillations of the system will be reduced until a degree of damping is reached where the output will move to the desired position as quickly as possible. Such a transient is called a critically damped transient.



Over damped transient

If the viscous damping is increased still further, the output of the system will become sluggish and take excessive time to reach the steady state condition. There will be no overshoot.



The value of the viscous damping is defined as the damping coefficient. In order to give a relationship between the various types of damping conditions one refers to the damping ratio.

$$\text{Damping ratio} \quad = \quad \frac{\text{Damping coefficient of the system}}{\text{Damping necessary for critical damping}}$$

The damping ratio ς (zeta) is a measure of the ratio between actual and critical damping:

When ς is greater than one the system is overdamped and responds in a sluggish manner.

When ς is equal to one, this is the critically damped condition no oscillations or overshoots appear in the step response. This is the point of change over from the overdamped condition to an underdamped condition.

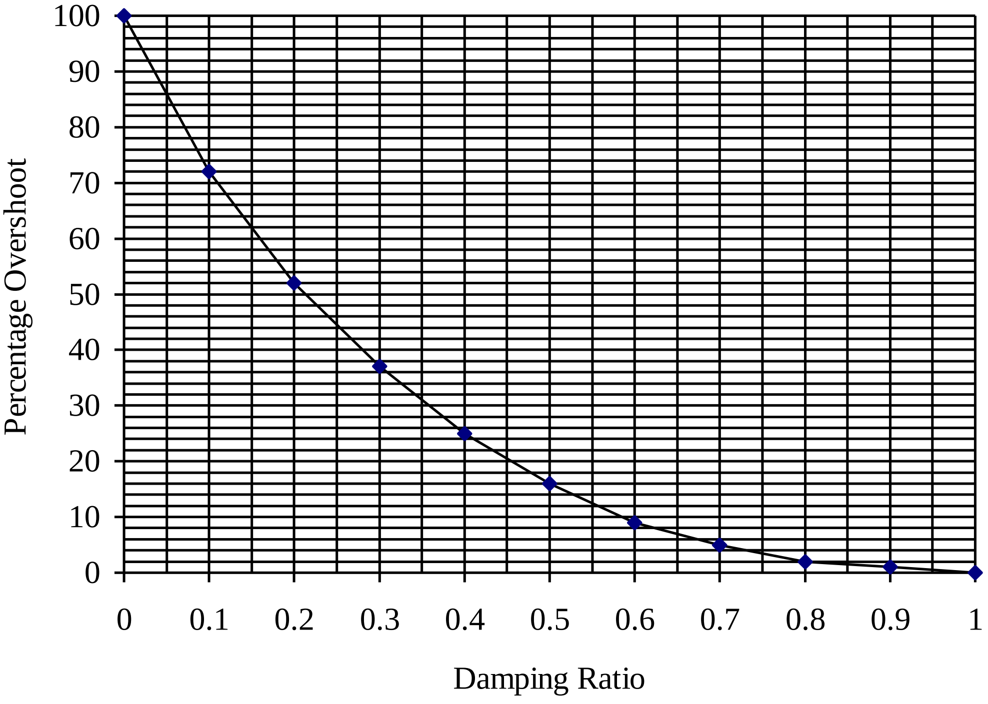
When ς is less than one the system is said to be underdamped and results in oscillations occurring in the step response.

The damping ratio ς can quite easily be calculated from the decrease in amplitude of successive half cycles of free oscillations.

$$\varsigma = \frac{\delta}{\sqrt{\pi^2 + \delta^2}} \qquad \text{where } \delta = \ln(\text{overshoot/next overshoot})$$

Question

The output of an automatic controller has a response to a step input the first three overshoots recorded. They are 40, 16 and 6.4. Calculate the damping ratio. A second method that gives an approximate damping ratio involves calculating the percentage overshoot with respect to the preceding overshoot and reading the ratio from the graph below.



Question

A number of instrumentation control systems are tested and the overshoots are as follows:

	Oscillations					
	1st	2nd	3rd	Calculations	Percentage	Graphically
a	160	80	40			
b	48	16	$5^{1}/_{3}$			
c	8	7.8	7.6			
d	140	5.6	0.224			
e	150	120	96			
f	7.8	7.41	7.04			
g	68	34	17			
h	380	19	0.95			
i	172	103.2	61.9			
j	250	212.5	180.6			

Calculate the damping ratio and verify the answer graphically.

Modes of control

The basic automatic control modes used in the pulp and paper industry for process control can be generally classified as either two-position or throttling. With two-position control, the valve or final control element is always either in the open or closed position. The controlling unit will never maintain the control element in a position between open and closed (or throttling position). There are number of methods of control that can be classified as two-position: (1) on-off, (2) differential gap, and (3) time proportioning. On-off is the most common two-position control used in the paper industry. Others are used on special occasions.

Any type of control in which the control element is maintained in a position between open and closed is generally known as a throttling control mode. Depending on their action, throttling control modes can be further categorised as proportional, integral, and derivative. Various combinations of these control modes are available for process control; however, those most commonly used in the pulp and paper processes are (1) Proportional. (2) Proportional plus integral (the integral mode is also referred to as the reset mode). (3) Proportional plus integral plus derivative.

To summarise controller actions come In four basic modes:

1. Two step (or on/off)
2. Proportional Symbol, P
3. Integral Symbol, I
4. Derivative Symbol, D

Combinations of these used are:

P

I

P + I

P + D

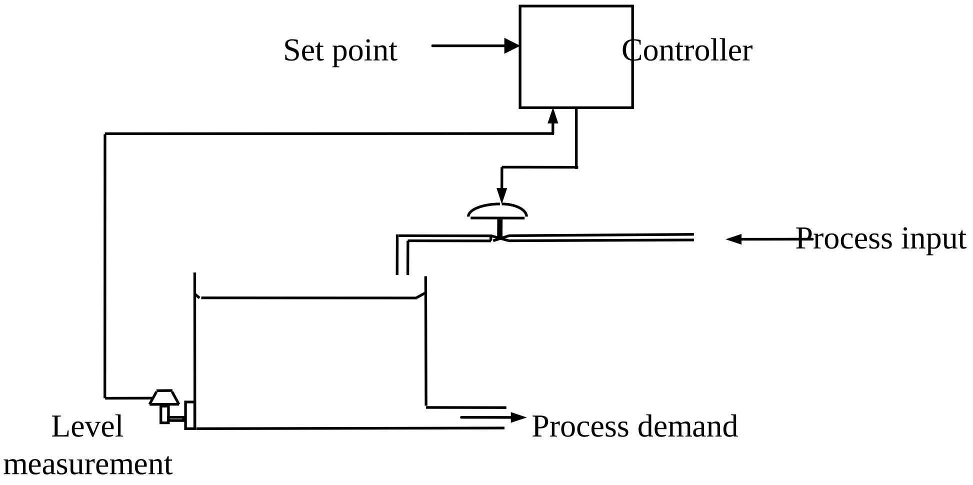
P + D + I

The only mode that is never used on its own is a derivative controller.

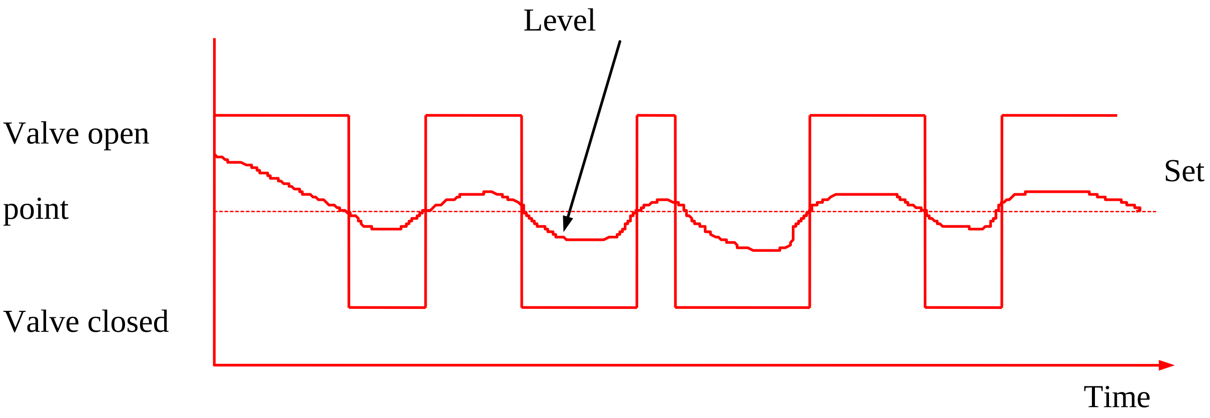
Two Position Control Modes

On-off.

With the on-off control mode, as soon as the measured variable differs from the desired control point (set point), the final control element is driven from one extreme to the other.

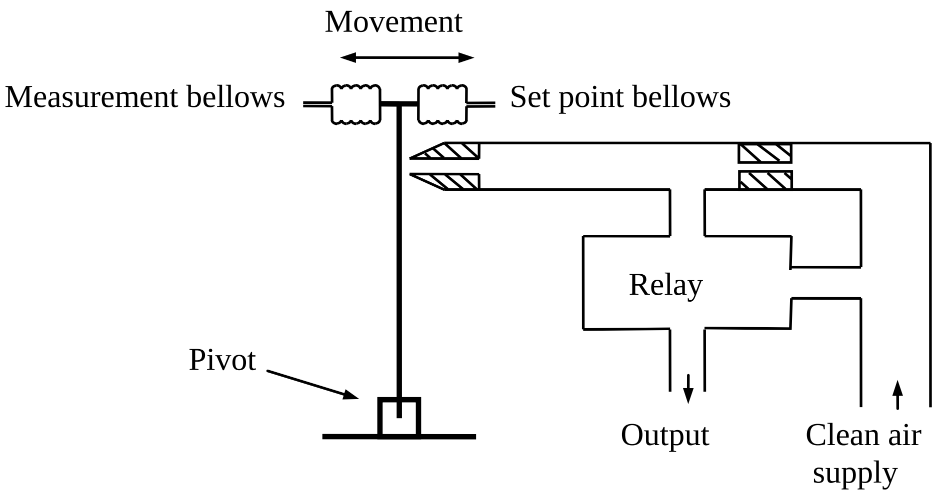


For example, as soon as the measured variable exceeds the control point, the valve (final control element) is closed. It will remain closed until the measured variable drops below the control point, at which time the valve is fully open. With this type of control the measurement is always cycling.



When properly applied, the amplitude of the cycles about the control point can be so small that the measurement record is very nearly a straight line and satisfactory control is obtained. Thermostatically controlled electric heaters, found in many parts of the plant and heating of white water are examples of on-off control systems.

A control mechanism, which could accomplish on-off control pneumatically, is shown below.

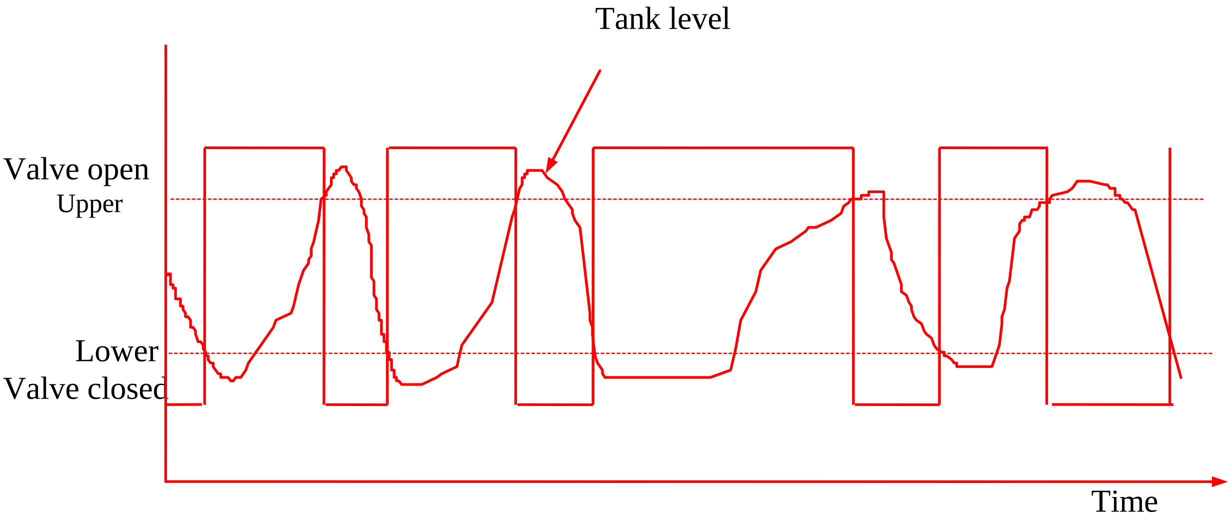


It consists, basically, of a measuring bellows, a set point bellows value and an air control relay which is an air amplifier. The flapper nozzle assembly is essentially an error detector that detects deviations of the measurement from the set point.

In operation, if the measurement bellows were at a pressure below the set point bellows, it would move the flapper through the lever system, uncovering the nozzle. This reduces the back pressure air signal from the nozzle to the relay and allows the ball valve in the relay to close. The change in the relationship of flapper to nozzle for a 3-15 psi relay output change is less than 0.001 inch. The output to the control valve assumes either a fully open or fully closed position depending on its design, and it remains in that position until the measurement changes. When the measurement signal increases, it causes the flapper to cover the nozzle, thereby increasing the air signal to the relay. This causes the ball valve of the relay to be lifted from its seat, thereby allowing full air supply pressure to actuate the control valve in the opposite direction.

Differential Gap

Differential gap is similar to on-off control except that a band exists around the control point. A typical response curve as well as the corresponding final operator action is shown below

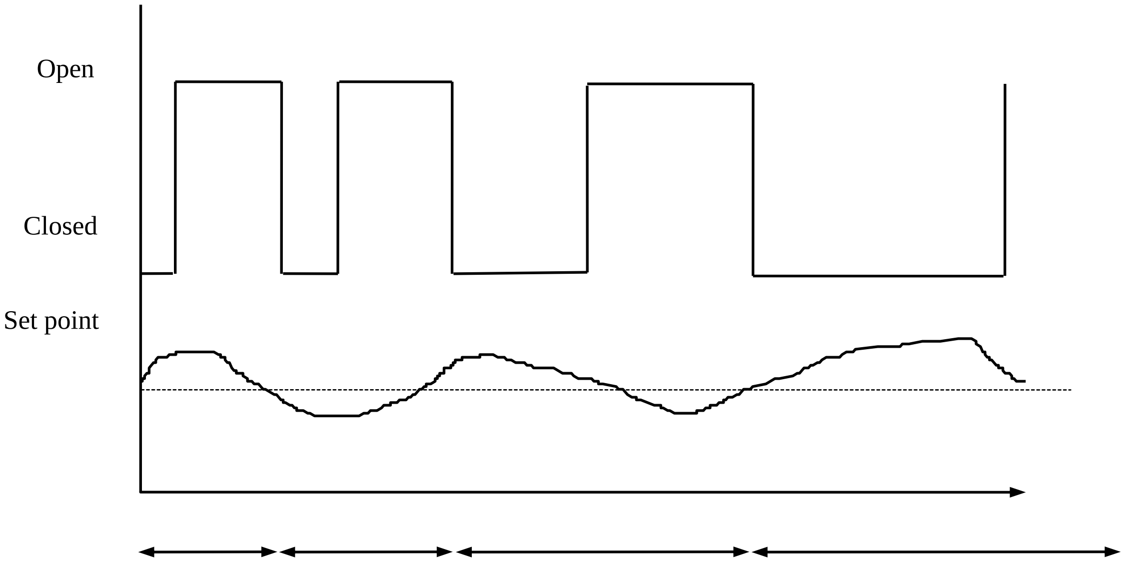


When the measured variable exceeds the upper boundary of the gap, the valve is closed. It will remain closed until the measured variable drops below the lower boundary. The valve operator will remain open until the measured variable again exceeds the upper boundary.

EXPLAIN DO NOT GIVE

Time Proportioning

In time proportioning control, a time base is established. During this time period, the final operator is closed for a certain percentage of the time and open for the rest. The ratio of the closed-to-open time is determined by the relationship between the measured variable and the control point.



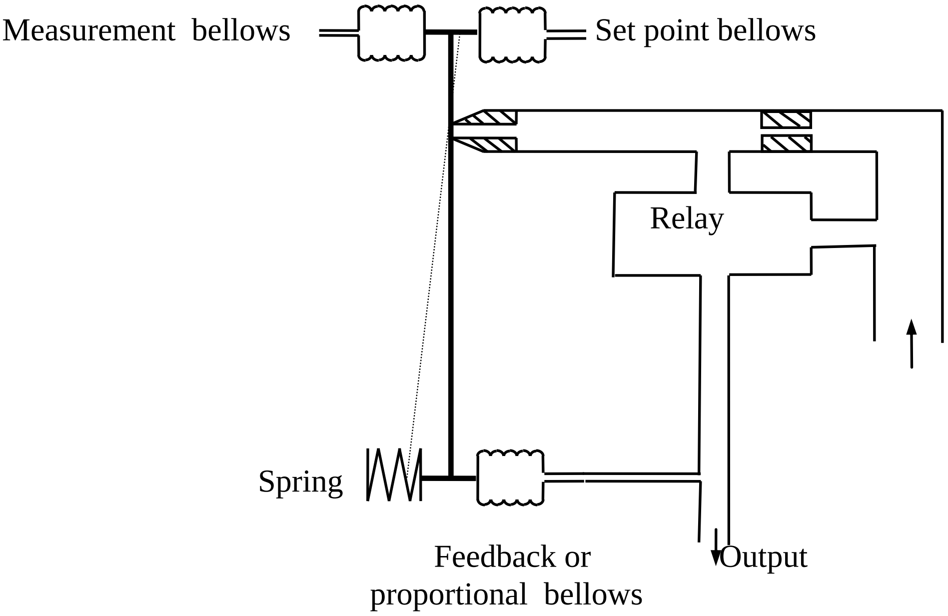
A time proportioning controller is normally set up so that when the measured variable equals the desired control point the final operator will be open for half the time cycle and closed the other half. As the measured variable drops below the control point, the final operator will remain open longer than it is closed.

Throttling Control Modes

Proportional Control

In proportional control, a throttling action is provided so that the final element (i.e. valve) balances the process input with the process demand by being positioned somewhere between fully opened and fully closed. This throttling action continuously actuates the valve so that the desired process control balance is maintained under varying conditions.

The valve position depends on the relation of the measurement to a set point. The set point is the point at which it is desired to maintain the measured variable. It is adjusted by manually positioning the control index. The control point is the value of measurement variable that the controller is maintaining. The term offset refers to the amount of deviation between the set point and control point.



The figure above shows schematically the working of a pneumatic proportional controller. It differs from the on-off controller in that a bellows and an opposing spring stabilising assembly have been added. This arrangement introduces negative feedback. The measurement bellows push the flapper close to the nozzle and the output increases, this increase is also passed to the feedback bellows which opposes the output increase and stabilises the output at some point between maximum and minimum. The proportional action may be made adjustable by the introduction of a second lever and a moveable pivot.

Proportional action may be described as output pressure change proportional to actuating signal change.

A proportional control mechanism changes the output in proportion to the change in measurement. This type of control can only keep a process variable within certain limits and, therefore, cannot be used to hold a definite or exact value. The amount that the measurement must change to move the valve from fully opened to fully closed is referred to as the proportional band.

In a sense it is the ratio of the measurement change to output change, expressed as a percentage of the total instrument range (100% change in output), which is adjustable to obtain stable control under differing process conditions.

For example, with the set point set at mid-scale (50%) and the proportional band set at 50% then the output of the controller will change from minimum to maximum for any measurement change from 25% to 75%.

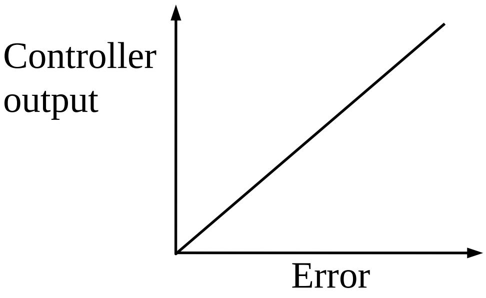
For a second example, with the proportional band set at 10% the measurement signal need only change from 45% to 55% for the output to change from minimum to maximum.

A final example, a proportional band of 200% means that the measurement signal would have to change from -100% of the set point (-50%) to +100% of set point (150%) for the output to change from minimum to maximum. Clearly this could not happen, the proportional action would only give an output change of 50%.

The measurement can stabilise at any point within the proportional band, which can be narrowed so that a greater output change will result from the same measurement change. However, there is a minimum below which the proportional band cannot be narrowed without causing the control mechanism to cycle as an on-off controller.

An alternative term for proportional action is gain, which is defined as change in output/change in input. It is a dimensionless number and is the reciprocal of proportional band. To convert percent proportional band to gain, the formula, gain = 100/PB is used.

With proportional control the size of the controller output is proportional to the size of the error, i.e. the controller input.



Thus we have a controller output proportional to the controller input. We can write this as:

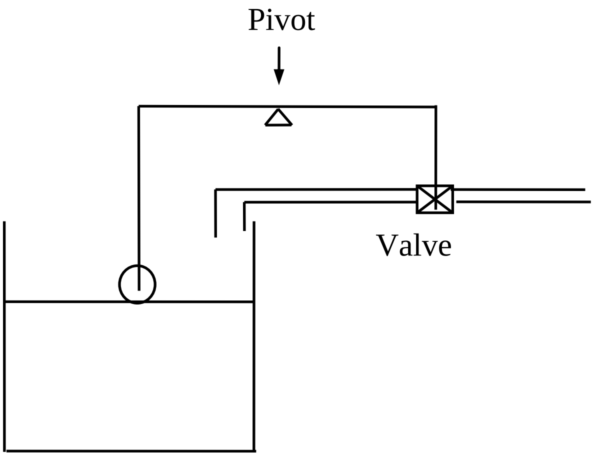
Controller output $= K_p$ x controller input

where K_p is a constant called the gain:

$$\text{gain } K_p = \frac{\text{controller output}}{\text{controller input}}$$

This means the correction element of the control system will have an input of a signal, which is proportional to the size of the correction required.

The float method of controlling the level of water in a cistern is an example of the use of a proportional controller. The control mode is determined in this case by a lever. The error signal is the input to the ball end of the lever, the output is the movement of the other end of the lever.



The error signal, which persists under steady state conditions, is termed the steady state error or the proportional offset. The higher the gain of the amplifier the lower will be the steady state error because the system reacts more quickly. All proportional control systems have a steady state error. The proportional mode of control tends to be used in processes where the gain K, can be made large enough to reduce the steady state error to an acceptable level. However, the larger the gain the greater the chance of the system oscillating and never settling down to a steady state value. The oscillations occur because of time lags in the system, the higher the gain the larger will be the controlling action for a particular error and so the greater the chance that the system will overshoot the set value

Example

A proportional controller has a gain of 3. Calculate the steady state error signal when the output of the controller is 21% different to the normal output that maintains a measurement at a set point value of 50%?

With a proportional controller we can write:

% controller output = gain x % error
21 = 3 x % error
∴ % error = 21/3
Hence the percentage error = 7%.

NOTE

Integral Action

example from control notes for C&G

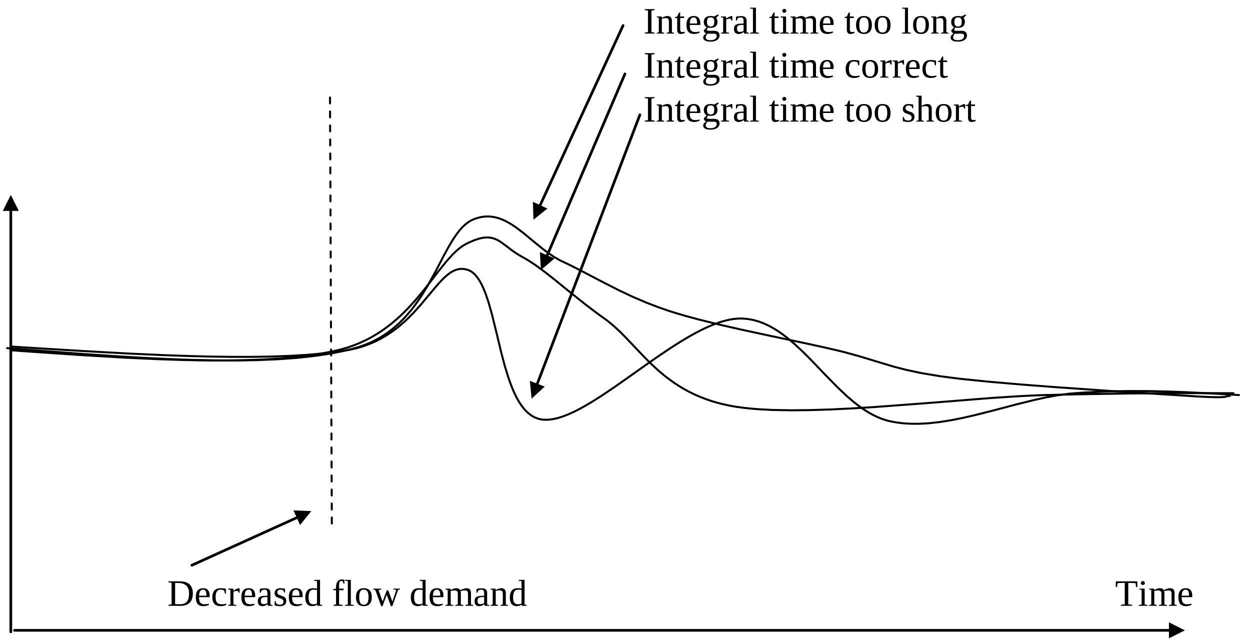
Proportional Plus Integral Control

When a process becomes more difficult to control, the proportional band must be increased in order to eliminate cycling. When the width around the set point in which the measurement will stabilise becomes so wide that poor control results, it then becomes necessary to introduce a control function which will maintain the measurement at a precise point instead of just within the band.

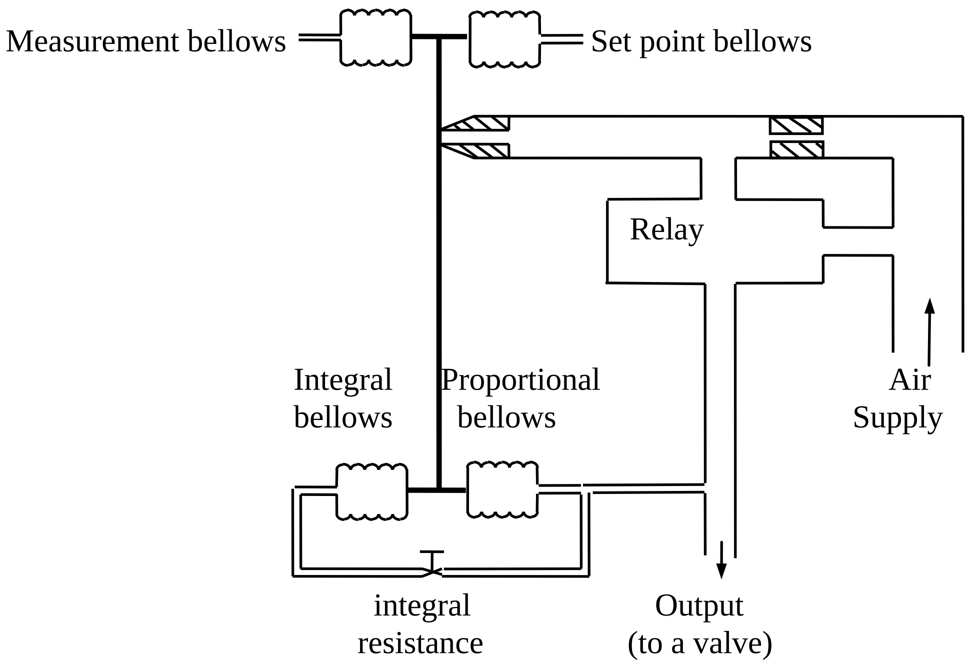
This control mode, known as integral or reset action, is added to the proportional control mode. With the integral control, the valve movement is a function of the magnitude and duration of the measurement deviation from the set point, whereas with the straight proportional controller it is a function of the deviation magnitude only.

Therefore, instead of having a specific valve position for each measurement deviation, the proportional-plus-integral controller can position the valve anywhere from fully opened to fully closed for a given measurement. The valve is continuously positioned as necessary to keep the measurement at the control point. The correct integral rate is determined by the process just as is the proportional band. This rate (time) is set in accordance with the natural reaction time of the process.

The proportional-plus-integral control response curves below show that when integral time is set correctly the valve is stroked at a rate at which the process can respond. If the integral time is set too fast, the valve will move faster than the measurement and cycling will result; if it is set too slow, the process will not return to the set point quickly enough.



The figure below shows schematically the operation of a pneumatic proportional plus-integral controller. It differs from the proportional controller in that the opposing spring has been replaced with an integral bellows and an integral resistance or restrictor has been added.



In operation, if the measurement signal increases the lever moves to the right, the flapper will approach the nozzle and the air pressure to the valve will be increased as with the proportional controller. This same pressure is applied directly to the proportioning bellows and through the integral resistance to the integral bellows. The function of the resistance is to control the integral time or rate at which the pressure in the integral bellows approaches the pressure in the proportioning bellows. When the pressures are equal the controller is in a balanced condition. If a process upset or load change takes place causing a deviation between measurement and set point, the pressure to the control valve and the proportioning bellows will increase or decrease. Simultaneously, the pressure in the integral bellows changes in proportion to the magnitude and duration of the deviation. As long as the deviation is other than zero there will be a difference in pressure between the two bellows, allowing the corrective action to continue. This resetting action by the integral bellows causes the controller to be in balance at whatever valve output pressure is necessary to keep the measurement at the control set point. The integral resistance is adjustable to permit matching of the controller response to the process characteristics.

Proportional plus Integral control

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

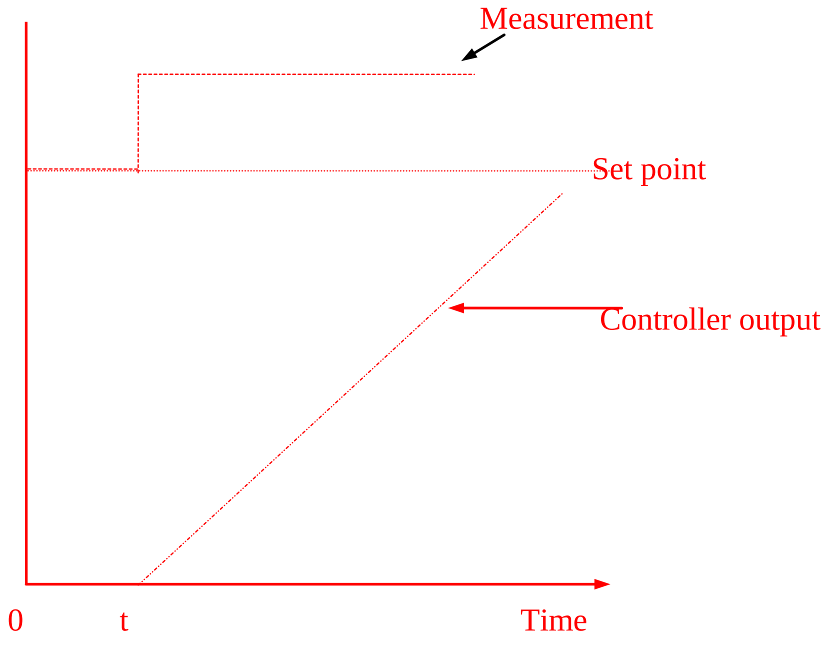
controller output is proportional to the integral of error with time

and so we can write:

controller output = K_I x integral of error with time.

Where K_I is the constant of proportionality and, when the controller output is expressed as a percentage and the error as a percentage has units of s^{-1}. The reciprocal of K_I is called the integral time T_I and is in seconds.

To illustrate what is meant by the integral of the error with respect to time, consider a situation where the error varies with time in the way shown below:



Integral control

The value of the integral at some time t is the area under the graph between *t* = 0 and *t*. We have therefore the controller output proportional to area under the error graph between *t* = 0 and *t*.

As *t* increases, the area increases and so the controller output increases. Since, in this example, the area is proportional to *t* then the controller output is proportional to *t* and so increases at a constant rate. Note that this gives an alternative way of describing integral control as:

rate of change of controller output is proportional to the error

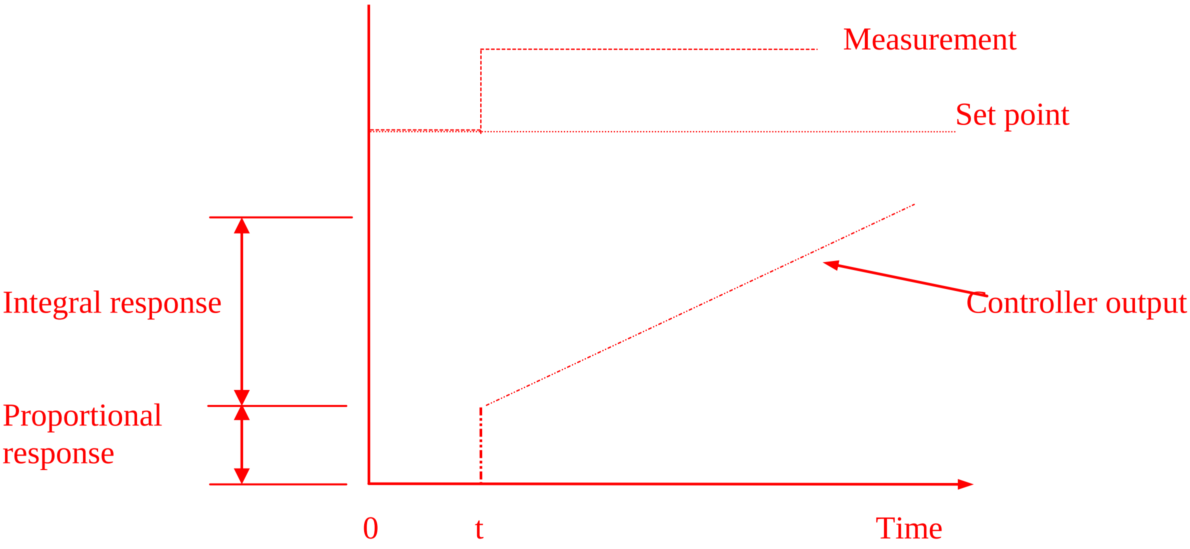
A constant error gives a constant rate of change of controller output.

The integral mode of control is not usually used alone but generally in conjunction with the proportional mode. When integral action is added to a proportional control system the controller output is given by:

controller output = K_P(error + integral of error with time)

Where K_P is the proportional control constant and K_I the integral control constant.

The figure below shows how the proportional-integral controller reacts when there is an abrupt change to the measurement.

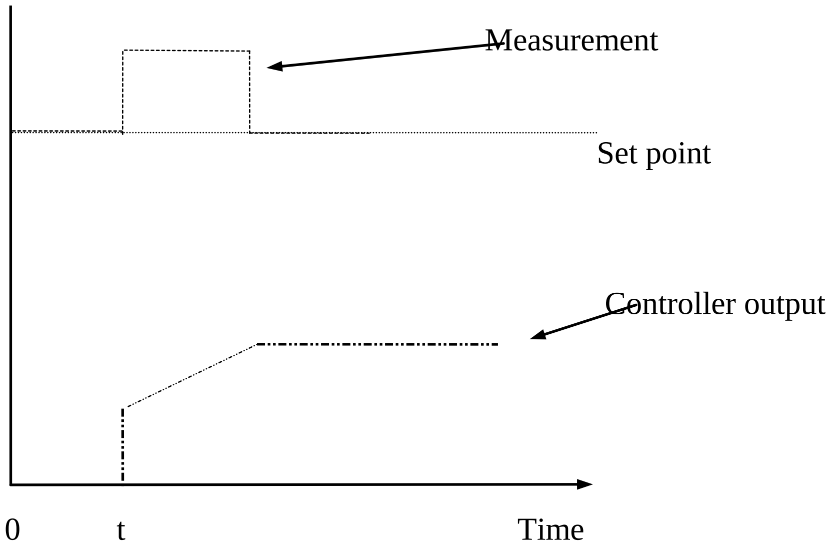


Proportional-Integral control

The error gives rise to a proportional controller output, which remains constant since the error does not change. There is then superimposed on this a steadily increasing controller output due to the integral action.

The combination of integral mode with proportional mode has one great advantage over the proportional mode alone: the steady state error can be eliminated. This is because the integral part of the control can provide a controller output even when the error is zero.

The controller output is the sum of the area all the way back to time *t* = 0 and thus even when the error has become zero, the controller will give an output due to previous errors and can be used to maintain that condition. The figure below illustrates this:

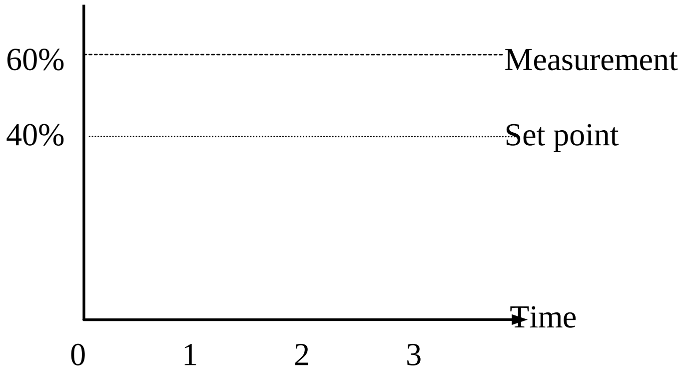


Proportional-Integral control

The lack of a steady state error with this type of controller means it can be used where there are large changes in the process variable. However, because the integration part of the control takes time, the changes must be relatively slow to prevent oscillations.

Example

An integral controller has a value of K_I of 0.10 s^{-1}. What will be the output after times? (a) 1 s, (b) 2 s, if there is a sudden change to a measurement/set point difference of 20%.



We can use the equation: controller output = K_I x integral of error with time

(a) The area under the graph between a time of 0 and 1 is 20% i.e. the difference between the set point and the measurement. Thus the controller output is

0.10 x 20 = 2%

(b) The area under the graph between a time of 0 and 2 s is 40 %s. Thus the controller output

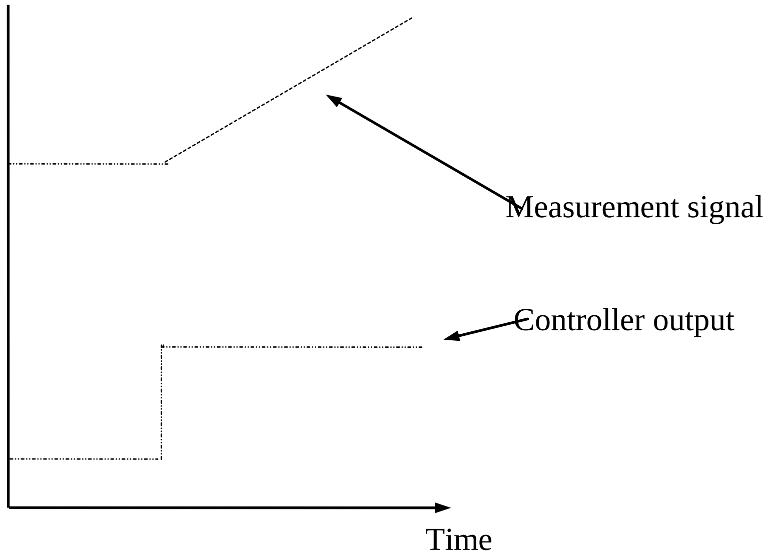
is 0.10 x 40 = 4%

Note: the increase is linear.

Proportional Plus Derivative Control

With derivative control the change in controller output from the set point value is proportional to the rate of change with time of the error signal, i.e. controller output is proportional to the rate of change of error. Thus we can write:
controller output = K_D x rate of change of error

It is usual to express these controller outputs as a percentage of the full range of output and the error as a percentage of full range. K_D is the constant of proportionality and is commonly referred to as the derivative time since it has units of time. The figure below illustrates the type of response that occurs when there is a steadily increasing error signal.



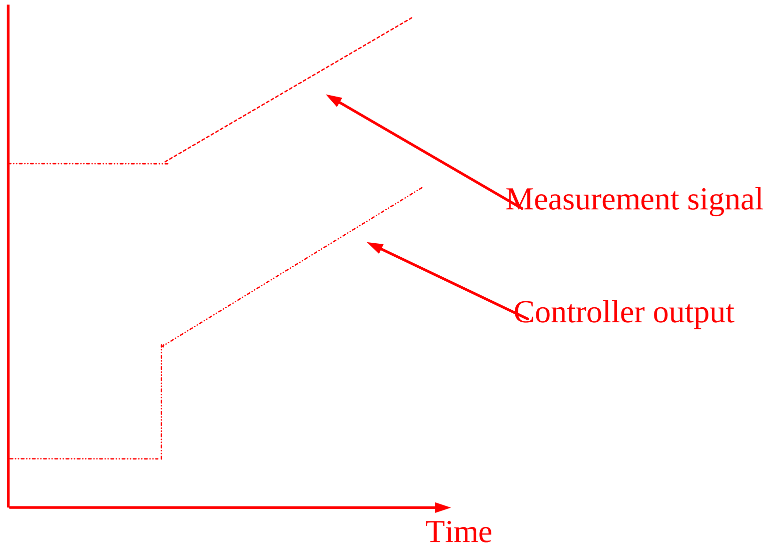
Because the rate of change of the error with time is constant, the derivative controller gives a constant controller output signal to the correction element. With derivative control, as soon as the error signal begins to change there can be quite a large controller output since it is proportional to the rate of change of the error signal and not its value. Thus with this form of control there can be rapid corrective responses to error signals that occur.

Derivative controllers give responses to changing error signals but do not, however, respond to constant error signals, since with a constant error the rate of change of error with time is zero.

Because of this, derivative control is combined with proportional control. Then we have:

controller output = K_P (error + K_D x rate of change of error with time)

The figure below shows how, with proportional plus derivative control, the controller output can vary when there is a constantly changing error.



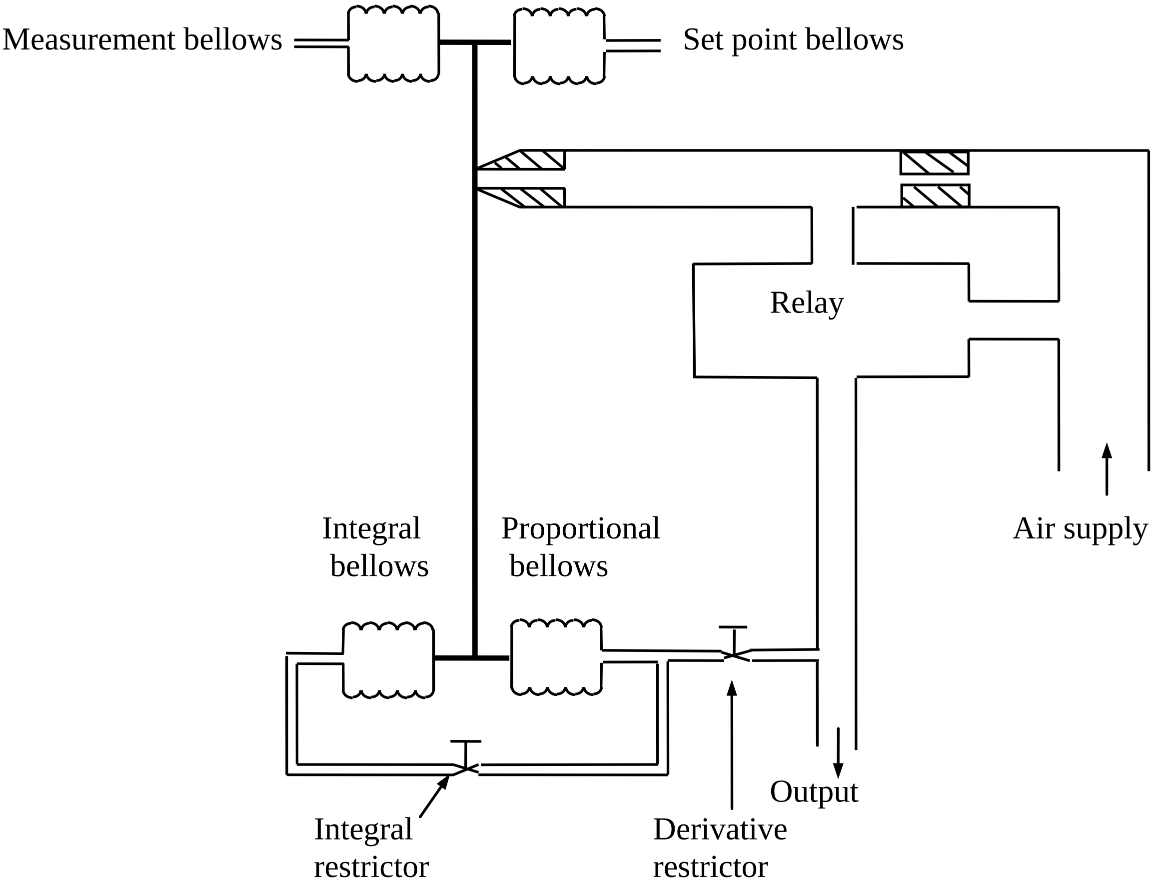
There is an initial quick change in controller output because of the derivative action followed by the gradual change due to proportional action. This form of control can thus deal with fast process changes better than just proportional control alone. It is still like proportional control alone and needs a steady state error in order to cope with a constant change in input conditions or a change in the set value.

Proportional Plus Integral Plus Derivative Control

There are processes in the pulp and paper industry with long time lags, some of which involve the measurement of temperature and pH, when the proportional-plus integral control mode response may not be sufficient to stabilise itself fast enough on the occurrence of an upset. Under these conditions an additional control mode, derivative, is used to improve the control. It has been shown that the proportional mode produces a valve response proportional to the deviation of the measurement from the set point, and integral response is proportional to the time that the measurement is away from the set point. Derivative response is proportional to the rate at which the measurement departs from the set point and is sometimes considered an anticipatory action. Because it is rate-sensitive, the derivative control mode when added to the proportional-plus-integral-plus-derivative control mode permits the use of a narrower proportional band, thus reducing the amount of possible measurement deviation and overshoot on process upset.

In effect, it functions to reposition the valve sooner in order to stabilise process upsets. The integral action continues to reposition the valve until any offset or deviation is eliminated, resulting in fast stabilisation of process at the set point.

A typical pneumatic proportional-plus-integral-plus-derivative controller is shown schematically below. It differs from the proportional-plus-integral controller previously described in that an adjustable derivative resistance (restrictor) is added to the feedback circuit.



With the measurement at the set point, pressures in the proportional and integral bellows are equal to the output pressure of the controller. If the measurement starts to increase at a uniform rate, the derivative restrictor will delay the output pressure from reaching the proportional and integral bellows and the effect of reducing the output by the proportional bellows will be delayed. During the duration of the change, a constant differential pressure is maintained across the derivative restrictor and there is a constant flow through it into the proportional bellows. Simultaneously, this flow establishes a differential pressure and, thus, a flow across the integral restrictor that increases linearly as measurement continues to increase. When measurement stops increasing, derivative action decreases control output by an amount proportional to the rate of change of the measurement. By design, this rate of change is equal to the initial rate of change; therefore, output changes equal amounts in the opposite directions. In this way, immediate response to measurement changes is obtained. Normally, derivative time is somewhat shorter than integral time but both restrictors must be adjusted to match process dynamics.

Three Term Control

Combining all three modes of control (proportional, integral and derivative) enables a controller to be produced, which has no steady state error and reduces the tendency for oscillations. Such a controller is known as a three term controller or PID controller. The equation describing its action is:

controller output = K_P(error + K_I x integral of error + K_D x rate of change of error)

where K_P is the proportionality constant, K_I the integral constant and K_D the derivative constant. A three-mode controller can be considered to be a proportional controller, which has integral control to eliminate the offset error and derivative control to reduce time lags.

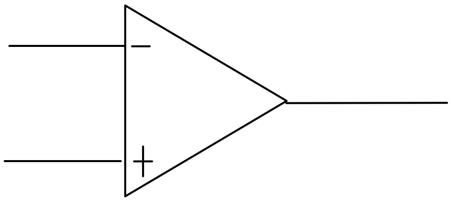
Operational Amplifier PID Control

Electronic control mechanisms can perform the same functions as their pneumatic counterparts. At one time, practically all electronic instrumentation was designed around slidewires, vacuum tubes, transformers, and other comparatively large-sized components. Today, all modern controllers are electronic using solid-state components such as diodes, transistors, magnetic amplifiers, ICs etc. The common signal levels for electronic controllers are 10-50 or 4-20 milliampere dc. Controller outputs as dc signals must be converted to air signals when used with pneumatic final control element operators.

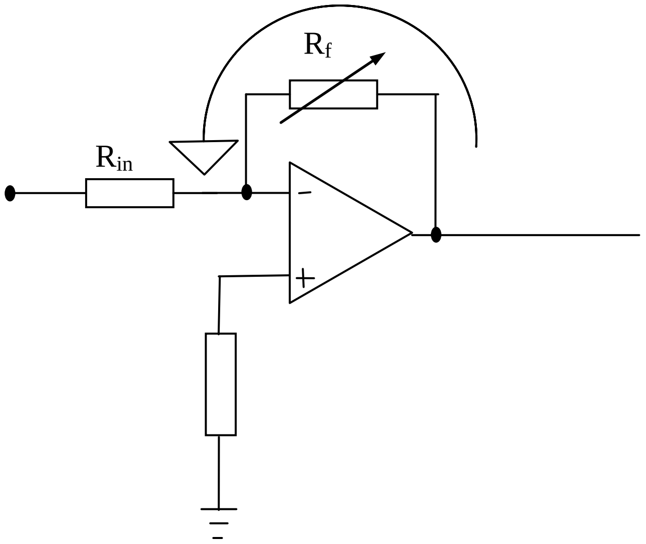
The early op-amps circuits were made out of discrete components i.e. individual components such as resistors, capacitors, transistors etc. but now the circuit which was once built from perhaps 100 components, can be built with a small Integrated circuit (IC) and a few external components. An IC contains a large number of components which are formed on a miniature silicon chip.

The operational amplifier is the basis of many signal processing elements, the basic amplifier being supplied as an integrated circuit on a silicon chip The symbol for an op-amp is given below and as you can see there are two inputs, one marked positive and one marked negative. The positive terminal is called the non-inverting input because any positive signal applied to this terminal will arrive at the output positive. The negative terminal is called the inverting input because a positive signal applied to this terminal will arrive at the output negative i.e. the signal has been inverted.

Put another way if the non-inverting (+) input is made more positive than the inverting (-) input then the output will be positive. But if the inverting (-) is made more positive than the non-inverting (+) input then the output will be negative.



The op-amp has a very large gain, which unless controlled, is of no use in a control situation. To control the gain of the op-amp we use negative feedback as illustrated below. R_f = feedback resistance.



The gain of an op-amp is so large it is convenient to consider it infinite.
The gain, symbol A, is given in the above diagram by:-

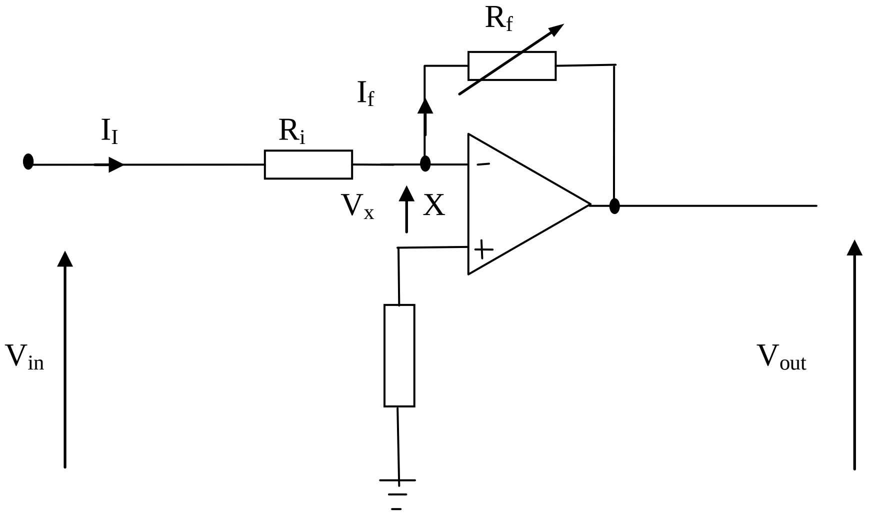
$$A = \frac{R_f}{R.in}$$

Proportional Action

To refresh your memory proportional action is when the rate of change of output is proportional to the rate of change of input. Or put another way the output of the controller is proportional to the input.

A proportional control circuit is one in which the output voltage of the controller (which drives the controlling device) is proportional to the difference between the system set point voltage and the measured value voltage.

The input to this amplifier will come from the comparison unit (i.e. the error signal).



The input is connected to the inverting input, the non-inverting input being connected to earth through a resistor. A feedback loop is connected, via the resistor R_f to the inverting input. The output voltage of such an amplifier is limited to about ±10 V.

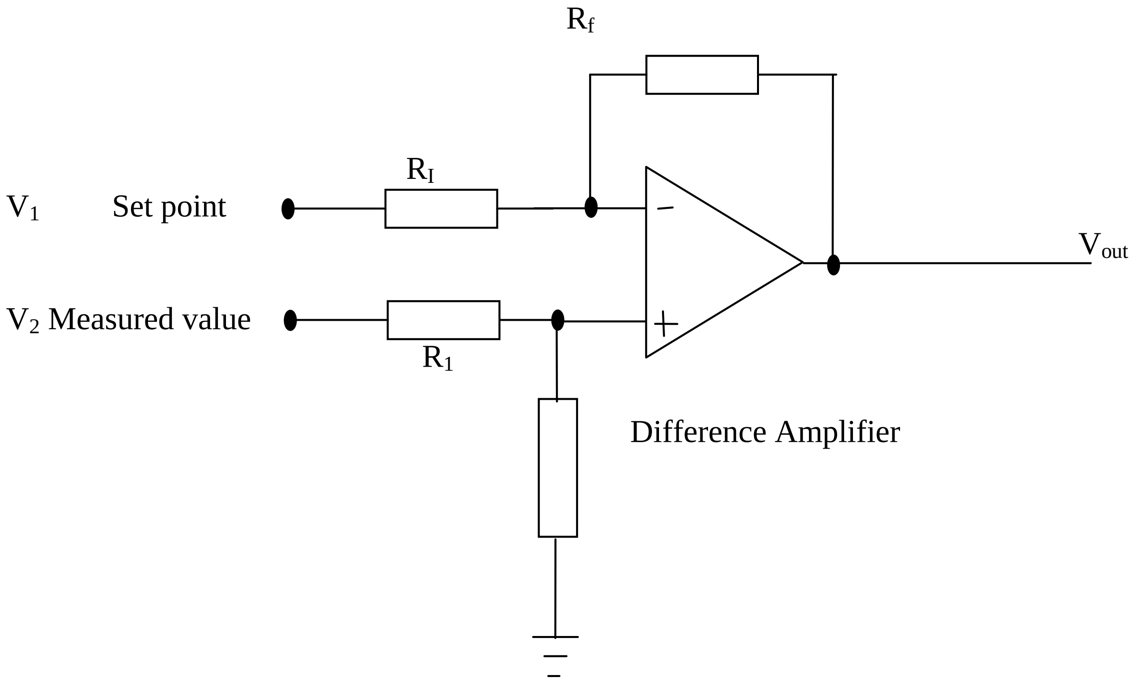
Since the gain is about 100 000, the input voltage to the inverting input at X, V_X, must be between about +0.0001 V and -0.0001 V.

This is virtually zero and so point X is at virtually earth potential.

For this reason it is called a **virtual earth**.

Comparison Unit

One basic function must be performed in any electronic controller, the difference between set point and measured value must be determined. Consider the diagram below:



From the diagram it can be seen that there are two inputs, set point and measured value. The main point to appreciate is that the amplifier amplifies the difference between the set point and the measured value, which therefore gives us an error signal. This error signal can then be applied to further stages of a controller before being used by the correcting device of the system (i.e. valve). An op-amp used in this way is know as a Difference Amplifier.

The output of the amplifier is given by:

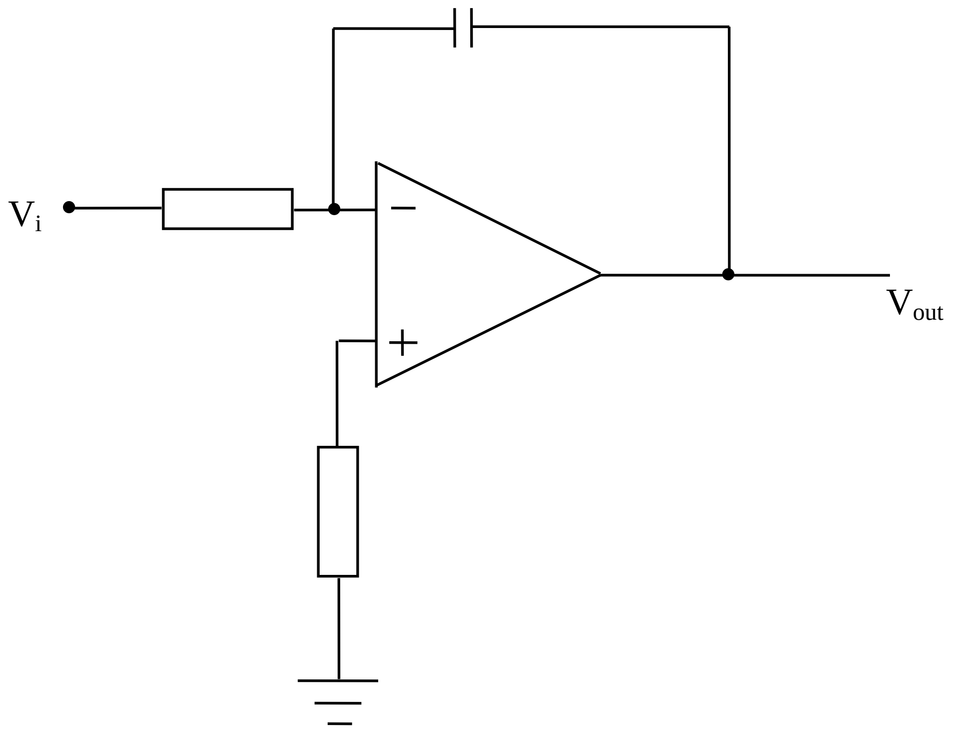
The output (V_{out}) = the gain (R_f/R_I) x the error signal (V_2-V_1)

$$V_{out} = \frac{R_f}{R_i} \times (V_2 - V_1)$$

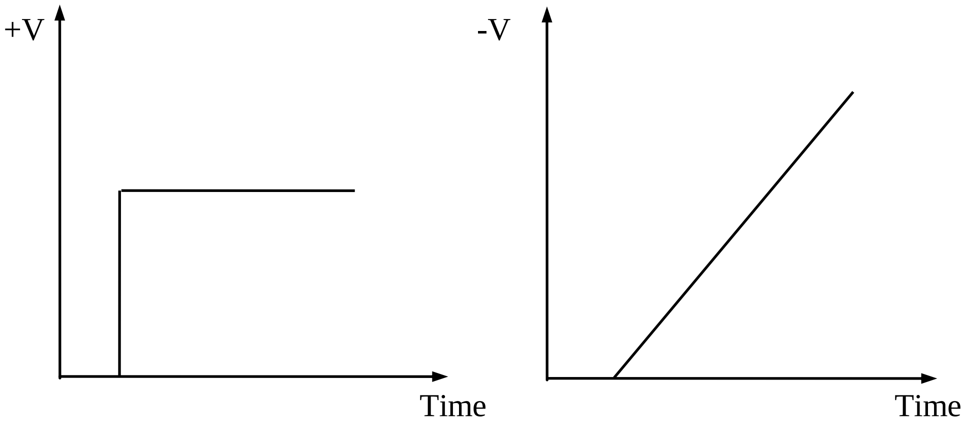
Integral Action

First, lets recall what we mean by Integral action. Integral action may be defined as a control action which varies at a rate which is proportional to the deviation (i.e. the difference between the measured variable and the set value).

In controller, if there is a difference between the measurement and set point signals then the difference amplifier will output a signal to the integrator. The amplifier which produces integral action is shown below.



As we know the Integral action will produce an output change while there is a difference between measured and set values. This can be seen in the figure below where (a) represents an Input from the difference amplifier and (b) represents the output of the integrator.



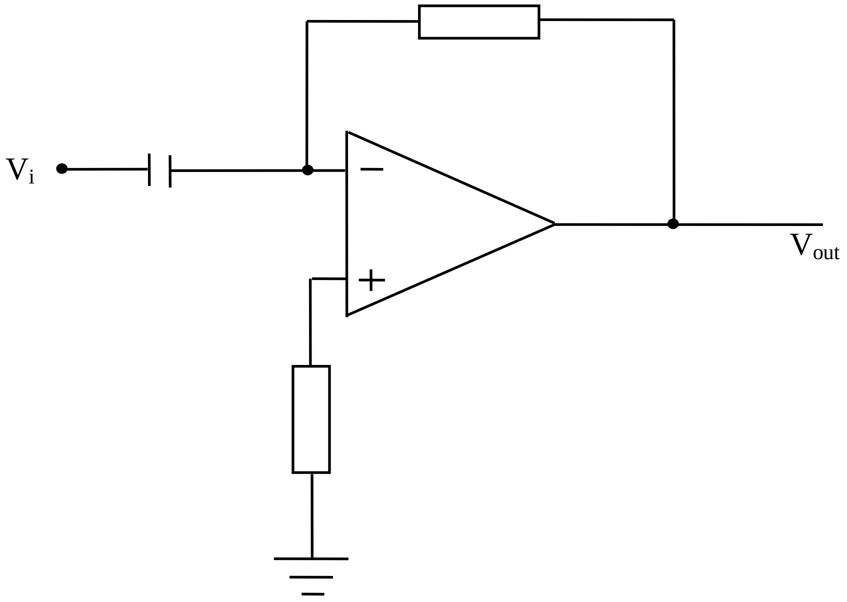
(a) Input to intergrator (b) Output from integrator

From the figure above it can be seen that the output of the integrator rises while there is an input from the difference amplifier. The output from the integrator would continue to rise until the output reached the supply voltage level of the amplifier.

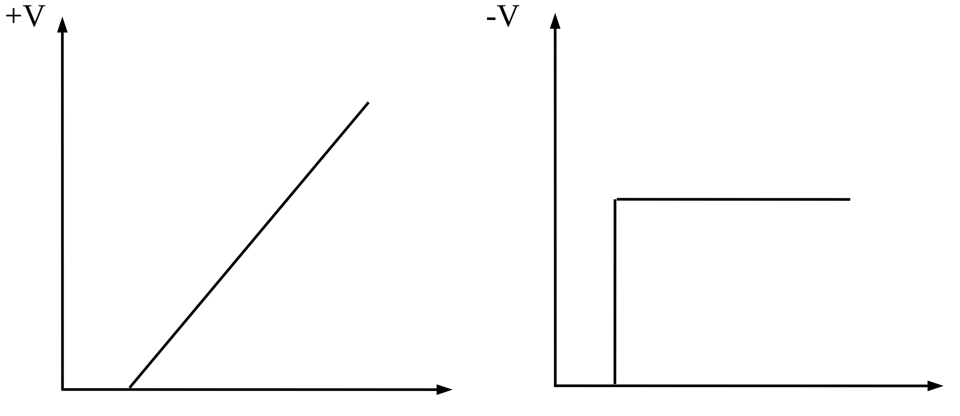
Derivative Action

Again, let us, refresh our memory. The derivative response can be defined as proportional to the rate at which the measured variable moves away from the control point.

We need therefore., a circuit which produces an output proportional to the rate of change of the input. The circuit which gives us this effect, is given below:



When considering the pneumatic controller we saw that if a ramp or sudden step change is applied the derivative response is an instant output. This is shown in the figure below:

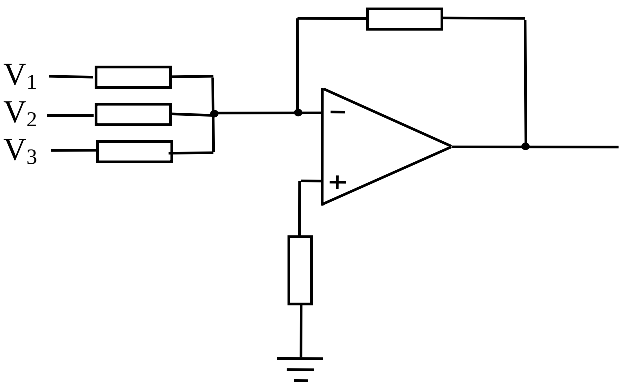


(a) Input to the differentiator (b) Output from the differentiator

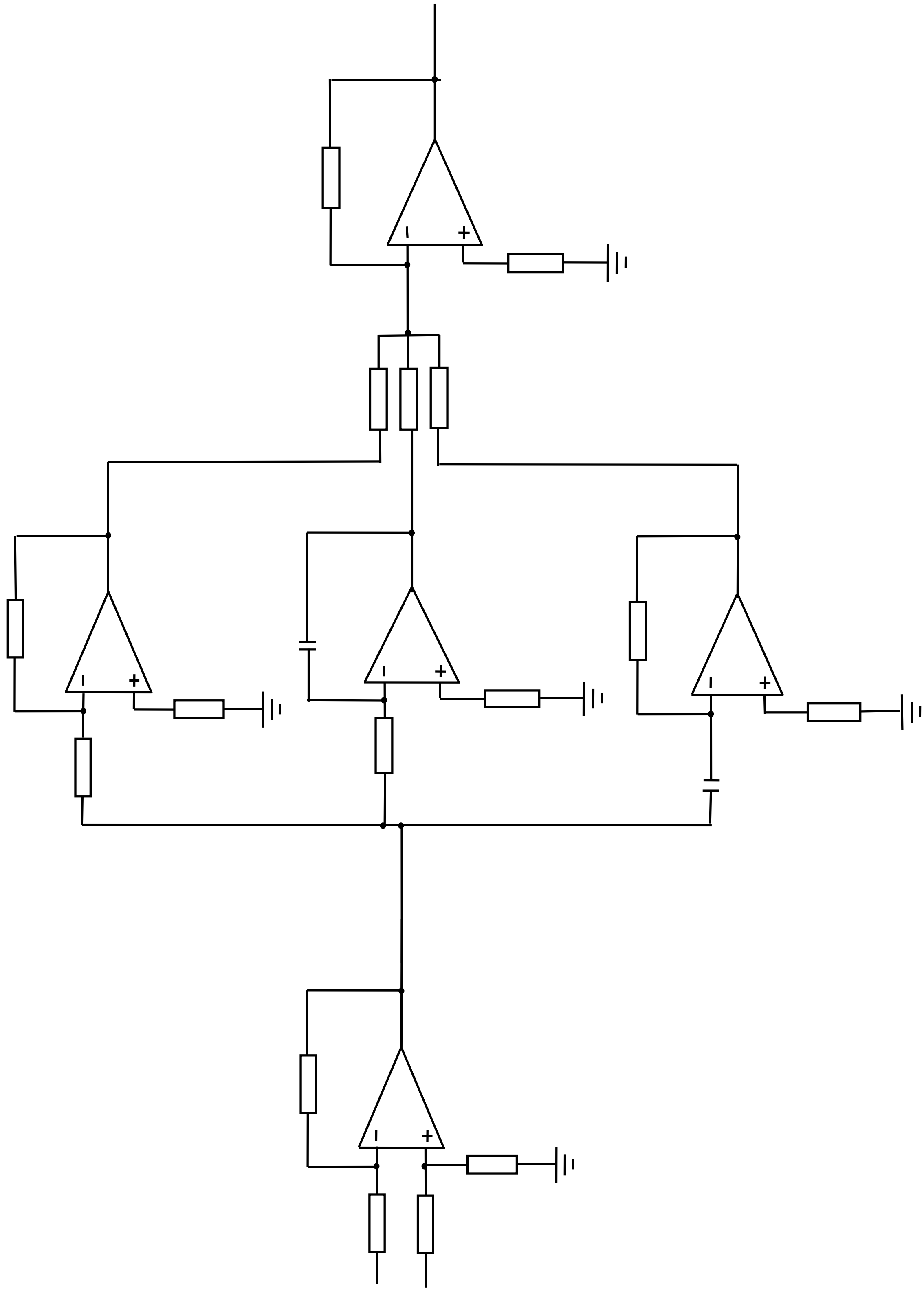
A complete electronic controller has all the control functions necessary to control but the output need to be combined. This circuit is called a summing amplifier and is covered below.

The Summing Amplifier

The summing amplifier does as the name implies - algebraically adds voltages. In the figure below the three voltages from the proportional (V1) integral (V2) and derivative (V3) circuits will be added together in the summing amplifier and the resultant output (Vout) would be used as an output to correct the error.

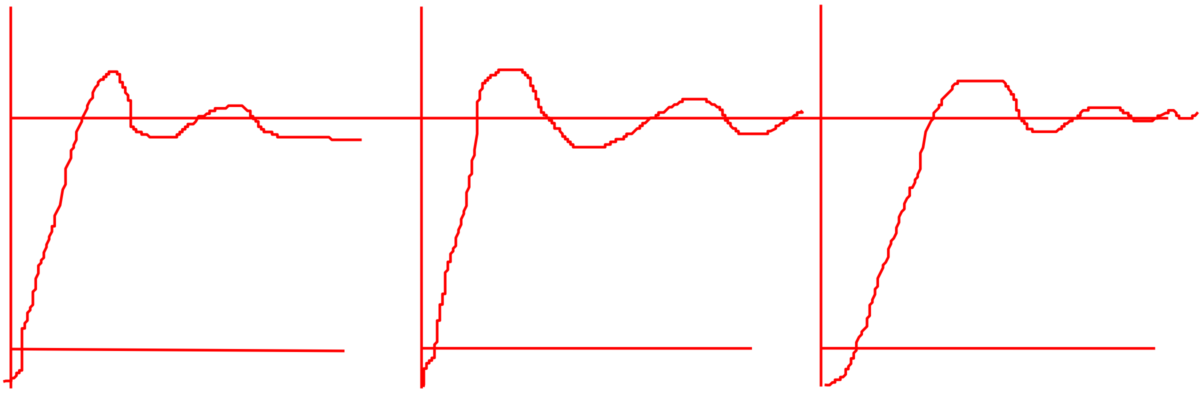


The necessary sections for an electronic three term controller (P + 1 + D), a two term proportional + Integral (P + 1) controller or a single term proportional controller. The figure below joins all parts in depicting a three term controller.



Controller Tuning

The purpose of tuning a controller is to match the gain and time functions of the controller with the rest of the elements in the control loop (process, transmitter, valve, etc.). There are a number of practical and theoretical approaches to controller tuning. Mathematical equations can be used to predict ideal proportional, integral, and derivative settings for a given process. The predominant practice in the pulp and paper industry is to tune controllers by practical experience and/or by trial-and-error method. This means determining whether P, P + I, or P + I + D is to be used (these are the most common configurations in the paper industry) and selecting the values of K_P, K_I and K_D. These determine how the system reacts to a disturbance or a change in the set value, how fast it will respond to changes, how long it will take to settle down after a disturbance or change to the set value, and whether there will be a steady state error.



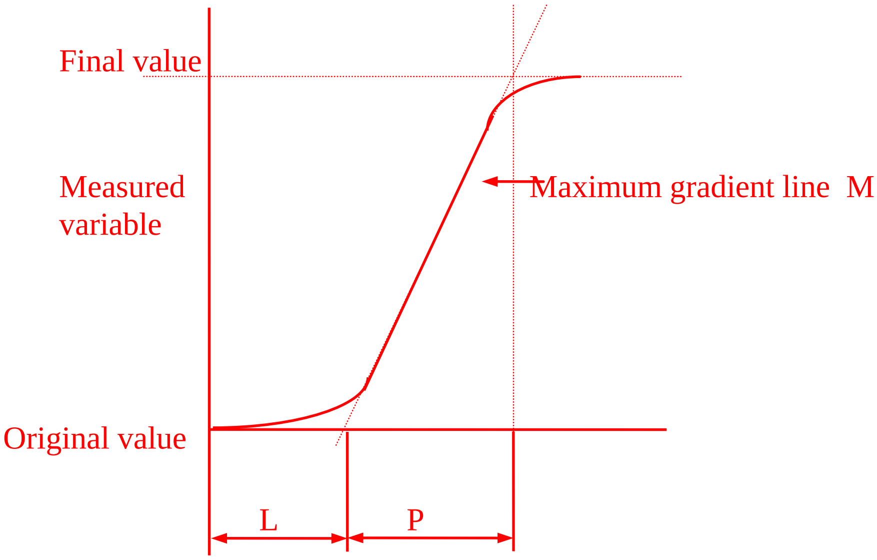
The figures above illustrates the types of response that can occur with the different modes of control when subject to a step input, i.e. a sudden change to a different constant set value or perhaps a sudden constant disturbance. Proportional control gives a fast response with oscillations which die away to leave a steady state error. Proportional plus integral control has no steady state error but is likely to show more oscillations before settling down. Proportional plus integral plus derivative control has also no steady state error, because of the integral element, and is likely to show fewer oscillations than the proportional plus integral control. The inclusion of derivative control reduces the oscillations.

The following are two methods that can be used; both devised by *Ziegler and Nichols.*

Process Reaction Method

This method uses certain measurements made from testing the system with the control loop open so that no control action occurs. The controller is placed on manual and the correction unit held in a fixed position. Alternatively a break can be made between the controller and the correction unit. A test-input signal then applied to the correction unit and the response of the process recorded.

The test signal is a step signal with a step size expressed as the percentage change in the correction unit (% change in valve position). The response of the controlled variable to such an input is monitored and a graph of the measured variable plotted, as shown below.



This graph produced is called the *process reaction curve.* A tangent is drawn to give the maximum gradient of the graph. The time between the start of the test signal and the point at which this tangent intersects the graph time axis is termed the lag L. If the value of the maximum gradient is M, expressed as the percentage change of the set value of the variable per minute, then the criteria recommended by Ziegler and Nichols for control settings are:

For Proportional control

$$K_p = \frac{P}{ML}$$

For Proportional & Integral control

$$K_p = 0.9 \frac{P}{ML}$$

$$K_I = \frac{0.3}{L} \text{ min}^{-1}$$

For Proportional, Integral & Derivative control

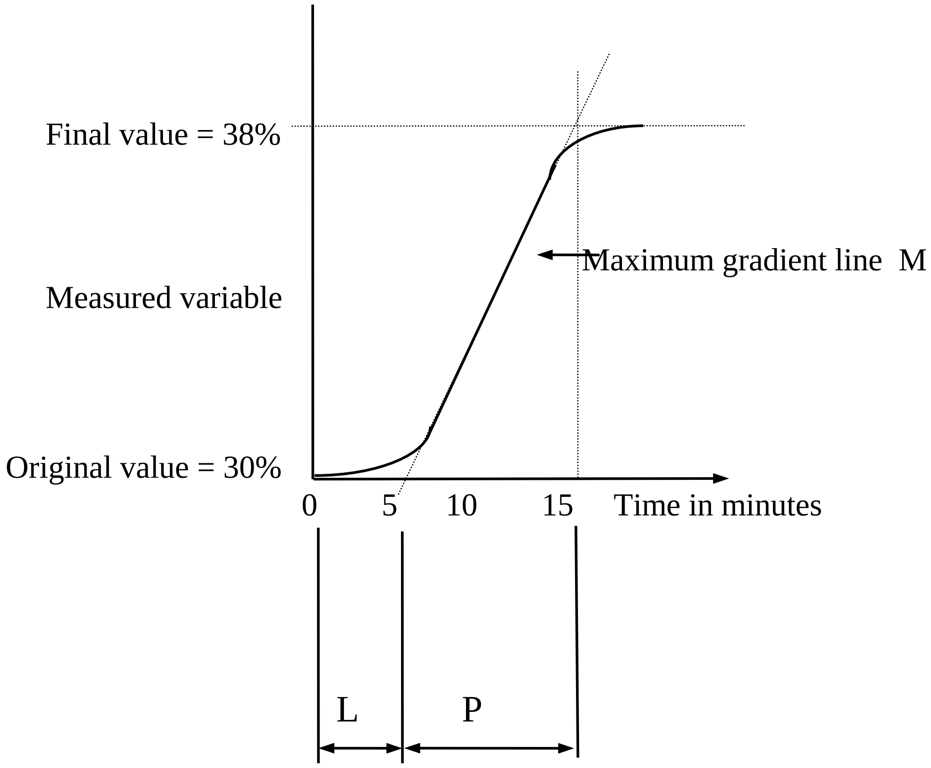
$$K_P = 1.2 \frac{P}{ML}$$

$$K_I = \frac{0.5}{L} \text{ min}^{-1}$$

$$K_D = 0.5L \text{ min}$$

Example

Determine the settings of K_P, K_I & K_D required for a three-term controller, which gave a process reaction curve shown below, when the test signal was a 10% change in the control valve position.



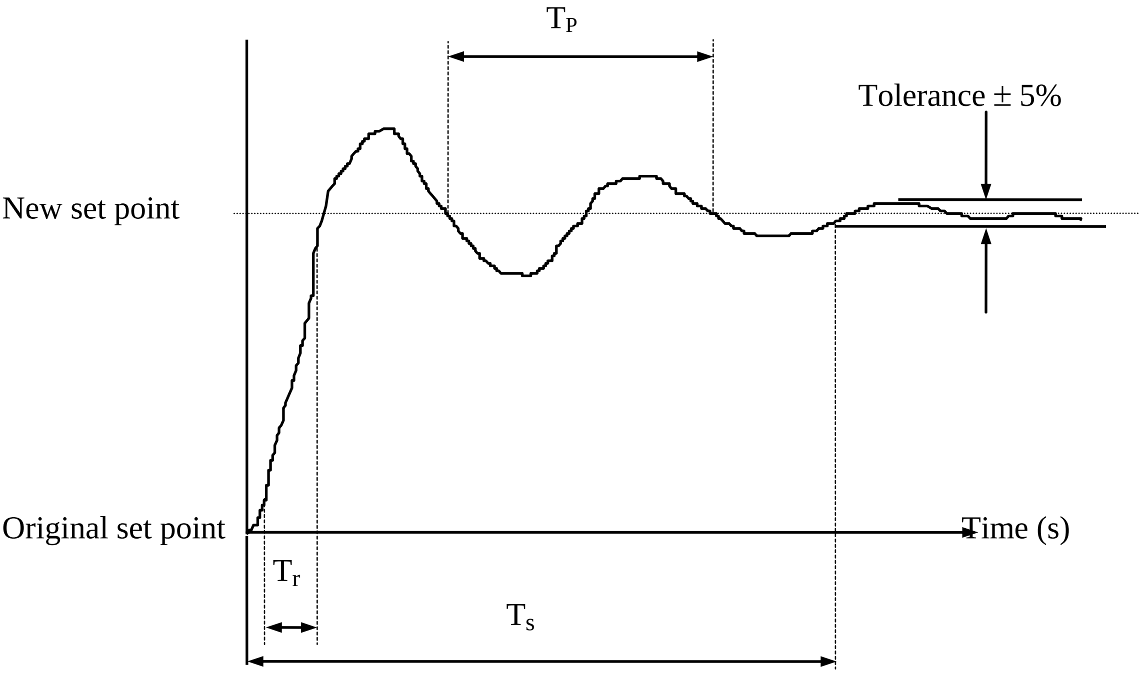
Drawing a tangent to the maximum gradient part of the graph gives:
a lag L of 5 minutes
a gradient M of 8/1 0 = 0.8 %/min. Hence:

$$K_P \quad \frac{1.2P}{ML} = \frac{1.2 \times 10}{0.8 \times 5} = 3$$

$$K_I = \frac{0.5}{L} = \frac{0.5}{5} = 0.1 \text{ min}^{-1}$$

$$K_D = 0.5L = 0.5 \times 5 = 2.5 \text{ min}$$

Response definitions



Rise Time T_r. The time needed for the response to rise from 10% to 90% of its final value.

Settling Time T_s. The time for the response to reach its final value (within its tolerance).

Periodic Time T_p. The time for one complete cycle of the system response.

Ultimate Cycle Method

With this method, the integral and derivative actions are first reduced to their least effective values. The proportional constant K_P, is then set low and gradually increased until oscillations in the controlled variable start to occur. The critical value of the proportional constant K_P at which this occurs is noted and the periodic time of the oscillations T_P, measured. The Ziegler and Nichols recommended criteria for controller settings are then:

For Proportional control

$$K_P = 0.5K_{PC}$$

For Proportional & Integral control

$$K_P = 0.45K_{PC}$$

$$K_I = \frac{1.2}{T_P}$$

For Proportional, Integral & Derivative control

$$K_P = 0.6K_P$$

$$K_I = \begin{matrix} 2.0 \\ T_P \end{matrix}$$

$$K_D = \frac{TP}{8}$$

Trial and error method

With a proportional controller, the following procedures may be followed:

1. Place the controller on manual.
2. Adjust the proportional band to maximum.
3. Place the controller on automatic.
4. Make a step change in controller set point.
5. Observe the resulting measurement cycle.
6. Reduce the proportional band and repeat steps 4 and 5.
7. Repeat steps 4, 5, and 6 until an amplitude cycle and optimum recovery to stability are observed.

With a proportional-plus-integral controller:

1. Place the controller on manual.
2. Adjust the proportional band to maximum.
3. Set the integral to maximum time.
4. Place the controller on automatic.
5. Adjust the proportional band to an optimum setting as with the proportional controller.
6. Reduce the integral time in steps until cycling begins.
7. Increase the integral time until cycling disappears.

A practical adjustment procedure for tuning a proportional-plus-integral-plus-derivative controller is:

1. Place the controller on manual.
2. Adjust the proportional band to maximum.
3. Set the integral to maximum time.
4. Set the derivative to minimum time.
5. Place the controller on automatic.
6. Adjust the proportional band to an optimum setting as with the proportional controller except that a slight cycle should remain in controller.
7. Increase the derivative time until the cycle stops.
8. Narrow the proportional band until the cycle starts again.
9. Repeat steps 7 and 8 until further increases in the derivative time fail to stop the cycle.
10. Widen the proportional band to stop the cycle.
11. Set the integral time equal to the derivative time.

CONTROL VALVES

Introduction

The control valve plays a very important part in the automatic control of modern plants, which depend on the correct distribution and control of flowing liquids or gases. Such control, whether for the exchange of energy, reduction of pressure, or simply to fill a tank, depends on some form of **final control element** to do the job. Final control elements may be considered the ‘muscle’ of automatic control. They furnish the necessary power amplification between the low energy levels in controllers and the higher energy levels needed to perform their function in controlling flowing fluids.

The control valve is the most widely used type of final control element. Other final control elements include metering pumps, dampers and louvers (a variation of a butterfly valve), variable pitch fan blades, electric current control devices, and electric motors for draw control and positioning devices other than valves.

Despite the control valves wide use, there is probably no other element in the control system that receives less attention. In many systems, a control valve is subjected to more severe conditions of temperature, pressure, corrosion and contamination than other components, yet it must perform satisfactorily, with a minimum amount of attention, as it manipulates the flow of process fluid.

A control valve functions as a variable resistance in a pipeline. It provides a pressure drop by changing the turbulence in the process fluid or, in the case of laminar flow, the changed valve resistance or ‘drag’ cause the pressure drop. This pressure drop process is often called ***throttling.***

A complete control valve consists of three major components:

1. The actuator transforms the controller signal into motion, providing power to vary the orifice.
2. The valve body assembly consists of a pressure-tight fitting.

The fitting is threaded, flanged, or welded in a fluid flow line and contains one or more internal orifices through which fluid flow is controlled,

3. A plug, damper, or louver is positioned in the orifice by the actuator to control the pressure drop and rate of flow,

ACTUATORS

Depending on the input signal, control valve actuators may be pneumatically, electrically, hydraulically, mechanically, or manually operated. Pneumatic operation is the most widely used actuation method in the pulp and paper industry. Some electric, hydraulic, electrohydraulic, and mechanical actuators have been used in areas where no operating air is available, or where low ambient temperatures create problems of water freezing in the air lines. The two major types used are the diaphragm type and the cylinder type. The diaphragm type may be either spring or spring-less while cylinder types are usually spring-less.

The valve body

Essentially the valve body is a pressure tight fitting that is screwed or flanged into a fluid flow line. The most common control valve body is the globe valve, it can be either single or double seated.

The single seated valve usually has a top guided construction; this means the valve plug is guided within the lower portion of the valve bonnet. The double seated valve is generally top and bottom guided, as shown above. The single seated valve is a tight shut-off valve, and this usually means that the leakage is less than 0.01% of the valves Cv (fluid velocity ratio). The practical leakage figure for a double seated valve approaches 0.5% of the rated CV, because of the fact it is nearly impossible to close the two parts simultaneously, particularly as expansion due to temperature after the valve is installed. The advantage of double seated valves is that the actuator force required moving the valve is very much smaller than single seated valves due to the pressure of the fluid on both valve plugs.

Valve Plugs and Characteristics

The valve plug is that movable part of the body assembly, which provides the variable restriction to flow, and is the principal functional part of the ‘trim’ portion of the valve body. Trim consists of those parts of the valve that come in direct contact with the process fluid. The design of the plug varies according to the specific set of flow characteristics desired to be imparted to the valve. When the percent of the valve lift is plotted against percent of maximum flow, significant curves are formed. Matching these characteristics with those required by the process and control loop enables correct process control.

Valve plugs used in throttling control are positioned at any point within their travel as dictated by process requirements. They are available in a variety of shapes, which determine the characteristics of operation. At one time, the most widely used plug style was the equal percentage characteristic. That is, for all positions of the plug relative to the port opening, a percentage of valve lift produced equal percentage changes in flow under constant pressure drop across the valve port. A later development was a valve plug design with linear characteristics; for example, a plug with a linear relationship between plug-to-port opening position and flow rate.

Plug flow characteristics

The flow characteristics of a control valve is the relation between flow through the valve and the valve travel as the travel is varied from zero to 100% and a constant pressure drop is maintained across the valve body. The most common characteristics encountered are:

(i) Equal percentage
(ii) Modified parabolic
(iii) Linear
(iv) Quick opening, or poppet

Rangeability

The term ‘Rangeability’ may be defined as the ratio of the maximum to minimum rates of controlled flow.

Consider a valve with a minimum controllable flow of 2.5% of the maximum controllable flow, then the rangeability is 100/2.5 = 40.

Turndown

Control valves are often not chosen to handle the maximum possible flow in a normal course of operation and the term turndown is used.

$$\text{The turndown ratio} = \frac{\text{normal maximum flow}}{\text{minimum controllable flow}}$$

This may be explained be example. A valve is required to handle a maximum flow, which is 65% of the maximum possible. With a minimum flow rate of 2.5% of the maximum possible, then:

The turndown ratio = 65/2.5 = 26.

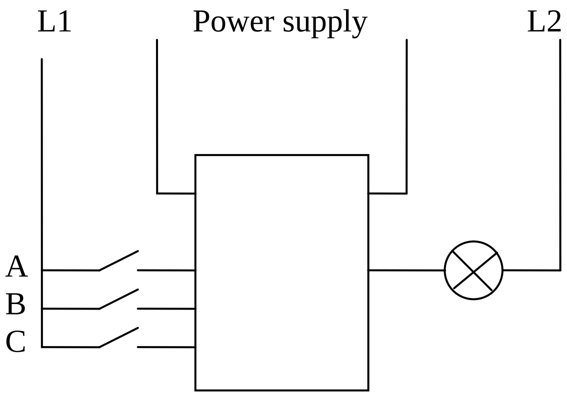
Programmable logic controllers (PLC)

A programmable logic controller (PLC) is an electronic device that uses a programmable memory to store instructions and to implement functions such as logic, sequencing, timing, counting and arithmetic in order to control machines and processes. The term logic is used because programming is primarily concerned with implementing logic operations such as OR, AND, etc. in switching circuits.

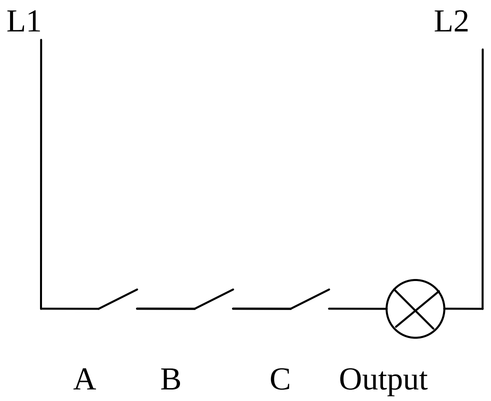
The input devices such as switches and sensors which respond to the conditions occurring and the output devices in the system being controlled, e.g., motors, are connected to the PLC. The input/output channels of the PLC provide signal processing and isolation functions so that sensors and actuators can be generally directly connected to them without the need for other circuitry. Outputs are often specified as being of relay type, transistor type or triac type. With the relay type, the signal from the PLC output is used to operate a relay and so is able to switch currents of the order of a few amperes in an external circuit. The relay isolates the PLC from the external circuit but is relatively slow to operate. The transistor type of output uses a transistor to switch current through the external circuit. This gives a faster switching action. Opto-isolators are used for the input signals plus for transistors and triacs in the output to enable the external a.c. power supply to be used and provide isolation.

The engineer enters a sequence of instructions, i.e. a program into the memory of the PLC. This program determines the control behaviour of the PLC. Its aims is to specify the precise conditions for turning on or off, or regulating each output of the controller. The program can be specified using a form of programming termed ladder/instruction/statement list programming. Such a program might be entered into the computer memory using a programming terminal which is plugged into the PLC. The PLC then monitors the inputs and outputs according to this program and controls the machine or process concerned.

To illustrate the above, consider a simple example. A lamp is to come on when three switches are closed. The figure (a) below shows the inputs, the switches, and the output, the lamp, connected to the PLC. Ll and L2 are the connections to the power supply. The program to be entered has then to instruct the PLC to effectively 'connect' the three inputs in series with the lamp so that power is applied to the lamp when all three switches are closed. Figure (b) shows the effective circuit with the switches and lamp connected in series between the power lines. This might then be one event in a controlled sequence.



(a)



(b)

The programmable logic controller is designed to carry out the logic functions previously carried out by such components as relays, mechanical timers such as cams, etc. PLCs have the great advantage that it is possible to modify a control system without having to rewire the input and output devices, the only requirement being that an operator has to key in a different set of instructions. The result is a flexible system which can be used to control systems which vary quite widely in their nature and complexity.

Fault Diagnosis

Introduction

Diagnosis is an activity that we are all engaged in every day. The doctor diagnoses the illness of the patient; the motorist judges if it is safe to turn right and the engineer diagnoses faults on plant and equipment.

Machine downtime and the resultant loss of production is expensive. Undue delay in finding and correcting faults must be avoided and this can best be done by equipping everyone with the essential requirements for successful fault finding. For key process employees in paper and board mills these essentials are:

- an understanding of instruments, their functions and use in control systems
- an understanding of the process and of the machinery and its related instrumentation
- a systematic approach to fault location and diagnosis.

The 'Trouble Shooter'

When any system is not functioning as it should then problems arise. How severe the problems are depend on what effect the fault has on the system, on production and quality. There is no set standard method for trouble shooting, the method depends upon several factors, but first of all let's consider what makes a good trouble shooter. The expert diagnostician displays a number of characteristics which are part of the skill, for example:

There appears to be a plan when searching for a fault

Before making any adjustments to the equipment stand back and weigh up all the available evidence in an attempt to decide what significant action could have been taken previously by machine operatives, supervisors etc. This is in direct contrast to the 'muddler' who acts on impulse making adjustments before mentally sifting through all the available evidence.

There is a need for intimate knowledge of the equipment on which you are trouble shooting. This is to be knowledge not only of the function and operation of each part of the equipment but also how each part relates to every other part. This knowledge is essential.

Experience will make the trouble shooter familiar with all of the common faults which occur on the equipment. This is extremely important information since it enables the trouble shooter to quickly survey the fault symptoms and decide which in each particular case are relevant and which are redundant and then speedily diagnose and rectify the fault.

Systematic Faults Location

Faults occurring on plants whether they are process faults or instrument faults can be divided into three categories. The first includes faults which are immediately identified by the symptoms - such as when a bulb is broken.

No systematic approach is necessary for faults in this category.

The value of a systematic approach is also doubtful in the second group where the symptom gives a clear indication of the area of the fault - such as every piece of electrical equipment failing simultaneously.

It is for the final category of fault that a systematic approach is essential. Here, the symptom does not indicate the area of a fault, and may, in fact, be misleading.

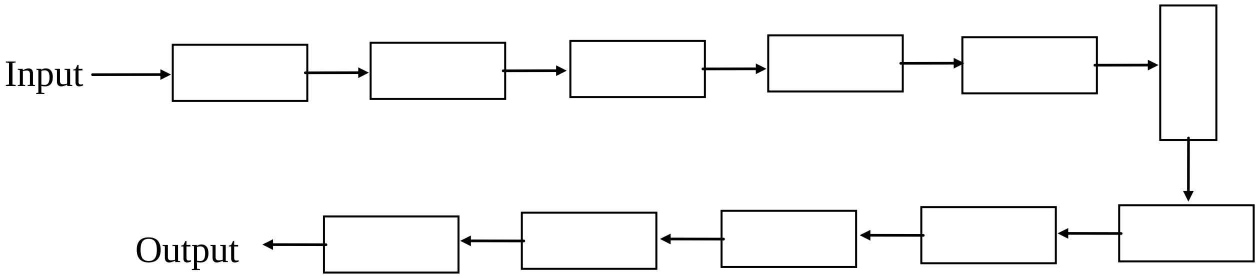
In the figure below there are a number of methods or search strategy which could be used for discovering which of the blocks is faulty. These are:-

a) input to output (beginning to end)

b) Output to input (end to beginning)

c) Half-split

d) Random



All of these methods have their own particular advantages and uses.

The input to output and the output to input methods are examples of a systematic approach even if the method is fairly obvious. If the process is started and each block checked in turn then the faulty block will be the one whose output is wrong. This method is the most used by service engineers on equipment and systems containing only a small number of blocks.

The half-split method is a very powerful method in locating faults in equipment and systems with a large number of blocks. The first check is made on the central block, from this it is possible to determine which half of the system is working. The faulty half is then divided and a check made half-way. The result of this will indicate again which half is faulty. in only two checks the fault is now narrowed down to 1/4 of the system and by continuing in this manner the fault can be quickly found.

The random method, which as the name implies is a totally non-systematic approach is based on the person trouble shooting having a wealth of knowledge and experience concerning a particular system. A check is made in a place that depends upon symptoms the process shows, and the area which normally gives those symptoms.

Faults Diagnosis

Instrument faults are in the main due to one or more of the following reasons:

1. Incorrect installation of the instrument
2. Misuse of the instrument
3. Physical damage (e.g. due to changes in environmental conditions)
4. Inadequate maintenance of plant (e.g. corrosion)
5. Fair wear and tear.

The approaches taken to identify the cause are significantly different from those indicated for the fault-location process. Thus, whilst fault-location is a convergent.. or closing-down, process, FAULT DIAGNOSIS is an essentially outward-looking activity in which both the likely and unlikely causes are investigated. Since evidence may be overlooked or destroyed during fault location, fault-diagnosis should proceed at the same time as fault-location.

For example, although a faulty control valve in a process line could have been caused by any one of the above five reasons, causes attributable to 1 and 4 may only be identifiable when the valve is in-situ. Thus once the valve has been stripped down the true cause may not be found.

Searching for causes should be based on asking the questions

WHY?
HOW?
WHERE?
WHEN?
WHO?

In respect of each of the five reasons given above., although all the questions may not be relevant in every case. In any event, it is vital that the search is not ended until the cause - or causes - is/are clearly identified.

Job Aids

Innumerable job-aids have been developed to assist the fault finding process. Some such as electrical circuit diagrams are more specialised than others, and some will commend themselves more readily than others to users with different backgrounds. Choice of a job-aid will depend on the environment and the user as on the system it is being applied to and in any particular case the final choice will necessarily be a compromise between factors such as:-

- The complexity of the system
- The frequency with which the aid will be used
- The frequency with which the system changes
- The preferences of the user for the written word or the illustration
- The quality of manufacturers' handbooks

Rectification of the Fault

Whilst you will not be involved in the actual rectification of a fault on an instrument or any part of a control system it is important to remember that the overriding objective of everyone on a machine is to keep it running, whilst maintaining safety. Thus the advantages of in-situ repairs whilst the process is controlled manually should always be considered. Some key considerations in deciding whether in-situ repairs are possible are:-

- Safety
- The effect of the fault on the overall process and its cost - in all senses - if the fault is allowed to remain
- The availability of manual over-rides and how difficult they are to use
- Whether any part of the machine will need to be shut down in order to replace the instrument
- How long a repair will take assuming the plant is off-line whilst the repair is made)
- Whether compatible replacement instruments are available
- How long it will take to replace the instrument with another to fulfil the same duty
- The cost of down time

Checking the System

It must be understood that all replacement components will ideally fall within the specified tolerance. After repair, the effect on the machine or the control loops of any new components in the instrument should be considered. For example, if a resistor with a tolerance of ±20% has been replaced in a circuit, the value of the new resistor could differ by up to 50% compared to that of the original one. it is the joint responsibility of the instrument and Process Personnel for the checking of instrumentation systems and plant after replacement or repair.

Questions

1. What is the difference between Fault Location and Fault Diagnosis?

FAULT LOCATION is the process which leads to the identification of the fault. FAULT DIAGNOSIS involves those activities involved in identifying the cause of the fault once it has been located.

2. List three methods that could be used as a search strategy when locating a fault.

Any three from:-

a) input to output
b) output to input
c) half-spilt
d) random

3. List four reasons that instrument faults are mainly due to.

Any four from:-

a) incorrect installation
b) misuse
c) physical damage due to changes in environment
d) inadequate maintenance
e) fair wear and tear

4. After the repair or replacement of an instrument in a control loop who is responsible for the checking of the system?

It is the joint responsibility of the Instrument and Process personnel for the checking of instrumentation systems and plant.