CHAPTER 1: INTRODUCTION TO CONTROL SYSTEMS

MODULE A: BASIC CONTROL SYSTEMS

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

1. the basic requirements for a typical process control system;
2. the significance of the various control regions as a function of process operating status
3. the hardware elements of typical control systems
4. the types of signal conversions used for digital computers in process control
5. the main steps to be followed in the design of a process control system

1.0 PROCESS CONTROL REQUIREMENTS AND IMPLEMENTATIONS

1.1 ensure that process operates

- safely
- meets performance specifications
- satisfies environmental regulations
- meets operational constraints
- as economically as possible

1.2 ensure that process parameters are at specified values

- maneuver to specified values
- suppress the influence of external disturbances
- ensure the stability of the process
- optimize the performance of the process

1.3 basic types of process control are:

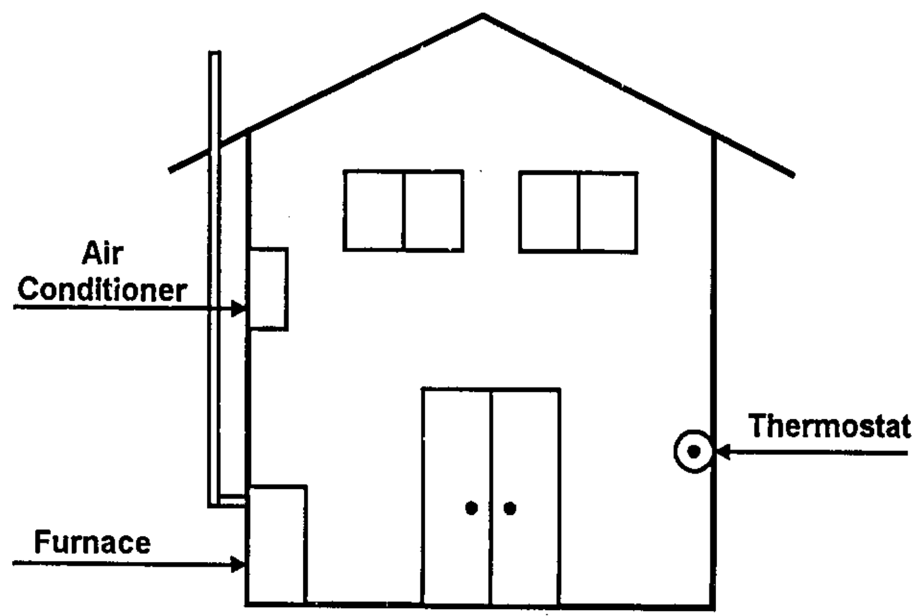
- manual control
- automatic control

1.4 automatic control configurations use one or more of:

- direct feedback
- inferential feedback
- feedforward

1.5 automatic control implementations include:

- on/off control
- analogue control
- digital control

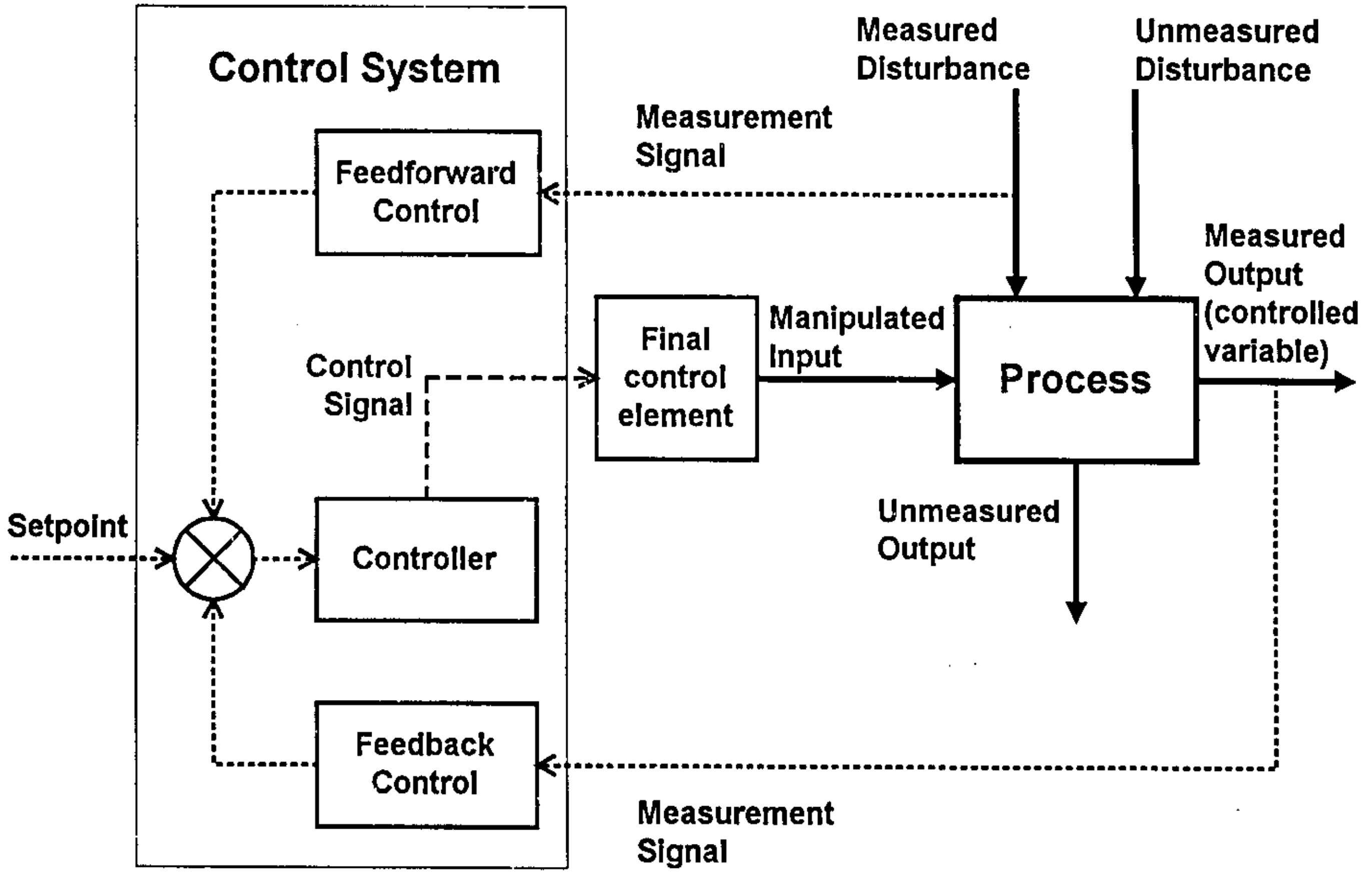


2.0 CONTROL SYSTEM TERMINOLOGY

- the **Process** is the system whose variable(s) are to be controlled
- the **Controller**(s) contains the control law (or algorithm)

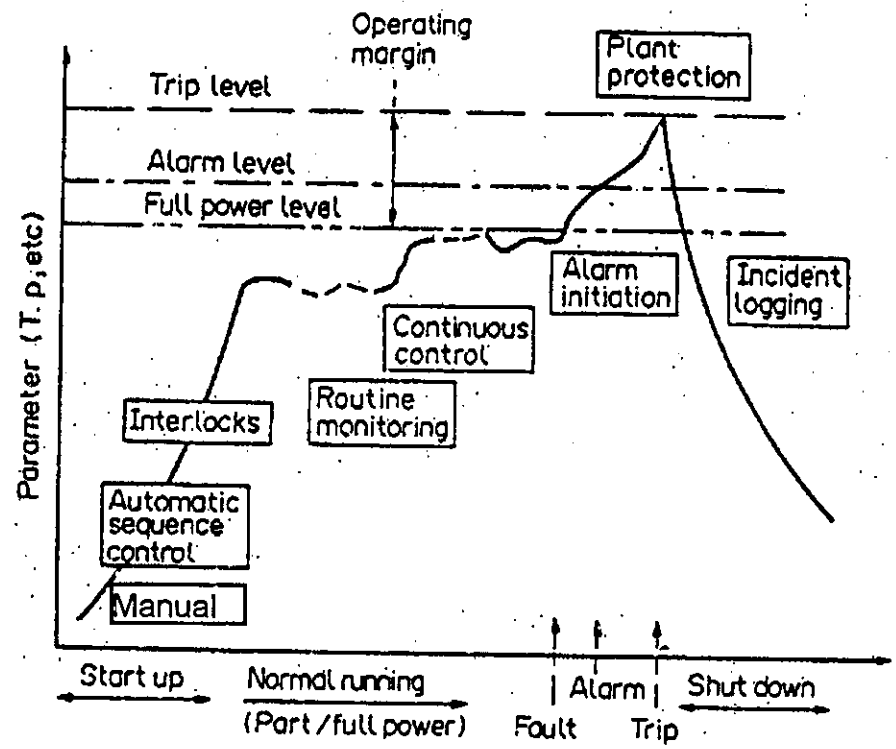
2.1 Classification of variables

- input variables
  - manipulated or adjusted variables
  - disturbances (measured or unmeasured)
- output variables
  - measured variables
  - unmeasured variables
- setpoint
  - desired value of output
  - set by human operator or computed by another control system
- signals:
  - measurement of variable
  - output of controller
  - to final control element



2.2 Control regions

- at or near complete shutdown, such as initial start-up or during an extended outage, MANUAL control is used extensively
- as the control systems are commissioned and calibrated, and as the process parameters come within the range of the control system input instruments, control is gradually transferred from MANUAL to AUTOMATIC SEQUENCE CONTROL
- INTERLOCKS often limit the range of automatic control
- as the normal operating range is reached (at or near full power) the process comes under CONTINUOUS AUTOMATIC CONTROL, with the human operator taking on a monitoring role
- ALARMS will warm the operator if parameters move beyond their designated operating range
- PLANT PROTECTION or SAFETY systems act automatically if designated parameters reach prescribed limits
- LOGGING and RECORDKEEPING of key events and parameter values is essential for subsequent even analysis



Changing roles of instrumentation and control systems as a function of plant operating status.

3.0 HARDWARE ELEMENTS OF TYPICAL CONTROL SYSTEMS

3.1 System or Process to be controlled

- must understand all of its characteristics relevant to the control problem

3.2 Measuring instruments or sensors

- must measure the controlled output variable, and as many of the input disturbances and other variables as needed to ensure that the control specifications are satisfied
- must be able transmit the reading if automatic control is required
- must be reliable for its intended use and location

3.3 Transducers and Converters (device to signal)

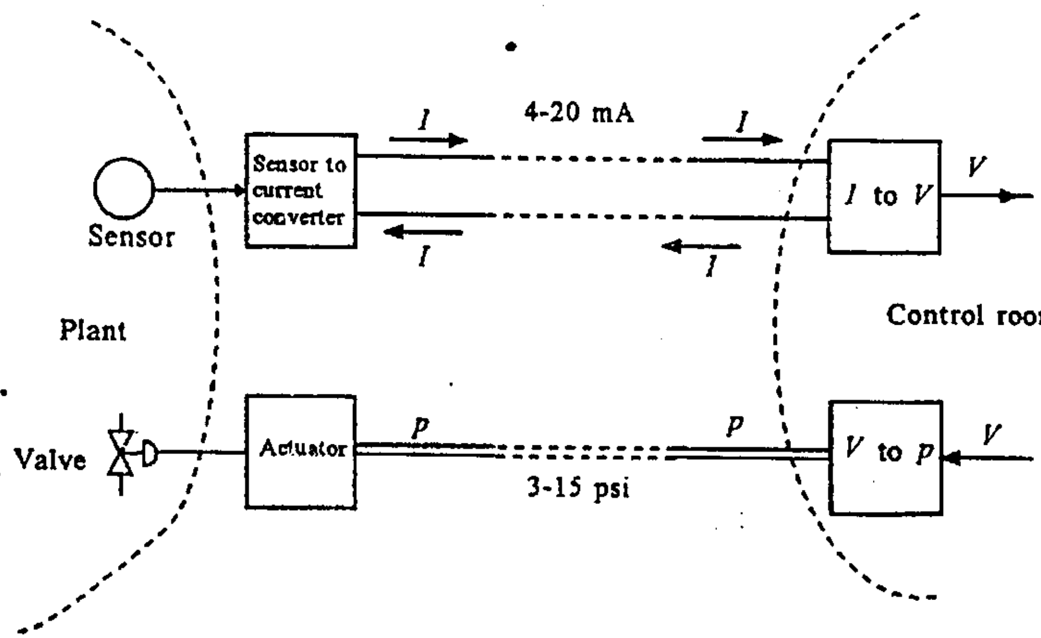
- measurements must be converted to an electrical or a pneumatic signal before they can be transmitted and further processed
- analogue signals must be converted to digital form if a digital controller is used

3.4 Transmission lines to Controller

- carry the measurement signal from the transducer to the controller
- a converter may be on either end of the transmission line
- amplification and other signal conditioning is often required

3.5 Controller

- contains the control law or algorithm, i.e. has the "intelligence" to decide based on the incoming signal(s) to produce the required output signal(s)
- may be simple or very complex, analogue or digital



3.6 Transmission lines from Controller

- complementary functions and requirements to the incoming transmission lines

3.7 Transducers and Converters (signal to device)

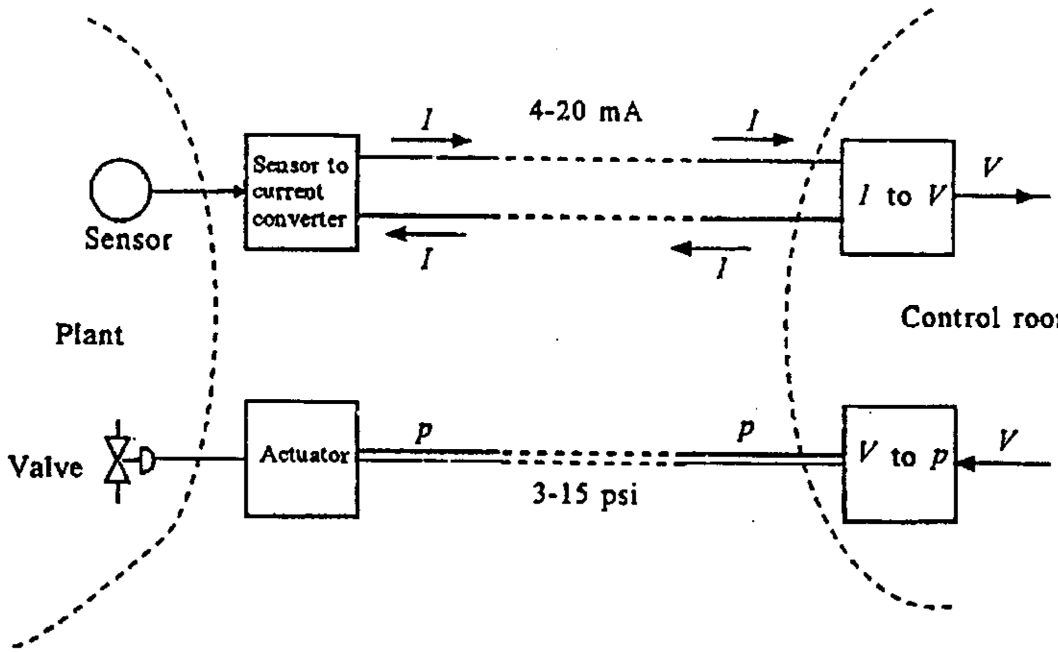
- convert signal to a form that can implement the command action of the controller

3.8 Final control element

- device that alters the behaviour of the process by changing the controlled parameter as directed by the controller
- valves, relay switches controlling motors and heaters are typical examples

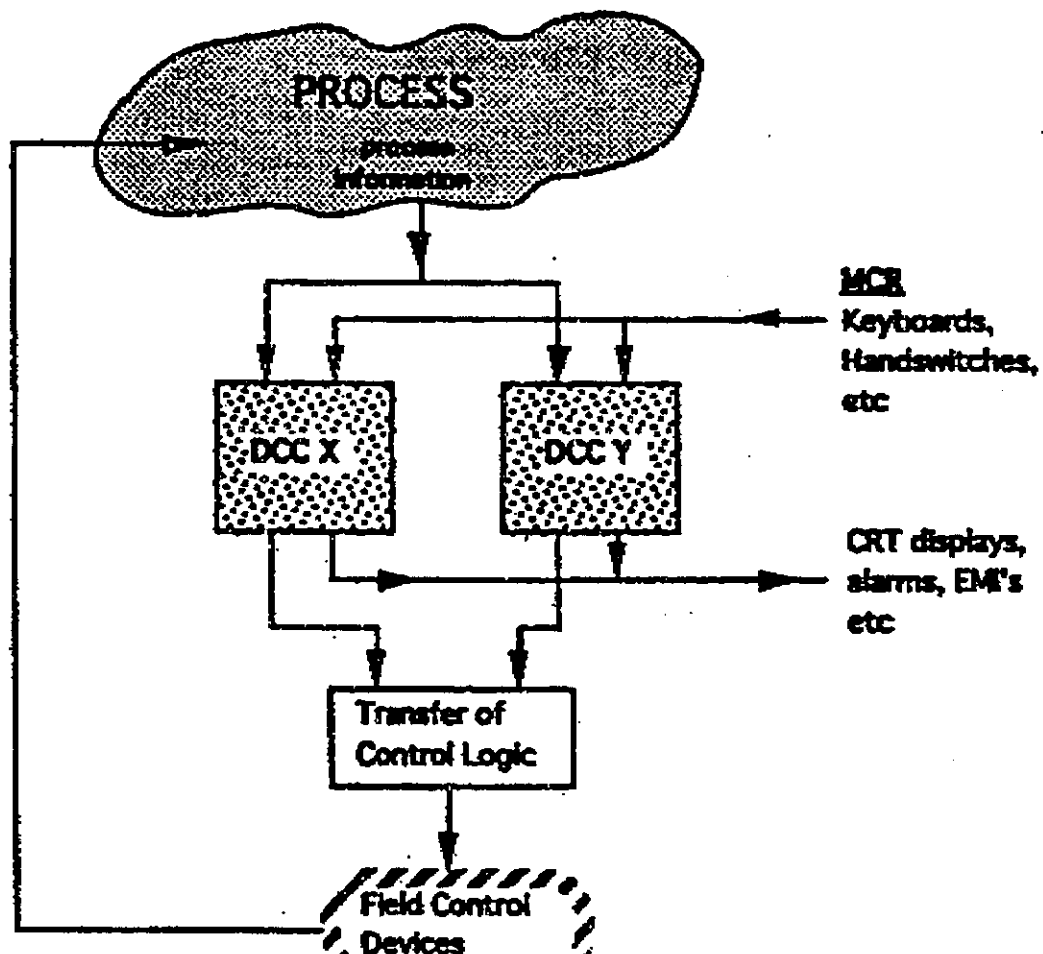
3.9 Input, display and recording devices

- setpoints and altering the state of valves, pumps, heaters, compressors and other devices is often done remotely from a control panel
- the state of controlled and many other variables needs to be displayed for visual verification and overall system control integration by a human operator
- annunciation of abnormal conditions, sounding of alarms, initiation of emergency actions need to be indicated
- recording as a function of time (continuous or sampled) of important parameters to show trends and to provide a permanent record
- recording of alarms and other important events



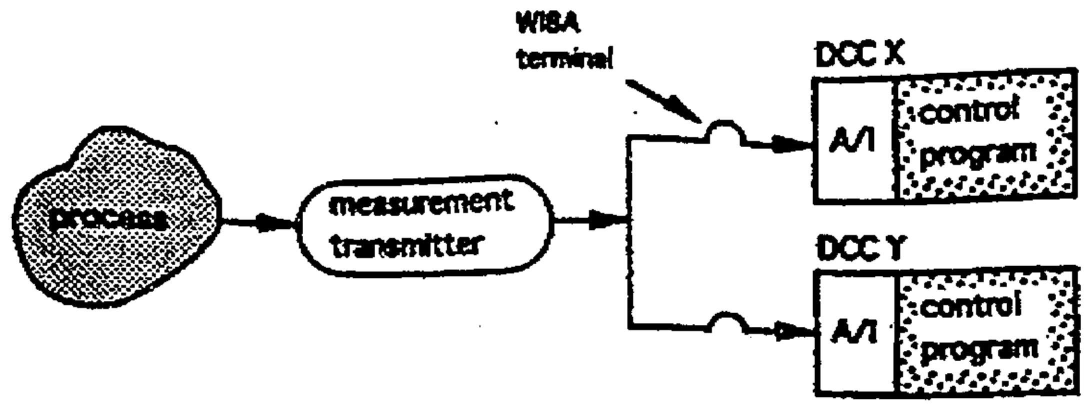
4.0 DIGITAL COMPUTER CONNECTIONS TO FIELD DEVICES

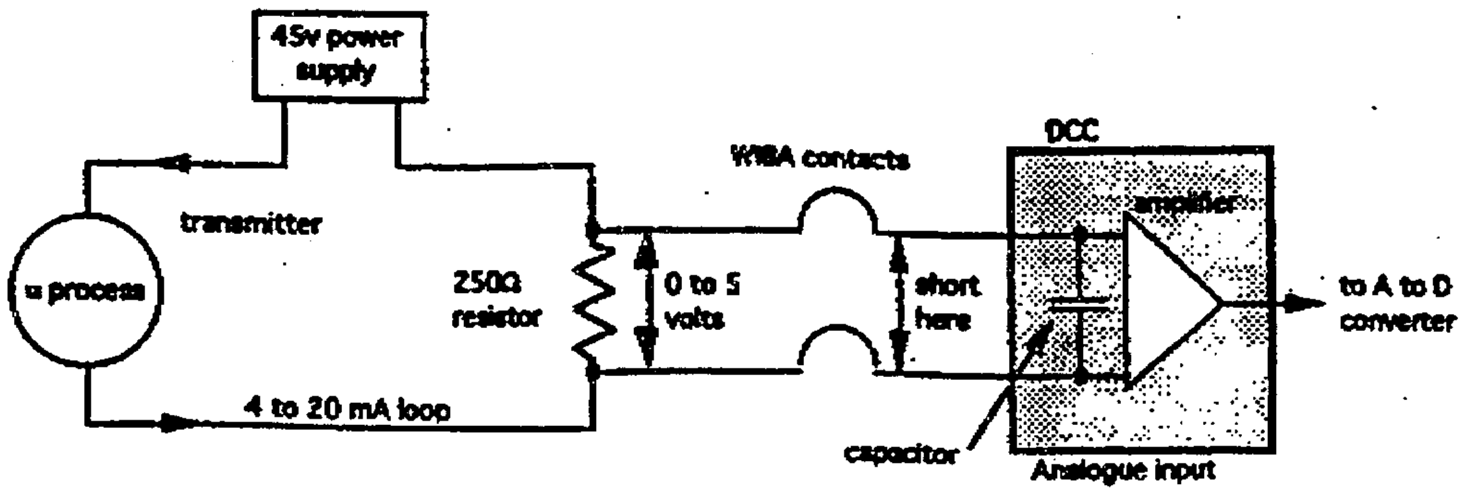
- there is an increasing use of digital computer control in industry world wide; all modern nuclear plants make use of digital control computer (DCC) technology
- the nature of nuclear power plants pose high reliability requirements on the control equipment: most analogue control system components are triplicated and contain various redundancy measures
- because of the inherently high reliability of digital computers combined with their ability to for self-diagnosis as well as to assess the validity of its input signals, duplication of digital computer controllers has been found to meet or exceed the reliability performance of the analogue systems they replace
- typically one computer is in control and the other on standby, the latter usually receiving all of its inputs, computing all its outputs, but only the signal's from the 'master' computer are connected to the field devices



4.1 ANALOGUE INPUTS

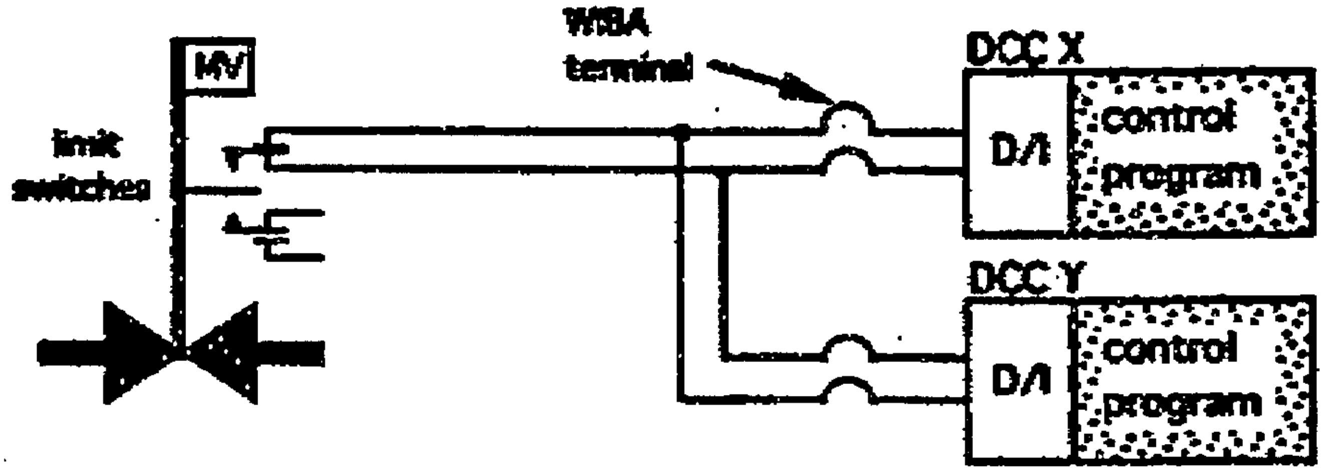
- most process parameters are of the continuous (analogue) nature, typically 0 to 5 volts, linearly proportional to the process parameters
- analogue signals must be converted to digital form before they can be processed by a digital computer
- typically each analogue measurement is sent to both DDCs, and each DCC makes its own analogue to digital (A/D) conversion
- following conversion to digital form, the computer program that will use the signal will usually perform a rationality check: for an input voltage range of 0-5 v the rational range is 0.5 to 4.5 i.e. the digital reading that corresponds to these voltage levels





4.2 DIGITAL INPUTS

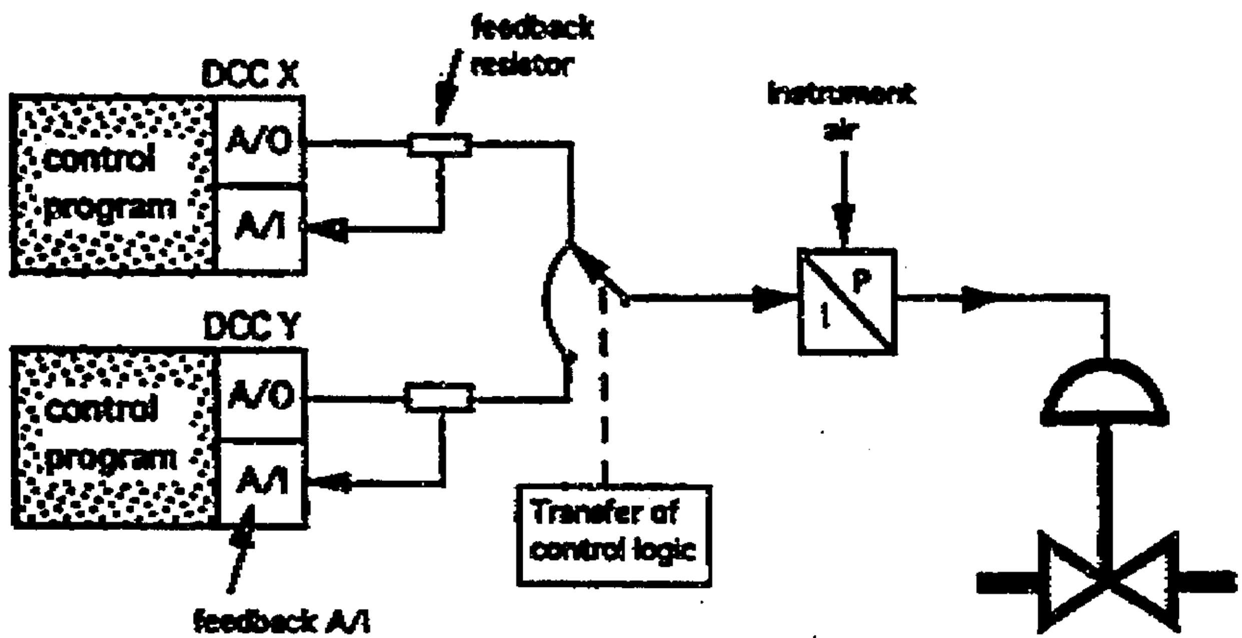
- **these signals usually measure the status of a pair of contacts, which are either open or closed, giving an indication of the state of field devices, for example a motor being on or off, a valve open or closed**



- **panel keyboard inputs are a convenient means for the operator to provide instructions to the computers; these can be in the form of either special purpose push-buttons or conventional computer keyboards**
- **process interrupts are special digital inputs that connected directly to the computer so as to produce an immediate action, instead of waiting until the next cycle of program execution**

4.3 ANALOGUE OUTPUTS

- the computers communicate their control signals to the field equipment and the operators via various output signals
- the analogue outputs (A/O)are used to operate field devices that vary in a continuous (analogue) manner
- accurate control to any value in a given operating range is the typical performance requirement
- analogue outputs typically generate a current signal in the 4-20 mAmp range, to operate pneumatic valves directly, or as inputs to hardware analogue systems
- for reliability purposes all A/Os have a feedback resistor in the loop which is used as signal to an A/I, called the A/O feedback A/I
- the A/Os are controlled by the transfer of control logic to ensure that only the A/Os from the controlling DCC are allowed to operate the field devices

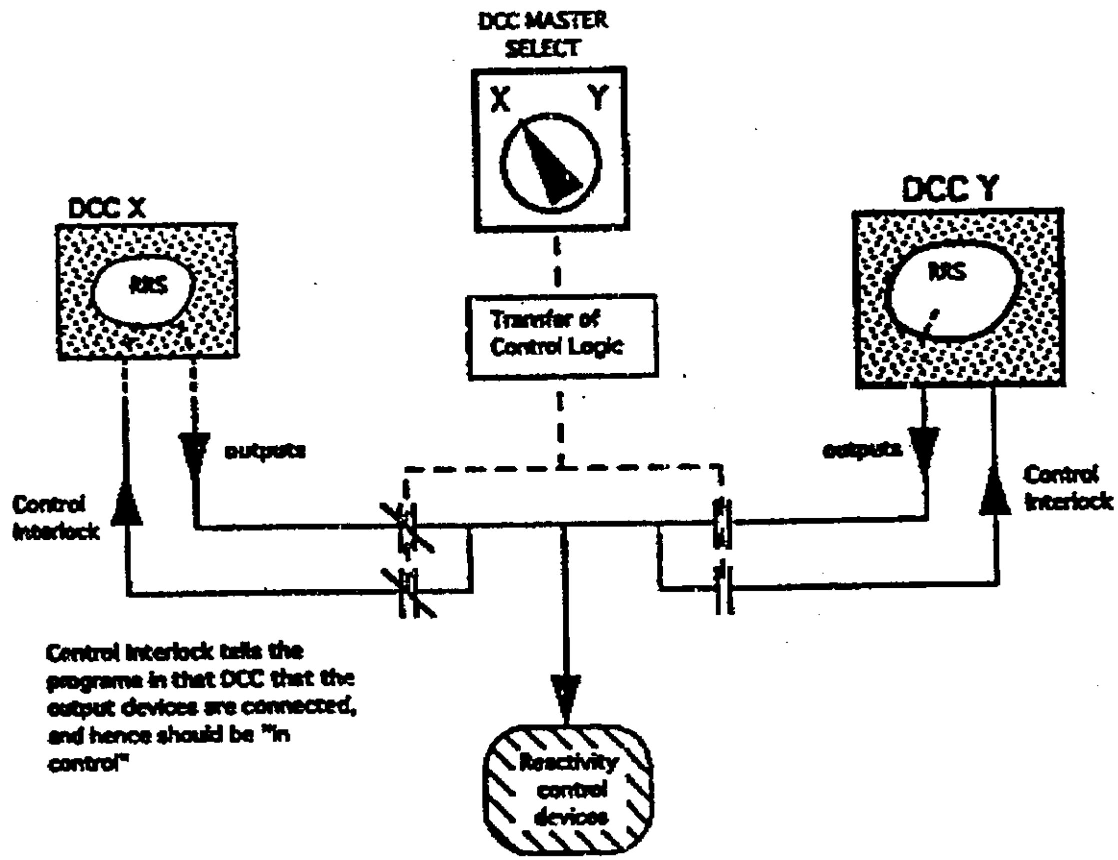


4.3 DIGITAL OUTPUTS

- D/Os are a pair of contacts operated by the DCC
- all the D/Os are connected to their respective logic circuits via the transfer of control logic, similarly to the A/Os
- D/Os are typically used to operate motor starters, or to give indications of on-off status, including alarms

4.4 TRANSFER OF CONTROL LOGIC

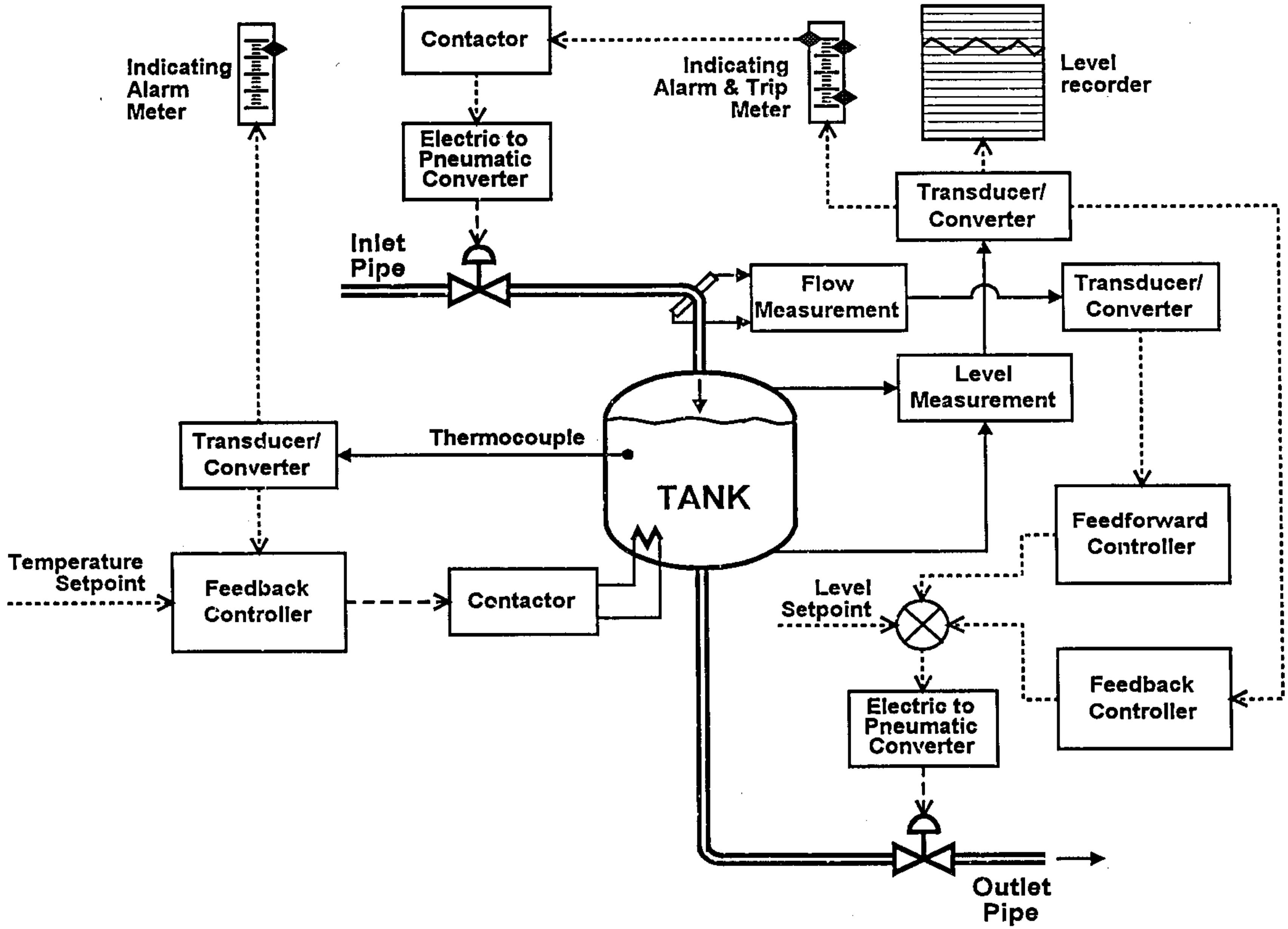
- the control programs normally execute in both computers, but only one of the (usually the MASTER) has its outputs connected to the field devices
- the connection of the output devices to one DCC or the other is determined by the "Transfer of Control Logic"; the requirements is that the computer be designated as the "Master" and that the control program be running in that computer



5.0 EXAMPLE OF TANK LEVEL AND TEMPERATURE CONTROL

- **Process to be controlled consists of a Tank containing a liquid; inflow and outflow are regulated by valves, the temperature of the liquid must be kept above 20°C using a heater, the tank must not overflow, nor can its level drop below the heater coils;**
- **the control system requirements are to adjust the inlet and outlet valves to maintain the tank level at or near the setpoint, a permanent record of the level must be available as well as alarms on excessively high and low levels, temperature display and the means to keep it above the setpoint are to be provided**
- **remote monitoring and control are required**

5.1 DESIGN OF TANK LEVEL AND TEMPERATURE CONTROL



CHAPTER 1: INTRODUCTION TO CONTROL SYSTEMS

MODULE B: CONTROL SYSTEM STABILITY

MODULE OBJECTIVES:

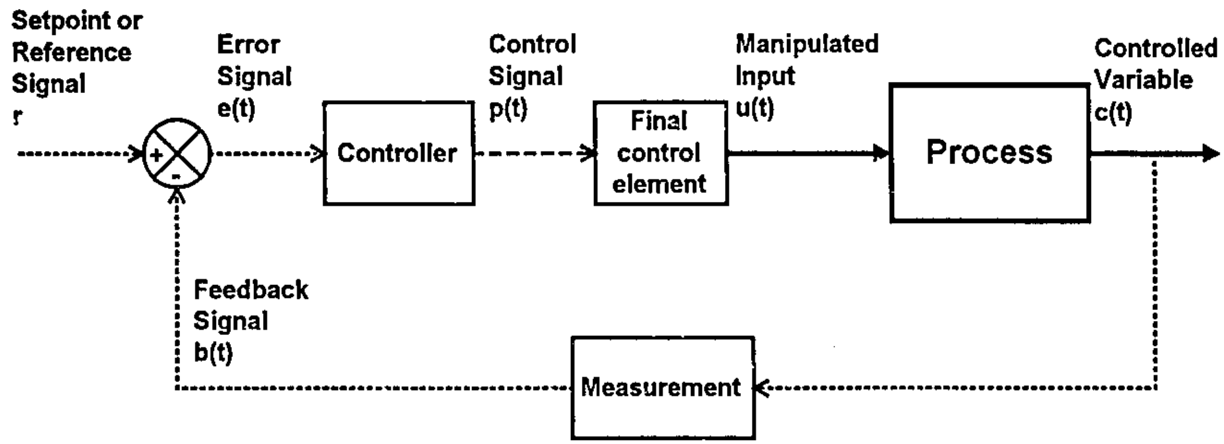
At the end of this module, you will be able to describe:

1. **how the performance of a control system is measured**
2. **the various types of feedback controllers and their main characteristics**
3. **how the stability of a feedback control system can be determined**

1.0 CONTROL SYSTEM PERFORMANCE

- the variable that is commonly used to measure the performance of a control system is the error e(t) between the desired setpoint or reference value 'r' (assumed constant for now), and the process output or controlled variable 'c'

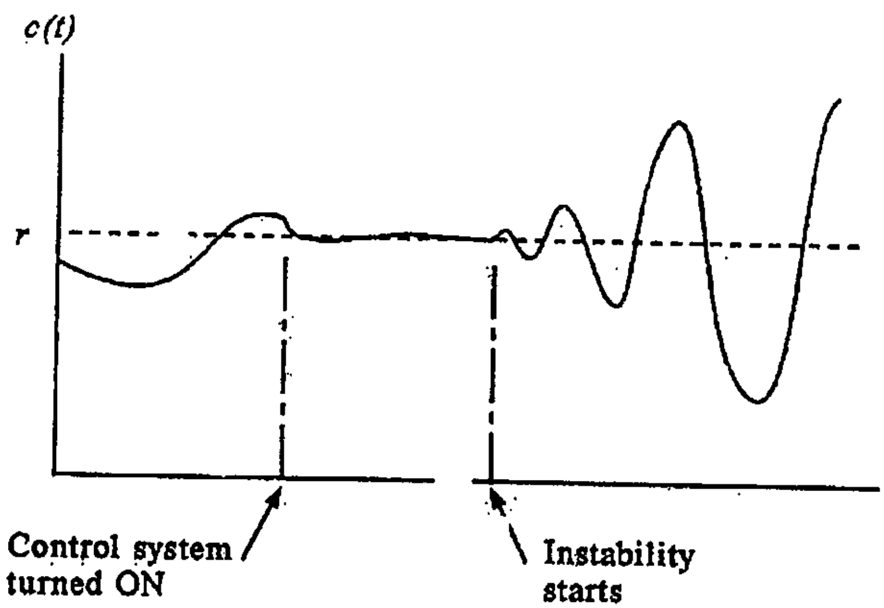
$$e(t) = r - c(t)$$

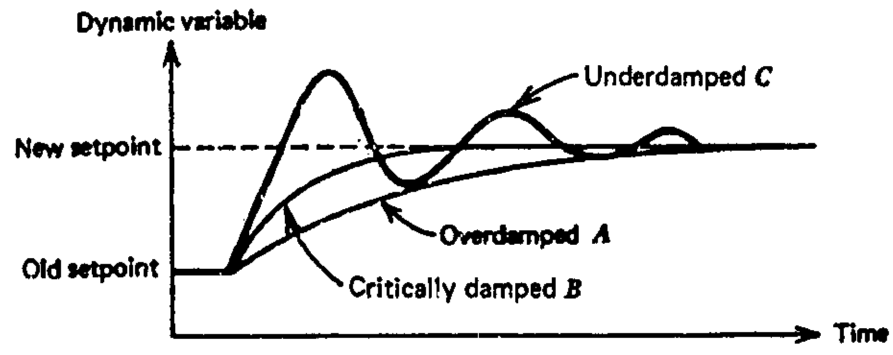


- the objective of a control system is to make the error, as defined above, to be zero: however since the control system works by acting on the error, the error cannot be zero at all times, or the control system would have no response
- the control system performance measure has to be in terms of how small the error is and over what time, from a given disturbance, was the error reduced below some specified level
- there are three basic types of disturbances that need to be considered:
  - transient (i.e. operation at a steady process output and constant internal setpoint, despite variations in process parameters or external conditions)
  - setpoint change (i.e. a desired change in the output of the process to match the new setpoint)
  - process condition change (i.e. the operating conditions of various internal process parameters are changed, but process output needs to be maintained constant)
- control system performance for the above disturbances is evaluated in terms of:
  - stability
  - minimum deviation (magnitude)
  - minimum duration (time)

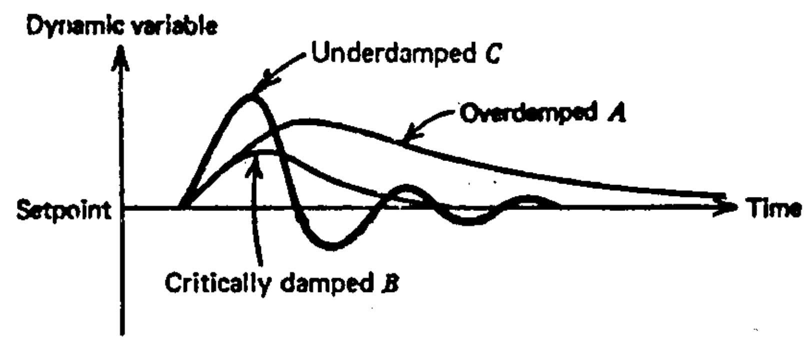
2.0 STABILITY

- stable control means that the variable does not keep increasing until it reaches limits imposed by other than the control system (increase may be linear, or non-linear, such as parabolic, exponential, oscillatory, etc.)
- steady state regulation is specified in terms of the allowable deviation in the controlled variable $\pm\Delta c(t)$ about the setpoint, i.e. some minimum error $\pm e(t)$





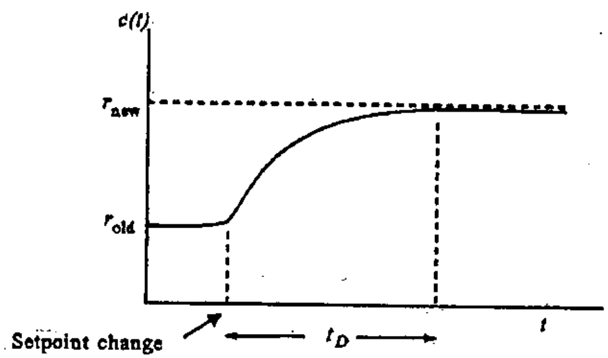
a) Reaction to a setpoint change



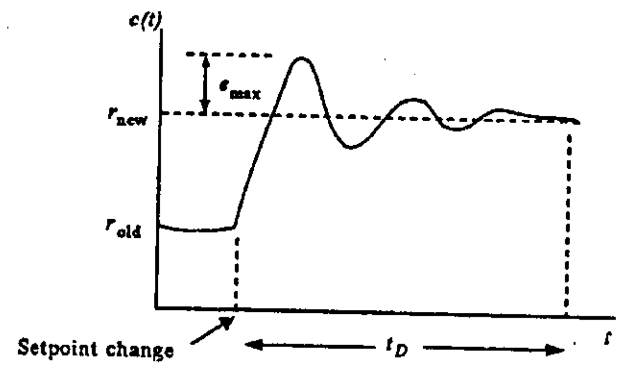
b) Reaction to a load change

2.2 TRANSIENT RESPONSE

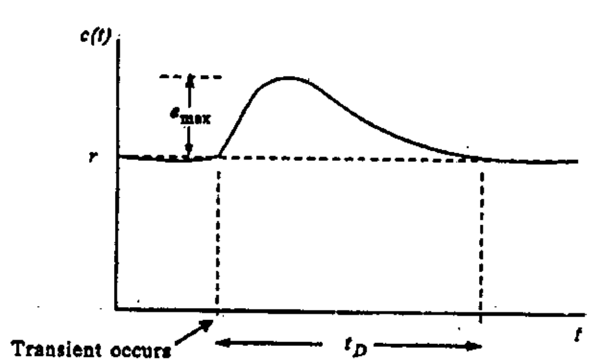
- **response to setpoint change and transient regulation: in addition to stable response and acceptable steady state regulation, we want the magnitude of the error (e_{max}) and the duration of the error (t_D) to be within specified limits**



(a)



(a)



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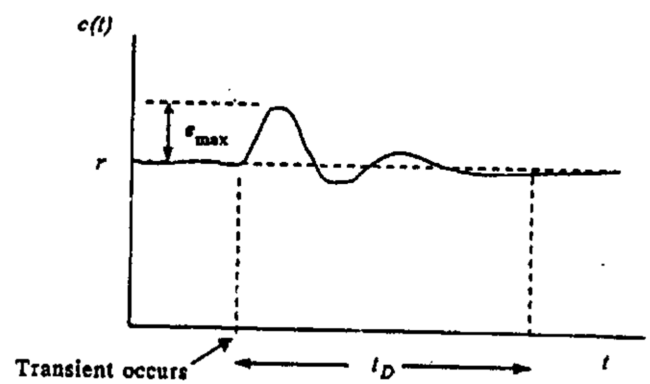
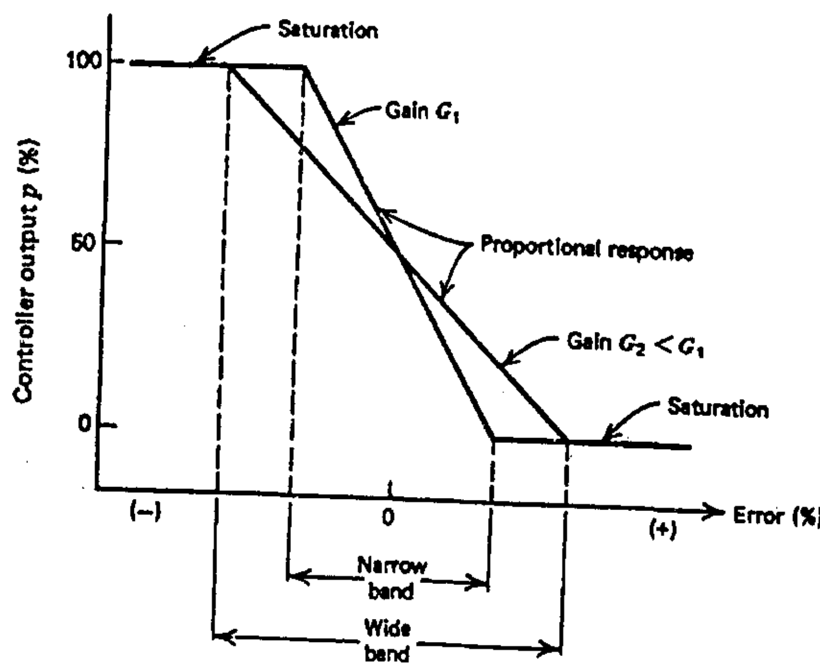


(b)

3.0 CONTROLLER TYPES

- traditionally controllers are regarded as either continuous or discontinuous, depending on the values that the controller output takes as a function of the error (note that analogue controllers may be discontinuous and digital controllers continuous)
- the simplest discontinuous controller is the two-position or on-off: below a certain error value the controller output has one state and above a certain error value the controller has the other state; there is usually neutral zone or deadband where a change in error does not cause a change in controller output, so as to avoid rapid switching (cycling) from one state to the other
- discontinuous controllers may have many steps in their output as the error changes

3.1 Continuous controllers



- as the size of the steps in a discontinuous controller get smaller and smaller, continuous operation is reached, and in the case of a linear set of small steps the output of the controller is directly proportional to the magnitude of error; the controller signal 'p' can be expressed as

$$p = K_p e_p + p_0$$

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

p_0 = controller output with no error (i.e. 0% bias)

- note that since the error was defined as

$$e(t) = r - b(t)$$

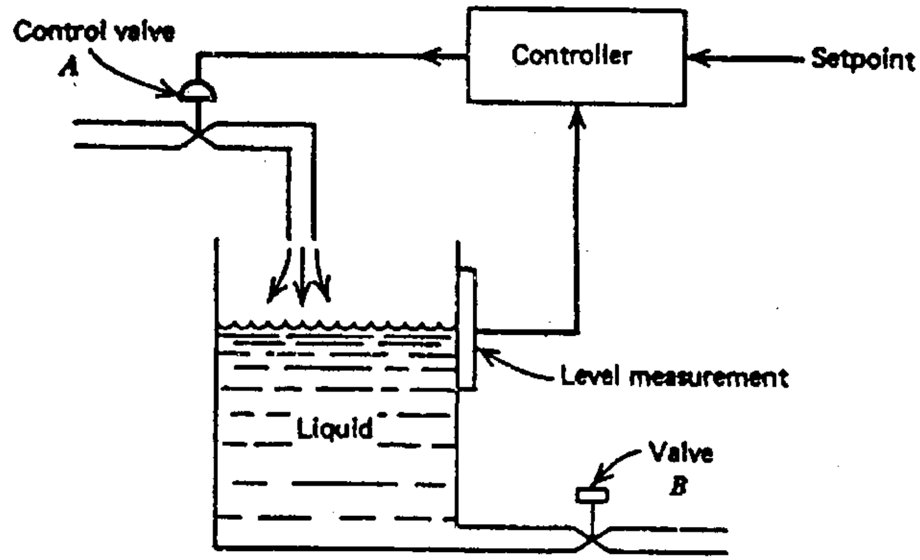
the controller has to be reverse acting, as shown, i.e. if the error is positive, the controller gain is reduced

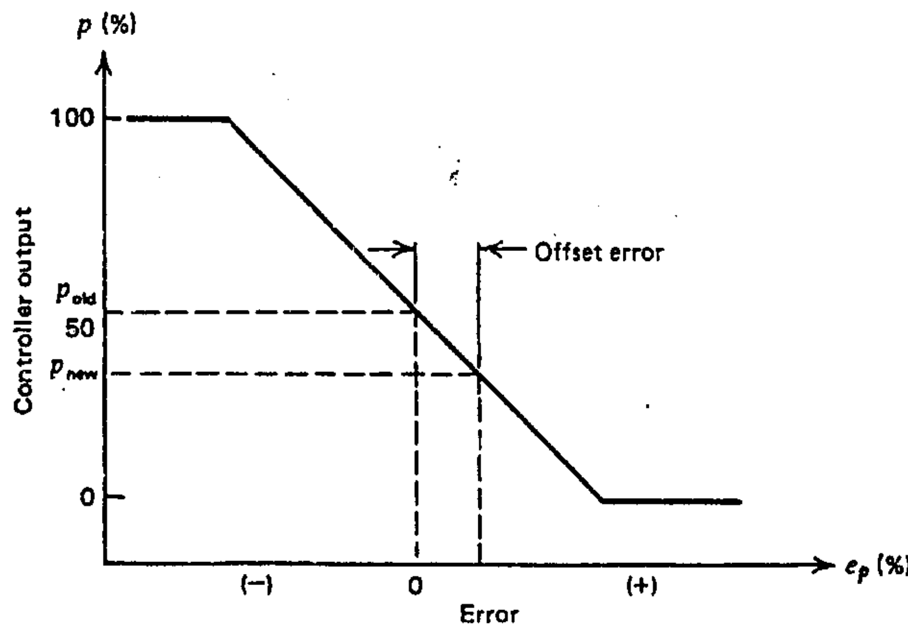
3.2 Proportional Controller Characteristics

- for zero error controller output is equal to p_0
- if there is an error, for every 1% of the error K_p % is added to (or subtracted from) p_0
- there is a range (or band) of error about zero error of magnitude PB within which the controller output changes linearly as a function of error, and beyond which the controller is saturated at 0% or 100%

$$PB = 100 / K_p$$

- an important characteristic of proportional control is that it operates with a permanent residual error or offset when operation deviates from the zero error condition that produces p_0
- proportional control is therefore used only when no changes in the operating point are expected, or if it is convenient to adjust the operating point bias p_0 to eliminate the error at the new setpoint





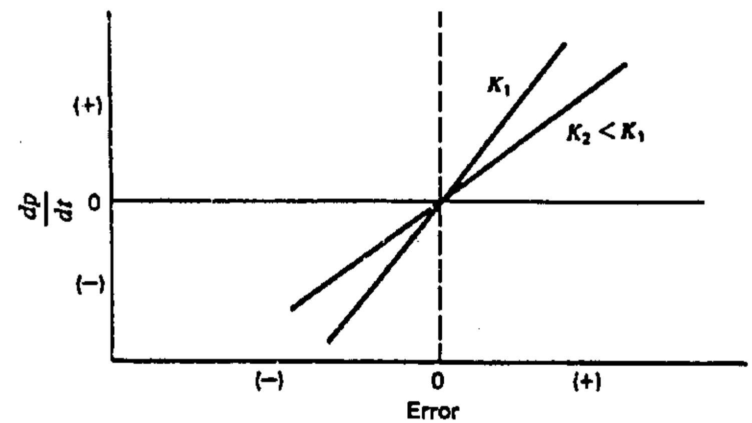
3.3 Integral Control

- the manual adjustment or 'reseting' of the operating point bias of a proportional controller may be automated
- in equation form:

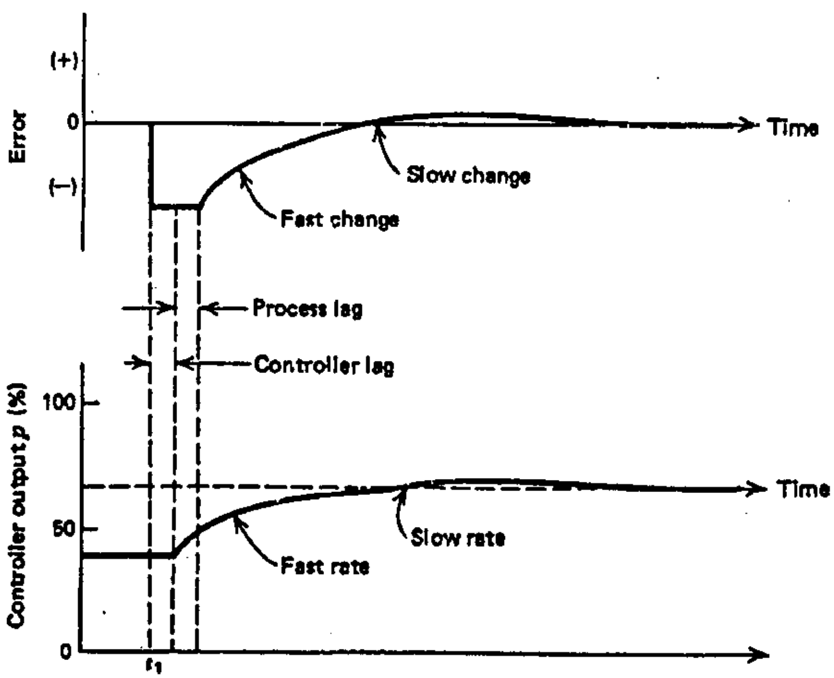
$$p(t) = K_I \int_0^t e_p(t)dt + p(0)$$

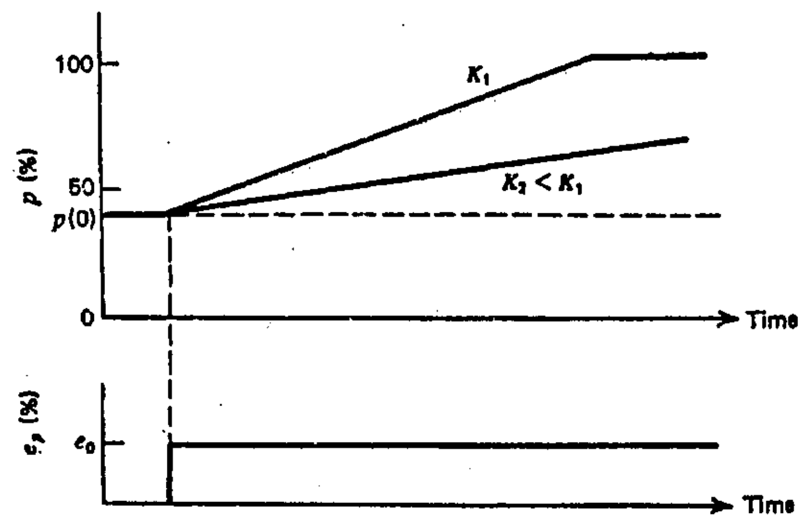
where K_I is the integral controller gain that relates the rate to the error (1/sec)

$p(0)$ is the controller output at t = 0



a) The rate of output change depends on gain and error



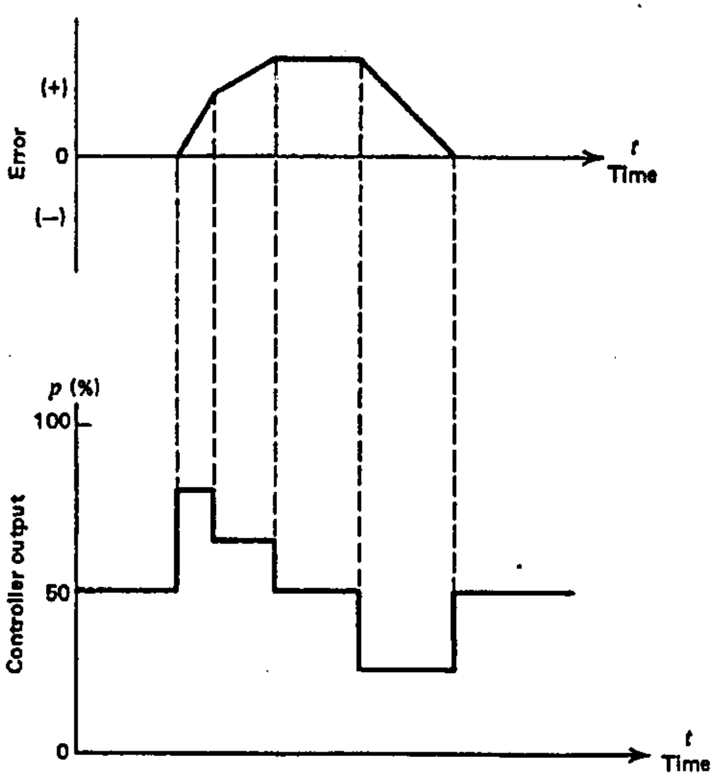


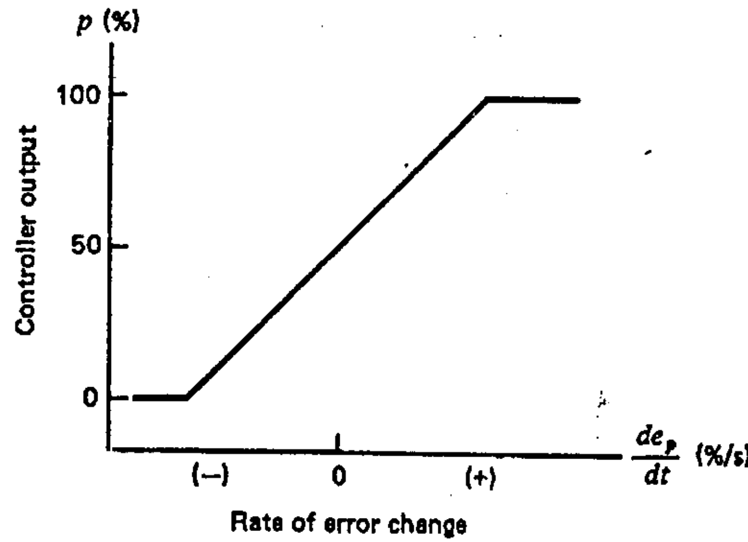
b) Illustration of integral mode response to a constant error

3.4 Derivative Control

- it is possible to design a controller that responds to the rate of change of the error, and is therefore also called ‘rate’ or ‘anticipatory’ control
- derivative control cannot be used by itself, because the controller produces no output at zero or constant error

$$p = K_D \frac{de_p}{dt}$$ where KD is the derivative gain constant





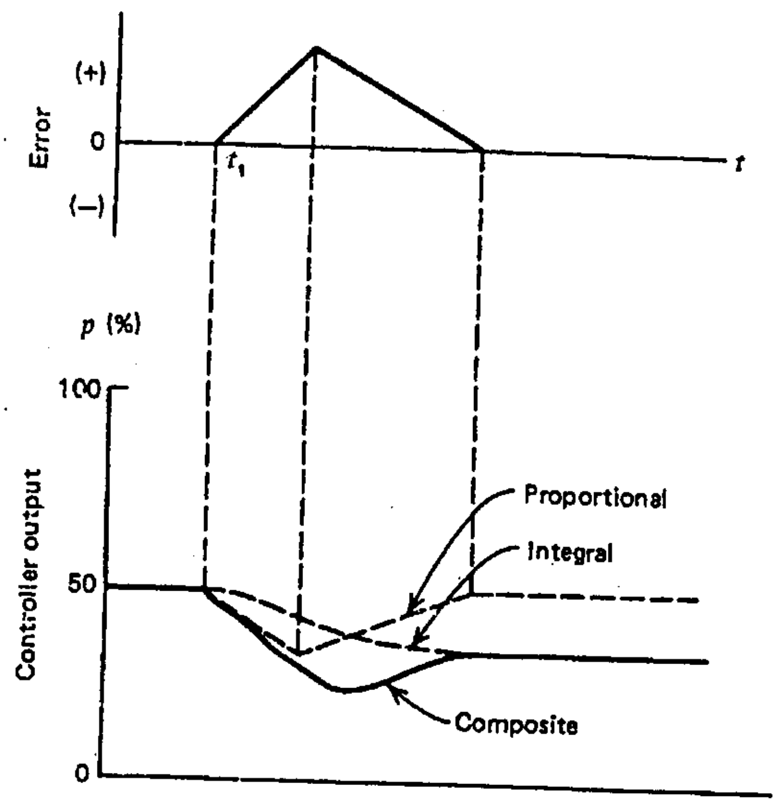
3.5 Proportional-Integral Control

- this type of controller combines the proportional and integral modes

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

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

- the advantage of this type of controller is that it gives the direct action of the proportional type yet it eliminates the offset inherent to proportional control by itself
- care must be taken in the use of this type of controller to ensure that it does not drive itself into saturation of the proportional band as the resultant error can cause 'reset wind-up' as the long term error is integrated

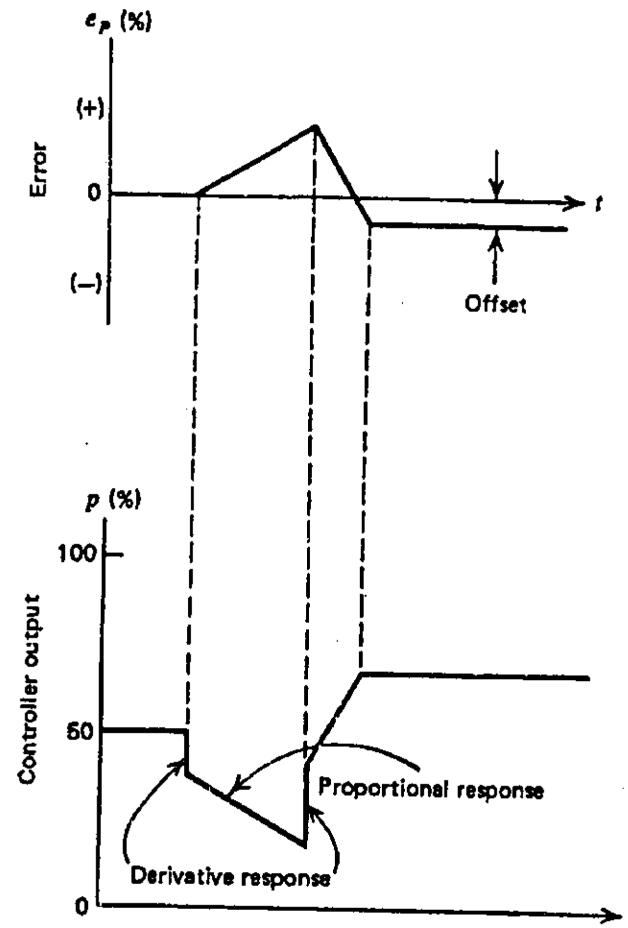


3.6 Proportional-Derivative Control

- proportional and derivative control is widely used in industry,

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

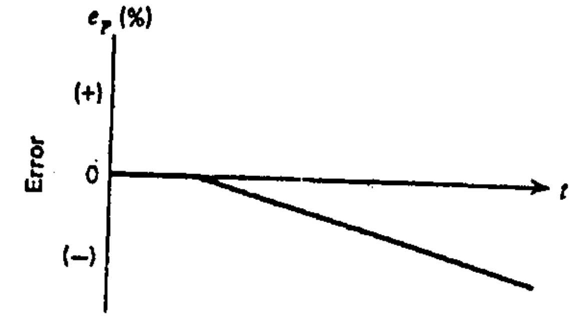
- this type of controller gives fast response to setpoint changes, but it cannot eliminate the residual error

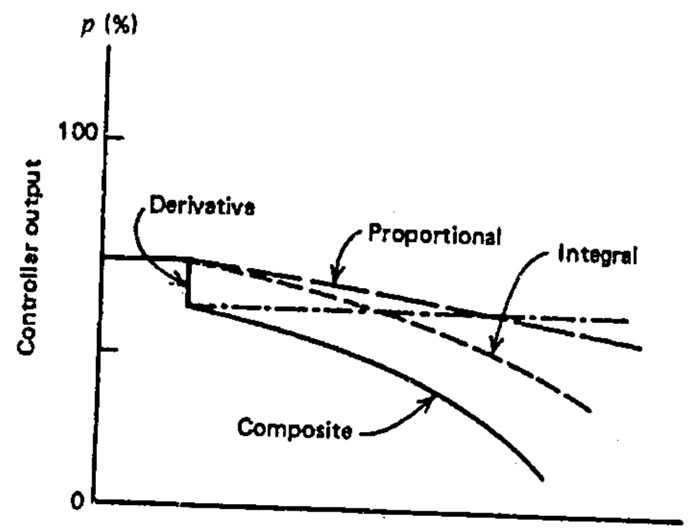


3.7 Proportional-Integral-Derivative (PID) Control

- this type of controller (also called three mode) is the most versatile as it can be used in any of the previous modes by simply setting the corresponding gain to zero
- using all three modes this type of controller can give fast response as well as eliminate the residual error

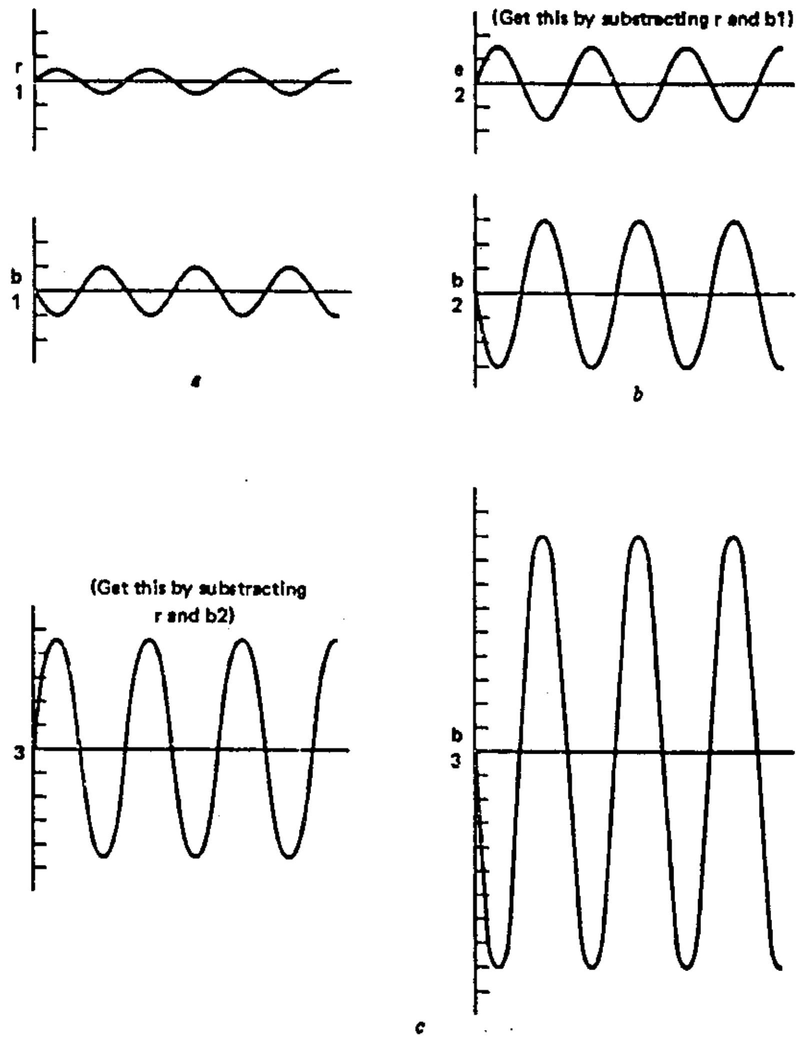
$$p(t) = K_p e_p + K_p K_I \int_0^t e_p(t)dt + K_p K_D \frac{de_p}{dt} + p_I(0)$$





4.0 STABILITY ANALYSIS

- in section 2 we looked at stability (and more important the lack of stability, i.e. instability), we didn't consider how a controller can influence the stability of a controlled process
- the potential for instability is inherent to every feedback control system, since the potential exists that the signal fed back and combined with the setpoint will increase it when it was intended to reduce it, and vice versa
- the instability illustrated in the diagram is due to the feedback signal being larger in magnitude than the reference signal, and 180° out of phase, which due to the negative sign in the error detector, results in a complete 360° net phase shift, so the feedback signal will in fact be added instead of being subtracted
- if the gain of the feedback loop is exactly one, then a constant disturbance will continue to exist; if the feedback gain is greater than one, the disturbance will grow in amplitude
- the system is only stable if:
  - the phase lag is < 180° for all frequencies at which the gain is ≥ 1
  - the gain is < 1 for all frequencies at which the phase lag is ≥ 180°



4.1 OPEN LOOP ANALYSIS

- the gain and phase response of a feedback control system can be determined by opening the feedback loop, applying a signal of variable frequency and measuring the amplitude and phase of the feedback signal
- the phase(s) at which gain is unity (or greater), and the gain(s) where phase is 180° (or greater) are easily determined from such a diagram