CHAPTER1: INTRODUCTION TO CONTROL SYSTEMS

1.1 Introduction

A control system is a device or set of devices to manage, command, direct or regulate the behavior of other devices or systems. Closed loop control systems are used in many industrial process applications for rotating speed of motors. Simple control loops include a set point or desired value input, a measurement input, which indicates the actual value of the parameter to be controlled, and a comparator to develop an error signal related to the difference between the desired and actual values. A control loop output signal, related to the error signal, is then applied to the control device whose parameter is to be controlled, such as a motor whose speed is to be controlled by the loop. The control accuracy and response characteristics of control loops, are conventionally enhanced by adding various control terms or weightings to the error signal in order to develop the control output signal. One classic enhanced servo control loop is known as the PID loop, which includes proportional, integral and derivative terms added to the error signal to develop the desired control signal. PID loops are often applied where the accurate maintenance of a controlled parameter is important, such as the control of the rotational speed of the capstan in a magnetic tape drive [1, 2].

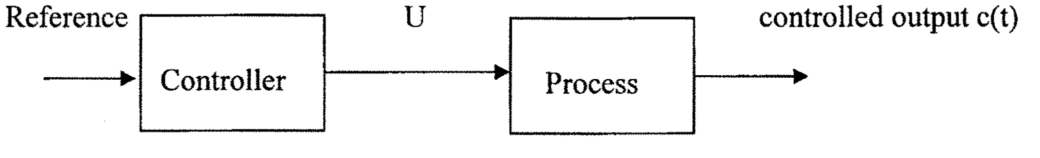
The first significant work in automatic control was James Watt's centrifugal governor for the speed control of a steam engine in the eighteenth century. Other significant works in the early stage of development of control theory were due to Minorsky, Hazen, and Nyquist, among many others. In 1922 Minorsky worked on automatic controllers for steering ship and showed how stability could be determined from the differential equation describing the system. In 1932 Nyquist developed a relatively simple procedure for determining the stability of closed-loop systems on the basics of open-loop response to steady-state sinusoidal inputs. In 1934 Hazen introduced the term "servomechanisms" for speed and position control system. During the decade of the 1940's frequency response methods made it possible for engineers to design linear feedback control system that satisfied performance requirement. From the end of the 1940's to early 1950's the root locus method in control system design was fully developed. As modern plants with many inputs and outputs became more and more complex, the description of a modern control system required a large number of equations. Classical control theory, which deals only with single input single output systems, became entirely powerless for multiple input multiple output systems. Since about 1960, modern control theory has been developed to cope with the increased complexity of modern plants and the stringent requirement on accuracy, weight, and cost in military, space, and industrial applications [3].

The art of automatic control dominates the modern way of life and can be used either in ensuring peace or destruction of the world. The every day gadget like automatic toaster, temperature control of a room, water level control in an overhead tank etc., have influenced the current way of life to a large extent and have made human being to enjoy more and more comforts. Also the control systems used in anti-aircraft gun control, guided missiles and other weapons using nuclear energy can cause destruction of mankind. The fly bàll governor for controlling the speed suggested by Jamès watt in 1788 can be thought of as the first feedback system not involving a human being. After this, many research publications appeared on the same and similar control system [4]. Automatic control has played a vital role in the advancement of engineering and science. In addition to its importance in space-vehicle, missile-guidance, and aircraft-piloting system etc., automatic control has become an important and integral part of modern manufacturing and industrial processes. For example, automatic control is essential in such industrial operations as controlling pressure, temperature, humidity, viscosity and flow in the process industries, tooling, handling and assembling mechanical part in the manufacturing industries among many others. An Autonomous Mobile Robot central control is regulated by an Industrial Process Control [IPC], which controls every function of security, steering, positioning localization and driving. Each traction wheel is operated by a DC motor with independent control system [5].

The conventional proportional control term is a linear gain factor related to the difference between the magnitude of the error signal and the magnitude of the control signal necessary to achieve the desired result. The conventional integral term is a long time constant linear gain term, related to the integral of error signal, used to reduce the residual error. Conventional derivative terms, related to the derivative of the error signal, are added to enhance system response to such short-term transients without reducing the long-term accuracy benefits of the integral terms. PID control applied in a software implementation by an appropriate algorithm is used to generate a value for the control signal in response to applied values for the measurement and set point inputs.

Control systems are classified into two general categories, open loop and closed loop control systems. Open loop control systems are control systems in which the output has no effect upon the control action. In an open-loop control system, the output is neither measured nor fed back for comparison with the input. For example, in a washing machine, soaking, washing, and rinsing are operated on a time basis. The machine does not measure the output signal, namely the cleanliness of clothes.

In any open-loop control system the output is not compared with the reference input. Hence, for each reference input, there corresponds a fixed operating condition. Thus, the accuracy of the system depends on the calibration. In the presence of disturbance, an open-loop control system will not perform the desired task. Open-loop control can be used in practice only if the relationship between the input and output is known and if there are neither internal nor external disturbances. Clearly such systems are not feed back control systems. Any control system, which operates on a time basis, is open loop.



U= Actuating signal

Fig 1.1 Block diagram of open loop control system

Advantages of open loop control systems are simple construction, very much convenient when output is difficult to measure, and such systems are easy from maintenance point of view. Generally these are free from with the pròblems of stability. Such system are simple to design, economical and give inaccurate results if there are variation in the external environment i.e. they cannot sense environmental changes. They are inaccurate and unreliable because accuracy of such systems is totally dependent on the accurate precalibration of the controller. Similarly they cannot sense internal disturbances in the system, after the controller stage. To maintain the quality and accuracy, recalibration of the controller is necessary from time-to-time. To overcome all the above disadvantages, generally closed loop systems are used in practice.

Closed-loop control system is one in which the output signal has a direct effect upon the control action. That is, a closed-loop control system incorporates feed back element. The actuating error signal, which is the difference between the input signal and the feedback signal (which may be the output signal or function of the output signal and its derivatives), is fed to the controller so as to reduce the error and being the output of the system to a desired value. In other words, the term 'closed loop' implies the use of feedback action in order to reduce the system error. The error signal produced in the automatic controller is amplified and the output of the controller is sent to the control valve in order to change the valve opening for steam supply so as to correct the actual water temperature. If there is no error, no change in the valve operation is necessary. The control of a complex system by a human operation is not effective because of the many interrelations among various variables. Automatic control systems eliminate any human error in operation. If high precision control is necessary, control must be automatic.

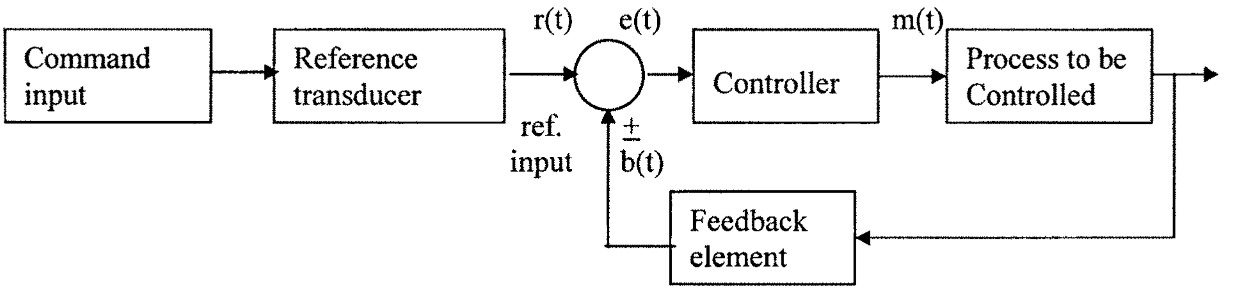


Fig 1.2: Block diagram of closed loop system

c(t)= controlled output m(t)= manipulated signal

b(t) = feedback signal. r(t)= reference input

e(t)= error signal

A system in which the controlling action or input is somehow dependent on the output or changes in output is called closed loop system. Feedback is a property of the system by which it permits the output to be compared with the reference input so that appropriate controlling action can be decided. In such system, output or part of the output is fedback to the input for comparison with the reference input applied to it. It is not possible in all the systems that available signal can be applied as input to the system. Depending upon the nature of controller it is required to reduce it or amplify to change its nature. This changed input as per requirement is called references input, which is to be generated by using reference transducer. The main excitation to the system is called its command input, which is then applied to the reference transducer to generate reference input. The output, which is to be decided by feedback element, is fed back to the reference input. The signal, which is output of feedback element, is called 'feedback signal' b (t). It is then compared with the reference input giving error signal $e(t)=r(t)\pm b(t)$. When feedback signal is positive it is called positive feedback system and if the signal is negative it is called negative feedback system. This modified error signal then actuates the actual system and produces the controlled output c (t).

An advantage of the closed loop control system is that the use of feedback makes the system response relatively insensitive to external disturbances and internal variations in system parameters. It is thus possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given plant, whereas this is impossible in the open-loop case. From the point of stability, the open-loop control system is easier to build since stability is not a major problem. On the other hand, stability is always a major problem in the closed-loop control system since it may tend to overcorrect errors, which may cause oscillations of constant, or changing amplitude. It should be emphasized that for systems in which the inputs are known ahead of time and in which there are no disturbances, it is advisable to use open-loop control. Closed-loop control systems have advantages only when unpredictable disturbances and/or unpredictable variations in system components are present. A proper combination of open loop and closed-loop control is usually less expensive and satisfies the overall system performance. The design and implementation of smart structural systems necessitates the integration of mechanical systems with sensors, actuators, and control systems for higher performance and self-diagnosis capabilities. A key element of this combination is the integration of the control system into the structure [6]. Control is important for most industrial processes to avoid disturbances which degrade the overall process performance, and a great deal of work is being done in this field [7]. The nice thing about tuning a PID controller is that the user need not have a good understanding of formal control theory to do a fairly good job of it. About 90% of the closed-loop controller applications in the world do very well indeed with a controller that is only tuned fairly well.

1.2 Process control system

The process control system is the entity that is charged with the responsibility for monitoring outputs, making decisions about how best to manipulate inputs so as to obtain desired output behavior, and effectively implement such decisions on the process [8]. The process has a property called self-regulation. A self-regulating system does not provide regulation of a variable to any particular reference value. In process control, the basic objective is to regulate the value of some quantity. To regulate means to maintain that quantity at some desired value regardless of external influences. The desired value is called the reference value or set point. In many industrial process control systems, the controlled process is complex in mechanism, and varying with time. So general PID control is very difficult to obtain satisfactory effects because it is not self-adaptive for many varying factors such as parameter varying.

The process dynamics are concerned with analyzing the dynamic (i.e., time dependent) behavior of a process in response to various types of inputs. In other words, it is the behavior of a process as time progresses [9, 10]. A process is a progressively continuing operation that consists of a series of controlled actions or movements systematically directed toward a particular result or end. When the automatic control is applied to system, which is designed to regulate the value of some variable to a set point, it is called process control. Examples are chemical, economic, and biological processes.

An automatic regulation system in which the output is a variable such as temperature, pressure, flow, liquid level, or pH is called a process control system. Process control is widely applied in industry. Programmed control such as the temperature control of heating furnaces in which the furnace temperature is controlled according to a preset program are often used in such systems. For example, a preset program may be such that the furnace temperature is raised to a given temperature in some given time interval and then lowered to another given temperature in some other given time interval. In such program control, the set point is varied according to the preset time schedule. The controller then functions to maintain the furnace temperature close to the varying set point. It should be noted that most process control systems include servomechanism as an integral part [11].

1.3 Servo control system

A servomechanism is a feed back control system in which the output is some mechanical position, velocity or acceleration. Servo mechanisms are extensively used in modern industry. For example, the completely automatic operation of machine tools, together with programmed instruction, may be accomplished by use of servomechanism. The specialized feed back control system called a servomechanism deserves special attention due to its prevalence in industrial application and control system literature. A servomechanism is a power- amplifying feed back control system in which the controlled variable is mechanical position, or a time derivative of position such as velocity or acceleration.

A simple example of servomechanism is a position control system. Consider a load, which requires a constant position in its application. The position is sensed and converted to voltage using feedback potentiometer. It is compared with input potentiometer voltage to generate error signal. This is amplified and given to the controller. The controller in turn controls the voltage given to motor, due to which it changes its position. In the servomechanism the objective is to force some parameter to vary in a specific manner. This may be called a tracking control system. Instead of regulating a variable value to a set point, the servomechanism forces the controlled variable value to follow variation of the references value. For example, in a robot arm, servomechanism forces the robot arm to follow a path from one point to another point. This is done by controlling the speed of the motors driving arm and the angles of the arm parts.

Advances in servomechanism has led to the development of the new field of automatic control, the robots and robotology. A robot is a mechanism devised to perform repetitive tasks that are tiresome for a human being or tasks to be performed in a hazardous environment say in a radioactive area. Robots are as varied as the tasks that can be imagined to be performed by them. Great strides are being made in this field with the explosion in the power of digital computer, interfacing and software tools which have brought to reality the application of vision and artificial intelligence for devising more versatile robots and increased applications of robotology in industrial automation. In fact in replacing a human being for a repetitive and/or hazardous task, robots can perform the task, at a greater speed and higher precision. Using robots (specially designed for broken-down tasks) in assembly line in a manufacturing process can be speeded up with added quality and reliability of the end product. Example can be cited of watch industry in Japan where as many as 150 tasks on the assembly are robot executed. For flexible manufacturing units mobile automation have been devised and implemented which are capable of avoiding objects while traveling through a room or industrial plant [12]. An automobile power-stering apparatus is a servomechanism. The command input is the angular position of the steering wheel. A small rotation torque applied to the steering wheel is amplified hydraulically, resulting in a force adequate to modify the output, the angular position of the front wheels. Negative feedback is necessary in order to return the control valve to the neutral position, reducing the torque from the hydraulic amplifier to zero, when the desired wheel position has been achieved [13]. Fractional horsepower dc drives are widely employed as servo means for positioning and tracking [14].

1.4 ON/OFF control

The most elementary controller mode is the ON/OFF, or two-position mode. The ON/OFF controller is the simplest controller that turns the actuator either hard ON or fully OFF. Generally, the two-position control mode is best adapted to large-scale systems with relatively slow process rates. Thus, in the example of either a room heating or air-conditioning system, the capacity of the system is very large in terms of air volume, and the overall effect of the heater or cooler is relatively slow. Sudden, large-scale changes are not common to such systems. Other examples of two-position control applications are liquid bath temperature control and level control in large-volume tanks. The process under two-position control must allow continued oscillation in the controlled variable because, by its very nature, this mode of control always produces such oscillations. When the measured value is less than the set point, full controller output results. When it is more than the set point, the controller out put is zero. To prevent excessive cycling or chattering, a dead band (hysteresis) is usually introduced to provide finer and smoother control.

One of the most elementary types of digital processing has been in use for many years, long before the advent of computers, in fact. This is called ON/OFF control because the final control element has only two states, on and off. Thus, the controller output can have only these two states as well. It can be said that the controller output is a digital representation of a single binary digit, 0 or 1. Our home and auto heaters and air conditioners, home water heaters, and host of other basic control systems work according to the same ON/OFF mode.

This is the simplest form of control, used by almost all domestic thermostats. When the oven is cooler than the set-point temperature, the heater is turned on at maximum power, M, and once the oven is hotter than the set-point temperature, the heater is switched off completely. The turn-on and turn-off temperatures are deliberately made to differ by a small amount, known as the hysteresis H, to prevent noise from switching the heater rapidly and unnecessarily when the temperature is near the set point.

1.5 Proportional Control [P]

In an analog system, a proportional control system amplifies the error signal to generate the control signal. If the error signal is a voltage, and the control signal is also a voltage, then a proportional controller is just an amplifier. In a digital control system, a proportional control system computes the error from measured output and user input to a program, and multiplies the error by a proportional constant, then generates an output control signal from that multiplication. Proportional control is the easiest feedback control to implement and probably the most common kind of control loop. A proportional controller is just the error signal multiplied by a constant and fed out to the drive.

Proportional gain. The action means that the controller moves in proportion to the error between set point (SP) and process output (PV):

$$\text{Controller output} = Kp*\text{error} = Kp*(SP - PV)$$

Where the gain is denoted by the parameter Kp. Different manufacturers to designate this action have used many terms like proportional gain, gain, throttling band, sensitivity and proportional band. For small gains (kp = 1) the motor goes to the correct target, but it does so quite slowly. Increasing the gain (kp = 2) speeds up the response to a point. Beyond that point (kp = 5, kp = 10) the motor starts out faster, but it overshoots the target. In the end the system doesn't settle out any quicker than it would have with lower gain, but there is more overshoot. If we kept increasing the gain we would eventually reach a point where the system just oscillated around the target and never settled out-the system would be unstable. The motor and gear start to overshoot with high gains because of the delay in the motor response. Plânts that have too much delay, like the precision actuator, can't be stabilized with proportional control. Some plants, like the temperature controller, cannot be brought to the desired set point. Plants like the motor and gear combination may work, but they may need to be driven faster than is possible with proportional control alone. To solve these control problems an integral or differential control or both need to be added.

A proportional control system is a type of linear feedback control system. The proportional control system is more complex than an on-off control system like a thermostat, but simpler than a proportional-integral-derivative (PID) control system used in something like an automobile cruise control.An on-off control is like driving a car by applying either full power or no power and varying the duty cycle, to control speed. The power would be on until the target speed is reached, and then the power would be removed, so the car reduces speed. When the speed falls below the target, with a certain hysteresis, full power would again be applied. It can be seen that this looks like pulse-width modulation, but would result in poor control. A proportional controller attempts to perform better than the On-Off type by applying power W, to the heater in proportion to the difference in temperature between the oven and the set point,

$$W=P*(Ts-To)$$

Where P is known as the proportional gain of the controller. As its gain is increased, the system responds faster to changes in set point but becomes progressively underdamped and eventually unstable. The final oven temperature lies below the set point for this system because some difference is required to keep the heater supplying power. The heater power must always lie between zero and the maximum because it can only source not sink heat.

The Proportional (P) controller is an improved controller over ON/OFF controller, wherein the dead band is replaced by proportional band. Over this operational band, the output of the proportional controller varies linearly with error around zero. Although capable of providing tight control than the ON/OFF controller, the proportional controller cannot fully eliminate the error to cause perfect steady state tracking between the set point and process variable. The controllers are designed to eliminate the need for continuous operator attention. A controller is one, which compares the output value (process variable) with the desired value (set point), determines the error and accordingly produces control action to minimize the error. Hence, the controllers are used to automatically adjust some variable to hold the measurement (process variable) at the desired level [15,16]. Proportional control makes systems run smoother than bang-bang. Most biological systems are proportional, while many engineered and all too many political and social systems are bang-bang.

The Proportional controller produces an output signal which is proportional error signal. The transfer funcation of Proportional controller is Kp. The term Kp is called the gain of the controller. Hence the Proportional controller amplifies the error signal and increases the loop gain of the system. If increased, the loop gain then improves the steady state tracking accuracy, distrubance signal rejection, and realive stability. It produces a constant steady state error.To handle the immediate error, the error is multiplied by a constant Proportional (P). If the error is zero, a Proportional controller's output is zero.

$$P=K_p\, e(t)$$

In the proportional control action, the relationship between the output of the controller m(t) and the actuating error signal e(t) is

$$m(t)= K_p e(t)$$

or

$$M(s)/E(s)=K_p$$

Kp is termed the actual mechanism, whatever may be the form of the operating power, the proptional controller is essentially an amplifer with an adjustable gain.

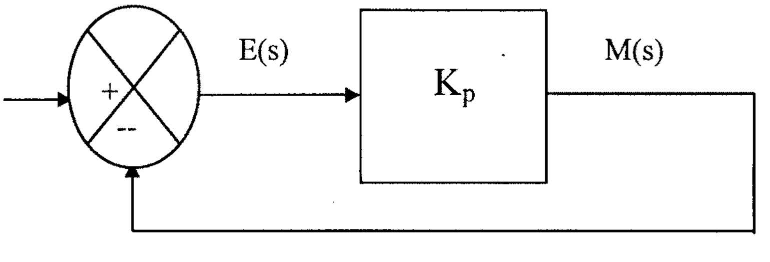


Fig 1.3: block diagram of Proportional control system

1.6 Integral Control [I]

Integral control is used to add long-term precision to a control loop. It is almost always used in conjunction with proportional control. Integral control by itself usually decreases stability, or destroys it altogether. The system doesn't settle. Like the precision actuator with proportional control, the motor and gear system with integral control alone will oscillate with bigger and bigger swings until something hits a limit. This system takes a lot longer to settle out than the same plant with proportional control, but when it does settle out to the target value even with the disturbance added in. If the problem at hand doesn't require fast settling, this might be a workable system. The easiest and most direct way to deal with integrator windup is to limit the integrator state.

To learn from the past, the error is integrated and multiplied by a constant I. Without integral term, a controller cannot eliminate error if the process requires a non-null input to produce the desired set-point, integral of the error constantly increases with time.

$$I = 1/Ti \int e(t)\, dt$$

In a controller with integral control action, the value of the controller output m(s) is changed at a rate proportional to the actuating error signal e(t).

$$m(t) = K_i \int e(t)\, dt$$

Where Ki is an adjuststable constant. The transfer funcation of the integral controller is

$$M(s)/E(s) = K_i/s$$

If the value of e(t)is doubled, then the value of m(t) varies twice as fast. For zero actuating error, the value of m(t) remains stationary. The integral control action is some times called reset control.

1.7 Proportional plus Integral control [PI]

A controller in the forward path, which changes the controller input to the proportional plus integral of the error signal is called PI controller. Sometimes, particularly when the sensor measuring the oven temperature is susceptible to noise or other electrical interference, derivative action can cause the heater power to fluctuate wildly. In these circumstances it is often sensible to use a PI controller or set the derivative action of a PID controller to zero. Although capable of providing tight control than the ON/OFF controller, the proportional controller cannot fully eliminate the error to cause perfect steady state tracking between the set point and process variable. An integrator must be added to the proportional controller so as to become proportional plus integral controller. This Proportional plus Integral (PI) controller will provide good steady state control, but responds sluggishly to transients.

The Proportinal plus integral action reduces the steady state error. The proprtional control produces the constant steady state error and integral control reduces the error to zero. A simple combination of the proportional and integral logic provides the porportional integral mode of controller action.

The control action of a proportional plus integral controller is defined by the following equation

$$m(t)=K_p e(t)+K_p/Ti \int e(t)\, dt$$

or

$$M(s)/E(s)=Kp(1+1/T_is)$$

Where K_p reprensts the proportional senstivity or gain, and T_i reprents the integral time. Both K_p and Ti are adjustable. The integral time adjusts the integral control action, while a change in the value of K_p affects both prportional and integral parts of the control action. The inverse of the integral time Ti is called the reset rate. The reset rate is the number of times per minute that the proportinal part of the control action is duplicated. Reset rate is measured interms of repeats per minute. If the actuating error signal e(t) is a unit-step function as shown fig 1.4, then the controller output m(t).

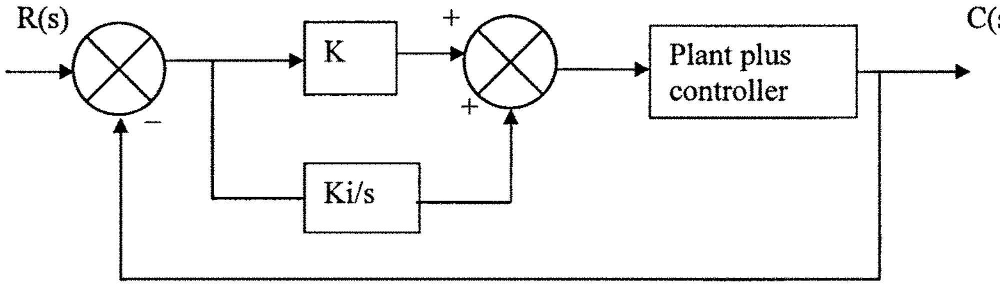


Fig 1.4: Block diagram of PI control system

PI controller has the following effects

1. It increases order of the system.
2. Design of Ki must be proper to maintain stability of system. So it makes system relatively less stable.
3. Steaday state error reduces tremendously for some type of input. i.e., in general this controller improves steady state part affecting the transient part.

1.8 Proportional plus Derivate control action [PD]

A controller in the forward path, which changes the controller input to the proportional plus derivative of error signal is called PD controller. The precision actuator cannot be stabilized with PI control. The proportional control deals with the present behavior of the plant, and that integral control deals with the past behavior of the plant. If we had some element that predicts the plant behavior then this might be used to stabilize the plant.
The stability and overshoot problems that arise when a proportional controller is used. Adding a term proportional to the time-derivative of the error signal can mitigate high gain, which is known as PD control.

$$W=p^*(Ts-To)+D^* \, d/dt \, (Ts-To)$$

The value of the damping constant, D, can be adjusted to achieve a critically damped response to changes in the set-point temperature. Too little damping results in overshoot and ringing, too much causes an unnecessarily slow response.

The proportional plus derivate controller produces an output signal consisting of two-terms one proportional to error signal and the other proprtional to the derivative of error signal.

The transformation controller is

$PD = K_p \, (1+T_d s)$

Where K_p is proprtional gain and T_d is derivative time.

$m(t) = K_p e(t) + K_p T_d\, de(t)/dt$

And transfer function is $M(s)/E(s)=K_p(1+T_d s)$

Both Kp and Td are adjustable. The derivative control action, sometimes called rate control, is where the magnitude of the controller ouput is proportional to the rate of change of the actuating error signal. The derivative time Td is the time interval by which the rate action advanced the effect of the proportional-plus detrivative controller. If the actuating error signal e(t) is a unit-ramp function, then the controller output is m(t). While derivative control action has an advantage of being anticipatory, it has the disvantage that it amplifies noise signal and may cause a saturation effect in the actuator. The derivative control action can never be used alone because this control action is effective only during transient periods.

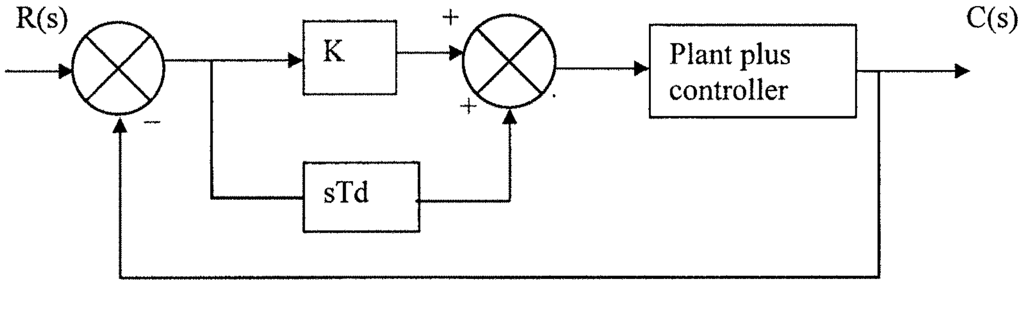


Fig 1.5: Block diagram of PD control system

As there are no changes in coeffiencients, error also will remain the same. Hence PD controller has the following effects on system.

1. It increases the damping ratio.
2. It reduces the peak over shoot.
3. It reduces the settling time.
4. Steady state error remains unchanged.

In general, it improves transient part without affecting steady state. In closed loop transfer function, it is observed that the PD controller introduces a zero in the system and increases the damping ratio. The additon of the zero may increase the peak overshoot and reduce the rise time. But the effect of increased damping ultimately reduces the peak overshoot.

1.9 Proportional plus Integral plus Derivative controller [PID]

As PD improves transient and PI improves steady state, combination of the two may be used to improve overall time response of the system. While PD control deals neatly with the overshoot and ringing problems associated with proportional control, it does not cure the problem with the steady-state error. Fortunately it is possible to eliminate this while using relatively low gain by adding an integral term to the control function. The integral gain parameter is sometimes known as the controller reset level. This form of function is known as proportional-integral-differential or PID control. The effect of the integral term is to change the signal power until the time-averaged value of the error is zero. The method works quite well but complicates the mathematical analysis slightly because the system is now third order.

PID controllers are most commonly used to regulate the time-domain behavior of many different types of dynamic plants. These controllers are extremely popular because they can usually provide good closed-loop response characteristics. They can be tuned using relatively simple design rules, and are easy to construct using either analog or digital components [17,18].

This deficiency can be over come by the addition of a derivative element, which constitutes a complete PID controller. This gives good transient as well as steady state control. It offers rapid proportional response to error, while having an automatic reset from the integral part to eliminate residual error. The derivative section stabilizes the controller and allows it to respond the rapid changes or transients in error [19].

As the PID controller is composed of three components, it produces an output signal consisting of three terms-one is proportional to the error signal e(t), another is proportional to integral of error signal e(t) and the third one is proportional to derivative of the error signal e(t) [20-22]. The equation of the PID controller is given as

$$u(t) \propto [\, e(t) + \int e(t)\,dt + de(t)/dt \,]$$

$$u(t) = K_p\, e(t) + K_p/T_i \int e(t)\,dt + K_p T_d\, de(t)/dt$$

where,

K_p is the proportional gain

T_i is the integral time

T_d is the derivative time

The transfer function can be written as,

$$U(s)/E(s) = Kp\,(1 + 1/T_i\,s + T_d\,s)$$

The block diagram representation of the PID controller is shown in Fig. 1.6 and block diagram of the PID based control system is depicted in Fig. 1.7.

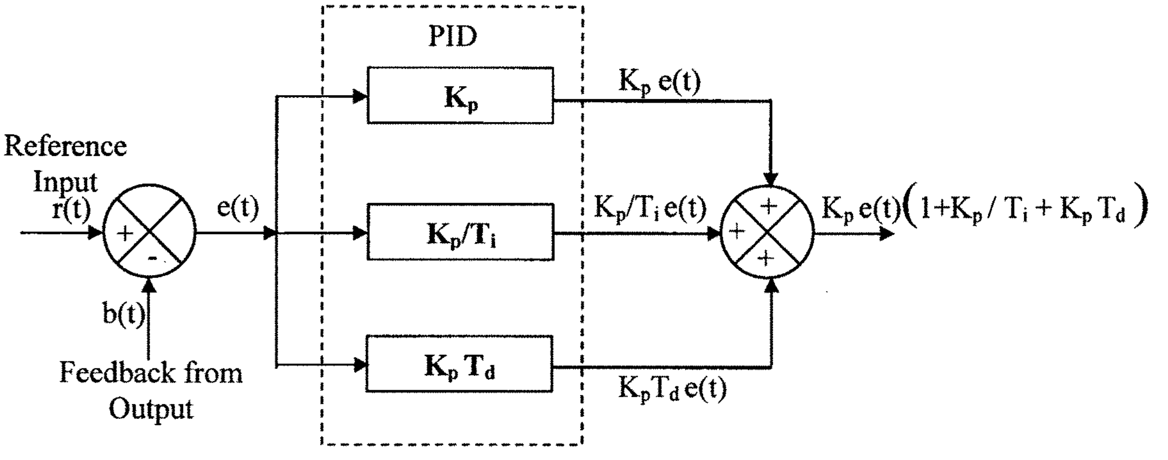


Fig 1.6 Block diagram representation of the PID controller

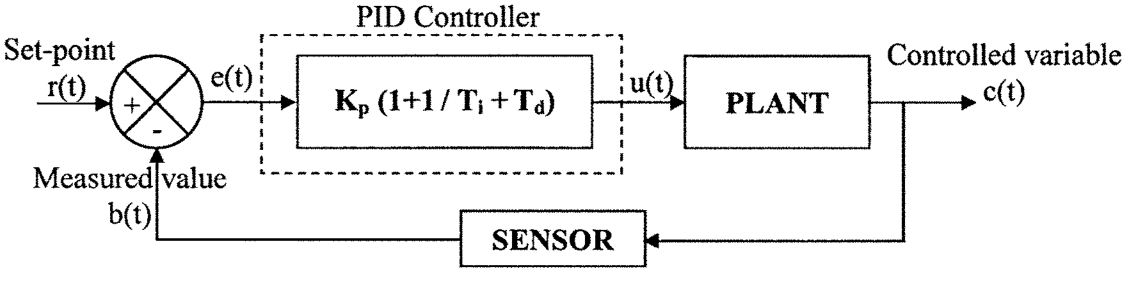


Fig 1.7 Block diagram of the PID based control system

To ensure the digital implementation of the PID control, the differential equation must be converted to a discrete differential equation as given bellow,

$$v_o = K_p (e) + K_i \int e(t)\, dt + K_d (de(t)/dt) \qquad .....(1.1)$$

At any instant of time, the current value of the PID output V_n is calculated based on the previous value of the PID output V_{n-1}, current error e_n, previous error e_{n-1}, previous to the previous error e_{n-2}, the cycle time T and weighing constant (K_p, K_i, K_d).

The great advantage of the proposed control architecture is that the parameters of PID controllers do not need to adapt. Furthermore, the design scheme provides an easy way to design the PID controller. The goal of the first Ziegler-Nichols PID controller is designed with fast response. Usually, it can be obtained after using the Ziegler-Nichols tuning algorithms. The second grey prediction is that PID controller is operated in slow response. It can be easily achieved through scheduling the system output. Most of the control techniques implemented in industrial processes employ PID controller. There are two reasons why nowadays it is still the majority in industrial processes. The first reason is that it's simple structure and the well-known Ziegler- Nichols tuning algorithms have been developed [23]. The second reason is that the controlled processes in industrial plant almost can be controlled through the PID controller [24-25]. However, the conventional PID controller design usually needs to retune the parameters (proportional gain, integral time constant and derivative time constant) mutually by a skilled operator. In the present work, an easy but effective control architecture of PID controller integrating the well-known Ziegler-Nichols PID controller with gray prediction controller is introduced.

In order to compensate the characteristic of original controller, the predicted system output feeds into the PID controller. Essentially, different system performance can be obtained if using the different prediction step.

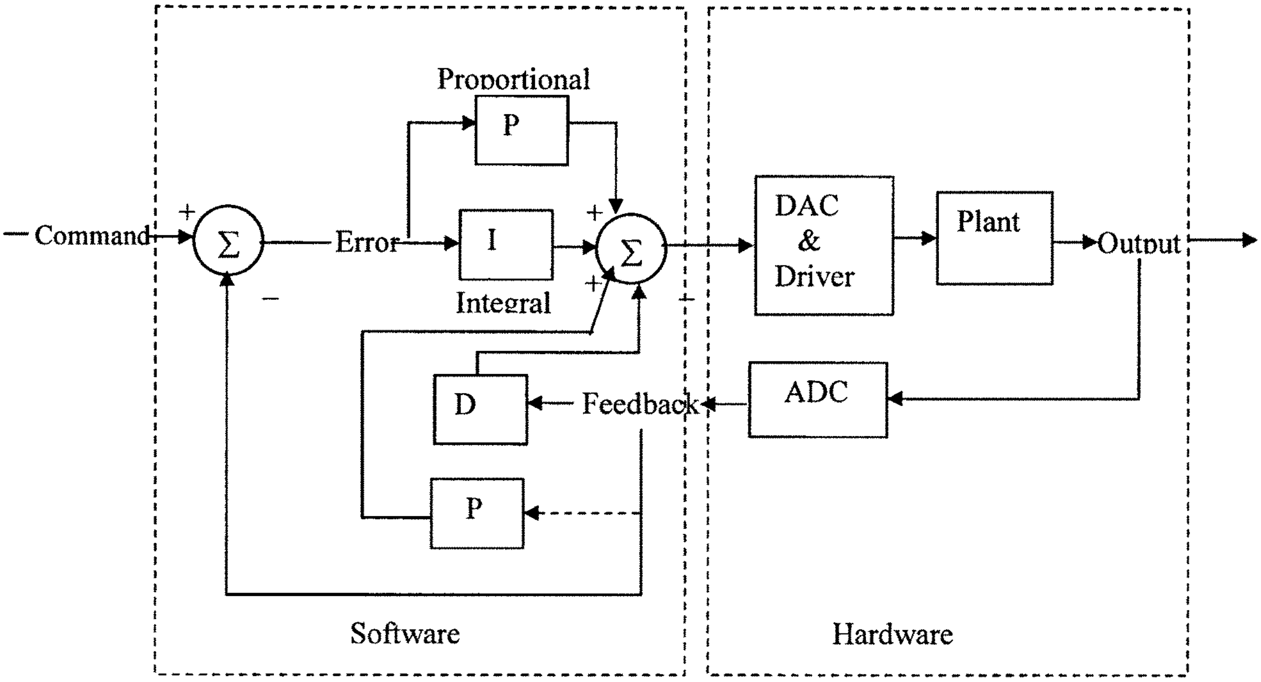


Fig 1.8 Block diagram of software and hardware of PID control system

1.10 Ziegler-Nichols (ZN method)

The PID tuning method is designed by Ziegler and Nichols (ZN) is based on the systems step response. It uses the fact that many systems in the process industry can be approximated by a first-order lag plus a time delay of the step response of the plant [26]. In Ziegler and Nichols method based on the frequency response of the closed-loop system under pure Proportional control, the gain is increased until the closed-loop system becomes critically stable. At this point the ultimate gain K is recorded together with the corresponding period of oscillation Tu known as the ultimate period. Based on these values Ziegler and Nichols calculated the tuning parameters as shown in Table 1.1.

The ZN methods were designed to give good responses to load disturbances. A quarter amplitude-damping criterion was used in the design giving a damping ratio close to 0.2. This is not satisfactory for many systems, since it does not give satisfactory phase and gain margins. The maximum sensitivity is also large, making systems sensitive to parameter variations. Additionally, ZN methods are not easy to apply in their original form on working plants. When critical processes are involved, sudden changes in the control signal or operation at the stability limit are not acceptable. Relay feedback and describing function analysis [27] are often applied for parameter identification to overcome the above problems. A further modification to the ZN methods can give a substantially improved system performance [28].

S.N0	Controller	K	Ti	Td
1	P	0.5 Ku		
2	PI	0.4 Ku	0.8Tu	
3	PID	0.6Ku	0.5 Tu	0.12Tu

Table 1.1: ZN PID frequency response tuning parameters

The PID controller is very widely used in industry. It's popularity stems from the fact that the control engineer essentially has to determine the best settings for the Proportional, Integral, and Derivative action terms needed to achieve a desired closed-loop performance [29]. PID is a common feedback loop component in industrial control system.The controller takes a measured value from a process or other apparatus and compares it with a reference setpoint value. The difference (or "error" signal) is then used to adjust some input to the process in order to bring the process' measured value to its desired setpoint. Unlike simpler controllers, the PID can adjust process outputs based on the history and rate of change of the error signal, which gives more accurate and stable control. In contrast to more complex algorithms such as optimal control theory, PID controllers can often be adjusted without advanced mathematics. However, pushing robustness and performance to the limits requires a good understanding of the theory and controlled process.

PID control provides a generic and efficient solution to real-world control problems. The wide application of PID control has stimulated and sustained research and development to "get the best out of PID", and "the search is on to find the next key technology or methodology for PID tuning"[1]. The proportional controller stablizes the gain but produces a steady state error. The integral controller reduces or eliminates the steady state error. The derivative controller reduces the rate of change of error. If the PID parameters (the.gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e. its output diverges, with or without oscillations, and is limited only by saturations or breakage. Tao and Sadler [30] designed a PID controller and applied nonlinear programming techniques to determine the optimal controller gains presenting the best constant speed behavior for a four-bar mechanism.

A PID controller is called a PI, PD, or P controller in the absence of respective control actions. The PID algorithm can be implemented in several ways. The easiest form to introduce is the parallel or "non-interacting" form, where the P,I and D elements are given the same error input in parallel. The output of the controller (i.e. the input to the process) is given by

$$Output(t)=P_{contrib}+I_{contrib}+D_{contrib}$$

where $P_{contrib}$, $I_{contrib}$, and $D_{contrib}$ are the feedback contributions from the PID controller, defined below:

$$P_{contrib} = K_p\, e(t)$$

$$I_{contrib}= 1/T_i \int e(t)\, dt$$

$$D_{contrib}= T_d\, de/dt$$

Where $e(t)$ = Setpoint − Measurement(t) is the error signal, and K_p, T_i, T_d are constants that are used to tune the PID control loop:

1. K_p: Proportional Gain - Larger K_p typically means faster response since the larger the error, larger is the feedback to compensate.
2. T_i: Integral Time - Smaller T_i implies steady state errors are eliminated quicker. The tradeoff is larger overshoot: any negative error integrated during transient response must be integrated away by positive error before steady state is reached.
3. T_d: Derivative Time - Larger T_d decreases overshoot, but slows down transient response.

1.11 PID Tuning Methods

PID tuning methods can be divided into the following categories, where the classification is based on the availability of a process model, and the model type as given Fig1.9

1. Model free methods.
2. Non-parametric model methods.
3. Parametric model methods

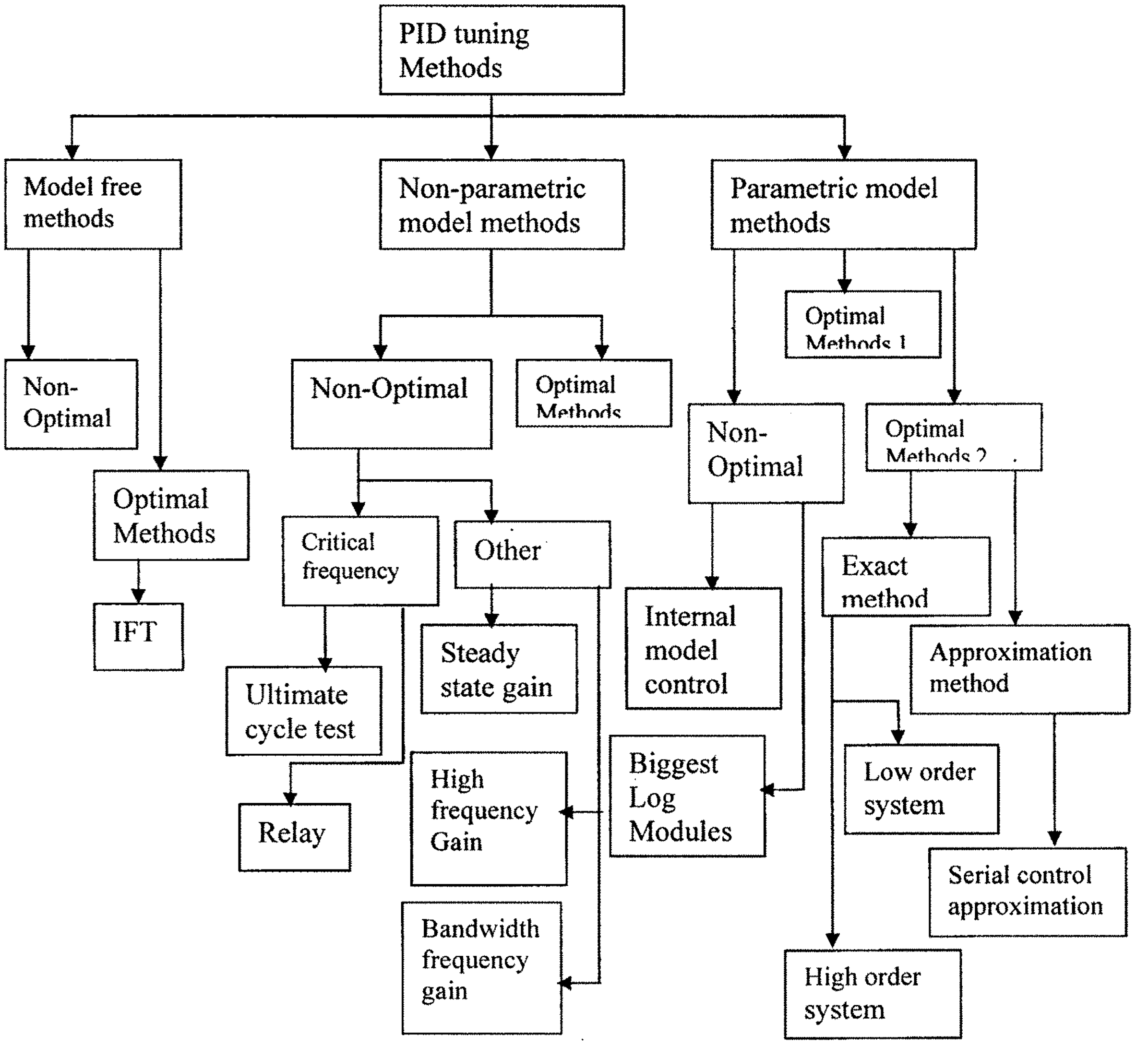


Fig 1.9 Block diagram of PID tuning methods

In model free methods, no model or any particular points of the process are identified (Johnson and Moradi, 2003).

The second group of methods uses only partial modeling information, usually steady state model and critical frequency points. These methods are more suitable for online use. These methods can usually be applied without the need for extensive prior plant information (Johnson and Moradi, 2003). For the third group, model data is available using standard offline or online identification methods. These methods require a linear model of the process, transfer function matrix or state space model [31]. These methods are more suitable for off-line PID tuning. The parametric methods can be divided into the following methods:

1. Non-Optimal Parametric Methods
2. Optimal Methods Type One (Restricted Structure control)
3. Optimal Methods Type Two (Control Signal matching (typically))

In non-optimal parametric method, the PID controller is tuned to closed loop system to meet specified system robustness and performance. In this method, the PID gains are found using well known standard methods and then these gains will be retuned until Biggest Log Module (BLM) becomes less than a specified value. Internal Model Control (IMC) is another method of the non-optimal parametric group. This method will find the PID gains for each element of transfer function G(s), and then the tuning matrix for the MIMO system is computed.

In optimal method one, different methods are used to tune PID parameters with respect to criteria, which usually is a minimization of cost functions. Some possible design specifications are:

1. Normal Performance.
2. Minimum Input Energy.
3. Robust Stability.
4. Operational constraints.

The optimal methods are used in a multivariable self-tuning PID control systems. The objective of the controller was to minimize the variance of output. This method minimizes the integrated control error to obtain good load disturbance responses. This method has been simplified for first order system with delay.

Optimal Methods Type Two (Control Signal Matching (Typically)): The academic control community has developed many new techniques for tuning PID controllers. Often these methods try to stretch the capabilities of PID control to match the performance of the advanced controller design. In some of these methods the control signal of advanced technique has been approximated by PID with respect to a cost function, which is usually the norm of error between output of PID controller and advanced controller [32].

The constraints, which are considered, are:

1. Saturation of actuator
2. Constraints on PID parameters
3. Constraints on initial optimal method

This optimization, depending on the order of system and time delay, leads to exact methods or approximation methods.

The manner in which a measured process variable responds over time to changes in the controller output signal is fundamental to the design and tuning of a PID controller. The best way to learn about the dynamic behavior of a process is to perform experiments, commonly referred to as "bump tests." Critical to success is that the process data generated by the bump test be descriptive of actual process behavior. Discussed are the qualities required for "good" dynamic data and methods for modeling the dynamic data for controller design. Parameters from the dynamic model are not only used in correlations to compute tuning values, but also provide insight into controller design parameters such as loop sample time and whether dead time presents a performance challenge. It is becoming increasingly common for dynamic studies to be performed with the controller in automatic mode. For closed loop studies, bumping the set point generates the dynamic data.

In cases where PID controllers have been installed previously, it is easier to add a set of supervisory controllers instead of rebuilding the whole structure. Another advantage is that if, for any reason, the expert system fails, the PID controller can be dropped back to a set of safe parameters, which will guarantee that the plant remains stable [33]. The popularity of PID controllers is due to their functional simplicity and reliability. They provide robust and reliable performance for most systems if the PID parameters are determined or tuned to ensure a satisfactory closed-loop performance [34]. PID control is a control strategy that has been successfully used over many years. Simplicity, robustness, a wide range of applicability and near-optimal performance are some of the reasons that have made PID control so popular in the academic and industry sectors. Recently, it has been noticed that PID controllers are often poorly tuned and some efforts have been made to systematically resolve this matter [35].

1.12 On/Off, P, PI, and PID controllers

The graphical representation of the response of a model PID controller is shown in Fig. 1.10 It is observed that PID controller has better response over all other mentioned controllers in terms of settling time, rise time, under shoots and over shoots. Hence, the PID controllers are still widely used in many industrial systems, despite the significant developments of recent years in control theory and technology [36-39]. This is because they perform well for a wide class of processes. Also, they give robust performance for a wide range of operating conditions. The digital implementation of P, PI, and PID control algorithms using microprocessors, microcontrollers and personal computers lead to automation, easy analysis and further intelligent control of a process.

The distributed-arithmetic based PID controller demonstrates 80% savings in hardware utilization and 40% savings in power consumption compared to the multiplier-based scheme. It also offers good closed-loop performance while using less resources, resulting in cost reduction, high speed and low power consumption, which is desirable in embedded control applications [40-42].

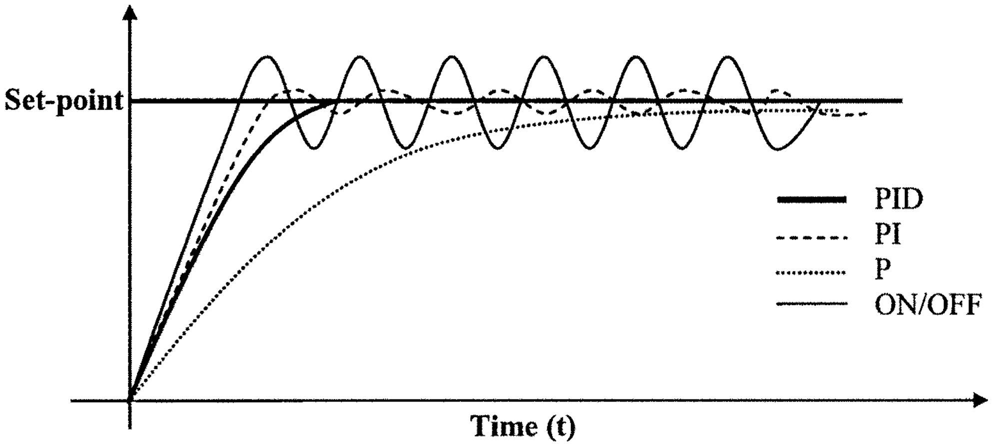


Fig 1.10 Model graph: Comparison of step responses of ON/OFF, P, PI, and PID controllers

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