Fundamentals of closed-loop control technology

This chapter outlines the differences between closed-loop and open-loop control and gives an introduction to closed-loop control technology. The control loop is explained, enabling you to carry out the following:

Recognize closed-loop control systems

- Analyze a control loop
- Understand the interaction of the individual systems
- Set a controller
- Evaluate control response

1.1 What is closed-loop control technology?

Variables such as pressure, temperature or flow-rate often have to be set on large machines or systems. This setting should not change when faults occur. Such tasks are undertaken by a closed-loop controller.

Control engineering deals with all problems that occur in this connection.

The controlled variable is first measured and an electrical signal is created to allow an independent closed-loop controller to control the variable.

The measured value in the controller must then be compared with the desired value or the desired-value curve. The result of this comparison determines any action that needs to be taken.

Finally a suitable location must be found in the system where the controlled variable can be influenced (for example the actuator of a heating system). This requires knowledge of how the system behaves.

Closed-loop control technology attempts to be generic – that is, to be applicable to various technologies. Most text books describe this with the aid of higher mathematics. This chapter describes the fundamentals of closed-loop control technology with minimum use of mathematics.

Reference variable

In closed-loop control the task is to keep the controlled variable at the desired value or to follow the desired-value curve. This desired value is known as the reference variable.

Controlled variable

This problem occurs in many systems and machines in various technologies. The variable that is subject to control is called the controlled variable. Examples of controlled variables are:

Pressure in a pneumatic accumulator

- Pressure of a hydraulic press
- Temperature in a galvanizing bath
- Flow-rate of coolant in a heat exchanger
- Concentration of a chemical in a mixing vessel
- Feed speed of a machine tool with electrical drive

Manipulated variable

The controlled variable in any system can be influenced. This influence allows the controlled variable to be changed to match the reference variable (desired value). The variable influenced in this way is called the manipulated variable. Examples of manipulated variable are:

Position of the venting control valve of a air reservoir

- Position of a pneumatic pressure-control valve
- Voltage applied to the electrical heater of a galvanizing bath
- Position of the control valve in the coolant feed line
- Position of a valve in a chemical feed line
- Voltage on the armature of a DC motor

Controlled system

There are complex relationships between the manipulated variable and the controlled variable. These relationships result from the physical interdependence of the two variables. The part of the control that describes the physical processes is called the controlled system.

1.2 What is a system?

System

The controlled system has an input variable and an output variable. Its response is described in terms of dependence of the output variable on the input variable. These responses between one or several variables can normally be described using mathematical equations based on physical laws. Such physical relationships can be determined by experimentation.

Controlled systems are shown as a block with the appropriate input and output variables (see Fig. B1-1).

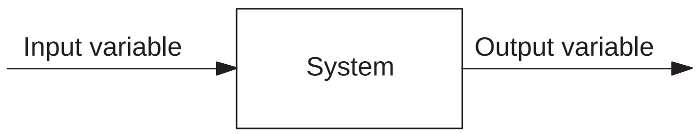


Fig. B1-1: Block diagram of a controlled system

Example
A water bath is to be maintained at a constant temperature. The water bath is heated by a helical pipe through which steam flows. The flow rate of steam can be set by means of a control valve. Here the control system consists of positioning of the control valve and the temperature of the water bath. This result in a controlled system with the input variable "temperature of water bath" and the output variable "position of control valve" (see Fig. B1-2).

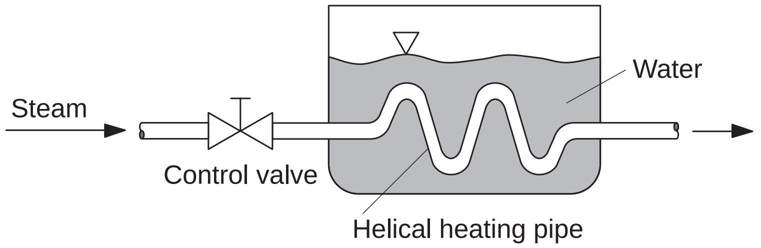


Fig. B1-2: Water bath controlled system

The following sequences take place within the controlled system:

The position of the control valve affects the flow rate of steam through the helical pipe.

- The steam flow-rate determines the amount of heat passed to the water bath.
- The temperature of the bath increases if the heat input is greater than the heat loss and drops if the heat input is less than the heat loss.
- These sequences give the relationship between the input and output variables.

Advantage of creating a system

The advantage of creating a system with input and output variables and representing the system as a block is that this representation separates the problem from the specific equipment used and allows a generic view. You will soon see that all sorts of controlled systems demonstrate the same response and can therefore be treated in the same way.

Section B 1.4 contains more information on the behaviour of controlled systems and their description.

1.3 Open-loop and closed-loop control

Having defined the term "controlled system" it only remains to give definitions of closed-loop control as contained in standards. First it is useful to fully understand the difference between open-loop control and closed-loop control.

Open-loop control

German standard DIN 19 226 defines open-loop control as a process taking place in a system where by one or more variables in the form of input variables exert influence on other variables in the form of output variables by reason of the laws which characterize the system.

The distinguishing feature of open-loop control is the open nature of its action, that is, the output variable does not have any influence on the input variable.

Example

Volumetric flow is set by adjusting a control valve. At constant applied pressure, the volumetric flow is directly influenced by the position of the control valve. This relationship between control valve setting and volumetric flow can be determined either by means of physical equation or by experiment. This results in the definition of a system consisting of the "valve" with the output variable "volumetric flow" and the input variable "control valve setting" (see Fig. B1.3).

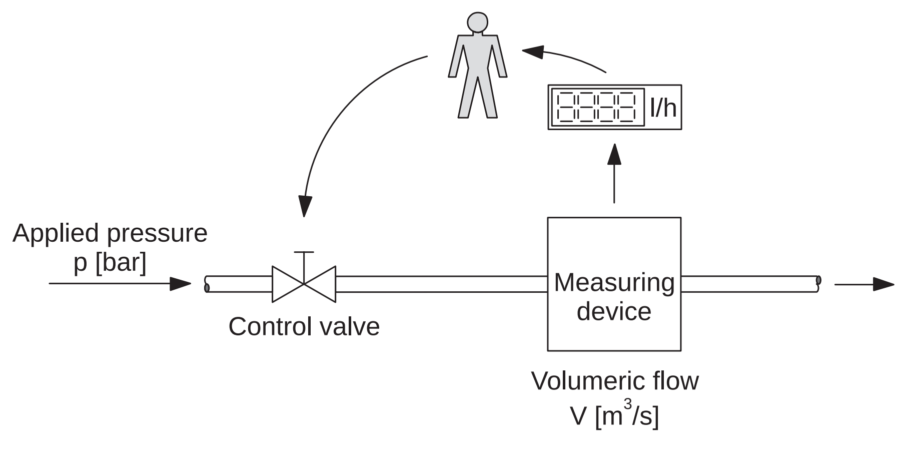


Fig B1-3: Open-loop control of volumetric flow setting

This system can be controlled by adjusting the control valve. This allows the desired volumetric flow to be set.

However, if the applied pressure fluctuates, the volumetric flow will also fluctuate. In this open system, adjustment must be made manually. If this adjustment is to take place automatically, the system must have closed-loop control.

Closed-loop control

DIN 19 226 defines closed-loop control as a process where the controlled variable is continuously monitored and compared with the reference variable. Depending on the result of this comparison, the input variable for the system is influenced to adjust the output variable to the desired value despite any disturbing influences. This feedback results in a closed-loop action.

This theoretical definition can be clarified using the example of volumetric flow control.

Deviation

Example

The volumetric flow (the output variable) is to be maintained at the predetermined value of the reference variable. First a measurement is made and this measurement is converted into an electrical signal. This signal is passed to the controller and compared with the desired value. Comparison takes place by subtracting the measured value from the desired value. The result is the deviation.

Manipulating element

In order to automatically control the control valve with the aid of the deviation, an electrical actuating motor or proportional solenoid is required. This allows adjustment of the controlled variable. This part is called the manipulating element (see Fig. B1-4).

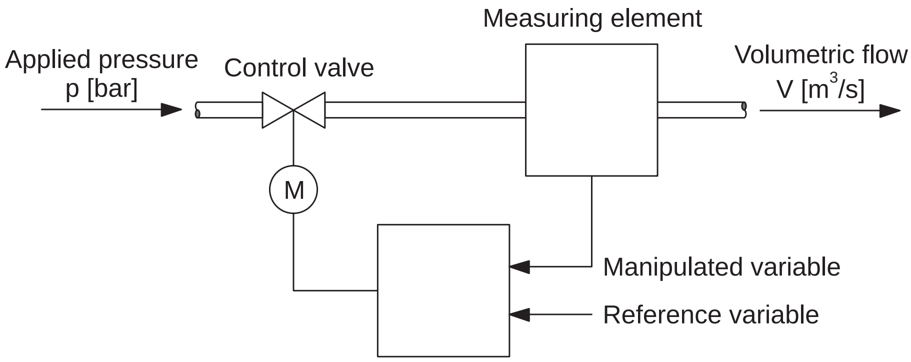


Fig. B1-4: Closed-loop control of volumetric flow

The controller now passes a signal to the manipulating element dependent on the deviation. If there is a large negative deviation, that is the measured value of the volumetric flow is greater than the desired value (reference variable) the valve is closed further. If there is a large positive deviation, that is the measured value is smaller than the desired value, the valve is opened further.

Setting of the output variable is normally not ideal:

- If the intervention is too fast and too great, influence at the input end of the system is too large. This results in great fluctuations at the output.
- If influence is slow and small, the output variable will only approximate to the desired value.

In addition, different types of systems (control system) require different control strategy. Systems that respond slowly must be adjusted carefully and with forethought. This describes some of the control engineering problems faced by the closed-loop control engineer.

Design of a closed-loop control requires the following steps:

- Determine manipulated variable (thus defining the controlled system)
- Determine the behaviour of the controlled system
- Determine control strategy for the controlled system (behaviour of the "controller" system)
- Select suitable measuring and manipulating elements.

1.4 Basic terminology

In Section B 1.3 we look at the difference between open-loop and closed-loop control using the example of volumetric flow for a control valve. In addition we look at the basic principle of closed-loop control and basic terminology. Using this example, let's take a closer look at closed-loop control terminology.

Controlled variable x

The aim of any closed-loop control is to maintain a variable at a desired value or on a desired-value curve. The variable to be controlled is known as the controlled variable x. In our example it is the volumetric flow.

Manipulated variable y

Automatic closed-loop control can only take place if the machine or system offers a possibility for influencing the controlled variable. The variable which can be changed to influence the controlled variable is called the manipulated variable y. In our example of volumetric flow, the manipulated variable is the drive current for the positioning solenoid.

Disturbance variable z

Disturbances occur in any controlled system. Indeed, disturbances are often the reason why a closed-loop control is required. In our example, the applied pressure changes the volumetric flow and thus requires a change in the control valve setting. Such influences are called disturbance variables z.

The controlled system is the part of a controlled machine or plant in which the controlled variable is to be maintained at the value of the reference variable. The controlled system can be represented as a system with the controlled variable as the output variable and the manipulated variable as the input variable. In the example of the volumetric flow control, the pipe system through which gas flows and the control valve formed the control system.

Reference variable w

The reference variable is also known as the set point. It represents the desired value of the controlled variable. The reference variable can be constant or may vary with time. The instantaneous real value of the controlled variable is called the actual value w.

Deviation x_d

The result of a comparison of reference variable and controlled variable is the deviation x_d:

$$x_d = w - x$$

Control response

Control response indicates how the controlled system reacts to changes to the input variable. Determination of the control response is one of the aims of closed-loop control technology.

Controller

The controller has the task of holding the controlled variable as near as possible to the reference variable. The controller constantly compares the value of the controlled variable with the value of the reference variable. From this comparison and the control response, the controller determines and changes the value of the manipulating variable (see Fig. B1-5).

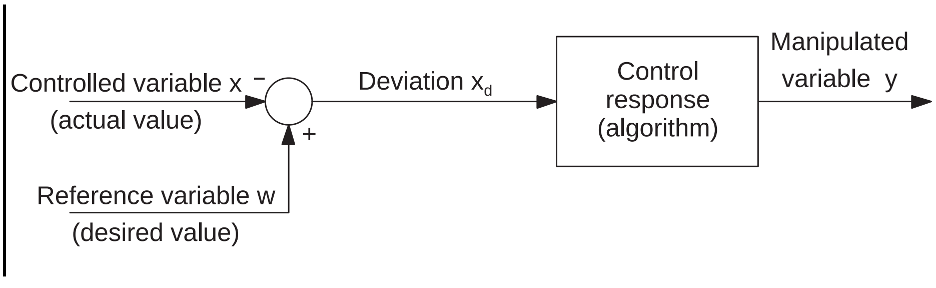


Fig. B1-5: Functional principle of a closed-loop control

Manipulating element and servo-drive

The manipulating element adjusts the controlled variable. The manipulating element is normally actuated by a special servo drive. A servo drive is required if it is not possible for the controller to actuate the manipulating element directly. In our example of volumetric flow control, the manipulating element is the control valve.

Measuring element

In order to make the controlled variable accessible to the controller, it must be measured by a measuring element (sensor, transducer) and converted into a physical variable that can be processed by the controller is an input.

Closed loop

The closed loop contains all components necessary for automatic closed-loop control (see Fig. B1-6).

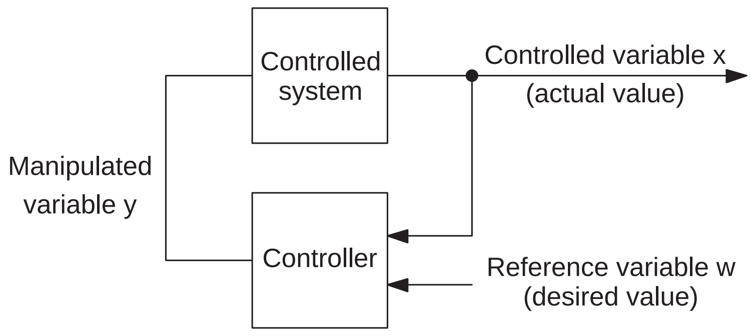


Fig. B1-6: Block diagram of a control loop

1.5 Controlled system

The controlled system is the part of a machine or plant in which the controlled variable is to be maintained at the desired value and in which manipulated variables compensate for disturbance variables. Input variables to the controlled system include not only the manipulated variable, but also disturbance variables.

Before a controller can be defined for a controlled system, the behaviour of the controlled system must be known. The control engineer is not interested in technical processes within the controlled system, but only in system behaviour.

Dynamic response of a system

The dynamic response of a system (also called time response) is an important aspect. It is the time characteristic of the output variable (controlled variable) for changes in the input variable. Particularly important is behaviour when the manipulated variable is changed.

The control engineer must understand that nearly every system has a characteristic dynamic response.

Example

In the example of the water bath in Section B1.2, a change in the steam valve setting will not immediately change the output variable temperature. Rather, the heat capacity of the entire water bath will cause the temperature to slowly "creep" to the new equilibrium (see Fig. B1-7).

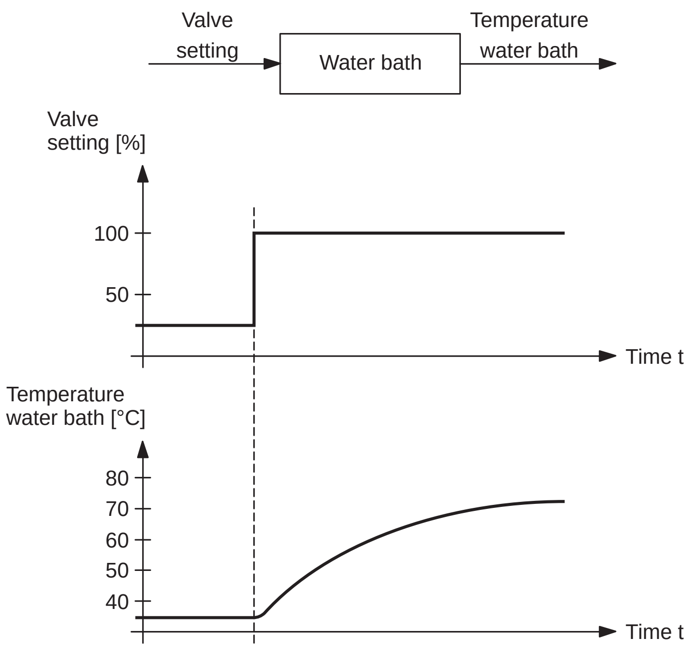


Fig. B1-7: Time response of the controlled system "water bath"

Example

In the example of a valve for volumetric flow control, the dynamic response is rapid. Here, a change in the valve setting has an immediate effect on flow rate so that the change in the volumetric flow rate output signal almost immediately follows the input signal for the change of the valve setting (see B1-8).

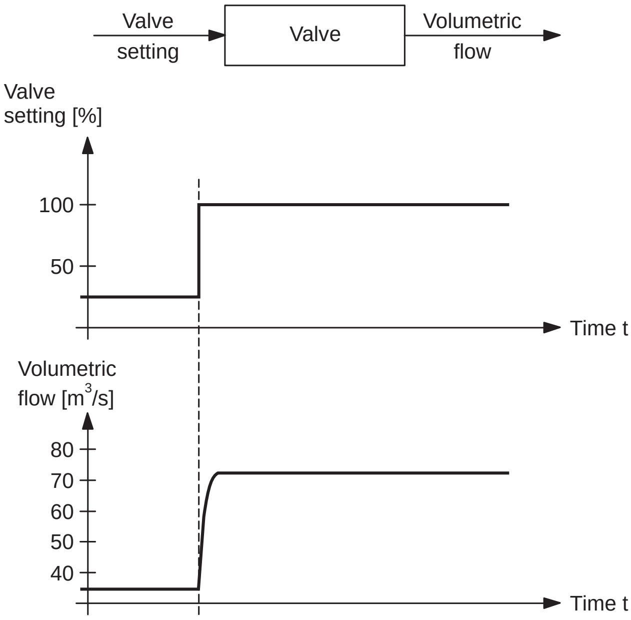


Fig. B1-8:
Time response of the controlled system "valve"

1.5.1 Description of the dynamic response of a controlled system

In the examples shown in Fig. B1-7 and Fig. B1-8, the time response was shown assuming a sudden change in input variable. This is a commonly used method of establishing the time response of system.

Step response

The response of a system to a sudden change of the input variable is called the step response. Every system can be characterized by its step response. The step response also allows a system to be described with mathematical formulas.

Dynamic response

This description of a system is also known as dynamic response. Fig. B1-9 demonstrates this. Here the manipulated variable y is suddenly increased (see left diagram). The step response of the controlled variable x is a settling process with transient overshoot.

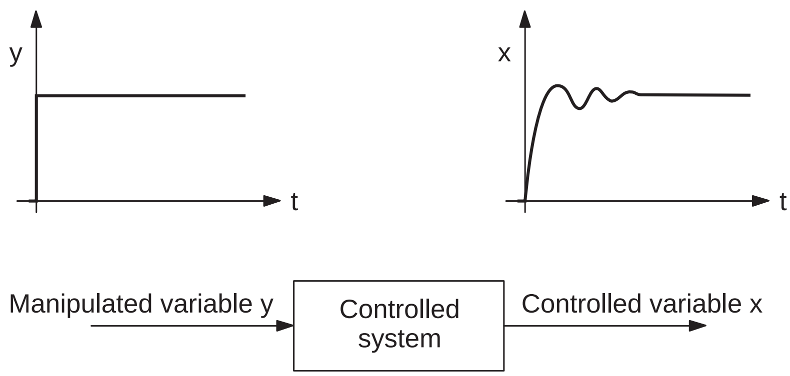


Fig. B1-9:
Step response

Equilibrium

Another characteristic of a system is its behaviour in equilibrium, the static behaviour.

Static behaviour

Static behaviour of a system is reached when none of the variables change with time. Equilibrium is reached when the system has settled. This state can be maintained for an unlimited time.

The output variable is still dependent on the input variable – this dependence is shown by the characteristic of a system.

Example
The characteristic of the "valve" system from our water bath example shows the relationship between volumetric flow and valve position (see Fig. B1-10).

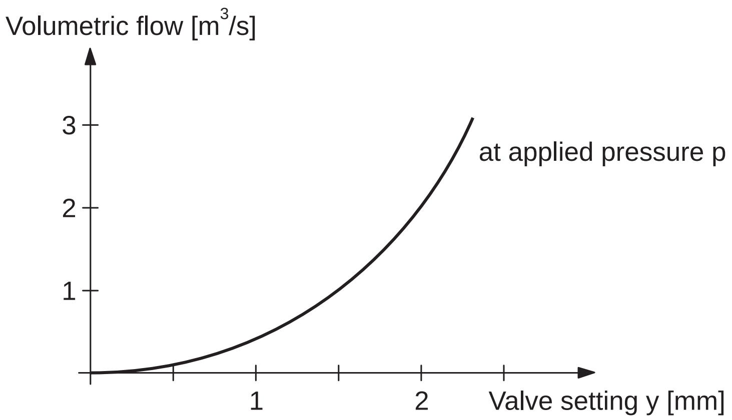


Fig. B1-10: Characteristic curve of the "valve" system

The characteristic shows whether the system is a linear or non-linear system. If the characteristic is a straight line, the system is linear. In our "valve" system, the characteristic is non-linear.

Many controlled systems that occur in practice are non-linear. However, they can often be approximated by a linear characteristic in the range in which they are operated.

1.6 Controllers

The previous section dealt with the controlled system - the part of the system which is controlled by a controller. This section looks at the controller.

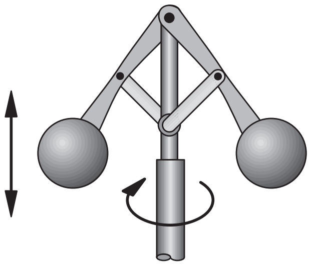
The controller is the device in a closed-loop control that compares the measured value (actual value) with the desired value, and then calculates and outputs the manipulated variable. The above section showed that controlled systems can have very different responses. There are systems which respond quickly, systems that respond very slowly and systems with storage property.

For each of these controlled systems, changes to the manipulated variable y must take place in a different way. For this reason there are various types of controller each with its own control response. The control engineer has the task of selecting the controller with the most suitable control response for the controlled system.

1.6.1 Control response

Control response is the way in which the controller derives the manipulated variable from the system deviation. There are two broad categories: continuous-action controllers and non-continuous-action controllers.

Continous-action controller

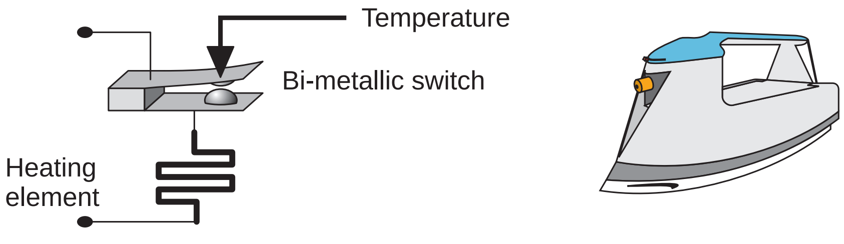


The manipulated variable of the continuous-action controller changes continuously dependent on the system deviation. Controllers of this type give the value of the system deviation as a direct actuating signal to the manipulating element. An example of this type of controller is the centrifugal governor. It changes its moment of inertia dependent on speed, and thus has a direct influence on speed.

Non-continous-action controller

The manipulated variable of a non-continuous-action controller can only be changed in set steps. The best-known non-continuous-action controller is the two-step control that can only assume the conditions "on" or "off".

An example is the thermostat of an iron. It switches the electric current for the heating element on or off depending on the temperature.



This section only deals with continuous-action controllers as these are more commonly used in automation technology. Further, the fundamentals of closed-loop control technology can be better explained using the continuous-action controller as an example.

1.6.2 Time response of a controller

Every controlled system has its own time response. This time response depends on the design of the machine or system and cannot be influenced by the control engineer. The time response of the controlled system must be established through experiment or theoretical analysis. The controller is also a system and has its own time response. This time response is specified by the control engineer in order to achieve good control performance.

The time response of a continuous-action controller is determined by three components:

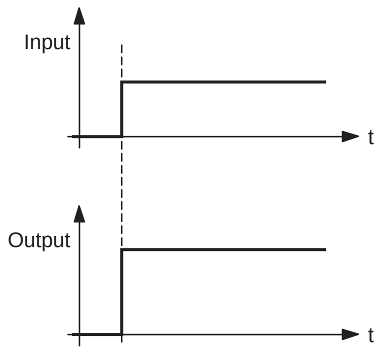
Proportional component (P component)

- Integral component (I component)
- Differential component (D component)

The above designations indicate how the manipulated variable is calculated from the system deviation.

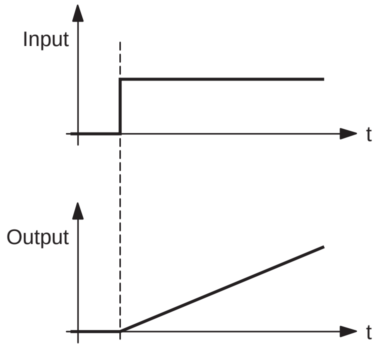
Proportional controller

In the proportional controller, the manipulated variable output is proportional to the system deviation. If the system deviation is large, the value of the manipulated variable is large. If the system deviation is small, the value of the manipulated variable is small. As the manipulated variable is proportional to the system deviation, the manipulated variable is only present if there is a system deviation.



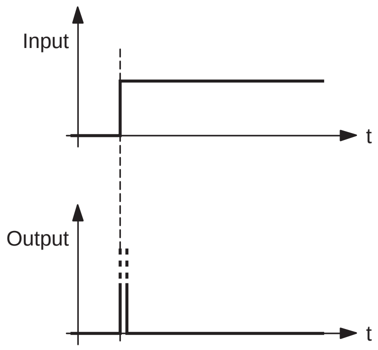
For this reason, a proportional controller alone cannot achieve a system deviation of zero. In this case no manipulated variable will be present and there would therefore be no control.

Integral-action controller



An integral-action controller adds the system deviation over time, that is it is integrated. For example, if a system deviation is constantly present, the value of the manipulated variable continues to increase as it is dependent on summation over time. However, as the value of the manipulated variable continues to increase, the system deviation decreases. This process continues until the system deviation is zero. Integral-action controllers or integral components in controllers are therefor used to avoid permanent system deviation.

Differential-action controller



The differential component evaluates the speed of change of the system deviation. This is also called differentiation of the system deviation. If the system deviation is changing fast, the manipulated variable is large. If the system deviation is small, the value of manipulated variable is small. A controller with D component alone does not make any sense, as a manipulated variable would only be present during change in the system deviation.

A controller can consist of a single component, for example a P controller or an I controller. A controller can also be a combination of several components - the most common form of continuous-action controller is the PID controller.

1.6.3 Technical details of controllers

In automation technology controllers are almost exclusively electrical or electronic. Although mechanical and pneumatic controllers are often shown as examples in text books, they are hardly ever found in modern systems.

for voltage	0 ... 10V	-10 ... +10V
for current	0 ... 20mA	4 ... 20mA

Electrical and electronic controllers work with electrical input and output signals. The transducers are sensors which convert physical variables into voltage or current. The manipulating elements and servo drives are operated by current or voltage outputs. Theoretically, there is no limit to the range of these signals. In practice, however, standard ranges have become established for controllers:

Internal processing of signals in the controller is either analog with operational amplifier circuits or digital with microprocessor systems

- In circuits with operational amplifiers, voltages and currents are processed directly in the appropriate modules.
- In digital processing, analog signals are first converted into digital signals. After calculation of the manipulated variable in the microprocessor, the digital value is converted back into an analog value.

Although theoretically these two types of processing have to be dealt with very differently, there is no difference in the practical application of classical controllers.

1.7 Mode of operation of various controller types

This section explains the control response of various controller types and the significance of parameters. As in the explanation of controlled systems, the step response is used for this description. The input variable to the controller is the system deviation – that is, the difference between the desired value and the actual value of the controlled variable.

1.7.1 The proportional controller

Proportional controller

In the case of the proportional controller, the actuation signal is proportional to the system deviation. If the system deviation is large, the value of the manipulated variable is large. If the system deviation is small, the value of the manipulated variable is small. The time response of the P controller in the ideal state is exactly the same as the input variable (see Fig. B1-11).

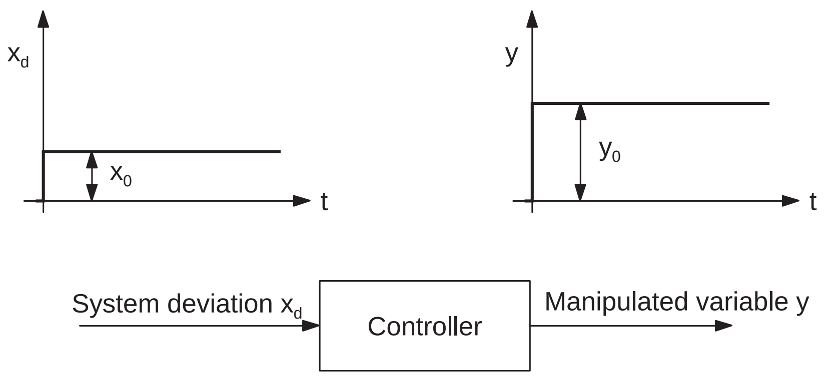


Fig. B1-11: Time response of the P controller

The relationship of the manipulated variable to the system deviation is the proportional coefficient or the proportional gain. These are designated by x_p, K_p or similar. These values can be set on a P controller. It determines how the manipulated variable is calculated from the system deviation. The proportional gain is calculated as:

$$K_p = y_0 / x_0$$

If the proportional gain is too high, the controller will undertake large changes of the manipulating element for slight deviations of the controlled variable. If the proportional gain is too small, the response of the controller will be too weak resulting in unsatisfactory control.

A step in the system deviation will also result in a step in the output variable. The size of this step is dependent on the proportional gain. In practice, controllers often have a delay time, that is a change in the manipulated variable is not undertaken until a certain time has elapsed after a change in the system deviation. On electrical controllers, this delay time can normally be set.

An important property of the P controller is that as a result of the rigid relationship between system deviation and manipulated variable, some system deviation always remains. The P controller cannot compensate this remaining system deviation.

1.7.2 The I controller

Integral-action controller

The I controller adds the system deviation over time. It integrates the system deviation. As a result, the rate of change (and not the value) of the manipulated variable is proportional to the system deviation. This is demonstrated by the step response of the I controller: if the system deviation suddenly increases, the manipulated variable increases continuously. The greater the system deviation, the steeper the increase in the manipulated variable (see Fig. B1-12).

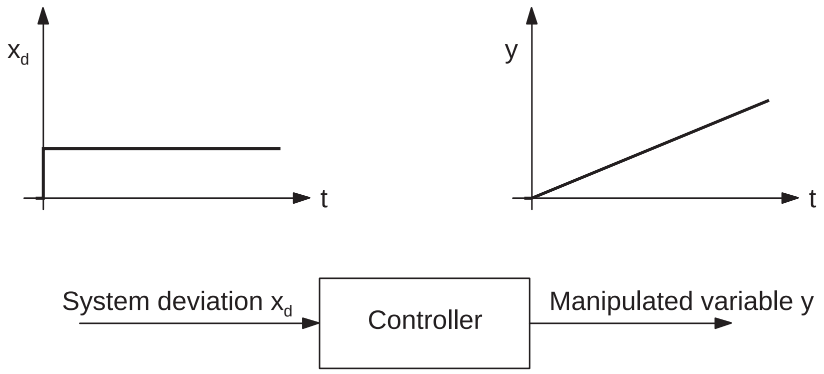


Fig. B1-12: Time response of the I controller

For this reason the I controller is not suitable for totally compensating remaining system deviation. If the system deviation is large, the manipulated variable changes quickly. As a result, the system deviation becomes smaller and the manipulated variable changes more slowly until equilibrium is reached.

Nonetheless, a pure I controller is unsuitable for most controlled systems, as it either causes oscillation of the closed loop or it responds too slowly to system deviation in systems with a long time response. In practice there are hardly any pure I controllers.

1.7.3 The PI controller

PI controller

The PI controller combines the behaviour of the I controller and P controller. This allows the advantages of both controller types to be combined: fast reaction and compensation of remaining system deviation. For this reason, the PI controller can be used for a large number of controlled systems. In addition to proportional gain, the PI controller has a further characteristic value that indicates the behaviour of the I component: the reset time (integral-action time).

Reset time

The reset time is a measure for how fast the controller resets the manipulated variable (in addition to the manipulated variable generated by the P component) to compensate for a remaining system deviation. In other words: the reset time is the period by which the PI controller is faster than the pure I controller. Behaviour is shown by the time response curve of the PI controller (see Fig. B1-13).

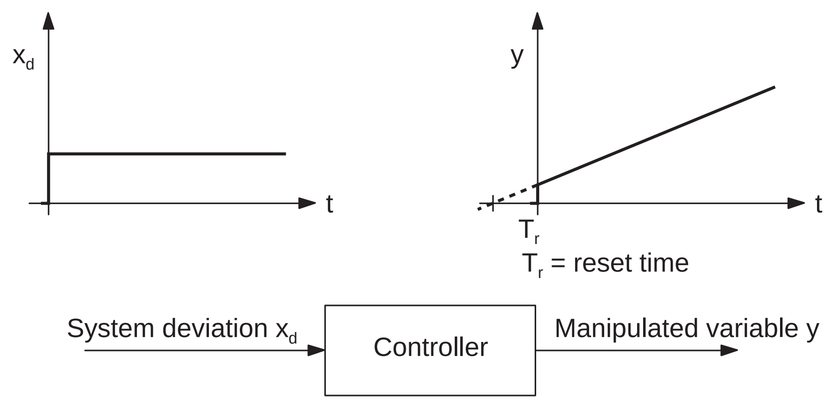


Fig. B1-13: Time response of the PI controller

The reset time is a function of proportional gain K_p as the rate of change of the manipulated variable is faster for a greater gain. In the case of a long reset time, the effect of the integral component is small as the summation of the system deviation is slow. The effect of the integral component is large if the reset time is short.

The effectiveness of the PI controller increases with increase in gain K_p and increase in the I-component (i.e., decrease in reset time). However, if these two values are too extreme, the controller's intervention is too coarse and the entire control loop starts to oscillate. Response is then not stable. The point at which the oscillation begins is different for every controlled system and must be determined during commissioning.

1.7.4 The PD controller

PD controller

The PD controller consists of a combination of proportional action and differential action. The differential action describes the rate of change of the system deviation.

The greater this rate of change – that is the size of the system deviation over a certain period – the greater the differential component. In addition to the control response of the pure P controller, large system deviations are met with very short but large responses. This is expressed by the derivative-action time (rate time).

Derivative-action time

The derivative-action time T_d is a measure for how much faster a PD controller compensates a change in the controlled variable than a pure P controller. A jump in the manipulated variable compensates a large part of the system deviation before a pure P controller would have reached this value. The P component therefore appears to respond earlier by a period equal to the rate time (see Fig. B1-14).

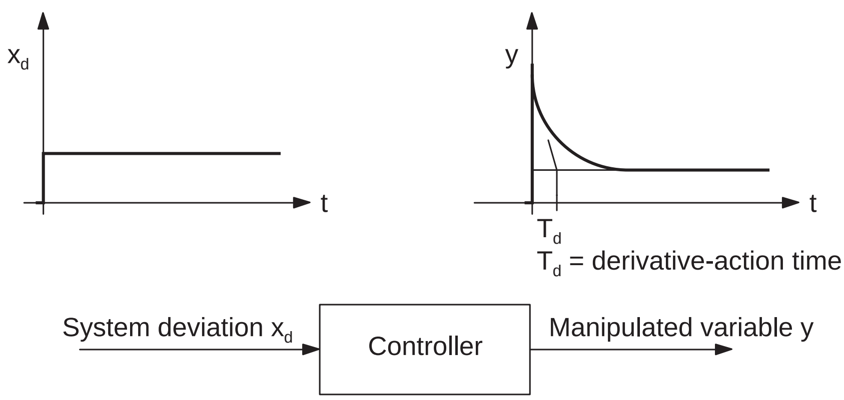


Fig. B1-14: Time response of the PD controller

Two disadvantages result in the PD controller seldom being used. Firstly, it cannot completely compensate remaining system deviations. Secondly, a slightly excessive D component leads quickly to instability of the control loop. The controlled system then tends to oscillate.

1.7.5 PID controller

PID controller

In addition to the properties of the PI controller, the PID controller is complemented by the D component. This takes the rate of change of the system deviation into account.

If the system deviation is large, the D component ensures a momentary extremely high change in the manipulated variable. While the influence of the D component falls of immediately, the influence of the I component increases slowly. If the change in system deviation is slight, the behaviour of the D component is negligible (see Section B1.6.2).

This behaviour has the advantage of faster response and quicker compensation of system deviation in the event of changes or disturbance variables. The disadvantage is that the control loop is much more prone to oscillation and that setting is therefore more difficult.

Fig. B1-15 shows the time response of a PID controller.

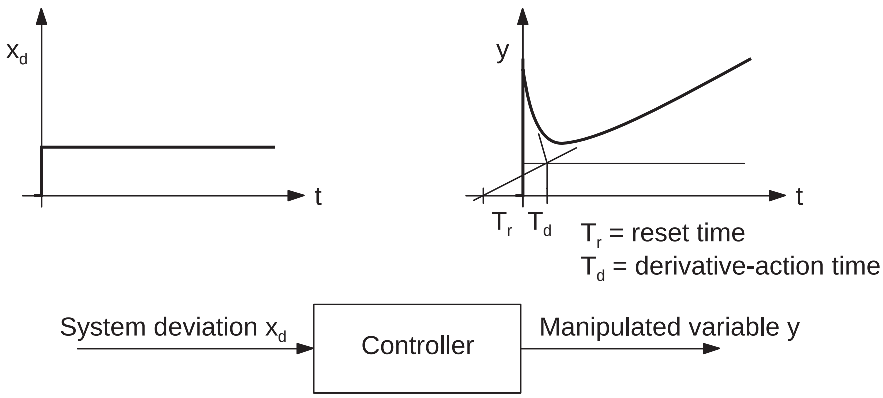


Fig. B1-15: Time response of the PID controller

Derivative-action time

As a result of the D component, this controller type is faster than a P controller or a PI controller. This manifests itself in the derivative-action time T_d. The derivative-action time is the period by which a PID controller is faster than the PI controller.

1.8 Summary

Here is a summary of the most important points to be taken into account when solving control problems.

1. **Assignment of controlled variables**
   Which machine or plant variable is the controlled variable, reference variable, manipulated variable etc. Where and how do disturbance variables occur? The selection of sensors and actuators is based on these factors.
2. **Division of the control problem into systems**
   Where is the controlled variable measured? Where can the system be influenced? What is the nature of the individual systems?
3. **Controlled system**
   Where is the controlled variable to be adjusted to the desired value? What is the time response of the controlled system (slow or fast)? The choice of controller response is based on these factors.
4. **Controller**
   What type of control response is required? What time response must the controller have, particularly with regard to fault conditions? What values must the controller parameters have?
5. **Controller type**
   What type of controller must be implemented? Does the time response and controlled system require a P, I, PI or PID controller?