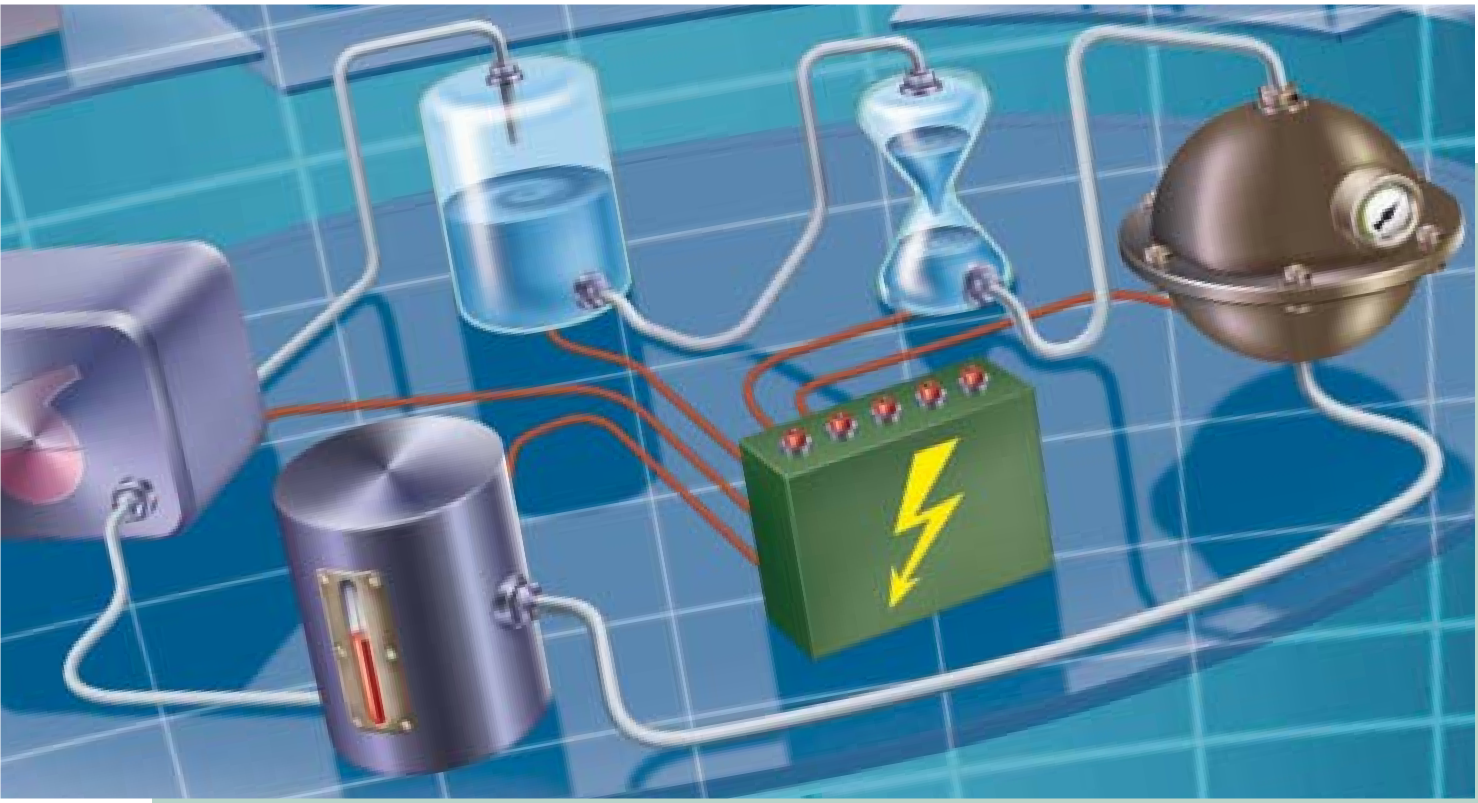
Competences



The smart choice of Fluid Control Systems

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Fluid Control Systems

Contents

1. Open-loop and closed-loop control

The terms “open-loop control” and “closed-loop control” are closely interlinked.

1.1. Function and sequence of an open-loop control system

An open-loop control system is characterized by the fact that one or more input variables of a system influence its output variables in accordance with the system’s own interrelations.

One everyday example of an open-loop control system:

The inside temperature of a room is to be maintained at a constant value as a function of the outside temperature.

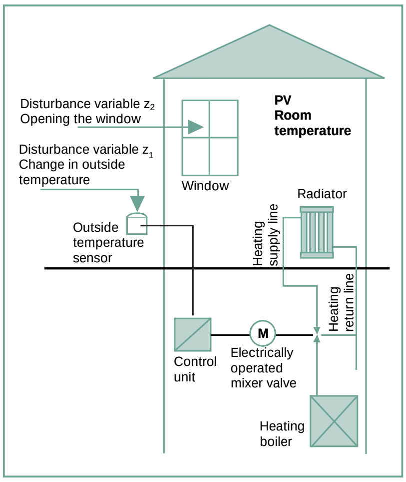


Figure 1: Open-loop control of the inside temperature of a room

The room temperature PV (output variable of the open-loop control system) is to be maintained at a constant value by adjusting the electrically operated mixer valve and thus, the temperature of the heating supply line or radiator.

If the outside temperature changes, the room temperature changes as a consequence of this. The outside temperature is referred to as the disturbance variable and identified with the letter z (z_1 in the example).
The task of the open-loop control system is to counteract the influence of the “outside temperature” disturbance variable.
For this purpose, the outside temperature is measured via the outside temperature sensor.
The mixer valve is adjusted or the temperature of the radiator varied via the control unit.
The interrelationship between the outside temperature and the heating output required for maintaining a constant room temperature must be stored in the control unit (e.g. in the form of characteristic curves). Use of such a control unit allows the influence of the outside temperature on the room temperature to be eliminated.

Besides the outside temperature, the example shown in Figure 1 also contains other disturbance variables which also affect the room temperature:
– opening a window or a door
– changing wind conditions
– presence of persons in the room.
Since it is not detected by the control unit, the effect of these disturbance variables on the room temperature is not compensated for by the open-loop control system.
The use of such an open-loop control system is practical only if it can be assumed that there is a low influence of (secondary) disturbance variables.

The block diagram in Figure 2 shows the open action sequence characteristic of an open-loop control system.

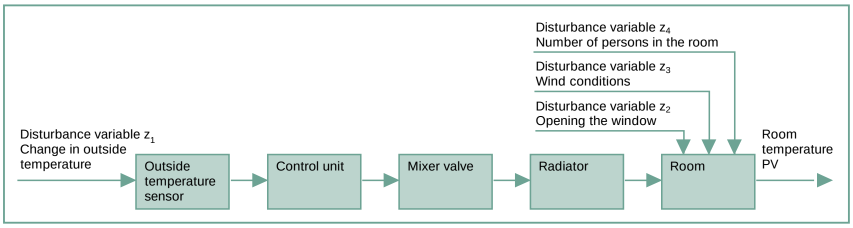


Figure 2: Block diagram of the open-loop control system for room temperature

However, if the effect of the other disturbance variables is so strong that it also needs to be compensated for, it becomes necessary to control the room temperature on the basis of a closed-loop control system. The block diagram in Figure 3 shows the closed action sequence that is typical of a closed-loop control system.

1.2. Function and sequence of a closed-loop control system

The fundamental difference with respect to an open-loop control system is that the output variable of the system (the actual value) is constantly measured and compared with another variable (the set-point value or the reference variable). If the actual value is not equal to the set-point value, the controller responds to this. It changes the actual value by adjusting it to the set-point value.

One everyday example of a closed-loop control system:
The inside temperature of a room is to be maintained at a preset temperature.

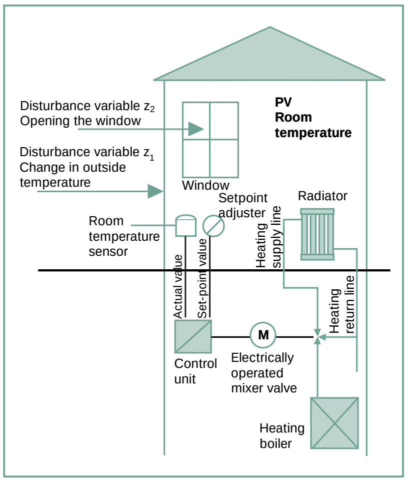


Figure 4: Closed-loop control of the inside temperature of a room

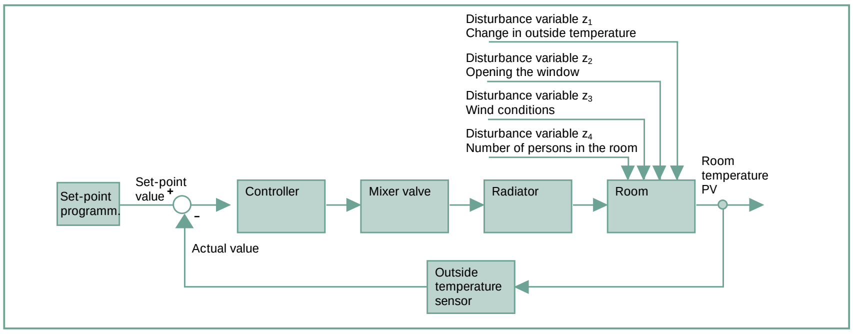


Figure 3: Block diagram of the closed-loop control system for room temperature

In this case, the effects of disturbance variables on the room temperature should be eliminated.

The effects of all disturbance variables influencing the room temperature:
– change in outside temperature
– opening a window
– changing wind conditions
are registered by measurement of the room temperature and comparing this with the set-point value. On the basis of the comparison between set-point and actual value, the controller adjusts the temperature of the heating supply line or radiator via the mixer valve until the required room temperature is reached.

The table below contains application recommendations for open-loop and closed-loop control.

	Open-loop control	Closed-loop control
Application	• If no or only one essential and measurable disturbance variable is present.	• If several essential disturbance variables are present. • If disturbance variables cannot be detected or can be only poorly detected with measuring systems. • If unforeseeable disturbance variables may occur.
Advantages	• Low implementation effort. • No stability problems due to the open action sequence.	• Disturbance variables are detected and compensated for. • The preset value (set-point SP) is more precisely complied.
Disadvantages	• Disturbance variables that occur are not detected automatically. • Measurement is required for each disturbance variable to be compensated for. • All interrelationships of the system to be controlled must be known in order to design the control unit optimally.	• The equipment effort and complexity are greater than with open-loop control. • A measurement is always required.

Table 1: Application, advantages and disadvantages of open-loop and closed-loop control

2. The control loop

Closed-loop control is a process that is used in more than just technical applications. Closed-loop control systems run virtually everywhere and always. The process of setting the required water temperature when showering or complying with a speed limit when driving a car involves closed-loop control. These two examples demonstrate the task of a closed-loop control system: adjusting, a specific variable such as temperature, speed, flow rate or pressure to a required value.

In principle, a closed-loop control process appears to be a very simple one. However, when implementing technical closed-loop control systems, problems are very quickly encountered. The precondition for correct functioning of a closed-loop control system is the interplay of the individual components involved in a closed-loop control system. The totality of components of a closed-loop control system is referred to as the control loop. In the following, the control loop is explained in further detail.

A control loop consists of the following components:

- the measuring instrument or sensor for detecting the variable to be controlled
- the controller, the core of the closed-loop control system
- the system to be controlled (this part is referred to as controlled system).

One example:
The fluid level in a tank is to be maintained at or adjusted to a preset value. In order to implement a closed-loop control system, it is necessary to continually measure the filling level in the tank (process value).
This is done here, for example, by an ultrasonic level transmitter. The process value is constantly compared with the preset target filling level (set-point value), which is set e.g. on a control unit via buttons or selector switches.
The comparison between process value and set-point value is performed by the controller. If a deviation occurs between the process and set-point value (control deviation), the controller must respond to it. The controller has to adjust a suitable final control element or actuator (a continuous-action control valve in the example shown in Figure 5) so that the process value adjusts to the set-point value, i.e. so that the control deviation becomes zero. If the process value is higher than the set-point value, the control valve must be closed further. If the filling level is too low, the valve must be opened wider.

Control deviations in a control loop are caused by two factors:

- disturbance variables
- changes in the set-point value.

In our example, the following two disturbance variables may occur:

- outflow from the tank, occurring abruptly due to opening of one or more ON/OFF valves
- slow filling-level change due to evaporation of the fluid from the tank.

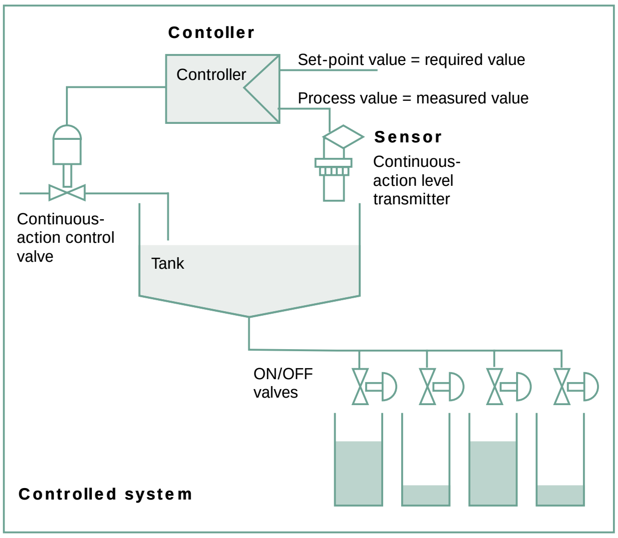


Figure 5: Hardware representation of a closed-loop filling-level control system

2.1. The elements of the control loop

Block diagrams are used to represent control loops. This mode of representation affords the advantage that it concentrates on the control-engineering problem. The interplay of the individual components of the control loop is represented graphically. For the example of a closed-loop filling-level control system, the block diagram looks as follows:

SP: Set-point value or reference variable (required filling level)
PV: Process value or controlled variable (measured filling level)
PV_d: Control deviation (actual value – set-point value)
CO: Manipulated variable or control output (output value of the controller)
z_1: Disturbance variable 1 (outflow from the tank)
z_2: Disturbance variable 2 (evaporation of fluid from the tank)

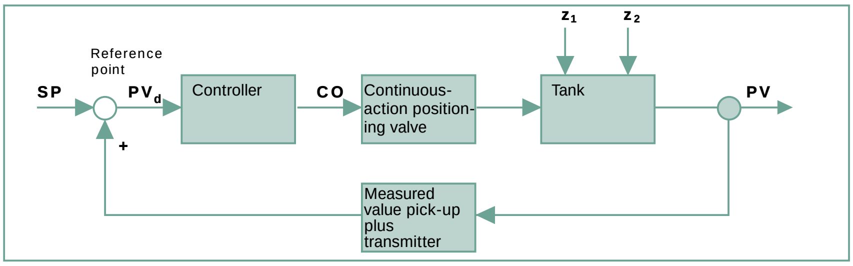


Figure 6: Block diagram of the closed-loop filling-level control system

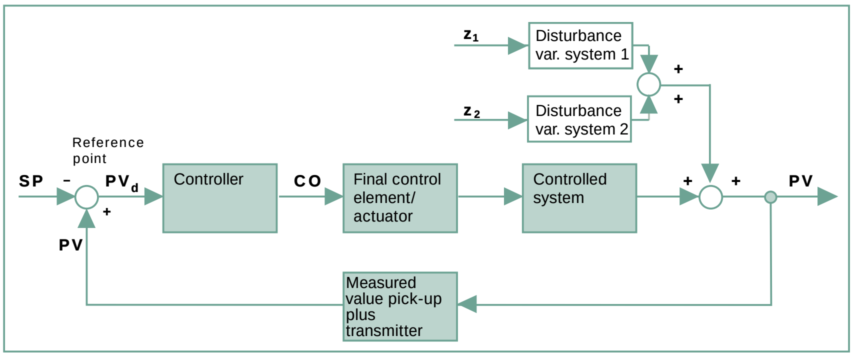


Figure 7: General block diagram of the control loop

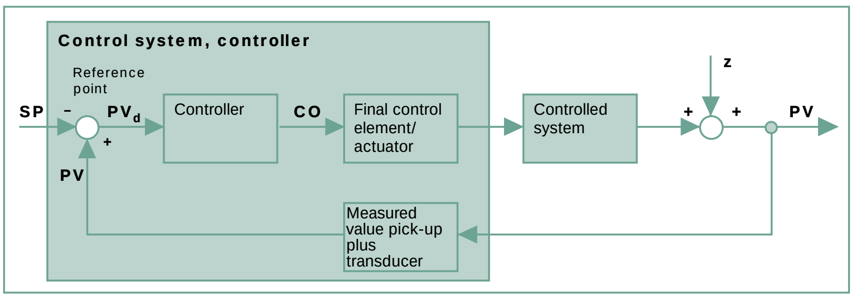


Figure 8: Simplified general block diagram of the control loop

The basic structure of this block diagram corresponds to that of the closed-loop room temperature control structure. Thus, the following general block diagram (shown in Figure 7) can be used to summarize the closed-loop control engineering.
In this case, it is assumed that the action point of the disturbance variables does not always need to be at the output of the controlled system, but that the action of the disturbance variables can be converted to this point.
Usually however, the simplified block diagram shown in Figure 8 is used.
The disturbance variables are combined and their action point is at the output of the controlled system.
Block diagrams are used to create a closed-loop control engineering model of a real system. The main components of the control loop are represented by function blocks, frequently also referred to as transfer elements. The functional relationship between the individual blocks and in regards to the environment is shown by action lines.
Each function block is characterized by the dependence of its output signal on the input signal. This dependence is described by the response. There are numerous possible ways of representing the response. The most conventional way is stating the step response or transfer function. It is plotted as a simple timing diagram in the relevant function block.
The step response is the characteristic of the output signal, which occurs when the input signal changes abruptly as a function of time. The transfer function (designated h(t)) is the step response standardized with respect to the magnitude of the input step or input signal (h(t) = $PV_o(t)/PV_{i0}$).

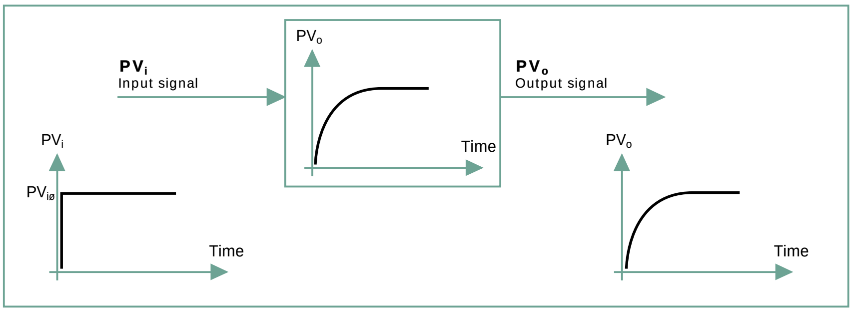


Figure 9: Step response of a transfer element

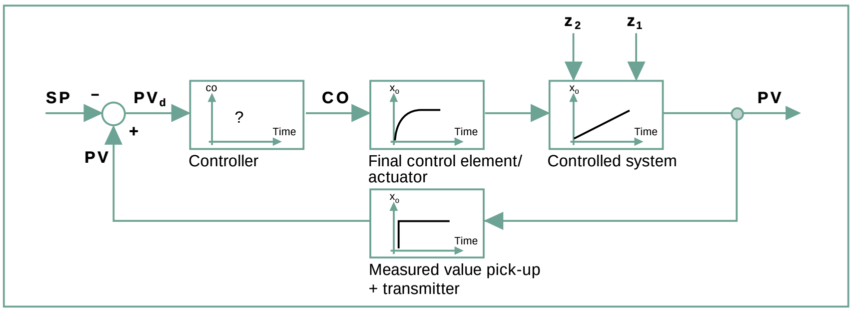


Figure 10: Signal flow diagram of the closed-loop filling-level control system

If, in the block diagram, we replace the individual control loop elements or function blocks by the form of representation shown in Figure 9, we obtain the signal flow diagram of the control loop. Figure 10 shows the signal flow diagram of the closed-loop filling-level control system.

The signal flow diagram or the block diagram is an important aid to designing control loops and for adapting the controller to the controlled system. In many cases, adaptation of the controller is one of the most demanding tasks, and one that requires basic knowledge of controlled systems and controllers. This is covered in the following sections.

2.2. The controlled system

In order to select a suitable controller and be able to adapt it to the controlled system (the system or equipment to be controlled), it is necessary to have precise information on the behavior of the controlled system. Factors that must be known include to what extent and in what timeframe the output signal of the controlled system responds to changes of the input signal.

Real transfer elements differ from ideal ones by virtue of the fact that they almost always feature a time-delayed response. This means that a certain time elapses until the output signal responds to a changing input signal.

Controlled systems can be subdivided into two categories in terms of their time response or steady state condition:

Controlled systems with compensation:
In the case of controlled systems with compensation, the output variable of the system reassumes steady-state condition within a specific period. One example of a controlled system with compensation is the flow rate in a pipe. If the degree of opening of a continuous-action control valve is changed, a constant flow rate is established after a specific period assuming constant pressure conditions. The transfer element shown in Figure 11 symbolizes a controlled system with compensation.

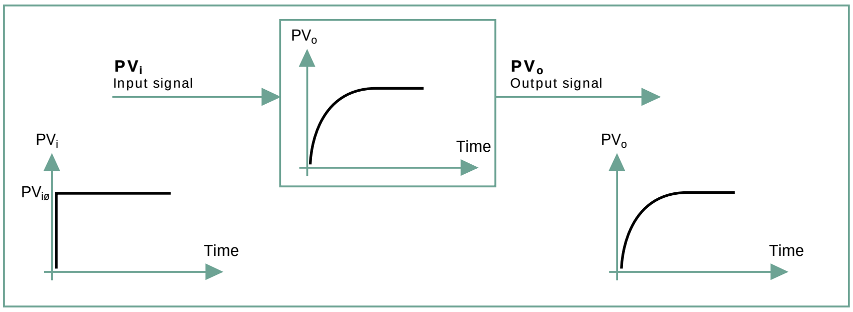


Figure 11: Transfer element with plotted step response of a controlled system with compenastaion

Controlled systems without compensation:

In the case of controlled systems without compensation, there is no steady-state condition. Even with a constant input variable (greater than 0), the output signal changes at a constant rate or acceleration. In the example of closed-loop filling-level control in a tank, this relates to a controlled system without compensation. If the valve for filling the tank is open and the ON/OFF valves are closed, the filling level increases continuously without assuming a steady-state condition. In the case of real controlled systems without compensation, there is generally a limitation: in the example of closed-loop filling-level control, this results from overflowing of the tank.

The transfer element shown in Figure 12 symbolizes a controlled system without compensation.

When selecting and setting the controller, the aspect of whether the controlled system is a controlled system with or without compensation is of crucial importance.

The most frequently occurring controlled systems and their transfer functions are described below in greater detail. Table 2 provides an initial overview.

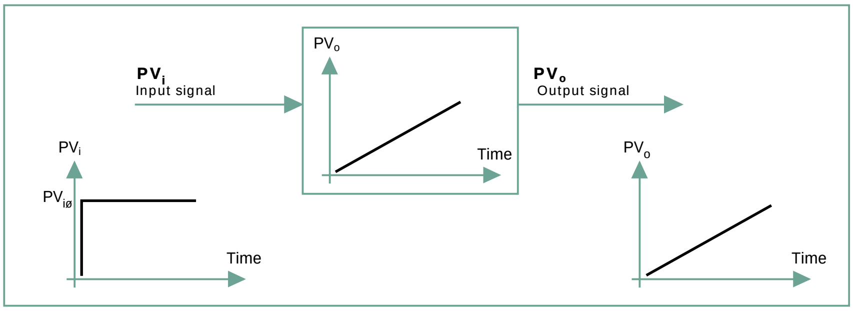


Figure 12: Transfer element with plotted step response of a controlled system without compensation

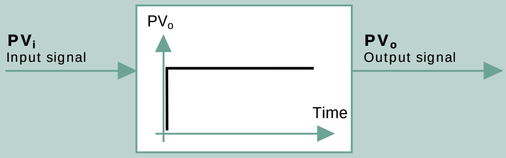
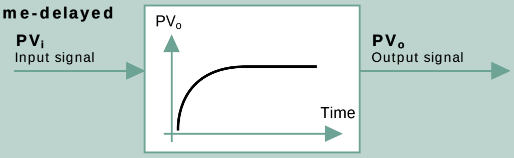
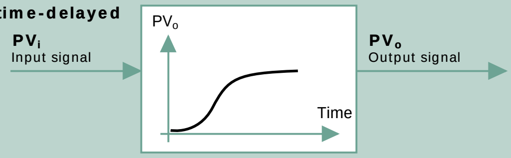
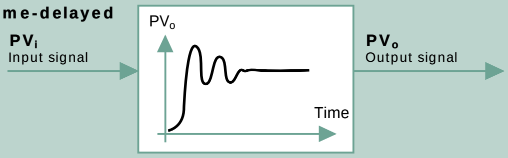
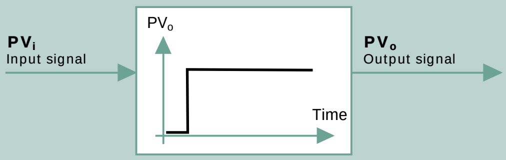
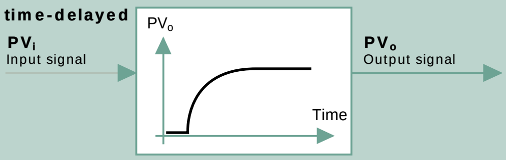
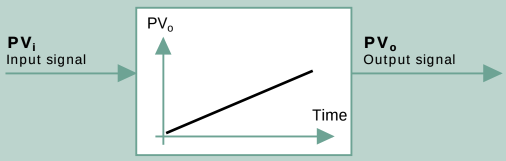
Designation	Transfer element	Application
P-system		Closed-loop pressure control with fluids Closed-loop flow-rate control with fluids
1st-order time-delayed system		Closed-loop pressure control with fluids and gases Closed-loop flow-rate control with gases Closed-loop rotational-speed control
2nd-order time-delayed system		Closed-loop temperature control
3rd-order time-delayed system		Closed-loop temperature control (steam via heat exchanger)
T_t-system		Closed-loop conveying quantity control on conveyor belts
T_1 1st-order time-delayed system		Closed-loop pH control Closed-loop conductivity control Mixing two fluid streams in one pipe
I-system		Closed-loop filling level control Closed-loop conductivity control

Table 2: Overview of typical controlled systems

The P-element:
On the P-element or proportional element, the output signal follows the input signal directly, with no time delay. Input and output signal are proportional to each other. There is no time delay. Figure 13 shows the behavior or step response of a P-element.

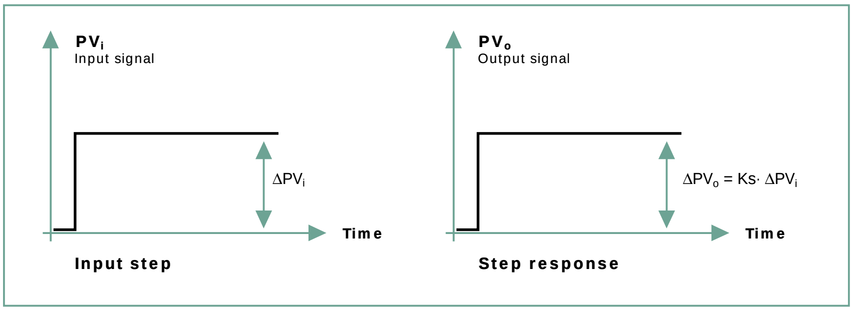


Figure 13: Step response of a P-element

The 1st-order time-delay element:
On the 1st-order time-delay element, the output signal follows the input signal with a time delay. In this case, the output signal changes immediately, but increases continuously to the full scale value with a time delay.
An analog response is shown by the voltage through a capacitor when charging via a series resistor.

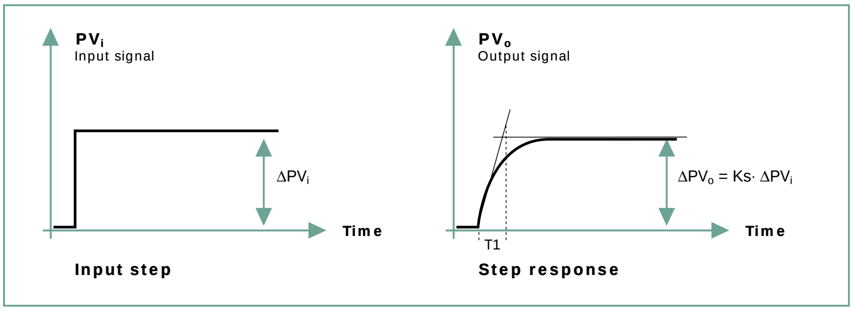


Figure 14: Step response of a 1st-order time-delay element

The 2nd-order time-delay element:
The 2nd-order time-delay element is a controlled system with two delays (two 1st-order time-delay elements connected in series). 2nd-order time-delay systems are characterized by three parameters, the system gain Ks and the two time constants Tu and Ta.
Unlike the 1st-order time-delay element, the step response is initially characterized by a horizontal tangent, features a flex point and then runs asymptotically towards the full scale value.
Real 2nd-order time-delay elements are controlled systems with two (energy) stores, such as those occurring when tempering a tank via a heat exchanger.

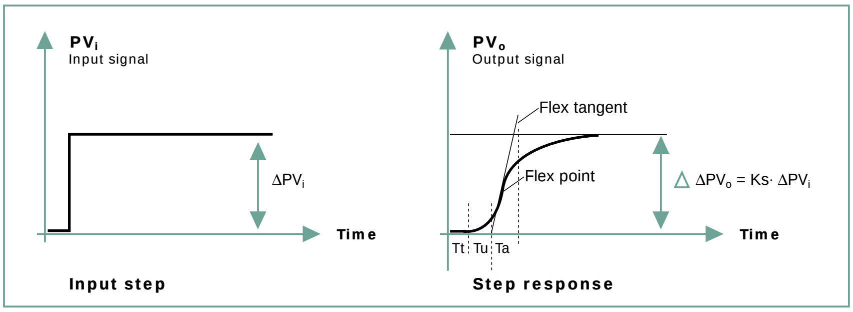


Figure 15: Step response of a 2nd-order time-delay element

What follows is a consideration of the controllability of controlled systems with compensation (with time delays/dead time). These controlled systems can be approximated by the approximate model shown in Figure 16.

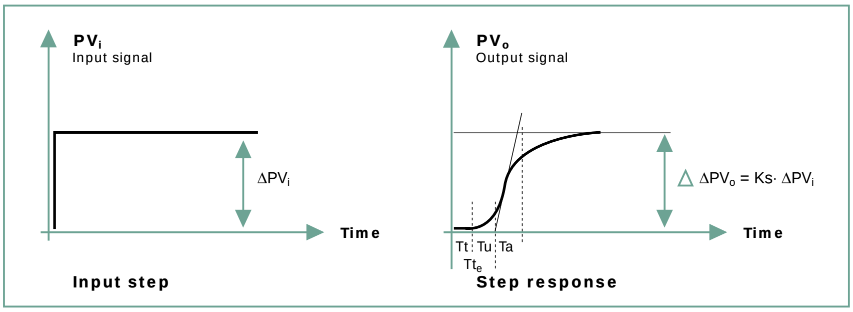


Figure 16: Approximate model for controlled systems with compensation and dead time

On the basis of practical experience, it is possible to make an approximate statement on the controllability of a controlled system with compensation and equivalent dead time via the ratio Tt_e/Ta.

Tt_e/Ta	Controllability	Control engineering effort
< 0.1	Very well controllable	Low
0.1 … 0.2	Well controllable	Moderate
0.2 … 0.4	(Still) controllable	High
0.4 … 0.8	Poorly controllable	Very high
> 0.8	Barely controllable	Special measures or controller structures required

Table 3: Estimation of the controllability of a system with compensation

The I-element:
On the I-element (integral element), the output variable is proportional to the time integral of the input variable. In the case of a constant input variable, the output variable increases continuously.

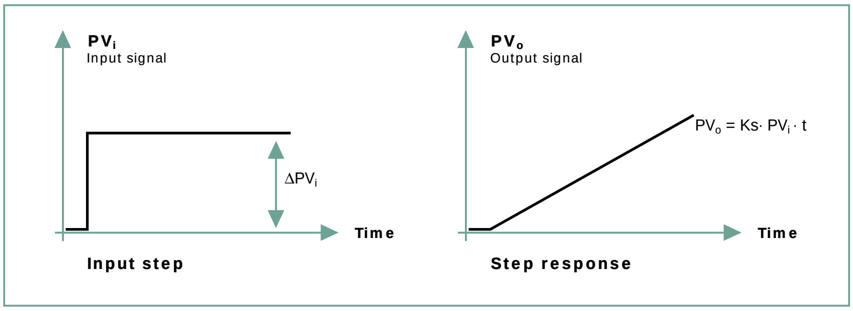


Figure 17: Step response of an I-element

The lag element:
On the lag element, there is a similar behavior to that on the P-element with system gain 1 (Ks = 1). However, the lag element does not respond immediately to changes of the input value. In the case of a stepped change of the input variable PV_i, the same stepped change of the output variable occurs upon expiration of time Tt.

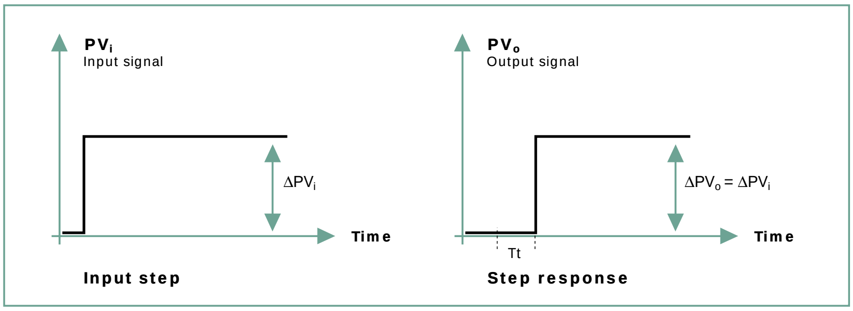


Figure 18: Step response of a lag element

2.3. The controller

A closed-loop control system must ensure that the process value is equal to the set-point value or is adjusted to the set-point value under all circumstances, even under the influence of disturbance variables, i.e. the control deviation must be 0.
In addition, the closed-loop control system must operate stably and the process value may neither drift from the required operating point nor oscillate around it as a consequence of a change of disturbance variable or set-point value.

In order to meet these requirements when designing a closed-loop control system or a control loop, the appropriate controller must be selected for the given controlled system and must be matched to the controlled system. In addition to knowledge of the dynamic and static behavior of the controlled system, this also necessitates knowledge of the characteristics of the individual controller versions or controller types.

In the following, the individual controller types are described in greater detail.
Controllers can initially be subdivided into two main groups:
– continuous-action controllers and
– on/off controllers.

2.3.1. On/off controllers

On/off controllers are frequently used in temperature, filling level, pressure, pH value and conductivity control loops. On/off controllers are also used in day-to-day applications or appliances such as automatic coffee machines, irons, refrigerators or building heating systems.

Two-point controller:
A two-point controller operates in the same way as a switch. Its output can assume only two states: switched on or switched off. This means that the controlled final control element or actuator is either switched on or opened or is switched off or closed. A two-point controller can be seen as a P controller (continuous-action controller) with very high gain.
A two-point controller can only be used in conjunction with time-delayed systems (1st-order or 2nd-order time-delay systems) or controlled systems without compensation (I-systems).

Figure 19 illustrates the principle of operation of a two-point controller.

Ideally, the switch-on point and switch-off point of the two-point controller would coincide. In practice however, the switch-on point and switch-off point are reciprocally offset. The interval between the two switching points is referred to as (switching) hysteresis and is identified with PV_h. If the process value PV drops below the preset set-point value SP minus half the hysteresis, the output of the controller is switched on (CO = 100 %).

If the process value rises above the set-point value plus the hysteresis, the output is switched off again (CO = 0 %). Half of the hysteresis prevents a constant switching on and switching off at the same point owing to very minor disturbances.

The described two-point controller can be used, e.g., for tempering a room. The control response of the two-point controller is illustrated below on the basis of this example.

The diagram in Figure 21 shows the principle characteristic of the process value (temperature in the room).

The upper diagram in Figure 21 shows the process value (temperature) and the set-point value (desired temperature) as a function of time and the lower diagram shows the manipulated variable (control output). At instant t = 0 (switch-on instant of the closed-loop control system), the controller switches its output on and thus opens the heating valve. For the period of the dead time (Tt), the actual value initially does not change. After the dead time expires, it increases. The characteristic of the process value corresponds to the step response of the controlled system (characteristic of the process value shown with a dashed line).

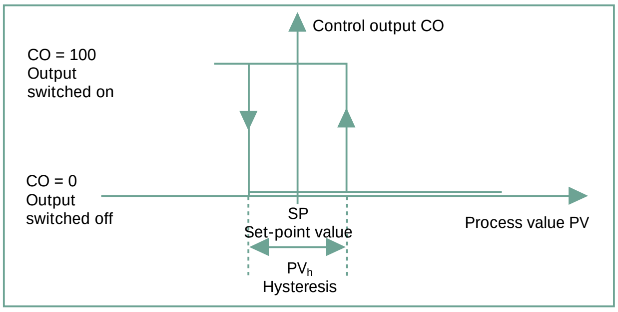


Figure 19: Principle of operation, characteristic of a two-point controller

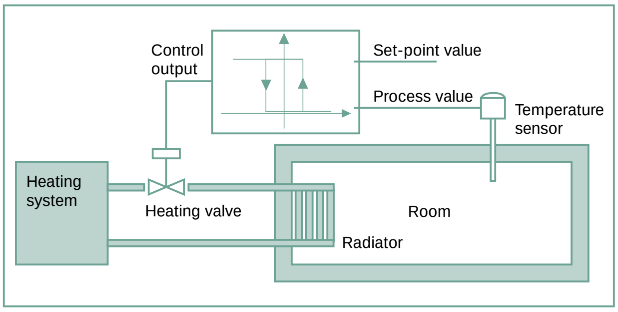


Figure 20: Hardware representation of a closed-loop temperature control system

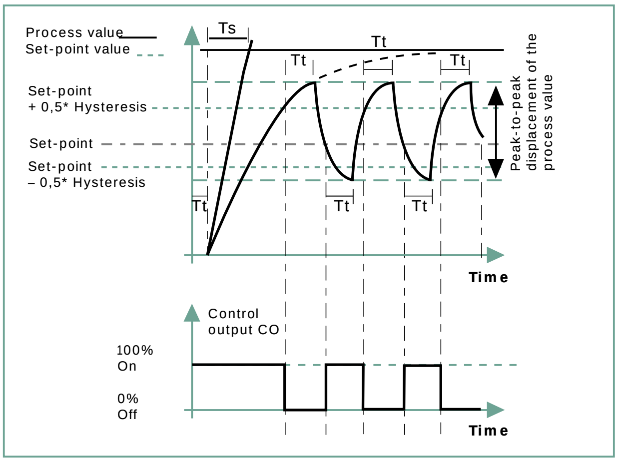


Figure 21: Process value and manipulated variable or controller output of the closed-loop temperature control system as a function of time
Tt: Dead time
Ts: System time constant

If the process value reaches the set-point value plus half the hysteresis, the controller switches its output off and thus closes the heating valve. For the duration of the dead time, the process value initially still rises. After the dead time elapses, it drops. If the process value drops below the set-point value minus half the hysteresis, the controller switches its output back on and the heating valve opens. In the same way as with the rise in temperature, it initially still drops before it rises again, due to the time delay or dead time of the system.
The control cycle then starts again. The dead time of the controlled system and the hysteresis of the controller result in periodic fluctuation of the process value about the set-point value.

In order to assess the controllability of a controlled system with compensation and dead time using a two-point controller, it is possible to use the ratio of equivalent dead time to system time constant (Tt/Ts). Figure 21 shows how the two times are determined from the step response of a controlled system.

Tt_e/Ts	Controllability
< 0.1	Well controllable
0.1 … 0.3	Controllable
> 0.3	Poorly controllable

Table 4: Estimation of the controllability of a system with compensation and dead time using a two-point controller

The peak-to-peak displacement of the actual value is chiefly dependent on two aspects:

– the controller hysteresis (this can generally be set on the controller). The peak-to-peak displacement increases with increasing hysteresis
– the system time constant (this generally cannot be changed and is determined by the structure of the controlled system).
  The lower the system time constant, the greater will be the peak-to-peak displacement.

The lower the time constant of the controlled system (system time constant) and the hysteresis of the two-point controller are, the more frequently the controller will switch. Depending on the design of the controller, the final control element/actuator and the system, increased wear on the control loop components will occur in the case of frequent switching. Consequently, a two-point controller cannot be used on controlled systems without time delay (P-systems).

The above-described response of the two-point controller is referred to as the "heating function". Besides this "heating function", two-point controllers are also used for the "cooling function". The principle of operation is similar in this case but the controller output is switched on when the set-point value is exceeded. Figure 22 shows this principle of operation.

On most modern two-point controllers, it is possible to set the circuit function so that they can be used for both applications, depending on the setting.

3-point controller:
A 3-point controller is a switch, like a two-point controller. In contrast to the 2-point controller, its output may assume three switch positions. 3-point controllers are used, for example, in the following applications:

– **Closed-loop temperature control**
  Closed-loop temperature control of a room on which the disturbance variables can be counteracted by heating and cooling.
– **Closed-loop pH control systems**
  For neutralization of media. The required pH value can be set by adding acid or lye.
– **Control of motorized actuators**
  Motorized actuators operate valves such as butterfly valves, ball valves or gate valves via mechanisms. The valves can be opened, closed or stopped at any position.

Figure 23 demonstrates the principle of operation of a 3-point controller.

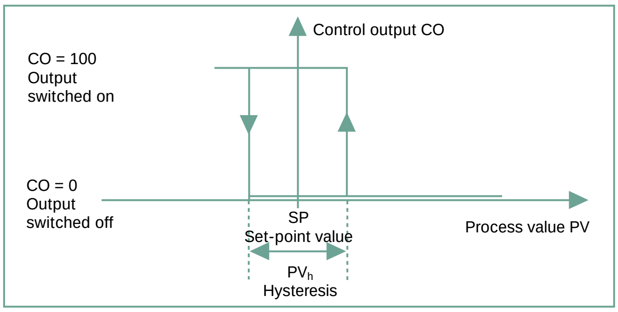


Figure 22: Principle of operation, characteristic curve of a two-point controller, cooling function

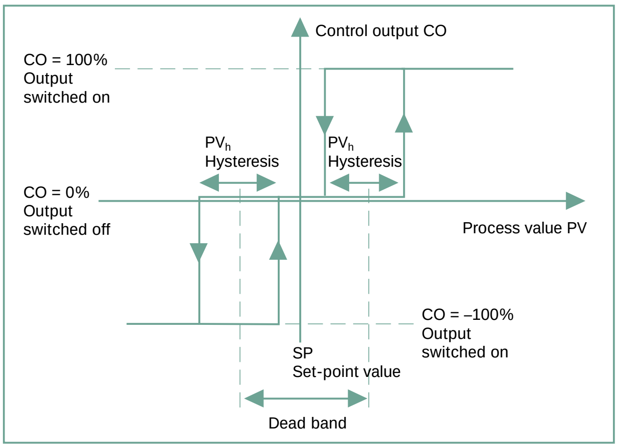


Figure 23: Principle of operation, characteristic curve of a three-point controller

If the process value PV rises above the preset set-point value SP plus half the dead band plus half the hysteresis, the output of the controller is switched on (CO = +100 %). If the process value drops below the set-point value plus half the dead band minus half the hysteresis, the output is switched back off again (CO = 0 %). The difference between the switch-on and switch-off point is referred to as the hysteresis (as on the 2-point controller).
The controller displays the same principle of operation in the other direction. If the process value PV drops below the preset set-point value SP minus half the dead band minus half the hysteresis, the output of the controller is switched on (CO = –100 %). If the process value rises again above the set-point value minus half the dead band plus half the hysteresis, the output is switched back off again (CO = 0 %).

A 3-point controller is shown by the following symbol:

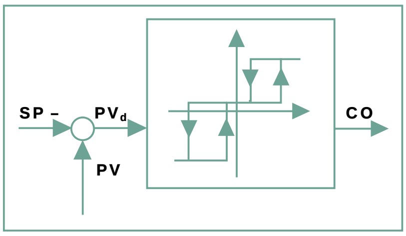


Figure 24: Symbolic representation of a 3-point controller

In principle, the 3-point controller comprises two 2-point controllers whose set-point values are mutually offset. One of the controllers must be operated in “cooling” mode and the other must be operated in “heating” mode.

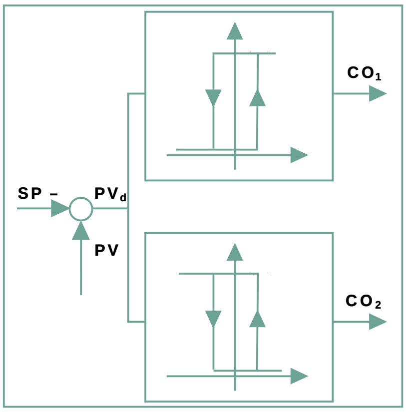


Figure 25: Symbolic representation of a 3-point controller comprising 2-point controllers

2.3.2. Continuous-action controllers

Continuous-action controllers are used for demanding control engineering tasks. Unlike on/off controllers, the manipulated variable of these controllers may assume any value within the range of the manipulated variable/control output (i.e. the range between the maximum and minimum possible value of the control output, e.g. generally between the positions “OPEN” and “CLOSED” on a control valve; this then generally corresponds to a range of 0 ... 100 %). These controller types are characterized by the fact that they respond to any change in control deviation (PV_d = set-point value – process value) at the output.

There are different types of continuous-action controller:
– P controller
– PI controller
– PD controller
– PID controller

These controller types differ by virtue of their dynamics, i.e. by virtue of their time response of their control output as a function of the control deviation. The various controllers are characterized by their step response, i.e. by the time characteristic of their control output after an abrupt change in input variable, the control deviation PV_d.

The individual types of controller are explained in greater detail below.

P controller
The P controller is a purely proportional-action controller. Its control output is directly proportional to its input variable, the control deviation PV_d, in stationary state. The control output of the P controller is calculated as follows:

$$CO = Kp \cdot PV_d$$
$$CO = Kp \cdot (\text{Process value} - \text{Set-point value})$$

Depending on Kp, the control output may drop below (Kp < 1) or increase above (Kp > 1) the control deviation. Kp is referred to as proportional gain factor or proportional coefficient.
As can be seen from the above calculation formula for the control output, the P controller requires a control deviation (PV_d = PV – SP) for forming a control output (CO = Kp • PV_d). For this reason, control loops with P controllers feature a permanent control deviation which decreases with increasing Kp. On the basis of dynamic aspects however, it is not possible to achieve Kp of any arbitrary magnitude. This may lead to instabilities of the control loop.

Figure 26 shows the step response of the P controller.

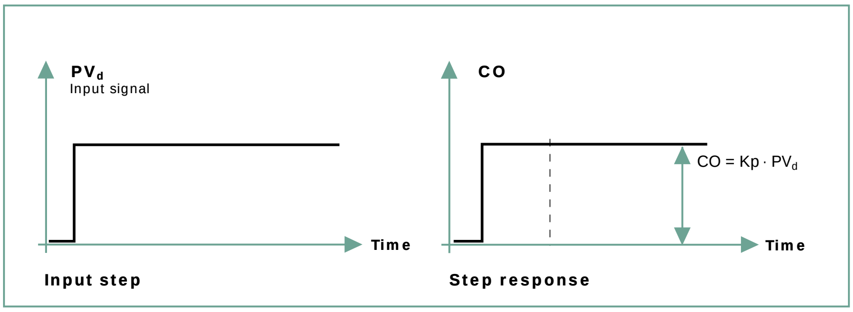


Figure 26: Step response of the P controller

The P controller is represented by the following symbol:

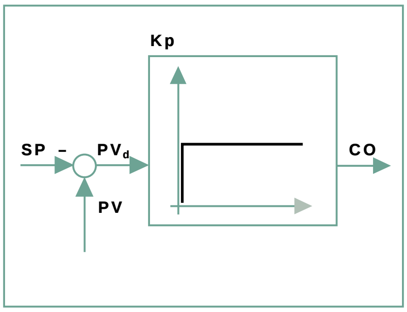


Figure 27: Symbolic representation of a P controller

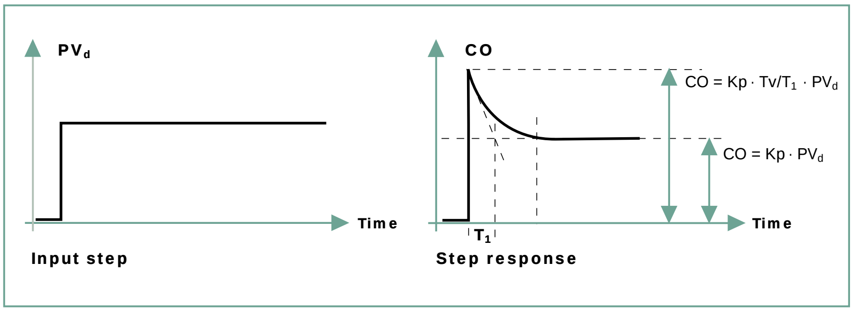


Figure 28: Step response of the PD controller

Characteristics of the P controller:

- The P controller operates without delay and very quickly; it responds immediately to changes in the control deviation.
- Control loops with P controller have a permanent control deviation.
- Setting parameter: Kp (proportional gain factor).

PD controller

On the PD controller, not only the control deviation, but also its rate of change is used to form a control output. The controller thus already responds when a control deviation occurs and counteracts the occurrence of a higher control deviation. The control output increases all the faster the control deviation changes. The control output of the PD controller is calculated as follows:

$$CO = Kp \cdot (Td \cdot \frac{d(PV_d(t))}{dt} + PV_d(t))$$

PV_d = PV – SP: Control deviation
Kp: Proportional gain factor
Td: Derivative-action time

As can be seen from the above calculation formula for the control output, the influence of the D-component is determined via parameter Td. The higher Td becomes, the higher the D-component becomes when calculating the control output.
As is also the case on the P controller, control loops with PD controller have a permanent control deviation which decreases with increasing Kp. However, the D-component produces a stabilizing effect which allows the proportional gain factor Kp to be set higher than on the pure P controller.

Figure 28 shows the step response of the PD controller. On real PD controllers, the D-component is time-delayed (time constant T1), which is allowed for in the transfer function shown. The time constant T1 can, however, not be set directly on most controllers.

The PD controller is represented by the following symbol:

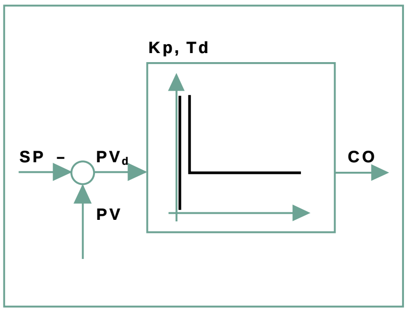


Figure 29: Symbolic representation of a PD controller

Characteristics of a PD controller:

- Like the P controller, the PD controller operates without delay and responds immediately to changes in the control deviation.
- The PD controller responds to the rate of change of the control deviation and thus counteracts the build-up of a higher control deviation.
- Control loops with PD controller have a permanent control deviation.
- The D-component of the controller may lead to a situation in which minor fluctuations of the process value, and thus minor fluctuations of the control deviation, as caused, for example, by disturbances in electrical transfer of the process value (e.g. by standardized signals), lead to constant fluctuations of the control output.
- Setting parameters:
  Kp (proportional gain factor)
  Td (derivative-action time)

PI controller

The PI controller consists of a proportional component and an integral component. The integral component calculates its share of the control output via the time integral of the control deviation. If there is a control deviation, the integral component increases the control output. This avoids a permanent control deviation as occurs on P controllers and PD controllers. The control output of a PI controller is calculated as follows:

$$CO = Kp \cdot (\frac{1}{Tr} \cdot \int (PV_d(t)dt) + PV_d(t))$$

PV_d = PV – SP: Control deviation
Kp: Proportional gain factor or proportional coefficient
Tr: Reset time

As can be seen from the above calculation formula for the control output, the influence of the I-component is determined by parameter Tr. The lower Tr becomes, the greater the I-component becomes when calculating the control output. Reset time Tr is the time which the controller requires to generate a control output of the same magnitude as that which occurs immediately as the result of the P-component by means of the I-component.

Figure 30 shows the step response of the PI controller.

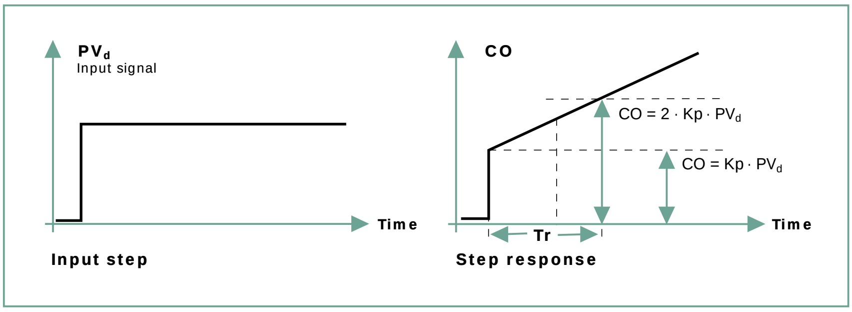


Figure 30: Step response of the PI controller

The PI controller is represented by the following symbol:

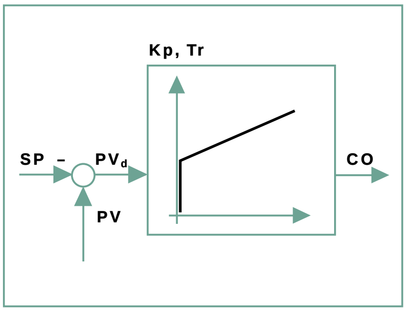


Figure 31: Symbolic representation of the PI controller

Characteristics of the PI controller:

– The PI controller is advantageous in that it responds quickly due to its P-component and eliminates permanent control deviations owing to the I-component.

– Since two parameters can be set on the PI controller (Kp and Tr), it is possible to better adapt it to the dynamics of the controlled system.

– Setting parameters:
Kp (proportional gain factor)
Tr (reset time)

PID controller

The control output of the PID controller is calculated from the proportional, integral and differential component. The control output of the PID controller is calculated as follows:

$$CO = Kp \cdot \left(\frac{1}{Tr} \cdot \int (PV_d(t)\,dt) + Td \cdot \frac{d(PV_d(t))}{dt} + PV_d(t)\right)$$

PV_d = PV – SP: Control deviation
Kp: Proportional gain factor or proportional coefficient
Tr: Reset time
Td: Derivative-action time

Figure 32 shows the step response of the PID controller.

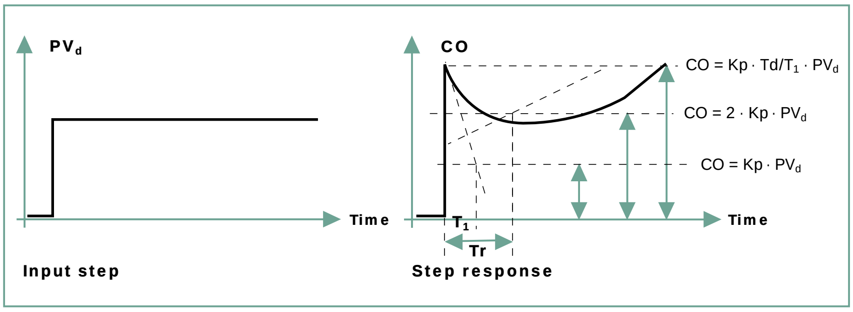


Figure 32: Step response of the PID controller

The PID controller is represented by the following symbol:

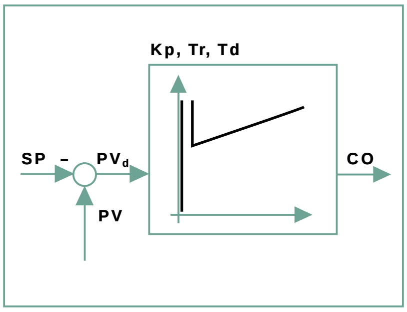


Figure 33: Symbolic representation of the PID controller

Characteristics of the PID controller:

- The PID controller unites the characteristics of the P controller, PD controller and PI controller.
- Setting parameters:
  Kp (proportional gain factor)
  Tr (reset time)
  Td (derivative-action time)

On the basis of practical experience, it is possible to provide the following estimation of the suitability of the various continuous-action controllers for closed-loop control of important technical controlled variables.

	Controller type			
	P	**PD**	**PI**	**PID**
Controlled variable	**Permanent control deviation**		**No permanent control deviation**	
Temperature	Conditionally suitable	Conditionally suitable	Suitable	Suitable for stringent demands
Flow rate	Unsuitable	Unsuitable	Suitable	Over-dimensioned
Pressure	Suitable	Suitable	Suitable	Over-dimensioned
Filling level	Suitable	Suitable	Suitable	Over-dimensioned

Table 5: Suitability of various continuous-action controllers for controlling important technical controlled variables

3. Adapting the controller to the controlled system

There are two requirements made on a controller or control loop.

Variable command control:
In the case of variable command control, the set-point value is not constant but changes over the course of time. The process value must be corrected to the set-point value. The behavior of a closed-loop control system in the case of changing set-point value is referred to as response to set-point changes.

Fixed command control:
In the case of fixed command control, the set-point value is constant. In this case, the closed-loop control system has the task of maintaining the process value at the value of the set-point. Disturbance variables acting on the controlled system should be compensated for in this case. The behavior of a closed-loop control system with changing disturbance variables is referred to as disturbance response.

In addition to having a good response to set-point changes, a closed-loop control system should, in most cases, feature a good disturbance response. If a disturbance occurs in a control loop, this leads to a control deviation which the controller must compensate for. When planning a closed-loop control system, disturbance variables are of special significance. If several disturbance variables act on a controlled system, the individual disturbance variables generally have a different time response. Many disturbance variables occur abruptly and others less abruptly. Even the magnitude of the influence on the process value differs with the individual disturbance variables.

When planning a closed-loop control system, there is the risk that the control loop becomes unstable due to the selected combination of controller and controlled system or owing to the selected parameters of the controller. The following behaviors may occur, e.g. after occurrence of a set-point change or disturbance variable change.

The control loop is at the stability limit; the process value oscillates at constant amplitude and frequency.

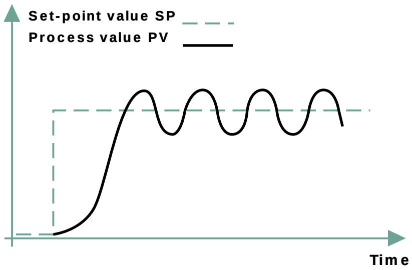


Figure 34: Process value characteristic, control loop at the stability limit

The control loop is unstable. The process value oscillates with increasing amplitude.

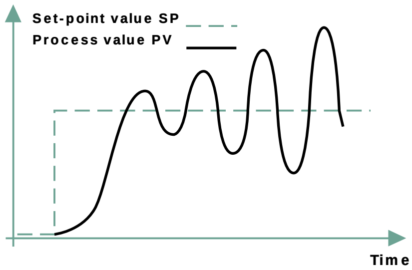


Figure 35: Process value characteristic, control loop unstable

The control loop is stable; the process value is corrected to the new set-point value.

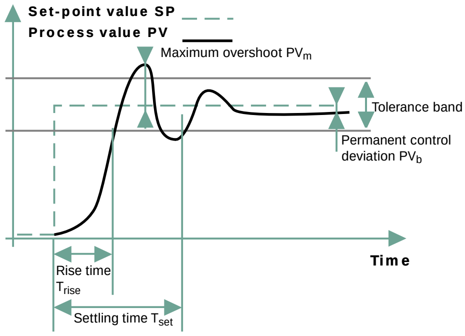


Figure 36: Process value characteristic after a set-point change in the case of a stably operating control loop

The behavior of a well-tuned or well-set control loop after a disturbance variable change is similar.

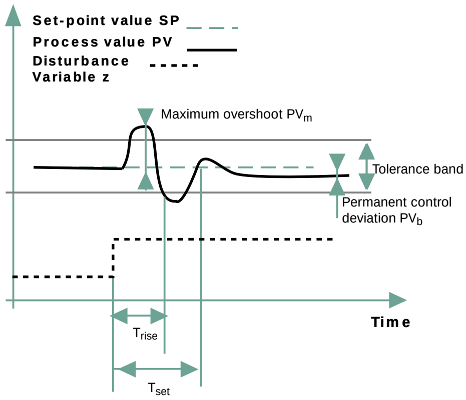


Figure 37: Process value characteristic after a disturbance variable change in the case of a stably operating control loop

The quality of a closed-loop control or a control loop is assessed on the basis of the following parameters.

Permanent control deviation PV_b
The permanent control deviation occurring after the adjustment process has decayed.

Overshoot PV_m
Maximum value of the process value or of the controlled variable minus the process value in steady state.

Rise time T_{rise}
The time which elapses after a set-point or disturbance variable change until the process value occurs for the first time in an agreed tolerance band (e.g. 2 % or 5 %) about its stationary end value.

Settling time T_{set}
The time which elapses after a set-point or disturbance variable change until the process value occurs and permanently remains in an agreed tolerance band (e.g. 2 % or 5 %) about its stationary end value.

On the basis of these parameters, it is possible to formulate the requirements made of an optimally tuned control loop:
- permanent control deviation PV_b = 0 wherever possible
- maximum overshoot PV_m as low as possible
- settling time T_{det} as low as possible
- rise time T_{rise} as low as possible.

3.1. Selecting the suitable controller

The controller must be matched to the controlled system in order for a control loop to operate optimally.

Suitable combinations of controllers and controlled systems on which a stable control response can be achieved by appropriate setting of the controller parameters:
- Kp (proportional gain factor)
- Tr (reset time)
- Td (derivative-action time)

can be established on the based on the dynamics and stability of control loops and allowing for empirical values. There are, of course, also control loops necessitating other combinations of controlled system / controller.
Table 6 provides an overview of suitable combinations of controllers and controlled systems.

3.2. Determining the controller parameters

After a suitable controller has been selected, a second step is to match the parameters of the controller to the controlled system.

A number of setting guidelines with which a favorable setting of the controller parameters can be determined experimentally are cited in control-engineering literature.
In order to avoid incorrect settings, the conditions under which the relevant setting guidelines were established must always be followed. Besides the characteristics of the controlled system and of the controller themselves, other important factors include whether a disturbance variable change or a reference variable change is to be compensated for optimally.

3.2.1. Setting guidelines in line with Ziegler and Nichols (oscillation method)

With this method, the controller parameters are set on the basis of the behavior of the control loop at the stability limit. The controller parameters are initially set so that the control loop starts to oscillate. Critical characteristic values then occur which allow conclusions to be drawn in terms of the controller parameters. The precondition for using this method is that the control loop can be caused to oscillate.

Procedure:
- Set controller as P controller (i.e. Tr = 9999, Td = 0), initially select a low value for Kp.
- Set the required set-point value.
- Increase Kp until the process value executes an undamped sustained oscillation (see Figure 38).

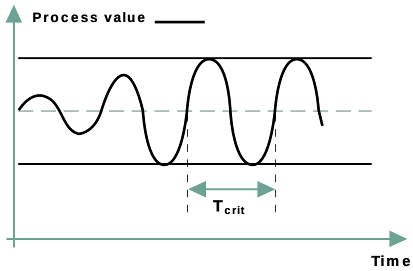


Figure 38: Process value characteristic of the control loop at the stability limit in order to determine the control parameters in line with Ziegler and Nichols

The proportional gain factor set at the stability limit is designated K_{crit}. The resultant period of oscillation is designated T_{crit}.

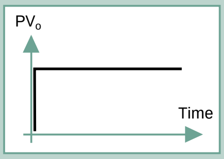
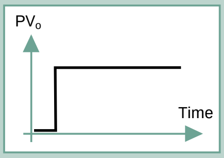
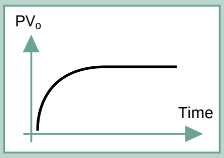
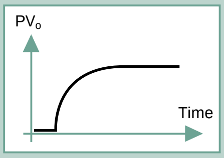
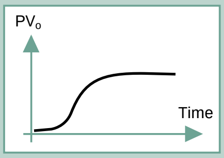
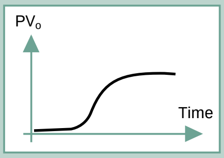
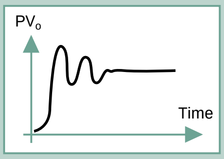
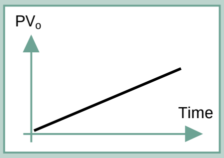
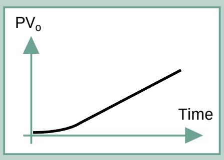
Controlled system		Continuous-action controllers				On/off controllers	
		P	PI	PD	PID	2-point	3-point
P-element		Unsuitable	Response to set-point changes well-suited Disturbance response well-suited	Unsuitable	Unsuitable	Unsuitable	Unsuitable
PTt-element		Unsuitable	Response to set-point changes suitable Disturbance response s.	Unsuitable	Unsuitable	Unsuitable	Unsuitable
1st-order time-delay element		Response to set-point changes well-suited	Disturbance response well-suited	Unsuitable	Unsuitable	Suitable	Suitable
1st-order time-delay element with dead time		Unsuitable	Response to set-point changes suitable Disturbance response suitable	Unsuitable	Response to set-point changes well-suited Disturbance response well-suited	Condition-ally suitable if hysteresis is low	Condition-ally suitable if hysteresis is low
2nd-order time-delay element		Unsuitable	Response to set-point changes suitable Disturbance response s.	Response to set-point changes well-suited	Disturbance response well-suited	Suitable	Suitable
2nd-order time-delay element with dead time		Unsuitable	Response to set-point changes suitable Disturbance response suitable	Unsuitable	Response to set-point changes well-suited Disturbance response well-suited	Unsuitable	Unsuitable
3rd-order time-delay element		Unsuitable	Response to set-point changes suitable Disturbance response suitable	Unsuitable	Response to set-point changes well-suited Disturbance response well-suited	Unsuitable	Unsuitable
I-element		Response to set-point changes well-suited	Disturbance response well-suited	Response to set-point changes suitable	Disturbance response suitable	Suitable	Suitable
I-element with 1st-order delay		Unsuitable	Unsuitable	Response to set-point changes well-suited	Disturbance response well-suited	Suitable	Suitable

Table 6: Suitability of continuous-action and on/off controllers for combination with various types of controlled system

The controller parameters can then be calculated in accordance with Table 7 from K_{crit} and T_{crit}.
The Ziegler and Nichols setting were determined for P systems with 1st-order time delay and dead time. They apply only to control loops with disturbance response.

Setting the parameters in line with Ziegler and Nichols:			
Controller type	**Setting parameters**		
P controller	$Kp = 0.5 \cdot K_{crit}$		
PI controller	$Kp = 0.45 \cdot K_{crit}$	$Tr = 0.85 \cdot T_{crit}$	
PID controller	$Kp = 0.6 \cdot K_{crit}$	$Tr = 0.5 \cdot T_{crit}$	$Td = 0.12 \cdot T_{crit}$

Table 7: Controller parameters in line with Ziegler and Nichols

3.2.2. Setting guidelines in line with Chien, Hrones and Reswick (control output step method):

With this method, the controller parameters are set on the basis of the transient response or step response of the controlled system. The controller emits a control output step. The times Tu and Tg are read off (see Figure 38) from the characteristic of the process value or the controlled variable. The control output step must be selected so that an process value is produced that lies within the range of the subsequent operating point of the controlled system. Ks is the proportional coefficient of the controlled system. It is calculated as follows:

$$Ks = \frac{\Delta PV}{\Delta CO}$$

ΔPV: Magnitude of the process value step
ΔCO: Magnitude of the control output step

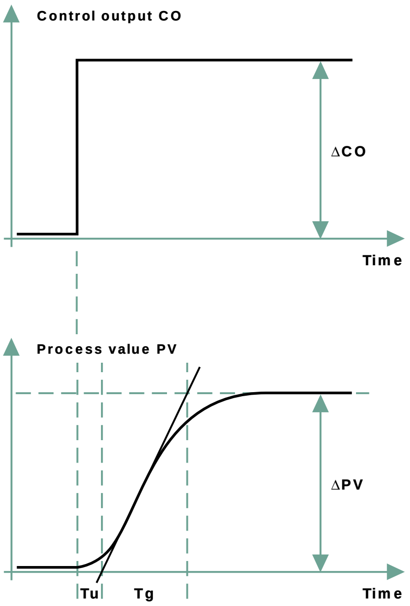


Figure 38: Step response of a controlled system for determining control parameters in line with Chien, Hrones and Reswick

Procedure for determining the step response of the controlled system:

- Switch the controller to manual operating mode.
- Emit a control putput step and record the process value with a recorder.
- In the case of critical controlled systems (e.g. in the case of the risk of overheating), switch off in good time.

It must be noted that the process value may increase again after switch-off on thermally sluggish systems.

Table 8 lists the controller parameter settings as a function of Tu, Tg and Ks for response to set-point changes and disturbance response and for an aperiodic control process and a control process with 20% overshoot. The figures apply to systems with P-response, with dead time and with 1st-order delay time.

Setting the parameters in line with Chien, Hrones and Reswick:				
Controller type	**Parameters settings**			
	Aperiodic control process		**Control process with overshoot (approx. 20% overshoot)**	
	Resp. to set-p. changes	**Disturbance response**	**Resp. to set-p. changes**	**Disturbance response**
P controller	$Kp = 0.3 \cdot \frac{Tg}{Tu \cdot Ks}$	$Kp = 0.3 \cdot \frac{Tg}{Tu \cdot Ks}$	$Kp = 0.7 \cdot \frac{Tg}{Tu \cdot Ks}$	$Kp = 0.7 \cdot \frac{Tg}{Tu \cdot Ks}$
PI controller	$Kp = 0.35 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 1.2 \cdot Tg$	$Kp = 0.6 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 4.0 \cdot Tu$	$Kp = 0.6 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = Tg$	$Kp = 0.7 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 2.3 \cdot Tu$
PID controller	$Kp = 0.6 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = Tg$ $Td = 0.5 \cdot Tu$	$Kp = 0.95 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 2.4 \cdot Tu$ $Td = 0.42 \cdot Tu$	$Kp = 0.95 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 1.35 \cdot Tg$ $Td = 0.47 \cdot Tu$	$Kp = 1.2 \cdot \frac{Tg}{Tu \cdot Ks}$ $Tr = 2.0 \cdot Tu$ $Td = 0.42 \cdot Tu$

Table 8: Controller parameters in line with Chien, Hrones and Reswick

4. Rating and selection of control valves

In addition to controllers and sensors, actuators or final control elements which intervene in the process to be controlled as a function of the signals preset by the controller and which change the process variable to be controlled are required for constructing closed-loop control systems.

4.1. Introduction and definition of terms

Valves are final control elements or actuators for influencing fluid streams in pipe systems. In accordance with DIN IEC 534, a positioning valve is a device, operated with auxiliary energy, which varies the flow rate in a process. It consists of a valve fitting, connected to the actuator, which is able to change the position of the restrictor in the valve as a function of the controller signal (control output). Generally, a control system is required between the actuator and controller to act as a signal transducer and/or amplifier. In the case of many positioning valves, the control system is integrated as far as a field bus interface in the actuator. In accordance with DIN IEC 534, positioning valves are subdivided on the basis of the following types:

Valve type	Restrictor
Lift-type valve Through-way valve 3-way valve Angle valve	The restrictor is generally designed as a cone. It moves perpendicular to the seat plane.
Gate valve	The restrictor is a flat or wedge-shaped plate.
Diaphragm valve	A flexible restrictor performs the function of of isolation and sealing.
Ball valve	The restrictor is a ball with a cylindrical bore or a segment of a ball.
Butterfly valve	A disc mounted in such a way as to allow it to rotate.
Plug valve	The restrictor may be a cylindrical, conical or eccentrically mounted ball segment.

Table 8: Classification of positioning valves in accordance with DIN IEC 534

Valves can also be classified in accordance with the distinction between the main functions of final control elements/actuators in compliance with DIN 19226, dividing them into CONTROL-final control elements and ON/OFF-final control elements.

ON/OFF valves having only two or a few circuit states are used for open-loop control tasks. Control valves which are able to continuously set the fluid stream are used for closed-loop process control tasks. ON/OFF valves and control valves have extremely different tasks in some cases, so that the rating and selection of both valve types necessitate greatly different procedures.

4.2. Rating and selection of ON/OFF valves

This kind of valves can either open or close a line (ON/OFF valve) or switch over a material stream from one line to another.

An important criterion for the valve to be selected is initially that the required fluid quantity be able to flow through the valve at a given pressure differential, i.e. the valve cross-section must be adequately large. The following rule of thumb frequently applies: the line cross-section is equal to valve (fluidic connection) cross-section. The next requirement is that the valve be able to switch against the maximum pressure differential, i.e. that the valve actuator be adequately powerful. The maximum switchable pressure differential is specified in the data sheet. If the type of auxiliary energy has been defined and the material suitability has been checked, it is already possible to define a specific valve type and to select the specific valve.

4.3. Rating and selection of control valves

Control valves are able to constantly change their opening cross-section and thus continuously influence fluid streams. They thus represent variable flow resistors.

4.3.1. Fluidics fundamentals

Flow resistances occur in process installations in various forms:

- as resistances in capillaries, gaps, nozzles, diaphragms and valves
- as line resistances in pipes, hoses and ducts
- as leakage resistances in gaps and porous components.

In general, the ratio of pressure drop Δp to fluid flow Q can be defined as the flow resistance R of a component.

$$R = \frac{\Delta p}{Q}$$

Basically, a distinction must be made between two types of resistance on the basis of the physical causes:

- frictional resistances due to flow involving friction
- cross-sectional resistances owing to variations in the flow cross-section.

The following distinction between cases for dependence between Δp and Q must be made for frictional resistances in non-compressible fluids as a function of the Reynolds number

$$Re = \frac{\bar{u} \cdot D_h}{v}$$

u ≡ mean flow velocity
D_h ≡ hydraulic diameter,
Dh = kA/U
v ≡ kinematic viscosity

Range of the Reynolds number	Flow form	Interrelationship between Δp and Q
Re low	Laminar	$\Delta p \approx Q$
Re high	Turbulent	$\Delta p \approx Q^{7/4}$
$Re \approx Re_{critical}$	Transitional form	To be determ. experimental.

From this, we can conclude that the flow resistance R is constant only in the case of laminar flow owing to $\Delta p \approx Q$. Otherwise, a non-linear relationship always applies between pressure drop Δp and fluid flow Q.

The following applies to fluid resistances in the case of cross-sectional variation in non-compressible fluids and with turbulent flow:

The permanent pressure loss Δp_{loss} is taken as the basis for the flow resistance R. The flow resistance coefficient ζ is introduced as a "non-dimensional pressure loss" by referring the permanent pressure loss to the dynamic pressure.

$$\zeta = \frac{\Delta p_{loss}}{\left(\frac{\rho \cdot u^2}{2}\right)}$$

The following applies to the model case of flow through an orifice plate:

$$\zeta = \left[\left(\frac{A_{pipe}}{\mu \cdot A_{orifice}}\right) - 1\right]^2$$

μ ≡ contraction coefficient

and

$$\Delta p_{loss} = (1 - m_b) \cdot \Delta p_B$$

Δp_B ≡ effect. press. through the orifice plate
$m_B \equiv \frac{A_{orifice}}{A_{pipe}}$ ≡ opening ratio

and, after introduction of a flow coefficient a, we obtain the flow-rate equation

$$Q = \alpha \cdot A_{orifice} \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

α ≡ flow coefficient
ρ ≡ density of the fluid

In the case of a high Reynolds number, i.e. in turbulent flow, the following applies to cross-sectional resistances in non-compressible fluids: $\Delta p \approx Q^2$.

The flow-rate variable kv which is defined as follows is used to identify valves as orifice-type fluidic components:
the kv value (in m^3/h) is the volume flow of water at +5 to +30 °C passing through the valve at the relevant stroke s with a pressure loss Δp_{0valve} = 100 kPa. (1 bar; 14.5 psi)

Analogous to this, the flow-rate coefficient cv is described in the American literature, defined as follows:
the cv value (in US gal/min) is the volume flow of water at 60 °F which passes through at a pressure loss of 1 psi with the relevant stroke s.

Moreover, the Q_{Nn}-Wert (in l/min) is specified as the flow characteristic for compressed air under standardized conditions for pneumatic valves.

The following conversion factors apply:

Kv ↔ cv: kv = 0.86 cv
Kv ↔ ζ: $kv = 4 \cdot d^2/(\zeta)^{1/2}$
Kv ↔ Q_{Nn}: $kv = 1078\, Q_{Nn}$

4.3.2. Characteristic curves

4.3.2.1. Valve characteristic

The valve characteristic represents the dependence of the aperture cross-section A on the stroke s of the valve spindle: A = f(s).
In the simplest case, the valve characteristic is linear, i.e. $A = K_1 \cdot s$:

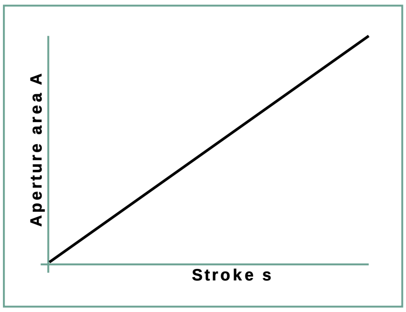


Figure 39: Linear valve characteristic of a control valve

Note: Despite the linearity of the valve characteristic, there is no linear interrelationship between the volumetric flow rate Q through the valve and the valve stroke s due to non-constant pressure drops through the valve.
The equal-percentage valve characteristic is described by a constant percentage increase in the aperture cross-section A with stroke s (referred to the relevant aperture cross-section A present).

$$\frac{dA(s)}{ds} \cdot \frac{1}{A(s)} = K_2$$

$$A = A_0 \cdot e^{K_2 s}$$

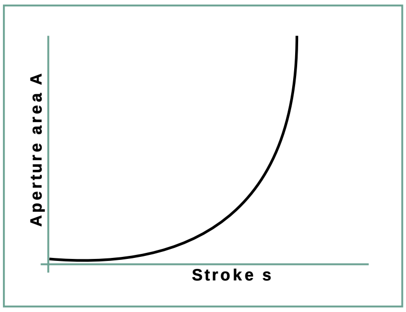


Figure 40: Equal-percentage valve characteristic of a control valve

The equal-percentage valve characteristic approximates practical requirements to a greater extent than the linear characteristic, since

– low variations in stroke Δs cause low ΔA, i.e. fine infeed movements
– high variations in stroke Δs cause high ΔA, i.e. coarse infeed movements.

In the case of s = 0, a minimum aperture cross-section A_0 is present. The valve closes only with an additional sealing edge.

Various valve characteristics are implemented by the contour of the closure elements, the valve cones. Conventional designs include, for example, parabolic cone, lantern cone, perforated cone, V-port cone and many others.

4.3.2.2. Flow characteristic and rangeability

The most conventional characteristic curve required for valve selection is the flow characteristic. The flow characteristic represents the dependence of the standardized flow rate kv on the stroke s: kv = f(s).

ON/OFF flow characteristic

Due to their plate cone, ON/OFF valves initially have a linear flow characteristic in the range of small stroke (up to approx. 30 % stroke). At an opening angle of 30 to 40 % stroke (s), such valves already achieve approx. 90 % flow rate (kv). As the aperture opens even further, the flow rate rises only very slowly through to the maximum, at full stroke. Since the total stroke of the ON/OFF valves is low in relation to the stroke of control valves, the actual task of producing a high change in flow rate with low stroke is performed.

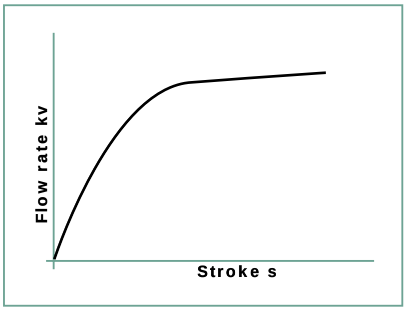


Figure 41: OPEN/CLOSE flow characteristic

Linear flow characteristic

In the simplest case, the flow characteristic is linear, i.e. $kv = K_1 \cdot s$:

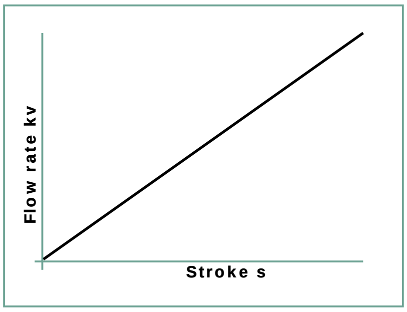


Figure 42: Linear flow characteristic

Note: Unlike the linear valve characteristic, the interrelationship between the volumetric flow rate Q through the valve and the valve stroke s is linear in the case of the linear flow characteristic.

Equal-percentage flow characteristic
The equal-percentage flow characteristic is described by a constant percentage increase in the flow rate kv with the stroke s (referred to the relevant flow rate kv present).

$$\frac{dkv(s)}{ds} \cdot \frac{1}{kv(s)} = K_2$$

$$kv = kv_0 \cdot e^{K_2 s}$$

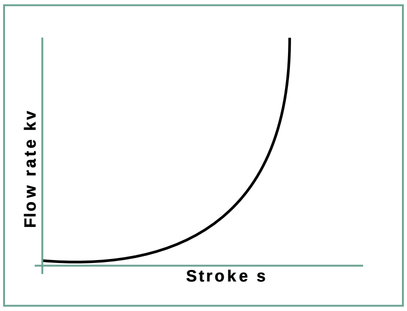


Figure 43: Equal-percentage flow characteristic

At $s \approx 0$ a minimum aperture cross-section A_0 is present, causing a minimum flow kv_0. The valve closes only with an additional sealing edge.

The maximum aperture cross-section A_{max} is reached at maximum stroke s. The related kv value is referred to as kv_s value. The range between kv_0 and kv_s is the total range of the manipulated variable of the valve.

The ratio of kv_0 to kvs is referred to as the rangeability and defines a valve characteristic value:

$$\frac{1}{\alpha} = \frac{kv_0}{kvs}$$

Conventional values are as follows:

$$\frac{1}{\alpha} = \frac{1}{25}; \frac{1}{30}; \frac{1}{50}$$

4.3.2.3. Operating characteristic and pressure ratio

The operating characteristic identifies the flow behavior of the valve under operating conditions in the installation. It represents the dependence of the volume flow $\dot{V}$ on the stroke s of the valve spindle.

$$\dot{V} = f(s)$$

The following main elements of the installation influence the operating behavior:

- the pump; the pressure generated by the pump drops as Δp over the entire installation
- the tubes with the pressure drops Δp_{Li}
- and other resistances $\Delta p'_i$ in the installation (shut-off valves, heat exchangers, pipe elbows, branches, changes in cross-section and other installed fittings).

The operating characteristic curve ($\dot{V}$ = f (s)) thus differs from the flow characteristic curve kv = f (s) of the valve considered in isolation.

The magnitude of the difference (the degree of characteristic distortion) is represented by the pressure ratio Ψ. The pressure ratio Ψ is stated for the fully open valve:

$$\psi = \frac{\Delta p_{vo}}{\Delta p_o} = \frac{\Delta p_{vo}}{\Delta p_{vo} + \Delta p_{Lo} + \Delta p'_o}$$

Δp_o: Pressure drop over entire installation
ΔP_{vo}: Pressure drop at fully opened valve (max. flow)
Δp_{Lo}: Pressure drop at tubes, fittings...
$\Delta p'_o$: Pressure loss at pump (at max. flow rate)

The behavior of the system as an interplay between source (pump) characteristic and load (valve) characteristic can be shown in the characteristic map (see Figure 45):

The following standardized equation applies to the operating characteristic

$$\frac{\dot{V}}{\dot{V}_{max}} = \frac{1}{\sqrt{1 + \psi\left[\left(\frac{kv_s}{kv}\right)^2 - 1\right]}}$$

i.e. the operating characteristic depends on the pressure ratio Ψ and the flow characteristic

$$\frac{kv_s}{kv} = \int\left(\frac{s}{s_{max}}\right)$$

Examples of operating characteristics (f. rangeability $\frac{1}{\alpha} = \frac{1}{30}$ and various ψ):

Control valve with linear flow characteristic:

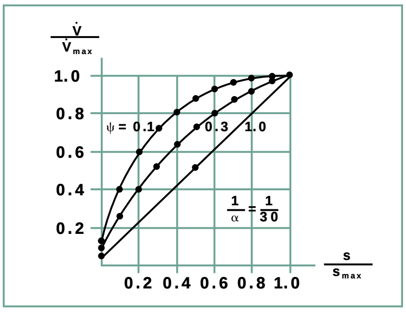


Figure 46: Control valve with linear flow characteristic

Control valve with equal-percentage flow characteristic

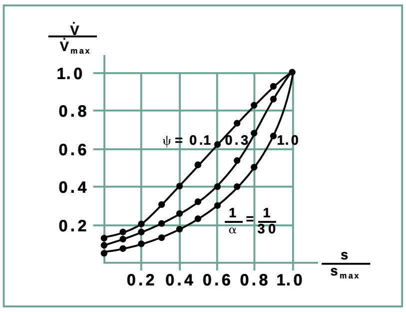


Figure 47: Control valve with equal-percentage flow characteristic

An approximation of a linear operating characteristic can be achieved

- in the case of linear flow characteristic with high pressure ratio ψ
- in the case of equal-percentage flow characteristic with low pressure ratio ψ.

The non-linearities for both valve types have approximately the same magnitude at $\psi \approx 0.3$.

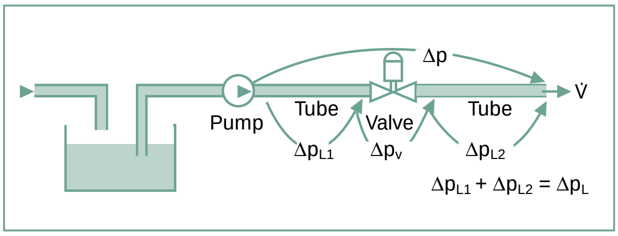


Figure 44: Pressure losses in an installation

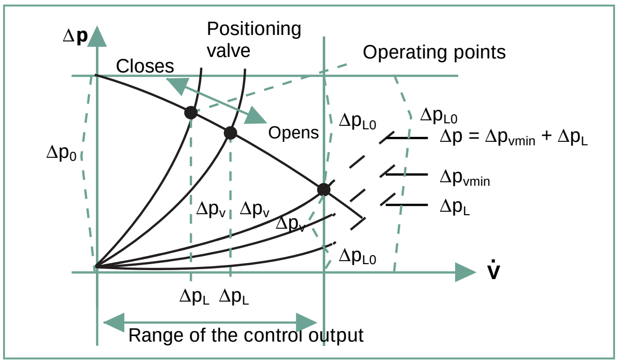


Figure 45: Characteristic map, source characteristic and load characteristics

A linear operating characteristic is achieved only if the valve features an optimum flow characteristic as the result of a special valve contour.

Flow and operating characteristics for valves with $\psi \approx 0.3$ and $\frac{1}{\alpha} = \frac{1}{30}$:

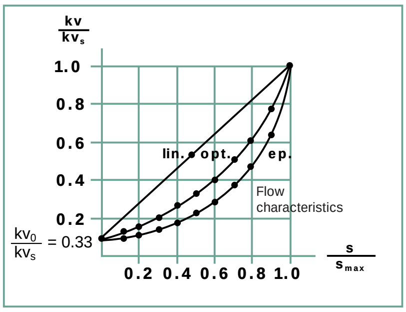


Figure 48: Flow characteristics: linear, optimum, equal-percentage

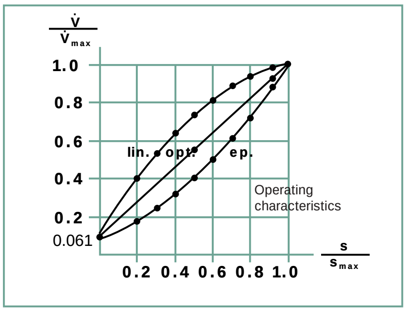


Figure 49: Operating characteristics: linear, optimum, equal-percentage

4.3.3. Rating and selection

Control valves must be rated and selected with a view to their specific task in order to be able to ensure a faultless control function.

Initially, the connection nominal diameter must be defined in accordance with the medium and the related, efficient flow velocity.

The following guideline values apply:
- 2 m/s for fluids
- 20 m/s for gases
- 45 m/s for steam.

The following formulae are helpful for practical application:

Fluids:

$$NW = 0.42 \cdot \sqrt{Q}$$

NW: Connection nominal diameter
Q: Volumetric flow rate in l/h

Gases:

$$NW = 4.2 \cdot \sqrt{\frac{Q_N}{p_1}}$$

Q_N: Volumetric flow rate in Nm^3/h
p_1: Pressure upstream of the valve in bar absolute

Steam:

$$NW = 2.8 \cdot \sqrt{G \cdot v''}$$

G: Mass flow rate in kg/h
v'': Specific volume in m^3/kg

General:

$$NW = 18{,}8 \cdot \sqrt{\frac{Q_B}{c}}$$

Q_B: Volumetric flow rate in m^3/h
c: Flow velocity in m/s

In the case of simple control valves on which a connection nominal diameter is assigned directly to a kvs value, the anticipated flow velocity should at minimum be checked.

The nominal pressure stage results from knowledge of the valve material, the operating temperature and the max. operating pressure, e.g. from DIN 2401, or from a valve data sheet.

The actual closed-loop control function, i.e. setting the fluid flow rate of a given temperature and given pressure while simultaneously producing a defined pressure loss, is determined by the flow characteristic, the kv value

The kv value is a reference variable and is defined as follows: kv value = quantity in m^3/h of cold water (+5 … +30 °C) which flows through the valve at 1 bar. differential pressure across the valve and at stroke s. The kvs value, analogously, is the quantity at stroke s = 100 %.

Analogous to the kv value the flow rate coefficient cv is described in the American literature. The following conversion factor applies: kv = 0.86 · cv.
See also chapter “4.3.1. Fluidics fundamentals”.

The kv value must be calculated for the current operating data. A distinction must be made between maximum load (maximum quantity Q_{max}, minimum $\Delta p_{min} \geqslant kv_{max}$) and minimum load (minimum quantity Q_{min}, maximum $\Delta p_{max} \geqslant kv_{min}$) Both load cases must be calculated individually and be adjusted on the basis of the valve rangeability.

The following applies to cold water:

$$kv = Q \cdot \sqrt{\frac{1}{\Delta p}}$$

Q: Volumetric flow rate in m^3/h
Δp: Pressure differential at the valve in bar

The following applies in general to fluids (sub-critical):

$$p_2 > ps_2$$

ps_2: Saturated steam press., in bar abs., related to the temperature downstream of the valve

$$kv = Q \cdot 0.032 \cdot \sqrt{\frac{\rho_1}{\Delta p}}$$

ρ_1: Density of the medium in kg/m^3
Δp: Pressure differential at the valve in bar

$$kv = G \cdot 0.032 \cdot \sqrt{\frac{1}{\rho_1 \cdot \Delta p}}$$

G: Mass flow rate in kg/h
Δp: Pressure differential at the valve in bar

The following applies to fluids in general (super-critical):

$$p_2 < ps_2$$

ps_2: Saturated steam pressure, in bar absolute, related to the temperature downstream of the valve

The kv value is calculated here in two steps: the kv value for the evaporating steam quantity kv_D and the kv value for the fluid kv_F are calculated separately and both values are added.

$$kv = kv_F + kv_D$$

The evaporating quantity is calculated from the mass and energy balance around the valve, assuming isenthalpic relaxation.

The following applies to saturated steam (sub-critical, i.e. $p_2 > \frac{p_1}{2}$):

$$kv = \frac{G_S}{22.4\sqrt{\Delta p \cdot p_2}}$$

G_S: Saturated steam quantity in kg/h
p_1: Pressure upstream of the valve in bar absolute
p_2: Pressure downstream of the valve in bar absolute

The following applies to saturated steam (super-critical, i.e. $p_2 < \frac{p_1}{2}$):

$$kv = \frac{G_S}{11.2 \cdot p_1}$$

p_1: Pressure upstream of the valve in bar absolute

The following applies to superheated steam (sub-critical, i.e. $p_2 > \frac{p_1}{2}$):

$$kv = \frac{G_S}{31.7 \cdot \sqrt{\frac{\Delta p}{v''_2}}}$$

v''_2: Specific volume at p_2, t_1 in m^3/kg

The following applies to superheated steam (super-critical, i.e. $p_2 < \frac{p_1}{2}$):

$$kv = \frac{G}{22.4 \cdot \sqrt{\frac{p_1}{v^*}}}$$

v^*: Specific volume at $\frac{p_1}{2}$, t_1 in m^3/kg

The following applies to gases (sub-critical, i.e. $p_2 > \frac{p_1}{2}$):

$$kv = \frac{Q_N}{514} \cdot \sqrt{\frac{\rho_N \cdot T_1}{\Delta p \cdot p_2}}$$

Q_N: Volumetric flow rate in Nm^3/h
ρ_N: Standard density in kg/m^3 (standard state: 0 °C and 1013 mbar)

The following applies to gases (super-critical, i.e. $p_2 < \frac{p_1}{2}$):

$$kv = \frac{Q_N}{257 \cdot p_1} \cdot \sqrt{\rho_N \cdot T_1}$$

T_1: $T_1 = 273 + t_1$

After calculating the kv values, the kvs value is determined with the aid of the tables in the data sheets. The kvs value should only be slightly higher than the kv_{max} value. Excessive kvs values diminish the usable rangeability and thus the control response when subject to weak load.

The kv_{min} value must be able to be reached with the selected control valve, i.e. it must lie within the rangeability. If kv_{min} lies below this limit, a consideration should be made as to whether to split the quantity over two differently sized valves, whereby the kvs value of the smaller valve should be approx. 10 % of the kvs value of the larger valve.

– Critical pressure gradient with water or fluid

If the outlet pressure p_2 is less than the saturation pressure p_S at the inlet of the control valve, evaporation will occur. This leads to a much higher stressing of the control valve. To prevent premature failure of the valve, special measures will be required, such as: use of perforated cones, armoring of the sealing edges, multi-stage pressure reduction. In this case, consulting the manufacturer is recommended.

– Critical pressure gradient with gases and vapors

Super-critical relaxation causes noise problems. Special noise-reduction measures such as perforated cones, restrictor plates, flow straighteners and sound-control insulation will be required. Individual restriction steps larger than 0.56 p_1 under full load should not be selected.

– kv value for valve groups connected in series

The total kv value can be calculated as follows for series connection of several valves:

$$kv_{tot.} = \frac{1}{\sqrt{\frac{1}{kv_1^2} + \frac{1}{kv_2^2} + \frac{1}{kv_3^2} + \ldots + \frac{1}{kv_n^2}}}$$

– kv value for valve groups connected in parallel

The total kv value can be calculated as follows for several valves connected in parallel:

$$kv_{tot.} = kv_1 + kv_2 + kv_3 + \ldots + kv_n$$

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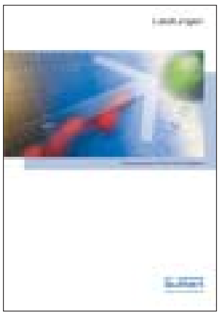
Information paves the path to the appropriate system solution. We provide five different levels for accessing information, products and services, so that you can easily find out everything you need to know to make the right choice.

Service brochure

A systematic overview of the range of products and services offered by Bürkert. A network of comprehensive solutions integrating coordinated services.



Competence brochures

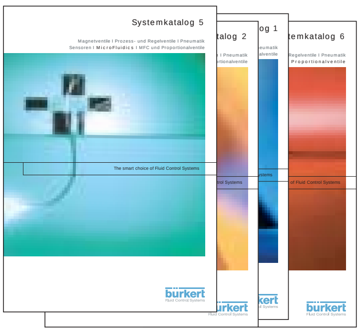
Essential information for the person planning control loops and field bus systems and who wants to ensure basic knowledge of the structure and selection of system components.

Application brochures

Example applications for deriving the appropriate system solution, supplemented by information on product advantages, user advantages and the range of products specifically available.

System catalogs

Background knowledge on product technology, including an up-to-date overview of the current offers. Rounded out with information to help you make your decision on the best application option.



Technical data sheets

Detailed technical information for checking specific suitability.
In addition, all the data needed for direct ordering.

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