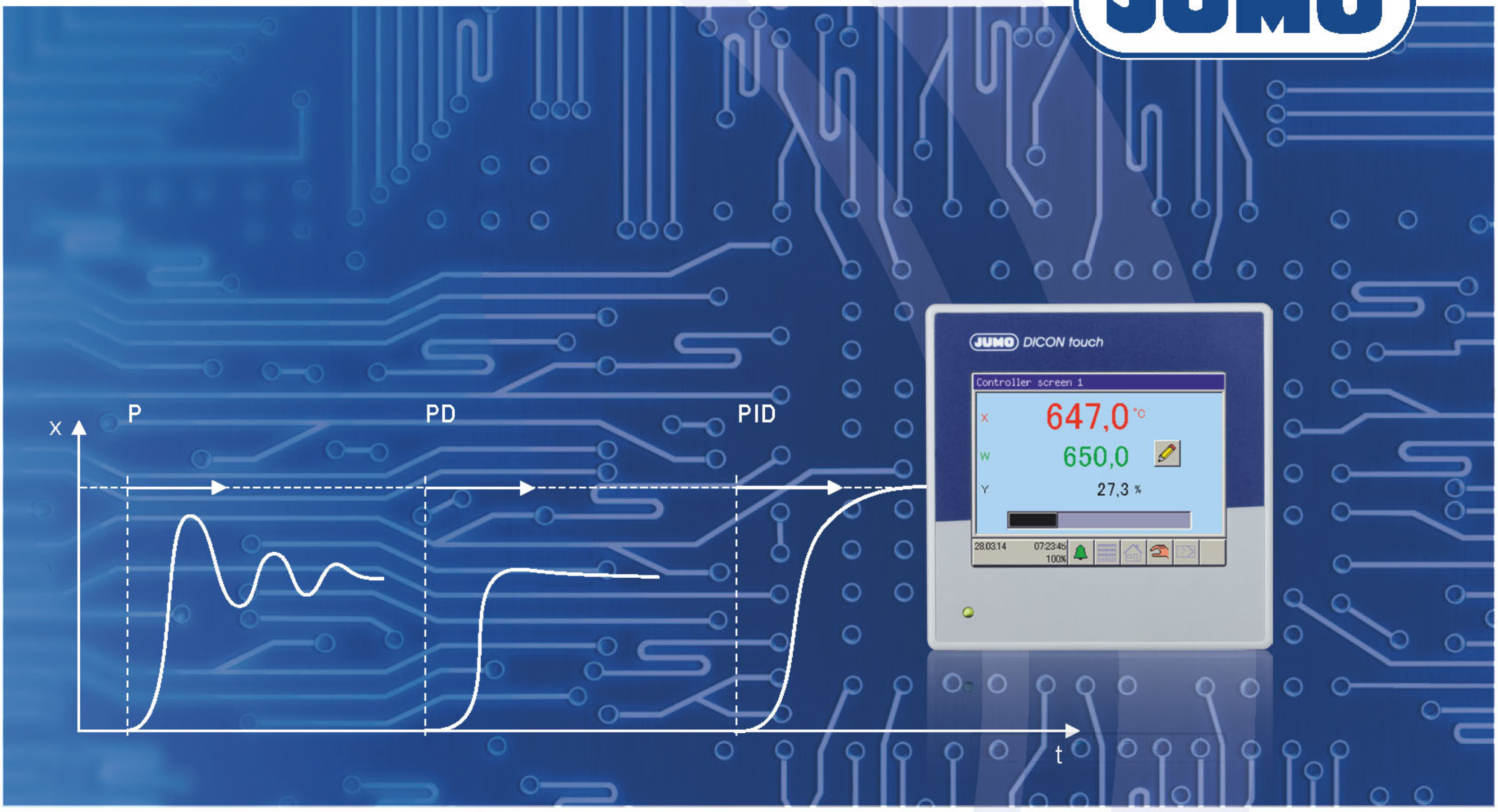


Control Engineering

Basic principles and tips for practitioners

Manfred Schleicher

Control Engineering

Basic principles and tips for practitioners

Manfred Schleicher

Preface

Control engineering is a key component in modern automation technology and is a central pillar of the industry. However, it is often considered to be highly theoretical and based on math. This reference work therefore places a strong emphasis on practical aspects of control engineering.

It is not intended as a scientific textbook, rather it has deliberately avoided unnecessary theoretical explanations and approaches each topic from the user's perspective, in order to explain how control paths can be defined, control parameters determined, and controllers tuned. This reference work is based on the author's experience as a lecturer in measurement and control engineering, which spans more than 20 years. Numerous practical tips and tricks from concrete startup scenarios have also been included.

In spite of its universal validity, this reference work focuses on the use of JUMO devices. The company can call upon decades of experience in the development and production of technical control devices. Its extensive product range stretches from single-channel controllers right through to complete automation solutions. The company's devices can be found in a multitude of applications right across the globe.

The reference work "Control Engineering – Basic principles and tips for practitioners" has for years been extremely popular with users from a range of industries as well as those studying this field. This new issue has been extensively revised and supplemented to provide a comprehensive insight into the entire subject.

JUMO seminars on measurement and control engineering
JUMO offers practical control engineering seminars that include a high proportion of practical work (http://seminare.jumo.info).

We hope that you enjoy reading this reference work and that it proves to be useful for you. We would be glad to receive any requests or suggestions that you might have for future issues.

Fulda, Germany, October 2014

Manfred Schleicher

Note
This reference work has been created to the best knowledge and belief. We assume no liability for possible errors. The definitive source of information is always the operating manual for the relevant device.

JUMO GmbH & Co. KG
Moritz-Juchheim-Strasse 1
36039 Fulda, Germany
Phone: +49 661 6003-396
Fax: +49 661 6003-500
Email: manfred.schleicher@jumo.net
Internet: www.jumo.net

Part no.: 00323761
Book number: FAS 525
Printing date: 2014-10
ISBN: 978-3-935742-01-6

Content

Content

Content

1.1 Closed control loop

Closed control loops comprise a control path, a controller, and an actuator:

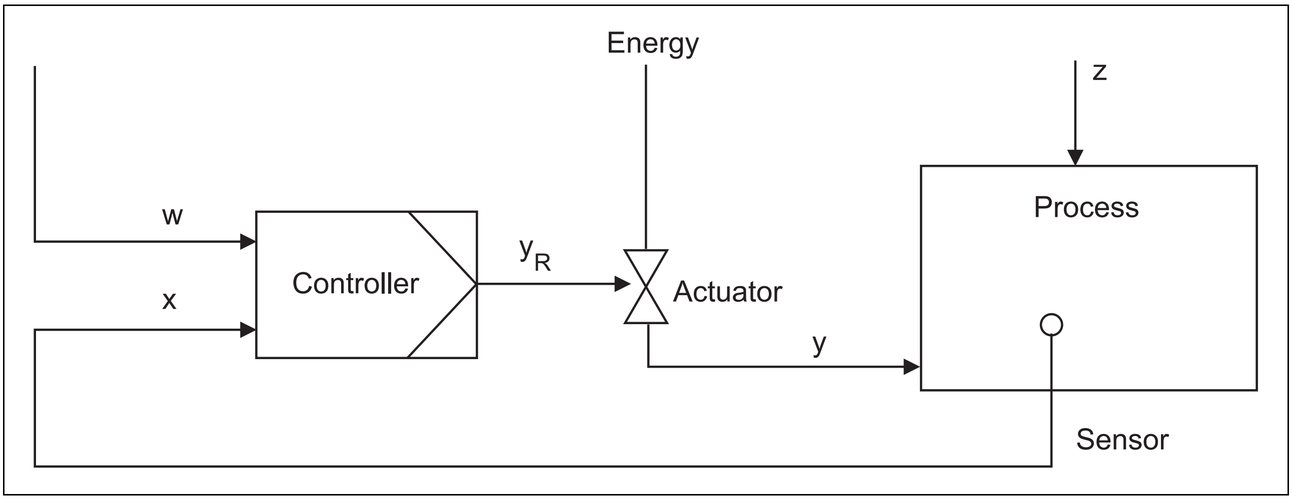


Figure 1: Closed control loop

Control path
The control path is the part of the plant where the **control variable (x)** is kept constant. One example of this is a gas-operated furnace (Figure 1). The control variable or actual value is the temperature inside the furnace. To measure the temperature, industrial processes generally employ RTD temperature probes or thermocouples. The electric thermometers can be directly connected to the controller, which determines the temperature on the basis of the measured resistance/the voltage. The actual value is influenced by the **output level (y)**. In the aforementioned example, the flow of gas is the output level.

Actuator
In most cases it is not possible for the controller to directly influence the output level; an actuator is used instead. The actuator is controlled by the controller output level, which is normally between 0 and 100 %. In the example shown (Figure 1) a proportional valve is used as the actuator. If the controller output level is 100 %, the maximum volume of gas enters the control path. Accordingly, if the controller output level is 50 % approximately half the volume of gas enters the path. The controller output level y_R indicates the approximate percentage of the maximum possible output and, when compared with the output level y, represents the more important of the two measurands for control engineers.

Controller
The controller adjusts the actual value to the **setpoint value (w)** configured on the controller by means of its controller output level. The difference between the setpoint and actual value (w - x) is known as the **control deviation e**.
If one of the **disturbances z** changes, this will have an undesired effect on the control variable.
More information on disturbances is provided in Chapter 2 "*The control path*".

1 Key terms and overview

Figure 2 shows the controller screen for a JUMO DICON touch with the actual value, setpoint value, and controller output level.

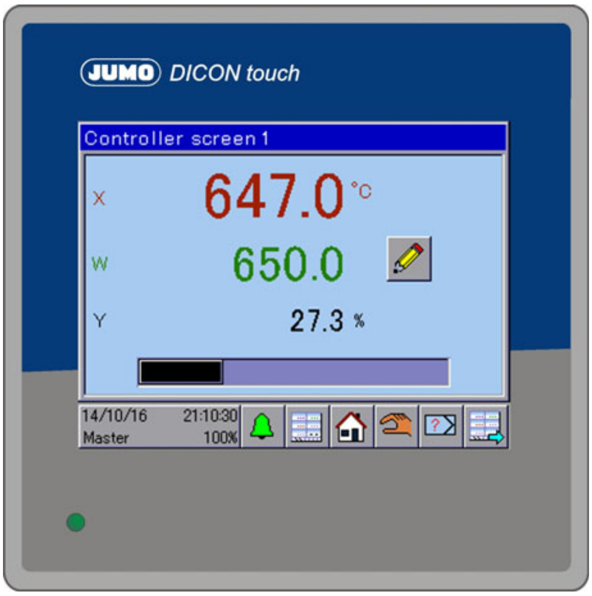


Figure 2: Controller screen for JUMO DICON touch

1.2 Open-loop control in manual mode

In automatic mode, the controller adjusts the actual value to the setpoint value as described above. Modern compact controllers also allow the actuator to be controlled manually – in this manual mode, a defined controller output level can be specified by hand. Based on the controller output level, the output provided by the actuator is determined and, ultimately, also an actual value for the plant concerned. In manual mode the actuator, and therefore also the actual value, are managed by open-loop control; closed-loop control is deactivated.

1.3 Control response

In most applications, compact controllers operate as PID controllers. The intensity of the components is adjusted in line with each control path through the dimensioning of the control parameters P_b (proportional band), r_t (reset time), and d_t (derivative time).

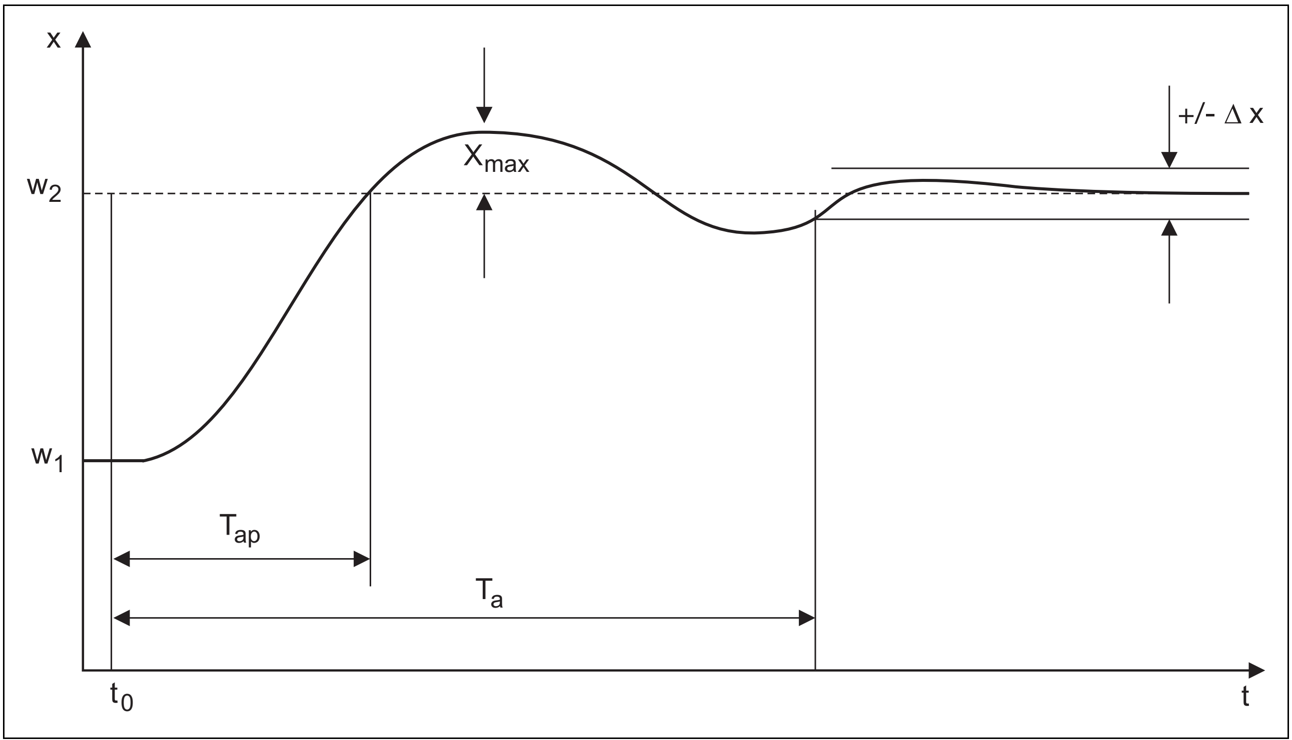


Figure 3: Criteria for the control quality

Figure 3 shows the potential control response after a sudden change to the setpoint value. The following measurands can be used to assess the control quality. The rise time (**T_{an}**) indicates the time during which the actual value reaches the setpoint value for the first time after having specified the step change. A band can be defined around the setpoint value (+/- Δx), where the dimensioning of this band depends on the requirements for the closed-loop control. The time after which the actual value lies permanently within this band is called the settling time (**T_a**).

If an overshoot occurs after having specified a new setpoint value, then the term overshoot (**X_{max}**) refers to the maximum difference between the actual value and the setpoint value.

The smaller the values for T_{an}, T_a, and X_{max}, the higher the control quality.

1 Key terms and overview

1.4 Recording the actual value

1.4.1 The sampling rate

Modern compact controllers operate on the basis of microprocessors that require a certain computing time. The actual value is recorded by the sensor, processed internally, and the output level is provided. Once the output has been updated, the input signal is read in again. The time between two read-ins of input signal is called the sampling rate.

The sampling rates for JUMO controllers typically range from 50 to 250 ms. 250 ms is usually sufficient for most control tasks in process technology. Very fast tasks (such as controlling the pressure of a press) require a lower sampling rate.

1.4.2 Universal inputs on JUMO compact controllers

Most JUMO compact controllers feature universal analog inputs, to which components such as the sensor for recording the actual value are connected.

In measurement and control engineering, the transfer of signals takes place using **standard signals**. A current signal of 4 to 20 mA is predominantly used for this purpose, but the signals 0 to 20 mA, 2 to 10 V, and 0 to 10 V are also available. Figure 4 shows the transfer of a pressure measured value using a signal of 4 to 20 mA:

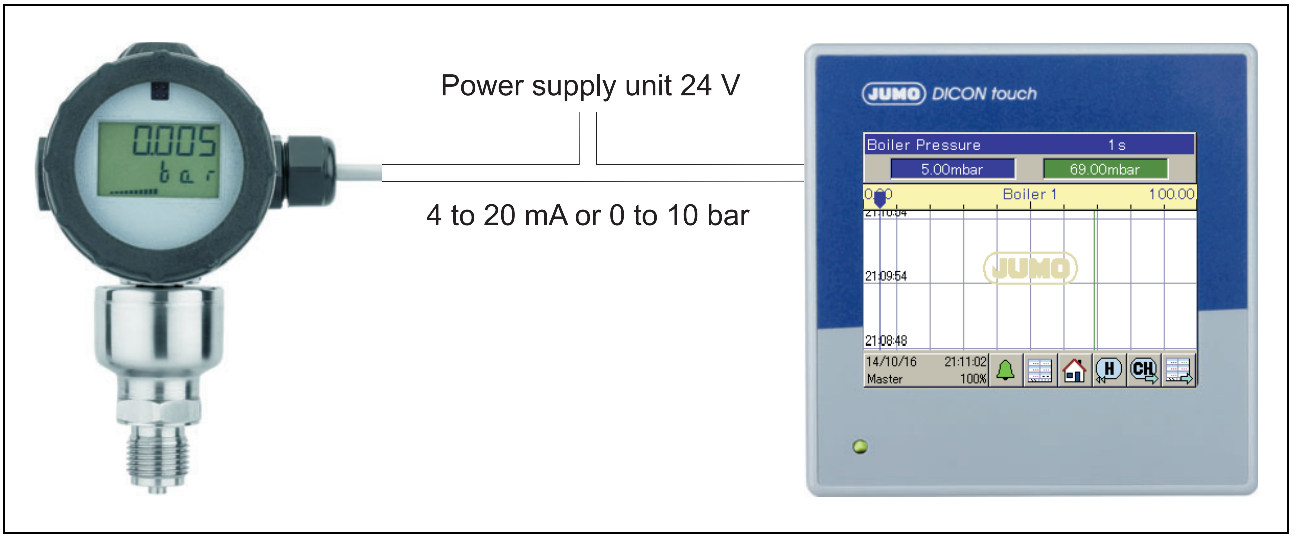


Figure 4: Example of signal transfer using a standard signal of 4 to 20 mA

The pressure transmitter shown has measured a relative pressure of 0 to 10 bar and outputs this information using an analog signal of 4 to 20 mA. The universal input of the controller is set to 4 to 20 mA and scaled to 0 to 10 bar. The pressure measured value is available in the controller and all settings refer to the scaled unit (bar). The power supply unit provides the voltage supply for the pressure transmitter.

JUMO compact controllers are used extensively for temperature control tasks. The devices allow **RTD temperature probes** to be connected directly:

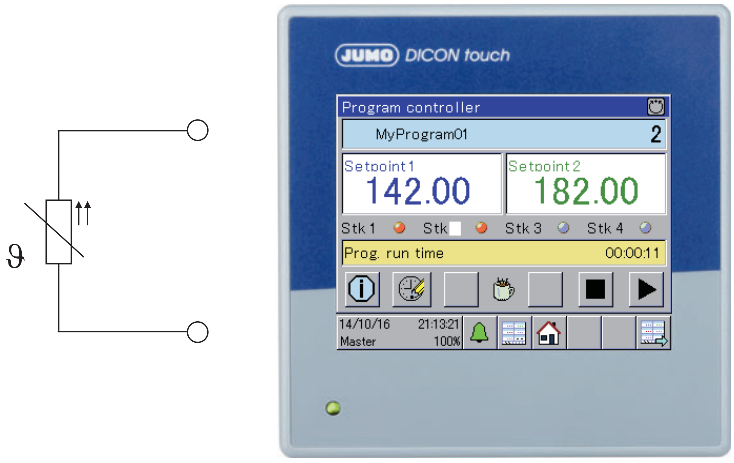


Figure 5: RTD temperature probe on JUMO DICON touch compact controller

The universal input of the controller must be configured for the RTD temperature probe (two-wire connection) and the relevant linearization (Pt100, Pt1000, etc.) must be stated. The controller uses the linearization to determine the temperature at the RTD temperature probe on the basis of the measured resistance value. The industry standard is a three-wire connection, but RTD temperature probes can often also be connected using a four-wire concept.

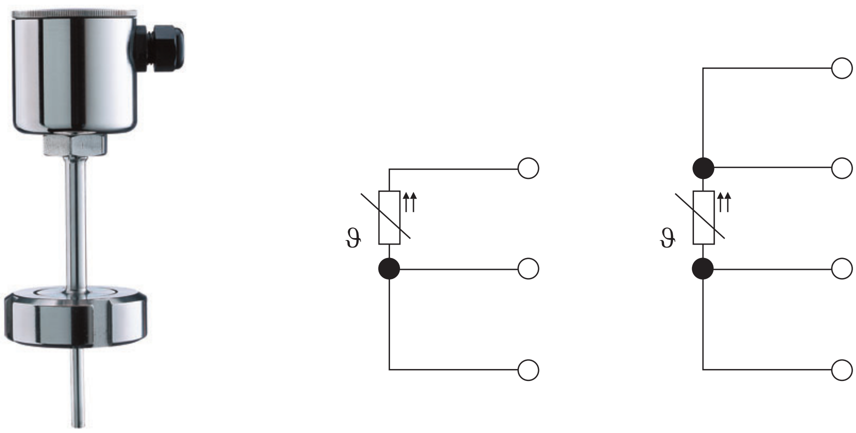


Figure 6: RTD temperature probe for the food industry and schematic diagram of three-wire and four-wire connection concept

1 Key terms and overview

The main reason for the use of **thermocouples** is a relatively high temperature (typically greater than 600 °C). The universal input on JUMO compact controllers also allows this type of thermometer to be connected:

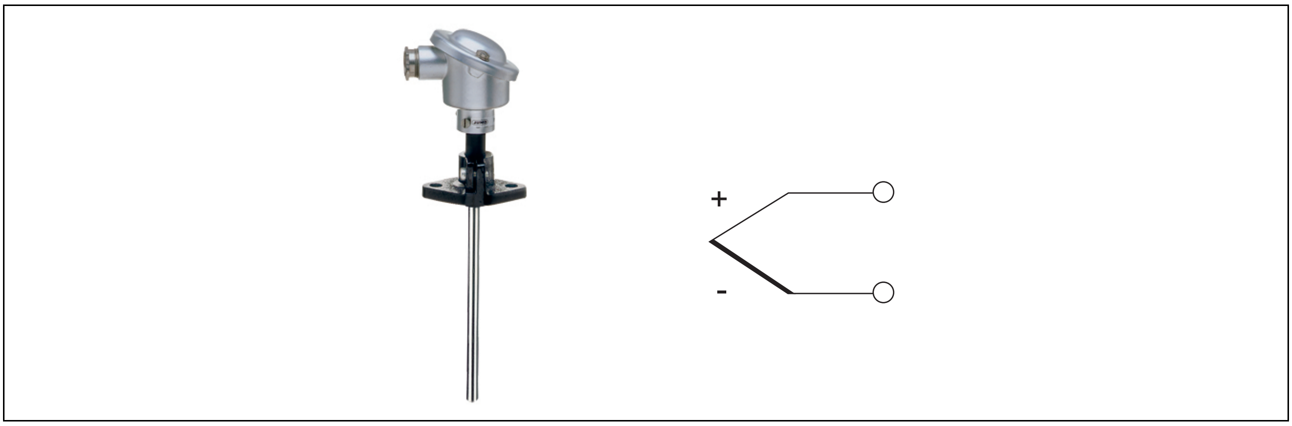


Figure 7: Push-in thermocouple and schematic diagram of thermocouple

The universal input of the controller must be configured for the thermocouple and the relevant linearization [such as NiCr-Ni (type K)] must be stated. With the aid of the linearization, the controller determines the temperature at the thermocouple on the basis of the measured thermoelectric voltage.

The feedback on the position of actuators such as valves, flaps, etc. can be provided via resistance transmitters. The elements are integrated in the actuator and the slider moves depending on the respective position:

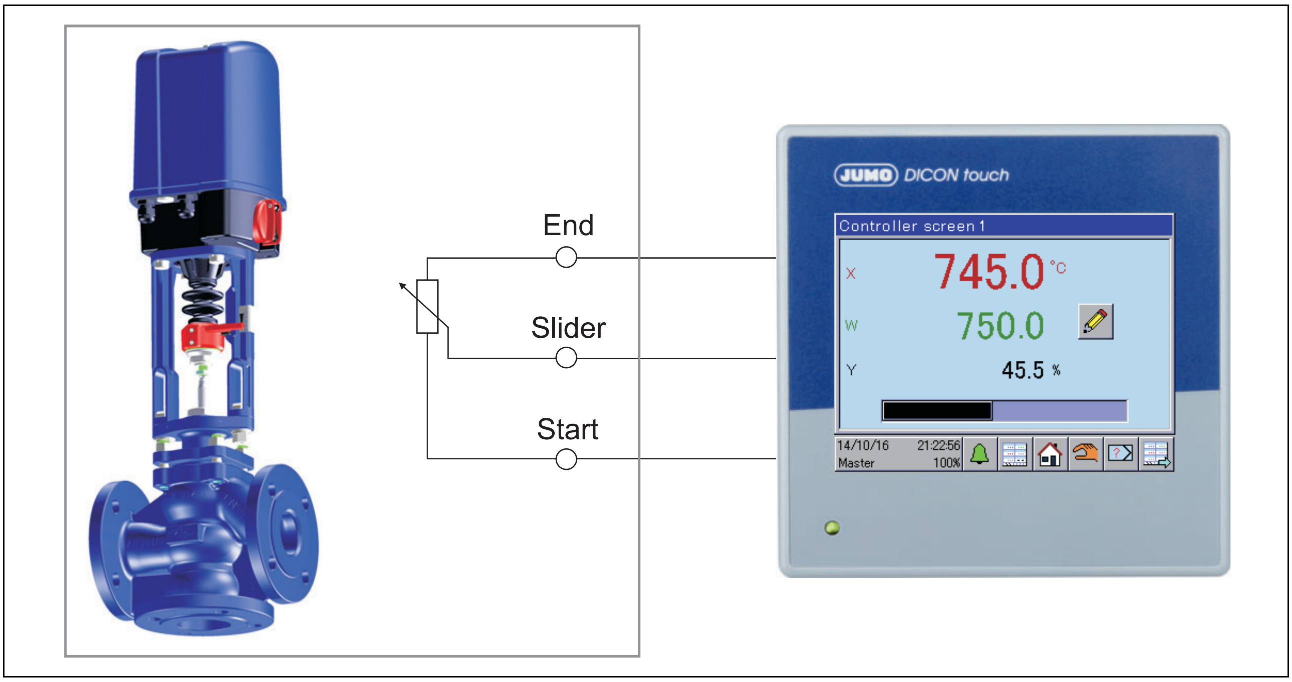


Figure 8: Actuator made by ARI Armaturen including the connection between the output level feedback and the JUMO DICON touch compact controller

The universal input of the controller must be configured for the resistance transmitter and the display values for "slider = start position" and "slider = end position" must be stated, usually 0 to 100 (%).

1.4.3 Inputs for electrochemical measurands

JUMO can call on decades of experience in the production of electrochemical sensors. Sensors to measure the pH-value, redox potential, and conductive and inductive conductivity can be directly connected to JUMO transmitters and controllers used in analytical measurement.

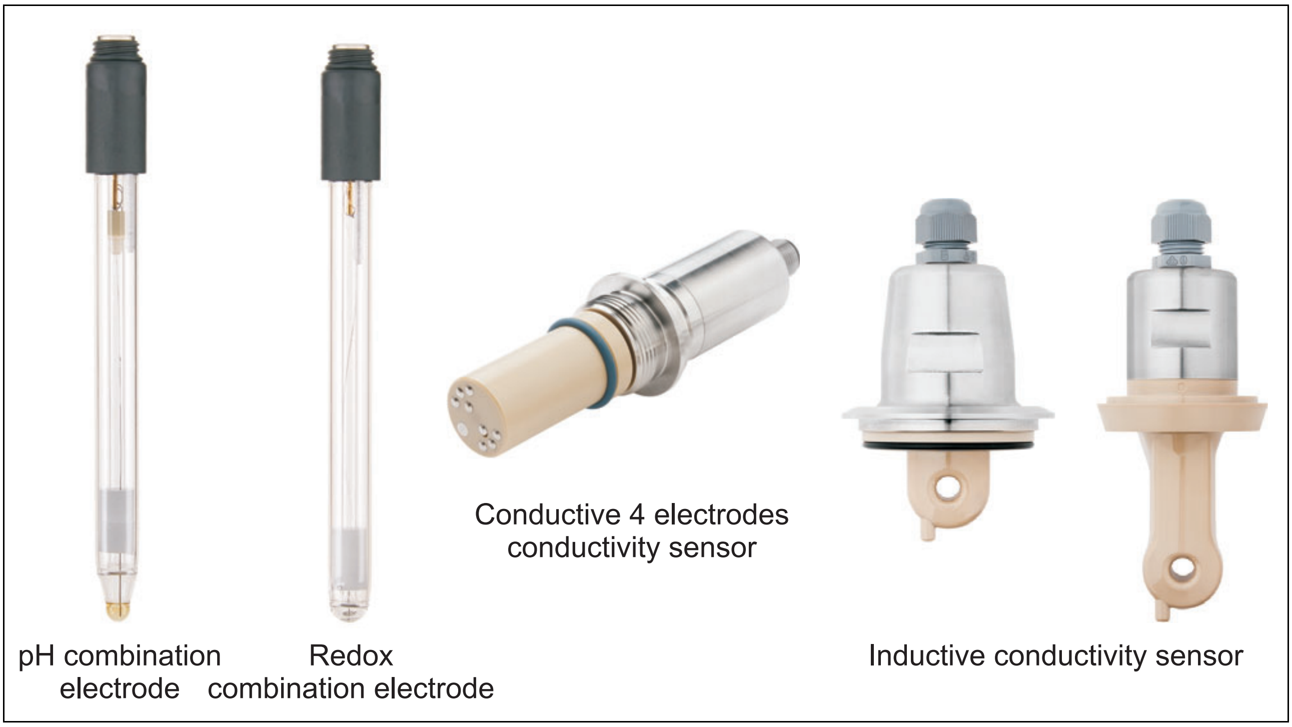


Figure 9: Sensors for pH-value, redox potential, and electrolytic conductivity (conductive and inductive)

1.5 Types of outputs on JUMO compact controllers

The control path at hand, required control quality, and availability are key criteria when selecting the most suitable actuator. The actuator, in turn, requires a certain control signal from the controller. JUMO controllers offer the following options when it comes to outputs:

1.5.1 Continuous output

Continuous actuators constantly change the output level depending on the controller output level. Examples include:

- Frequency converters for controlling the speed of an asynchronous motor
- Proportional valves for changing the flow
- SCR power controllers for controlling electrical power

The actuators are controlled with standard signals (Chapter 1.4.2 "*Universal inputs on JUMO compact controllers*") via a continuous output.

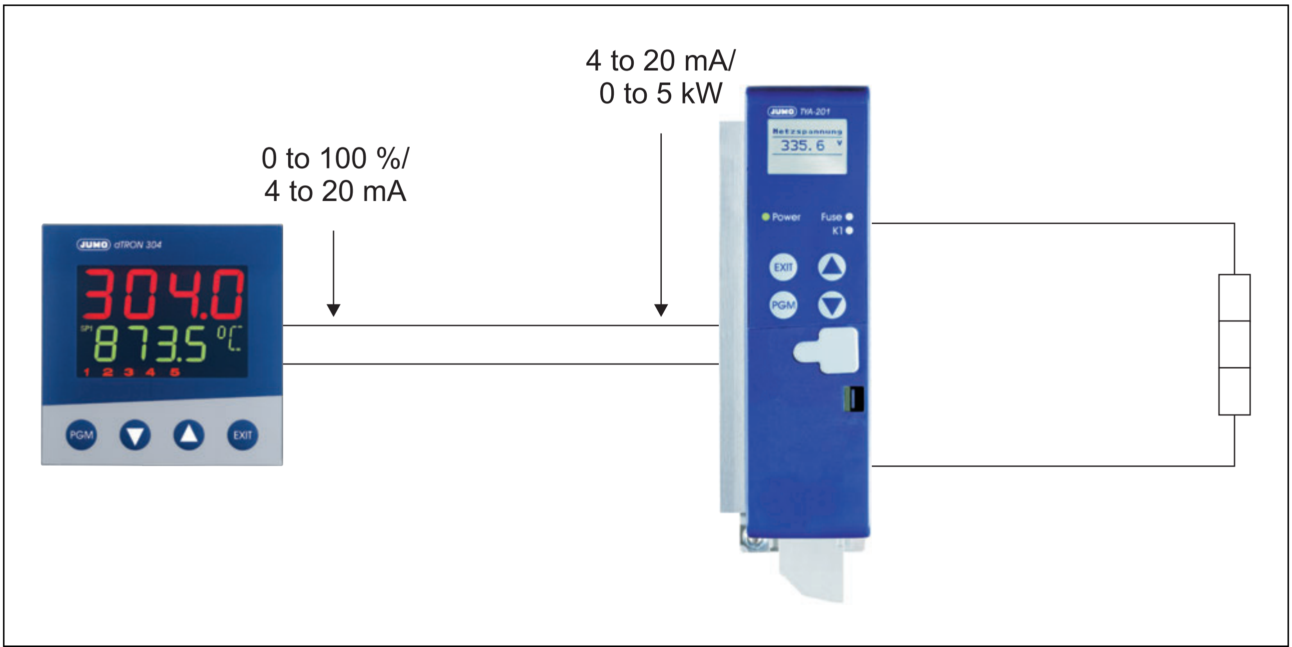


Figure 10: JUMO dTRON 304 compact controller, JUMO TYA 201 SCR power controller, and heating element

The controller (Figure 10) provides the controller output level in the form of a 4 to 20 mA signal. The SCR power controller changes the power for the heating element in proportion to the current signal.

1.5.2 Digital output types

JUMO compact controllers are ideally suited to controlling a wide range of physical measurands. The components are used widely for temperature control in particular. Digital outputs are often used to control this measurand. This type of output can be used wherever the control path smoothes out the energy (which has been supplied intermittently) on account of its slowness.

The classic digital output type is the relay output. It is available as a normally open contact or changeover contact. The mechanical output is used for control tasks that involve a low switching frequency (power contactors, solenoid valves, etc).

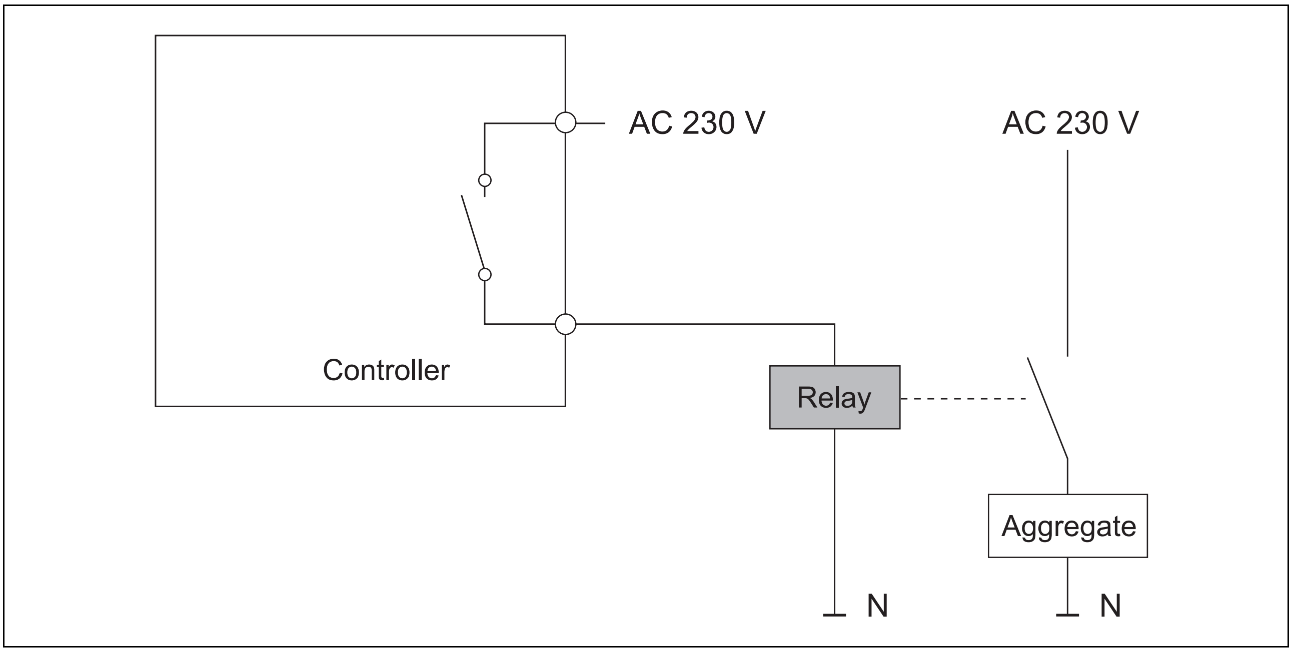


Figure 11: Normally open contact for controlling a relay

In order to use relay outputs consideration must be given to the contact life. For example, the technical specification of a compact controller may include the following information concerning the switching contact: *contact life of 350,000 switching operations at the rated load or 750,000 switching operations at 1 A*. The faster that a process responds over time, the higher the required switching frequency.

Solid state relays or **Triacs** are used for higher switching frequencies and to switch an alternating voltage (!):

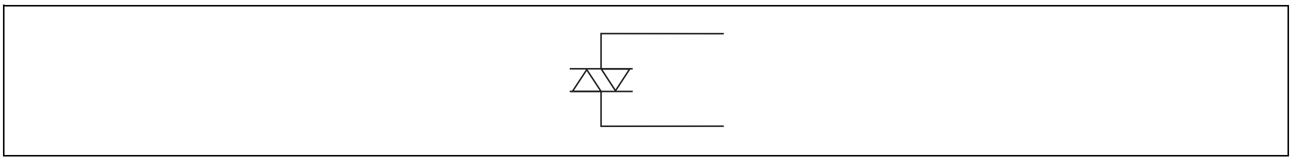


Figure 12: Schematic diagram of a solid state relay or Triac

The element comprises two thyristors connected in an antiparallel manner and switches the alternating voltage with virtually no wear at all.

1 Key terms and overview

Digital outputs (for example 0 to 12 V) are used for controlling actuators with a direct voltage and low power requirements. Typical applications include the control of SCR power switches for supplying electrical power to heating elements:

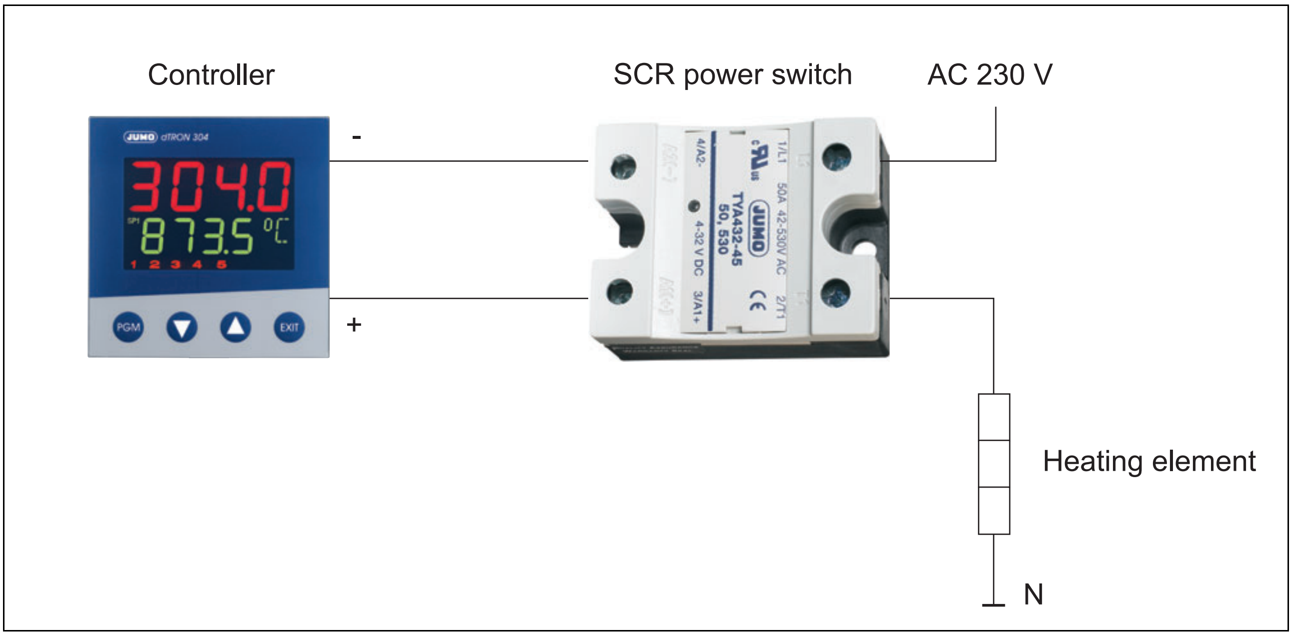


Figure 13: Controlling an SCR power switch via the logic output of a controller

Dosing pumps are used to add acids, lyes, or chlorine, for example. The actuators often feature a pulse input that can generally be controlled with a relay output. In most cases the switching frequency is high, necessitating the use of PhotoMOS® relays:

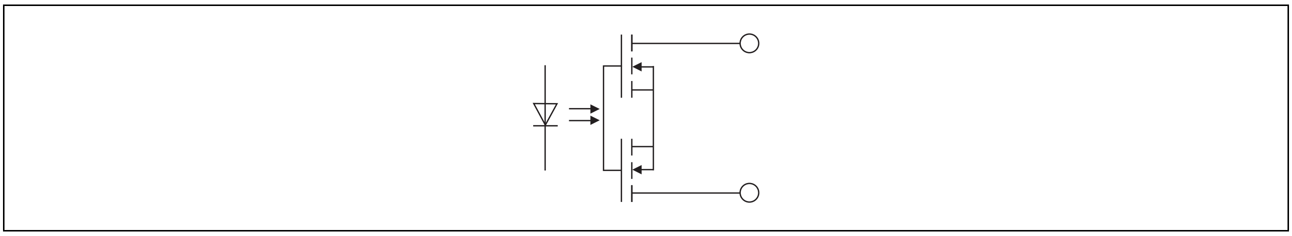


Figure 14: Symbolic diagram of a PhotoMOS® relay

PhotoMOS® relays enable wear-free and potential-free switching of direct and alternating voltages (the potential is separated between the controller and dosing pumps).

1.6 Overview of controller types

The following types of JUMO controllers are available:

Continuous controllers control continuous actuators using a continuous output. The controllers change their output signal in proportion to the respective output level (usually 4 to 20 mA).

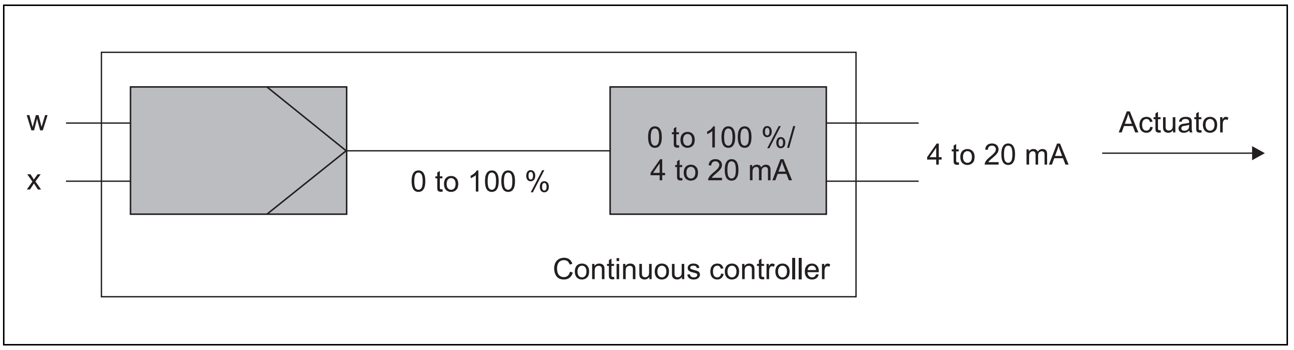


Figure 15: Schematic diagram of a continuous controller

Two-state controllers feature a digital output for controlling the actuator. In addition to a relay output, the digital outputs described in Chapter 1.5.2 "*Digital output types*" are also possible. As a PID controller, the controller varies the ON period of the digital output in proportion to the determined output level.

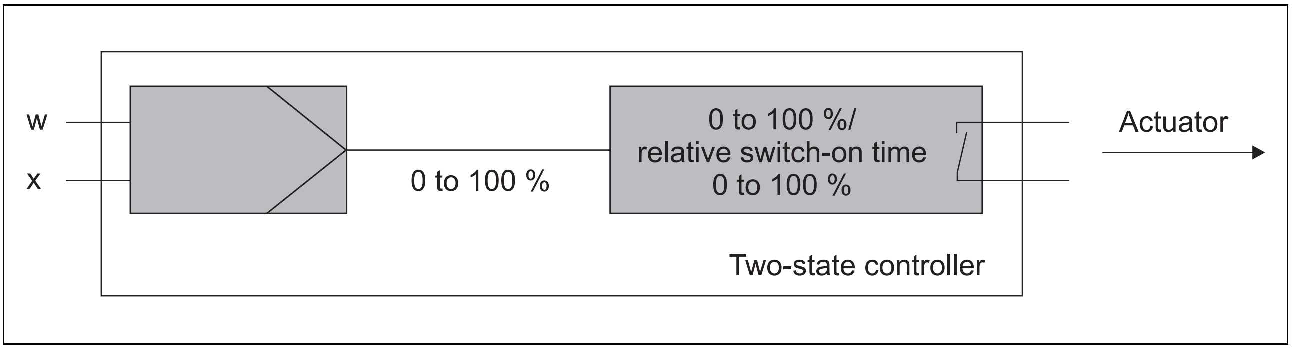


Figure 16: Schematic diagram of a two-state controller

Controllers used for analytical measurement can also be operated with a pulse frequency output. In this case, the digital output is controlled with a frequency that rises in proportion to the output level. The pulse frequency output is used for controlling dosing pumps.

1 Key terms and overview

Three-state controllers allow the control variable to be influenced in two different directions. Examples include heating and cooling, humidification and dehumidification, and neutralization with lyes and acids. The controller calculates an output level in the range from -100 to +100 %. If the output level is positive, the relative duty cycle for actuator 1 is increased in proportion to the output level. If the controller is operating with a negative output level, the relative duty cycle of actuator 2 is increased accordingly:

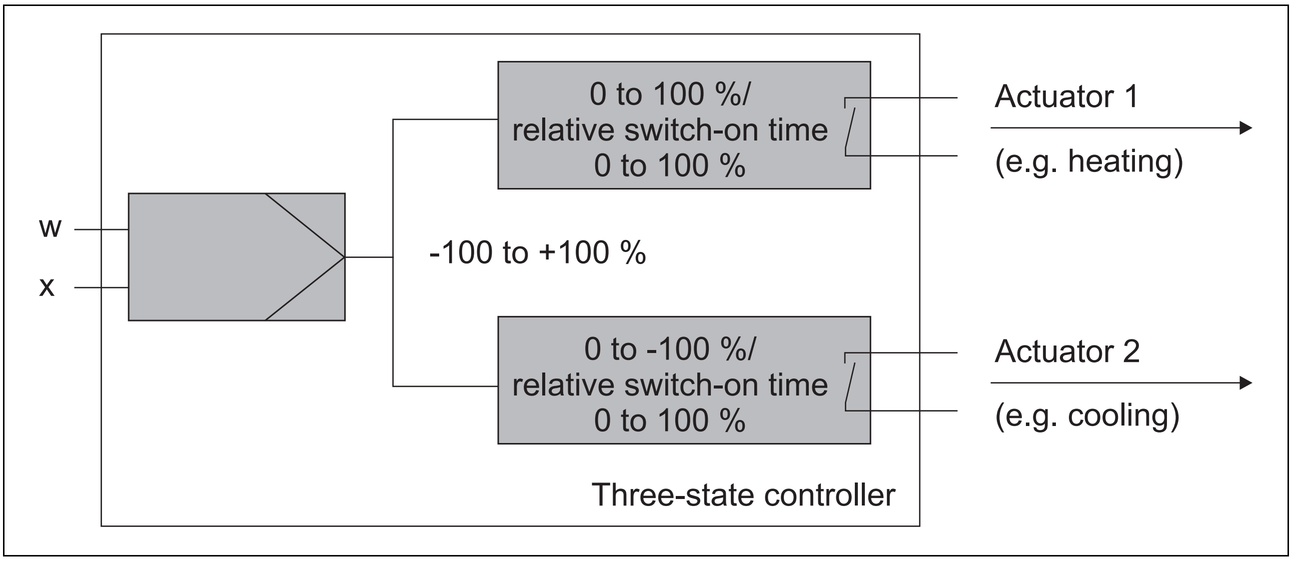


Figure 17: Schematic diagram of a three-state controller

All digital outputs described in Chapter 1.5.2 "*Digital output types*" are also available for three-state controllers. When using JUMO controllers from the field of analytical measurement, both outputs can be operated as pulse frequency outputs.

Instead of providing the output level using digital outputs, continuous outputs can also be used.

Modulating controllers and **position controllers** are well suited to controlling motor actuators. Two of the controller's outputs open and close an actuator accordingly via the servomotor. The position controller requires feedback on the position of the actuator. The modulating controller does not require this output level feedback.

2 The control path

2.1 General information on the control path

The control path is the part of the plant where the control variable is adjusted to a setpoint value. When assigning the actuator to the control path, the control path starts at the point where the controller provides its output level. The control path ends at the point where the actual value is recorded – at the sensor. Disturbances influence the control path, and any changes to these disturbances will affect the control variable.

Figure 18 shows a gas-operated furnace as an example of a control path:

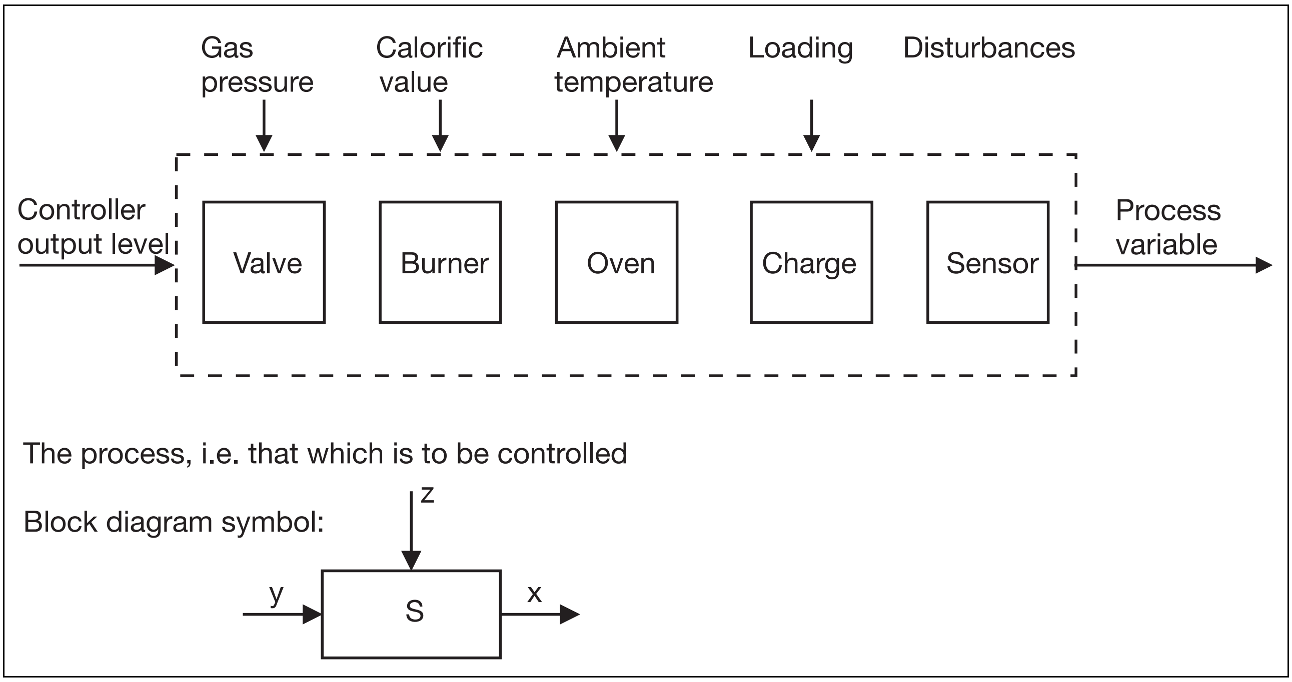


Figure 18: Example of a control path

The controller output level is provided for the valve. The temperature in the furnace product needs to be controlled. A temperature sensor is located in the product and thus at the end of the control path.

The control path includes timing elements and energy stores, which slow down the dispersal of the energy: if the controller output level changes, the valve moves into the new position relatively quickly. A new flow of gas for the burner is quickly established. The inside of the furnace slowly heats up and the temperature of the furnace product will increase after a long delay.

Changes to disturbances will influence the actual value. One disturbance in the system is the gas supply pressure. If the system is in an adjusted state, dynamic control deviations will occur if the gas pressure changes. The controller counteracts by changing the output level and compensates the effect of the disturbance.

2.2 Paths with and without compensation

2.2.1 Paths with compensation

The control path shown in Figure 18 is a path with compensation. The specified output level and the adjusted actual value behave in proportion to one another. Figure 19 shows the course of the actual value for a path with compensation after sudden increases in the output level:

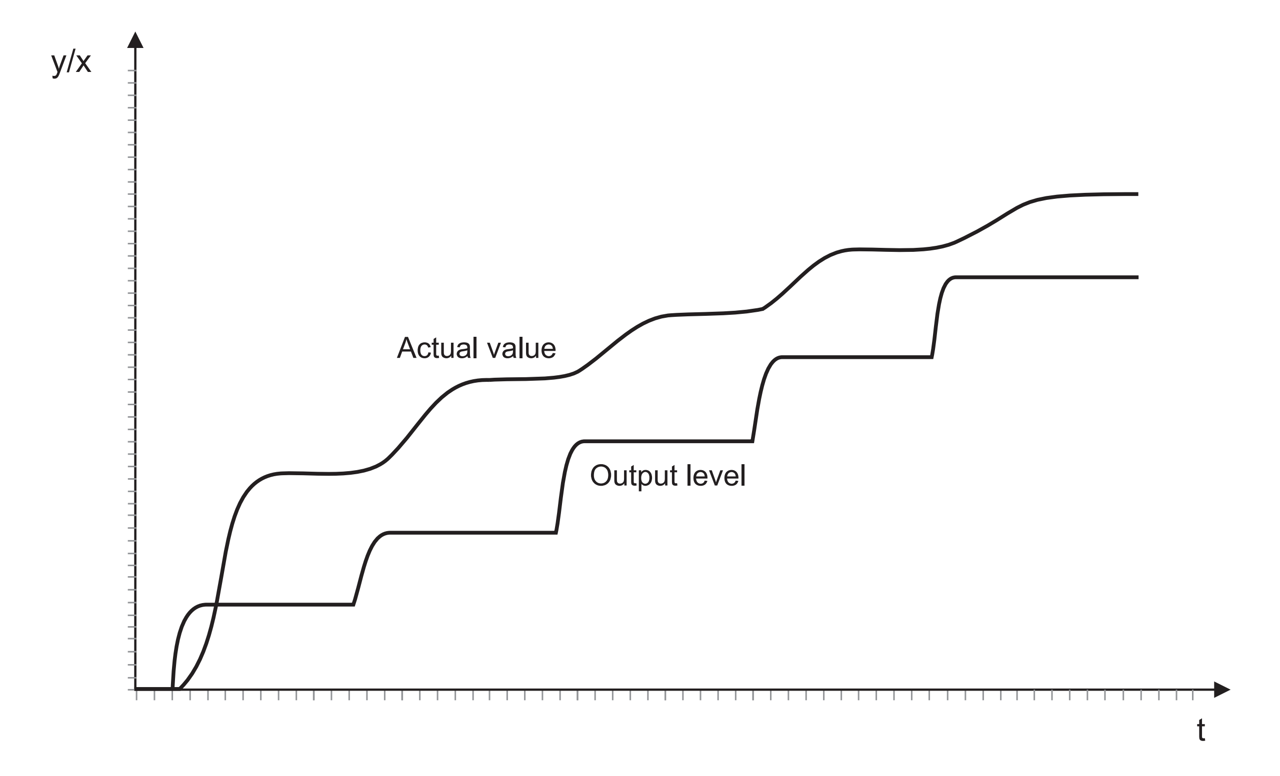


Figure 19: Course of the actual value for a non-linear control path with compensation in the case of stepped increases in the output level

In the example shown the output level suddenly increases by the step size, which is always the same. The resulting change to the actual value gradually decreases. The control path with compensation behaves in a non-linear manner.

The transfer coefficient for the control path indicates the ratio of the change to the actual value/ change to the output level. Non-linear control paths change the transfer coefficient according to the working point. This may necessitate a change to the control parameters for different setpoint values.

2.2.2 Paths without compensation

Paths without compensation respond to a step change in the output level with a constant change to the actual value. Alongside the path characteristics, the slope of the actual value is proportional to the specified output level.

Figure 20 shows the behavior of a path without compensation, whereby the example path shown has no delays or dead-time elements:

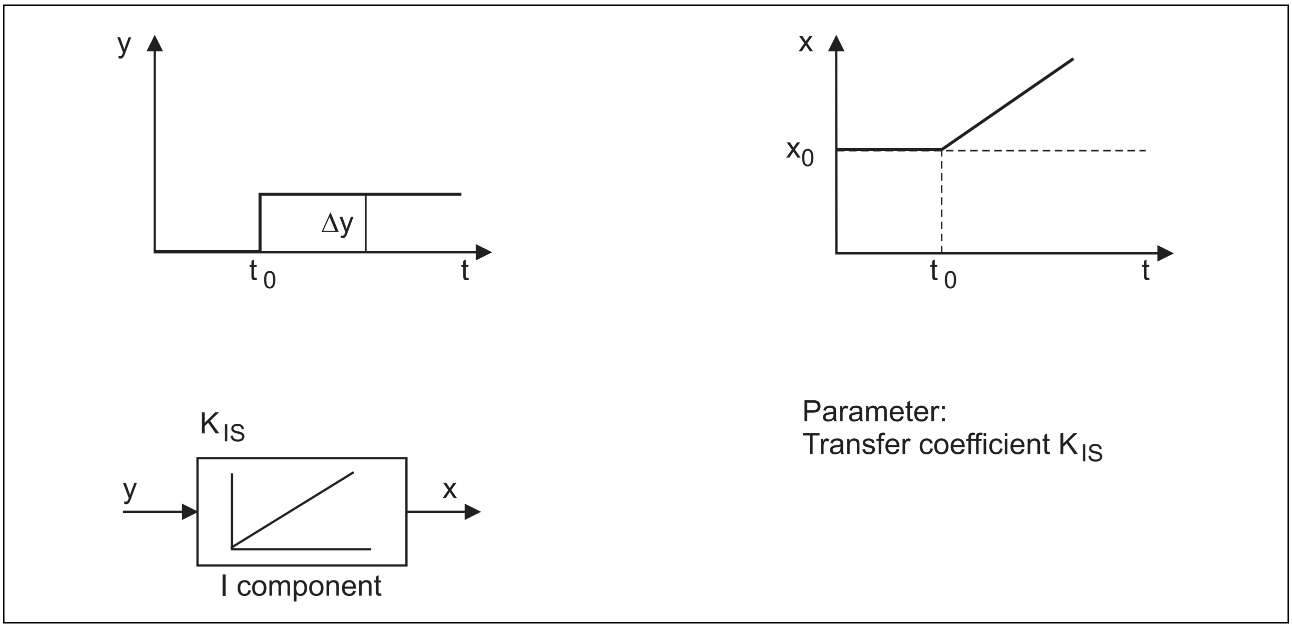


Figure 20: Step response of a path without compensation and block symbol

If the output level for the path is 0 % (Figure 20), the actual value remains unchanged. A sudden increase in the output level results in a ramped change to the actual value until it reaches the limit. The ramp slope is proportional to the specified output level. The description "I-Glied" (integral element) is derived from the integral-action behavior.

To specify a step change to the output level, the following applies:

$$\Delta x = K_{IS} \bullet \Delta y \bullet t \qquad (1)$$

K_{IS} Transfer coefficient of a control path without compensation

For a non-constant output level, the following applies:

$$\Delta x = K_{IS} \bullet \int_{t_0}^{t} y \bullet dt \qquad (2)$$

Examples of paths without compensation include:

- Level control (Figure 21)
- Linear drives for positioning workpieces

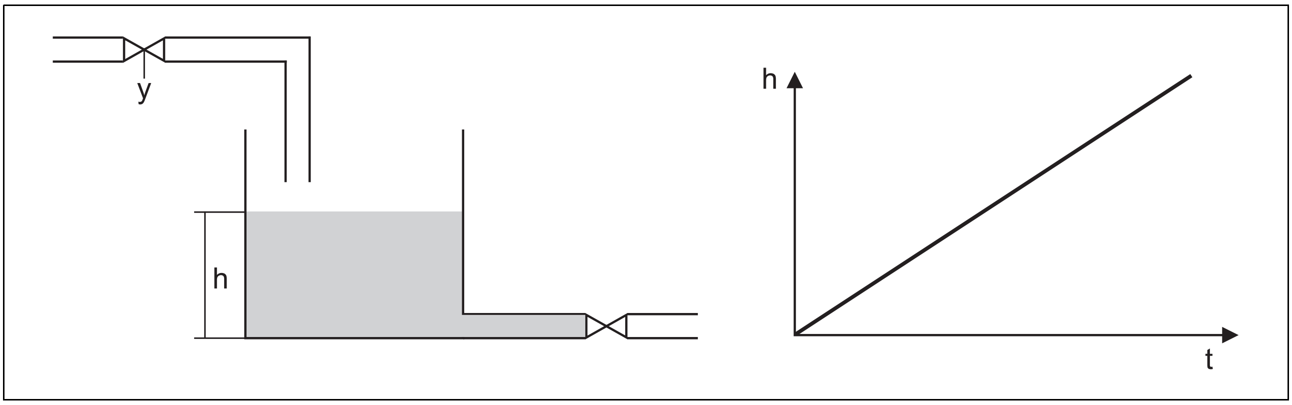


Figure 21: Level control path

Figure 21 shows the classic example of a path without compensation, where the level of liquid inside a container is controlled by a supply valve. The container also features a drain valve, which is closed for the purposes of the analysis. Opening the supply valve causes an even increase in the level.

The further the valve is opened, the quicker the increase in the level. The level increases until the container overflows; there is no self-stabilization.

In contrast to a path with compensation, a balanced state is not established even if the disturbance changes (except if drain = supply).

2.3 Paths (path sections) with proportional response, dead time, and delay

All of the following observations apply to paths with compensation.

2.3.1 Paths with proportional response

Proportional control paths increase the specified output level with transfer coefficient K_S with no delay:

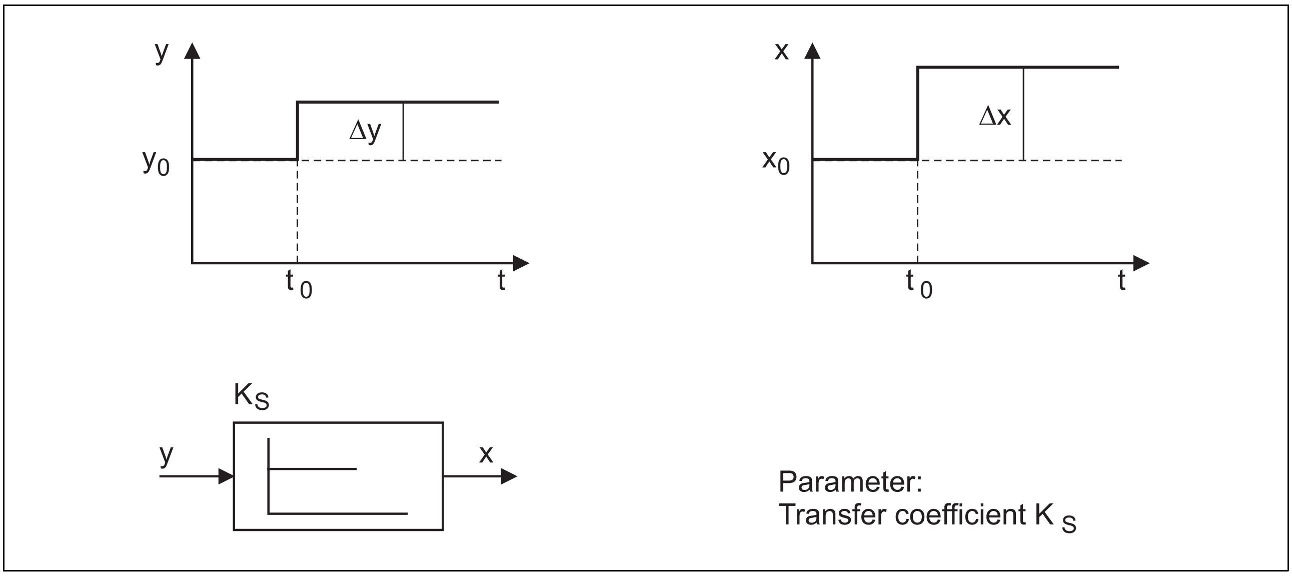


Figure 22: Step response of a P control path and block symbol

If there is a sudden increase in the output level, the actual value increases in proportion. The relationship described above applies to the relationship between the control-variable change Δx and an output-level change Δy:

$$\Delta x = K_S \bullet \Delta y \tag{3}$$

The proportional response described here is usually linked with the following timing elements.

2.3.2 Paths with dead time

P paths frequently occur in combination with dead-time elements. Alongside the transfer coefficient, these PT_t paths are defined by the dead time:

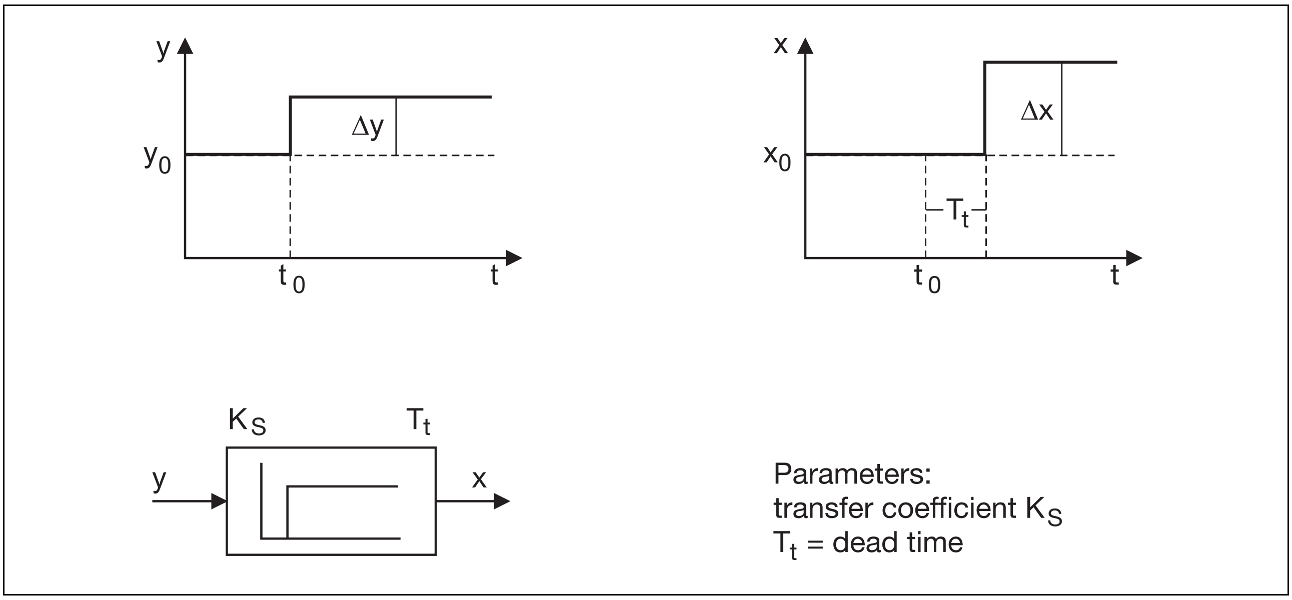


Figure 23: Step response of a PT_t path and block symbol

The path responds like a P control path, but in the event of a step change to the output level the actual value only changes once the dead time has elapsed. The following applies for the relationship between the actual-value change and the output-level change:

$$\Delta x = K_S \bullet \Delta y \text{, but delayed by the dead time } T_t \qquad (4)$$

One example of a PT_t path would be a conveyor belt where a constant quantity of bulk material needs to be maintained:

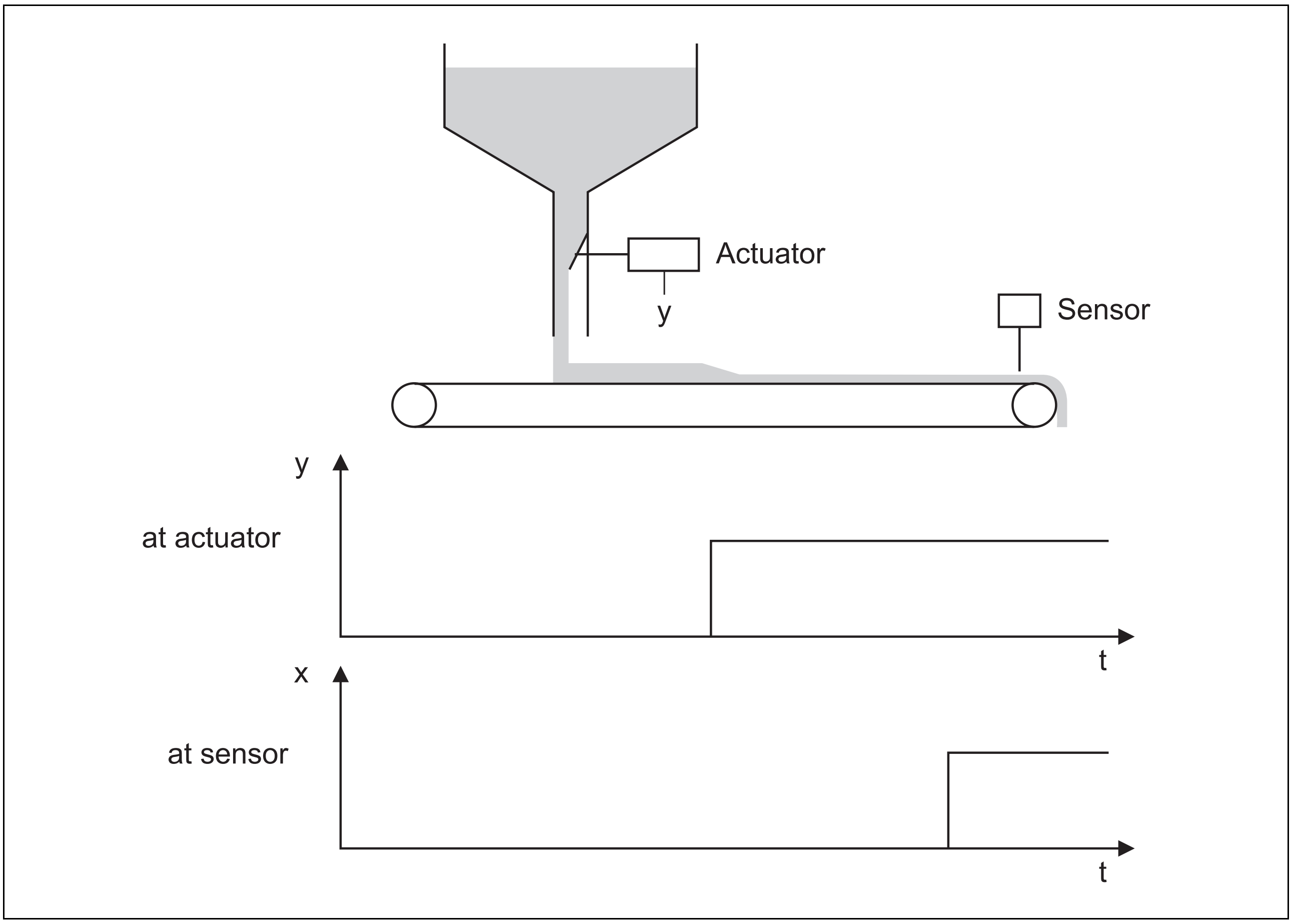


Figure 24: Control of bulk material quantity on a conveyor belt

A controller controls the flap using its output level. If there is a sudden increase in the output level at the controller, the flap opens without a delay (assumption). A certain quantity (bulk material/time unit) falls onto the conveyor belt. However, the conveyor belt requires the dead time to transport the bulk material to the sensor.

Numerical example for determining the parameters:
An output level specified at 50 % results in a control variable of 100 t/h. If there is a step increase in the output level to 75 %, this results in a sudden change to the bulk material quantity to 150 t/h after 10 s.

The following applies to calculate the transfer coefficient:

$$K_S = \frac{\Delta x}{\Delta y} = \frac{150\frac{t}{h} - 100\frac{t}{h}}{75\% - 50\%} = \frac{50\frac{t}{h}}{25\%} = 2\frac{t}{h \bullet \%} \quad (5)$$

The transfer coefficient of $2\,\frac{t}{h \bullet \%}$ means that a 1 % increase in the output level will result in an $2\frac{t}{h}$ increase in the bulk material quantity. Alongside the transfer coefficient, the path is defined by the dead time of 10 s.

The longer the dead time, the more difficult it will be to tune the controller being used. Where possible, dead times should already be minimized through project planning.

2.3.3 Paths with delay

In paths with a delay, if the output level changes the new actual value is established with a delay. The delay is due to the required charging of energy stores. The process is comparable to that for charging capacitors.

In math terms, the paths can be described by an equation with a term (an exponential element) for each energy store. As a result of this relationship, these types of paths are called paths of the first order, second order, third order, etc.

Control paths **with a delay** and/or an energy store change the control variable without a delay following a step change to the output level. Immediately after having specified the step change, the change is made at the highest speed. The actual value then tries to reach the end value at an ever-slower speed (Figure 25).

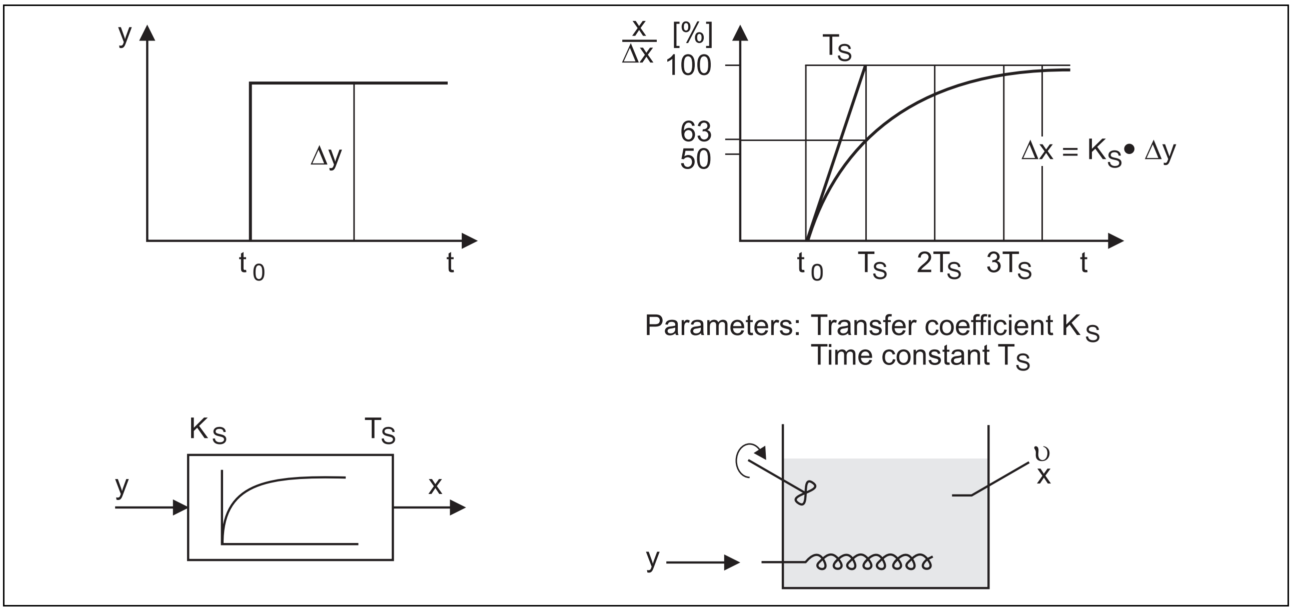


Figure 25: Path of the first order; PT_1 path

Figure 25 shows an example of a path of the first order at the bottom right:
A water bath is heated electrically by means of a heating coil. The heating coil is unable to store energy and is immediately heated once the output level has been provided in the form of electrical power. The thermal energy reaches the water without a delay and the water temperature immediately increases. The sensor being used has a very low mass and measures the water temperature without a delay. In this system, only the water is able to store energy.

If there is a sudden increase in the output level, the water temperature will change according to the following equation:

$$\Delta x = K_S \bullet \Delta y \bullet \left(1 - e^{\frac{-t}{T_S}}\right) \quad (6)$$

The parameters for a path of the first order are the transfer coefficient K_S and the path time constant T_S. The two measurands can be determined from the path's step response. To this end, for example, 5 kW of electrical power is applied to the coil and the actual value (the water temperature) is recorded.

The following figure shows the course of the actual value after having specified the step change to the output level:

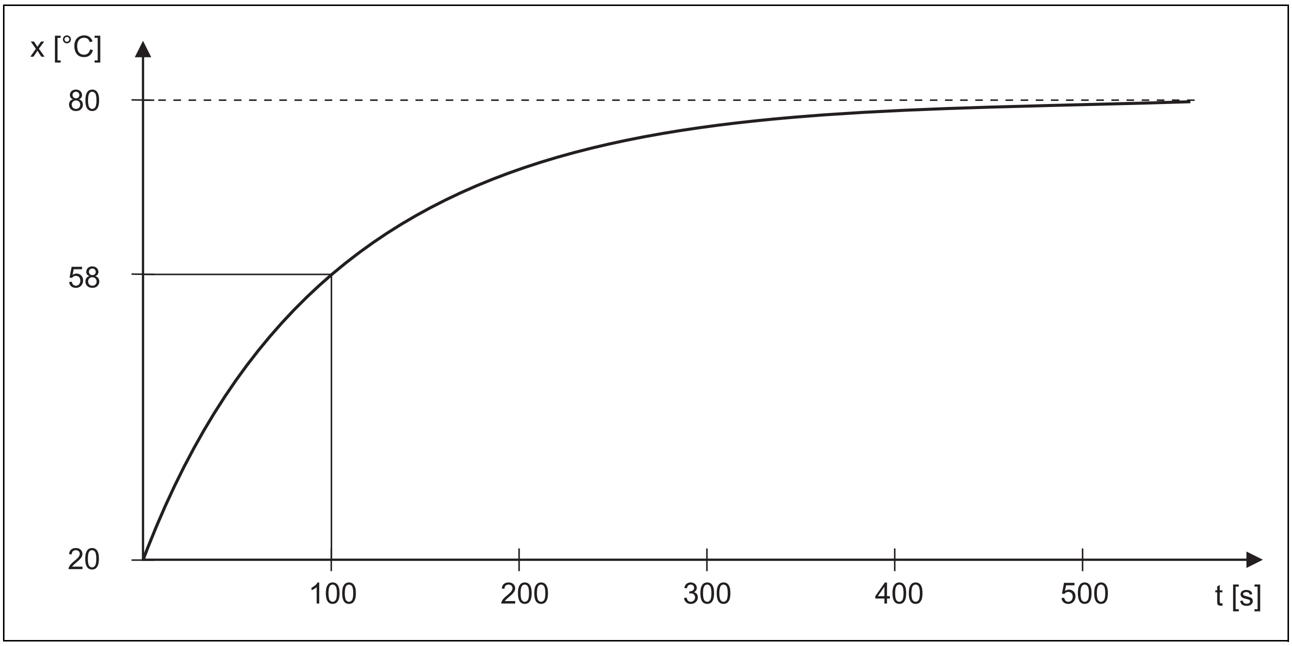


Figure 26: Example diagram of the step response of a path of the first order

The actual value is 20 °C and increases to an end value of 80 °C after having specified the step change. The change to the actual value is therefore 60 K.

The **transfer coefficient** of the control path becomes:

$$K_S = \frac{\text{Control variable change}}{\text{Output level change}} = \frac{60\ \text{K}}{5\ \text{kW}} = 12\frac{\text{K}}{\text{kW}} \tag{7}$$

The control path increases the output level with the transfer coefficient. Assuming a linear response, a power increase of 1 kW will result in a temperature increase of 12 K.

The **path time constant T_S** corresponds to the time after which the actual value has increased by 63 % of the overall change.

$$20\ °\text{C} + 60\ \text{K} \bullet 63\ \% \approx 58\ °\text{C} \tag{8}$$

In the example shown, a temperature of 58 °C is reached after 100 s.

With the two parameters for the path of the first order (K_S and T_S), the formula for the path step response is as follows:

$$x = 12\frac{\text{K}}{\text{kW}} \bullet 5\ \text{kW} \bullet \left(1 - e^{\frac{-t}{100\ \text{s}}}\right) + 20\ °\text{C} \tag{9}$$

or

$$x = 60\,K \bullet \left(1 - e^{\frac{-t}{100\,s}}\right) + 20\,°C \qquad (10)$$

Paths **with two delays (second order)** have two energy stores.

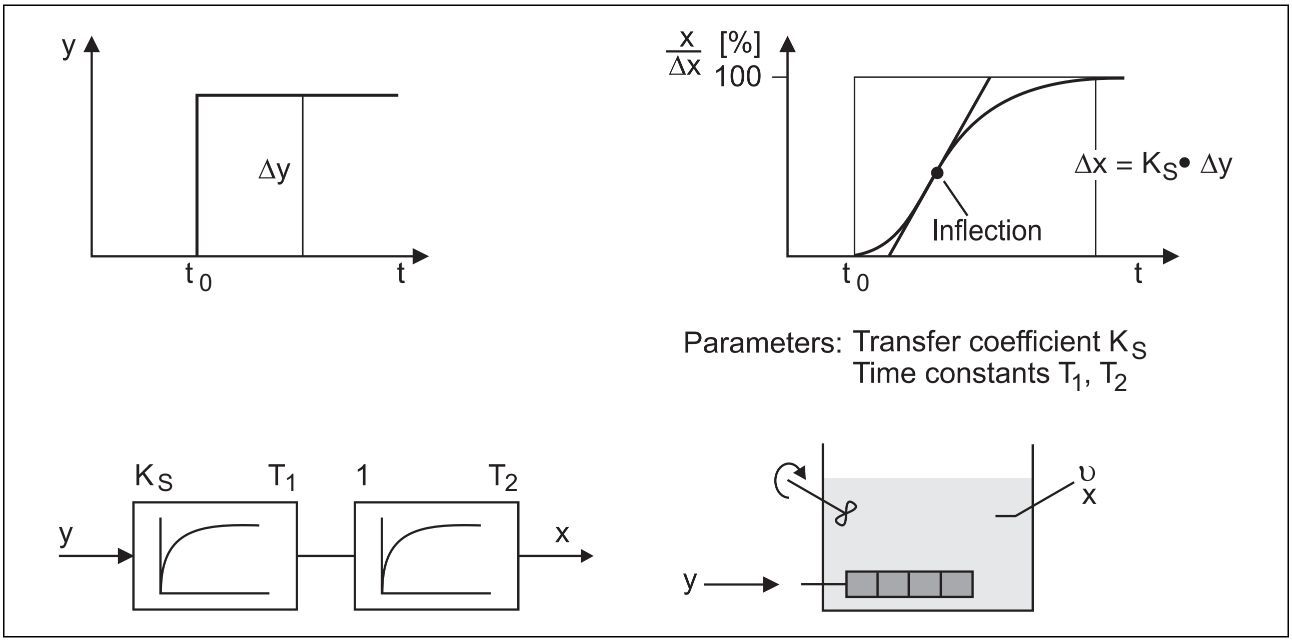


Figure 27: Path of the second order; PT_2 path

A heating rod with a relatively large mass is used to heat the water bath. The heating rod functions as the second energy store. If there is a sudden increase in the heating power, this is used at the beginning to heat the heating rod. A significant energy flow is not established until the temperature of the heating rod is considerably higher than that of the water. The actual value increases with a delay after the step change to the output level (Figure 27) and then has an increasingly steep course. After some time the slope of the actual value becomes increasingly flat and it ultimately reaches its end value. Figure 27 shows the tangent at the steepest point.

The PT_2 path is defined by the two time constants and the transfer coefficient. The step response is calculated according to the following equation:

$$\Delta x = K_S \bullet \Delta y \bullet \left(1 - \frac{T_1}{T_1 - T_2} e^{\frac{-t}{T_1}} + \frac{T_2}{T_1 - T_2} e^{\frac{-t}{T_2}}\right) \quad \text{Equation applies to T1} \neq \text{T2} \qquad (11)$$

It is not feasible to determine the two path time constants from the step response. In practice, the behavior of paths of the second and higher orders over time is characterized by substitute variables (Chapter 2.4 "*Recording the step response for paths with at least two delays and dead time*").

Paths of a higher order
In practice, control paths usually comprise more than two energy stores. However, the character of the step responses is the same as that of the aforementioned paths of the second order.

2.4 Recording the step response for paths with at least two delays and dead time

Control paths usually comprise several elements with delays and dead time:

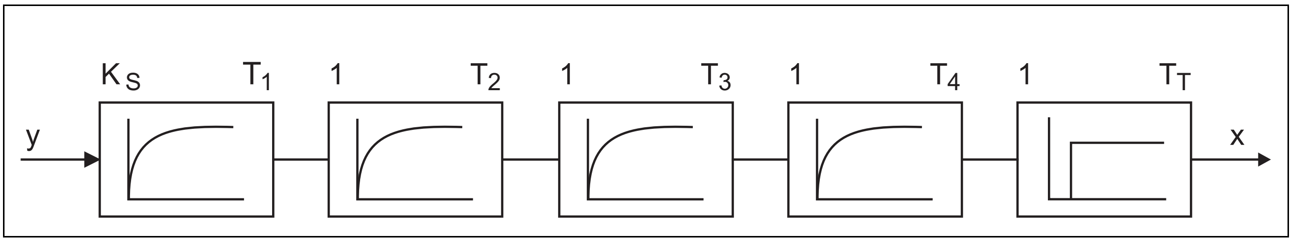


Figure 28: Block diagram of a control path with several delays and dead time

The block diagram in Figure 28 shows four energy stores and a dead-time element. With real paths, the professional does not know the order of the path or its time constants. He/she also has no knowledge of how many dead-time elements are present.

Paths of the second order and higher (including dead-time elements) are characterized by substitute variables. The substitute variables and rules of thumb allow optimal control parameters to be determined at a later stage. The substitute variables are the transfer coefficient (K_S) (discussed above), the delay time (T_u), and the compensation time (T_g).

The parameters are determined by recording the step response:
A step change to the output level is supplied to the control path and the course of the actual value is recorded (see Figure 29). A line is plotted parallel to the time axis at the level of the actual value after the step change. By applying the tangents to the actual value, it is possible to determine the point at which the slope of the actual value is greatest. The tangent with the greatest slope is plotted (inflectional tangent). The time from the step change to the output level until the intersection of the inflectional tangent with the time axis is the delay time (T_u); the time from the intersection with the time axis until the intersection of the inflectional tangent with the max. line corresponds to the compensation time (T_g). The transfer coefficient is calculated by dividing the change to the actual value by the step change in the output level.

Example:
K_S, T_u, and T_g need to be calculated for an industrial furnace. The furnace has cooled down and the temperature inside the furnace is 20 °C. Using the controller, the output level is suddenly increased from 0 to 50 % in manual mode and the actual value is recorded. Figure 29 shows the course of the actual value:

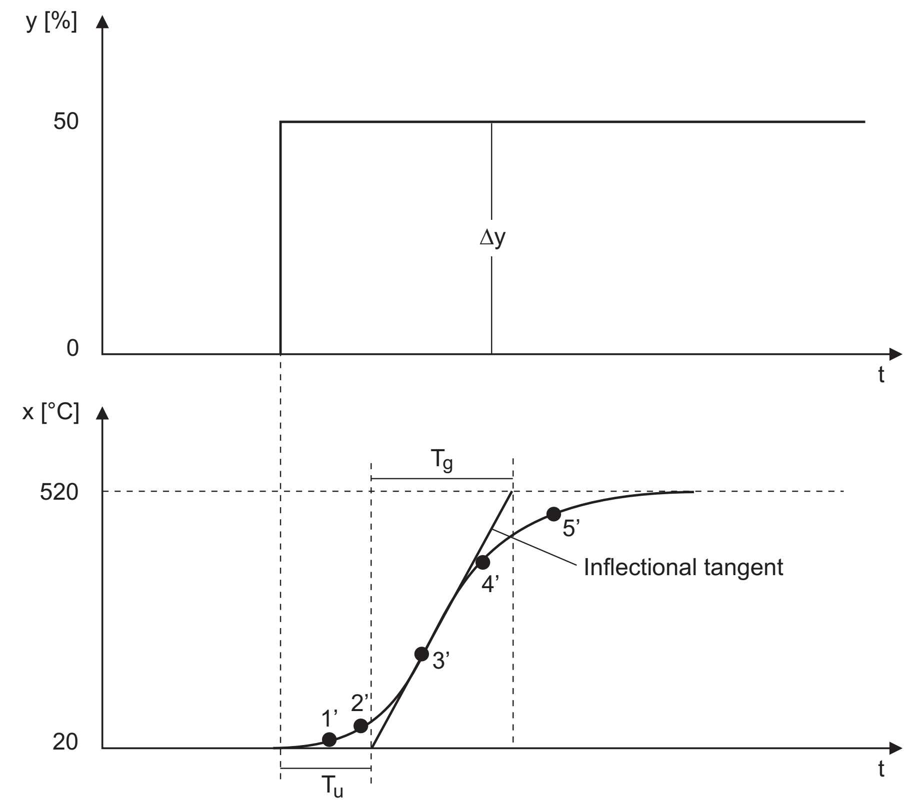


Figure 29: Calculating the delay time and compensation time

A straight line is plotted parallel to the time axis at the level of the maximum actual value (520 °C). The system gain can therefore already be calculated. To calculate the inflectional tangent, the tangents are applied to imaginary points on the course of the actual value (from left to right: 1', 2', etc.). Starting at 1', the first tangent is applied, which is relatively flat. The tangents at the imaginary points 2' and 3' are steeper. The tangents at points 4' and 5' are flatter again. The steepest point is calculated in this way. In Figure 29 the tangent at point 3' is the steepest. The specified times are calculated with the aid of the inflectional tangent.

The ratio T_g/T_u can be used as a measure of the extent to which a path can be controlled:

$T_g/T_u > 10$	easy to control
$T_g/T_u = 10$ to 3	somewhat easy to control
$T_g/T_u < 3$	difficult to control

The higher the number of energy stores in a control path, the smaller the ratio T_g/T_u will be and control will become increasingly difficult. Indeed, large energy stores have a considerable influence on the ratio.

Example:
A path of a relatively high order includes two energy stores with large time constants. The behavior corresponds to a path of the second order and the ratio T_g/T_u will be relatively large.

If the parameters are used in the rules of thumb according to Chapter 4.3.2 "*Method on the basis of the path step response according to Chien, Hrones, and Reswick*", this usually results in suitable control parameters for a PID controller, for example.

3 Controller components PID and control parameters

This chapter explains the controller components P, I, and D and the control parameters K_P (P_b), r_t, and d_t using the example of a continuous controller (output signal 0/2 to 10 V, 0/4 to 20 mA).

3.1 P controller

A P controller (proportional controller) forms the control deviation on the basis of the setpoint value and actual value, and increases this deviation with the proportional coefficient K_P. The result is output as the output level (Figure 30).

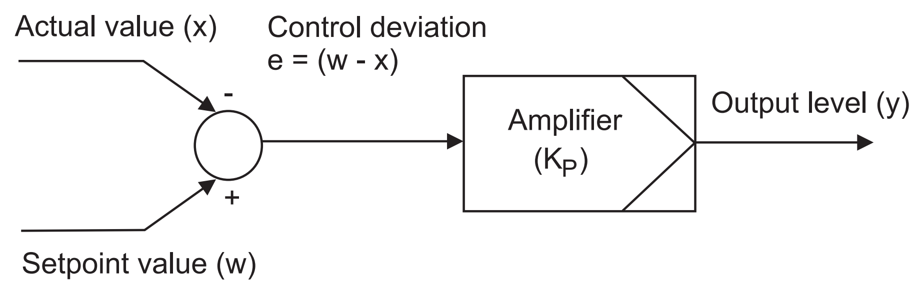


Figure 30: Function principle of a P controller

The proportional coefficient is freely defined on the controller.

$$y = K_P \bullet (w - x) \tag{12}$$

The controller operates with the dimensionless numerical value of the control deviation.
K_P is generally expressed by the unit % divided by the unit of the control variable (%/Kelvin, %/bar, % (U/min), etc.).

Examples:
If the control deviation is 5 K, a P controller for a temperature control path with a K_P set to 10 %/K provides an output level of 50 %.

If the control deviation is 20 bar, a P controller for pressure control with a K_P set to 4 %/bar calculates the output level as 80 %.

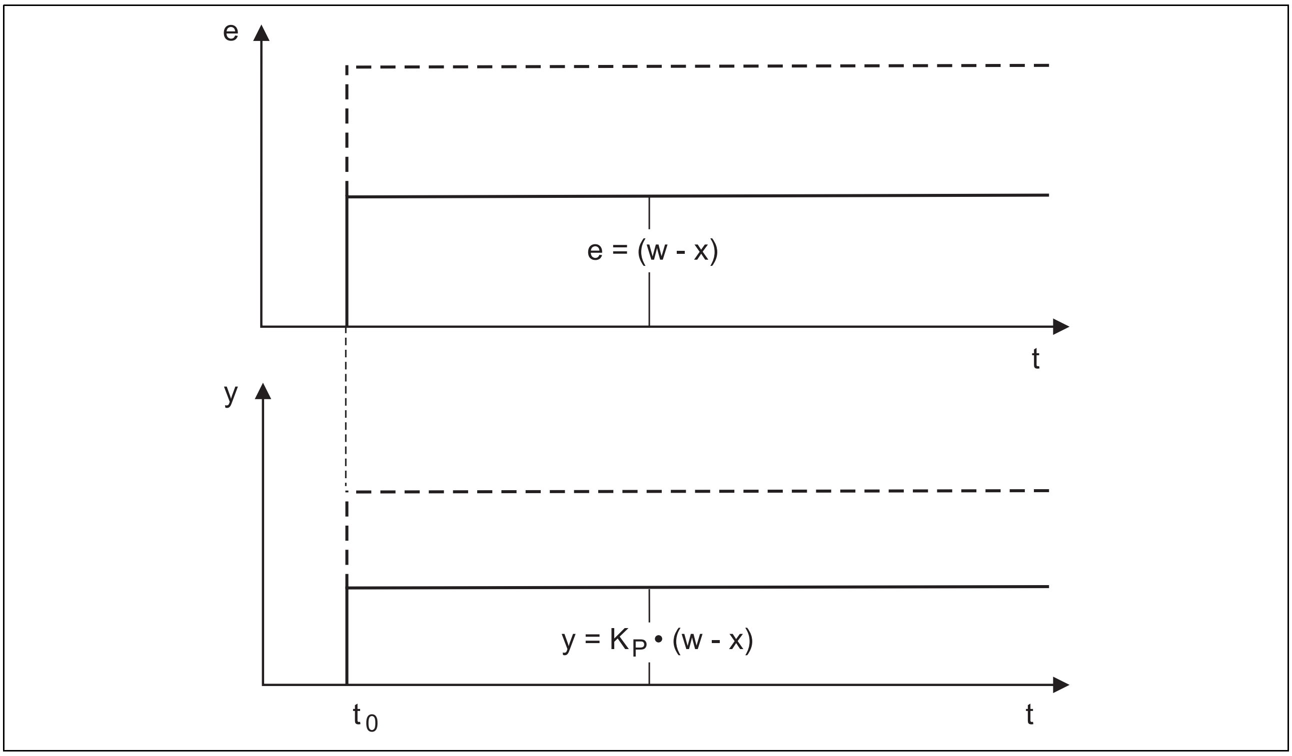


Figure 31: Step response of a P controller

Figure 31 shows the step response of a P controller – here, the response of the output level to a suddenly changing control deviation is analyzed. The P controller changes its output signal in proportion to the control deviation without a delay time.

3.1.1 The proportional band

A P controller with a proportional coefficient K_P set to 2 %/K by way of example increases the control deviation in a linear manner until it reaches 50 K (Figure 32).

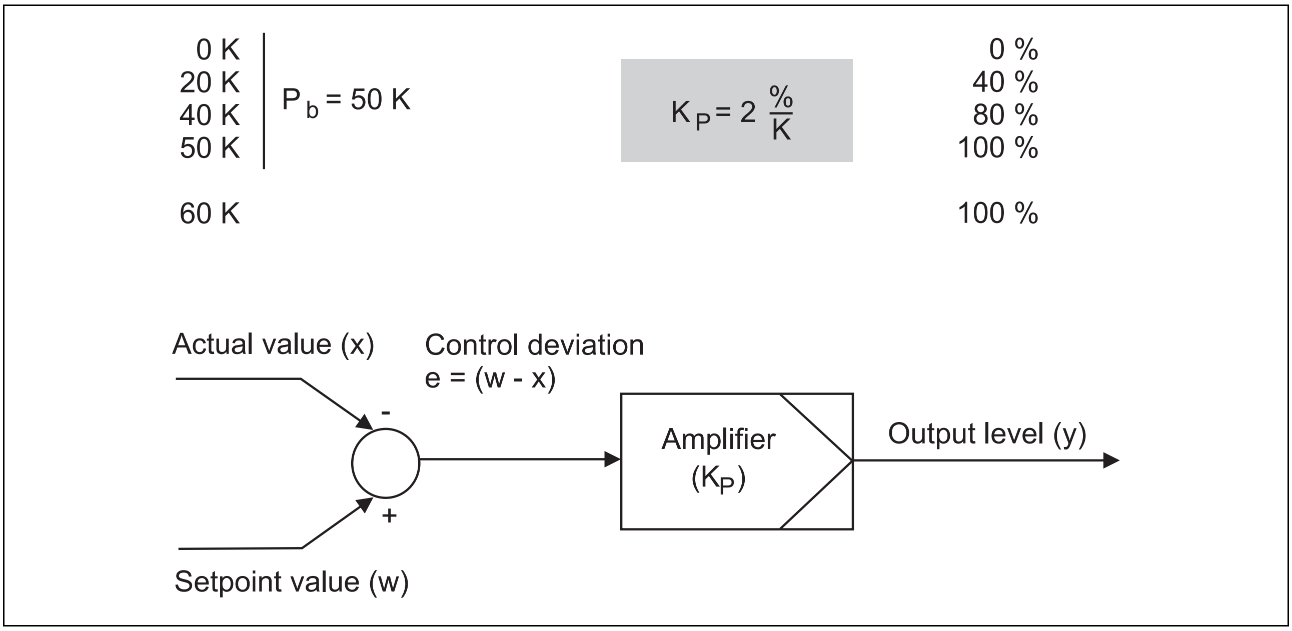


Figure 32: Proportional coefficient K_P and proportional band P_b

3 Controller components PID and control parameters

The control deviation at which the controller outputs exactly 100 % with an increasing control deviation, is defined as the proportional band (P_b). On a controller used for heating, the proportional band is less than the setpoint value:

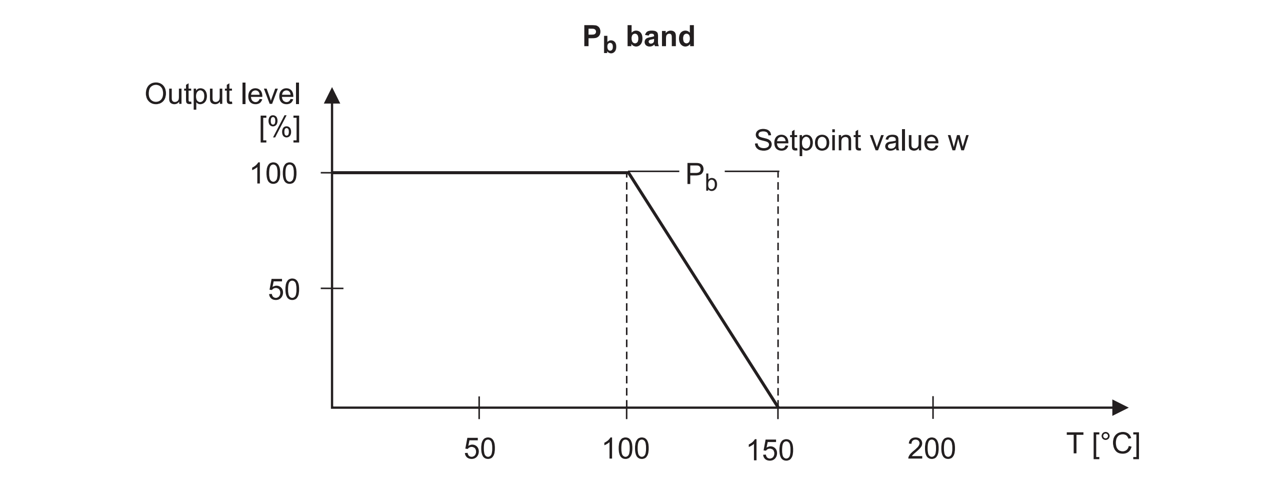


Figure 33: Characteristic line of a proportional controller

The characteristic line (Figure 33) indicates the behavior of a P controller. The output level is plotted on the Y-axis. The setpoint value can be found on the X-axis (the characteristic line intersects with the X-axis here, at 150 °C in the example shown). The actual value is also plotted in figure 34:

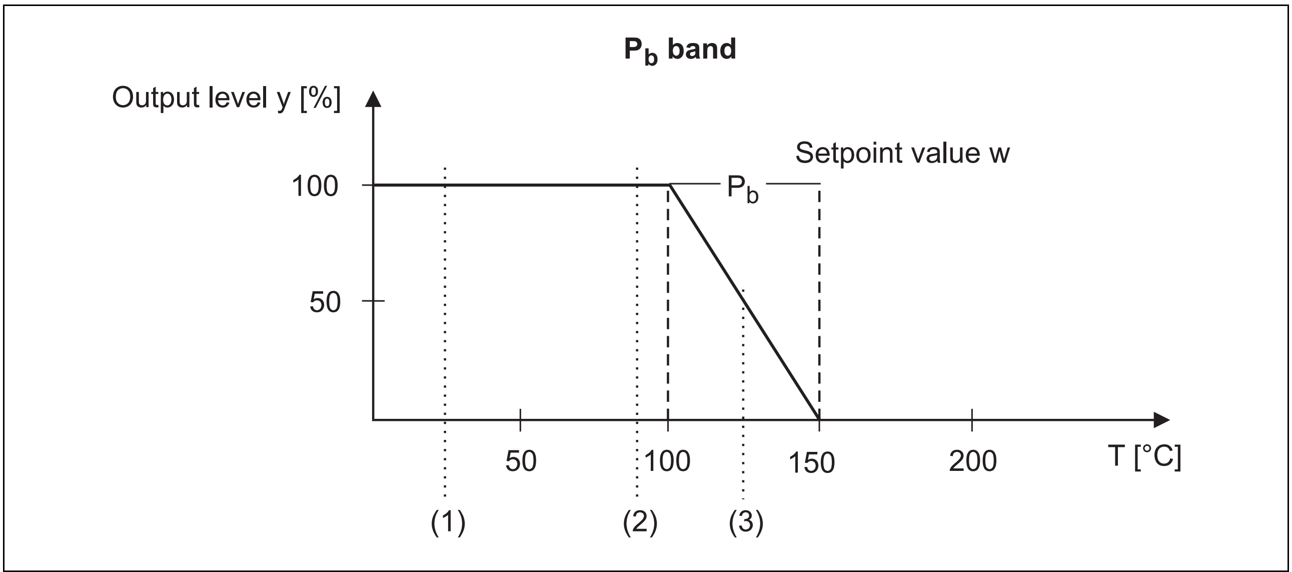


Figure 34: Characteristic line of a proportional controller with plotted actual value

The proportional band in Figure 34 is 50 K. If the control deviation is > 50 K the output level is 100 %. If the control deviation is smaller than the proportional band, the output level is reduced in proportion to the control deviation.

If the actual value is approx. 25 °C (1), it is evident from the intersection with the characteristic line that the controller is supplying an output level of 100 %. The actual value increases due to the high output level and subsequently reaches approx. 90 °C (2). The output level is still 100 % and is reduced as from a value of 100 °C. As from 100 °C, the actual value lies in the proportional band (P_b). If, for example, the actual value is in the center of the proportional band (125 °C), the output level is still 50 % (3). If the actual value is 150 °C or higher, the output level is 0 %.

3 Controller components PID and control parameters

Steady-state control deviation

Heating power is no longer fed into the system from an actual value of 150 °C or higher (Figure 34). In the case of a furnace, the furnace will no longer be heated. The temperature will drop below 150 °C and the output level will increase. The process will reach a balanced state (this is the case if an output level of 50 % is required for an actual value of 125 °C).

The disadvantage of the P controller is the changing control deviation. As a result, this controller is only used rarely. The component is usually combined with an I component and in many cases also a D component.

The steady-state control deviation can be reduced by reducing P_b. In the example shown, the actual value stagnates at 125 °C and an output level of 50 %. If the proportional band is reduced to 25 K, the output level increases to 100 % and the actual value moves closer to the setpoint value.

However, as P_b decreases the tendency of the actual value to oscillate increases:

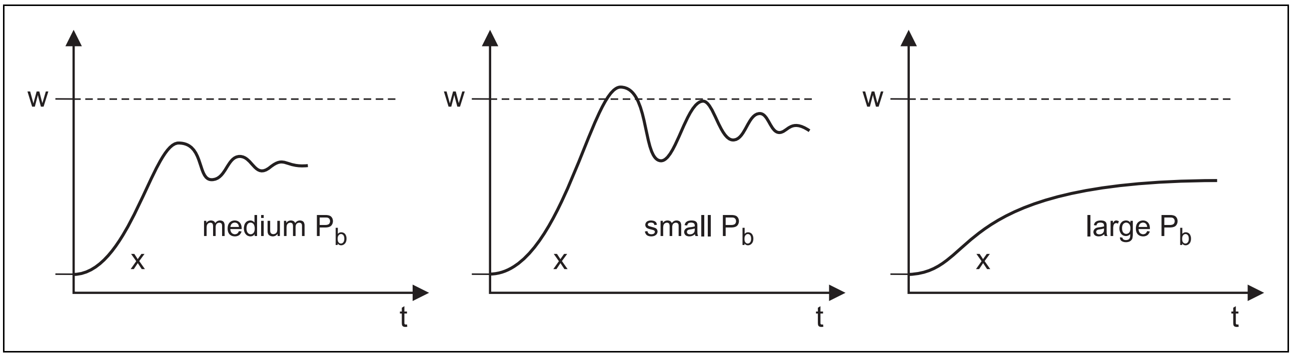


Figure 35: Control response for various P_b

The large oscillations occurring with a small P_b are due to the fact that the power is reduced very quickly when the actual value enters the proportional band, meaning a balanced state cannot be established immediately.

Relationship between proportional coefficient and proportional band

$$K_P = \frac{1}{P_b} \bullet 100\ \% \quad \text{or} \quad P_b = \frac{1}{K_P} \bullet 100\ \% \qquad (13)$$

An P_b of 50 K (Figure 33) therefore corresponds to a K_P of 2 %/K.

Inverse and direct control direction

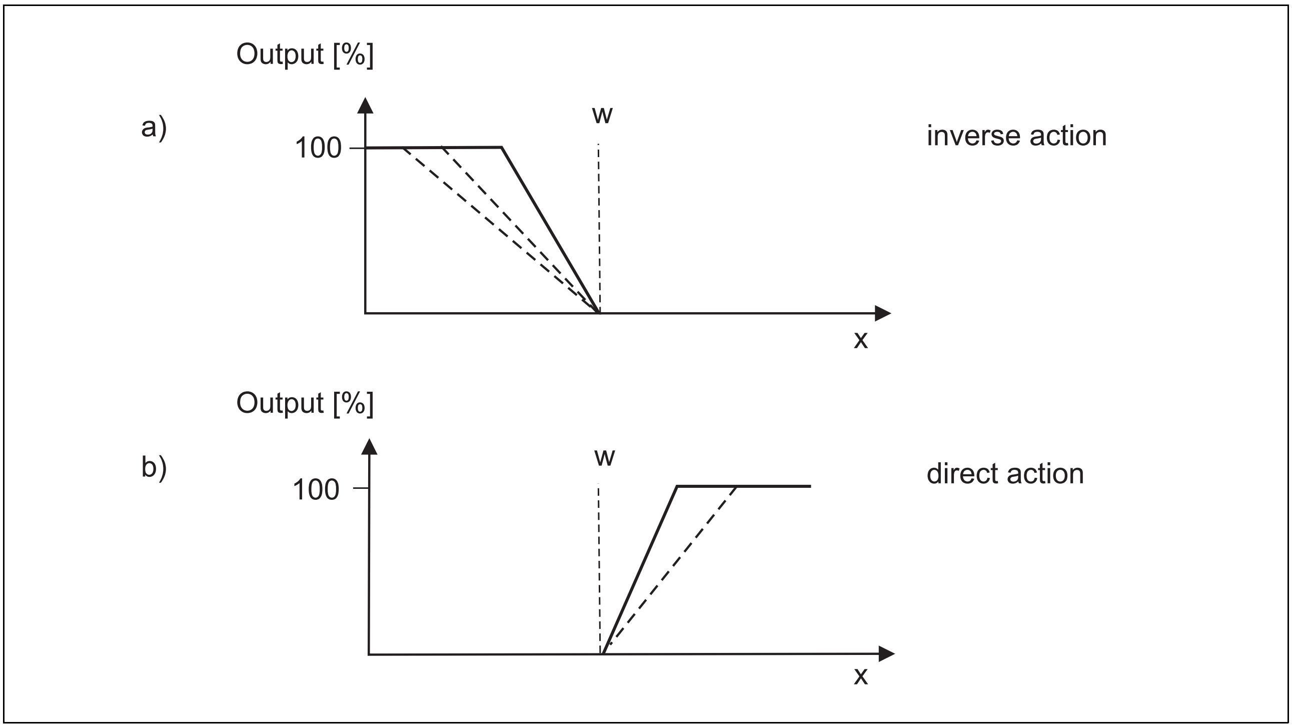


Figure 36: Inverse and direct control direction

The relevant control direction is defined on the controller depending on whether the controlled actuator increases or decreases the actual value.

For an inverse control direction, see a), with an increasing actual value the output level is reduced after reaching the proportional band. If the actual value = setpoint value, the power is 0 % (the inverse control direction is required for heating, humidification, increasing pressure, etc.).

If the direct control direction has been set, see b), with an increasing actual value the output level is increased starting from 0 % upon exceeding the setpoint value. If the actual value is at or above the upper limit of the proportional band, the output level is 100 % (the direct control direction is required for cooling, dehumidification, reducing pressure, etc.).

Output level limiting

Controllers with a controller output generally provide the output level in the range from 0 to 100 %. In the case of oversized actuators, the output level can be given an upper limit:

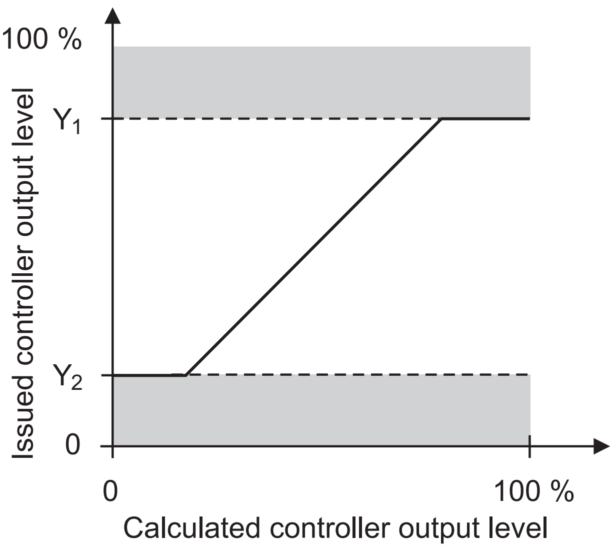


Figure 37: Using the upper output level limit

In JUMO controllers, the upper output level limit is set using parameter Y_1 and the output level is limited to this maximum value.

Three-state controllers (which are described later on) influence the control variable in two directions. The overall output level is -100 to 100 %. The maximum possible output level for the second controller output can also be restricted using the lower output level limit Y_2 (for instance, to 50 % if Y_2 is set to -50 %).

When using continuous controllers, a minimum output level is defined with Y_2 (Figure 37), which means that this output level will be provided at the very least, regardless of the control deviation.

3.2 I controllers

I controllers (integral-action controllers) form the areas that are enclosed over time between the control deviation and time axis:

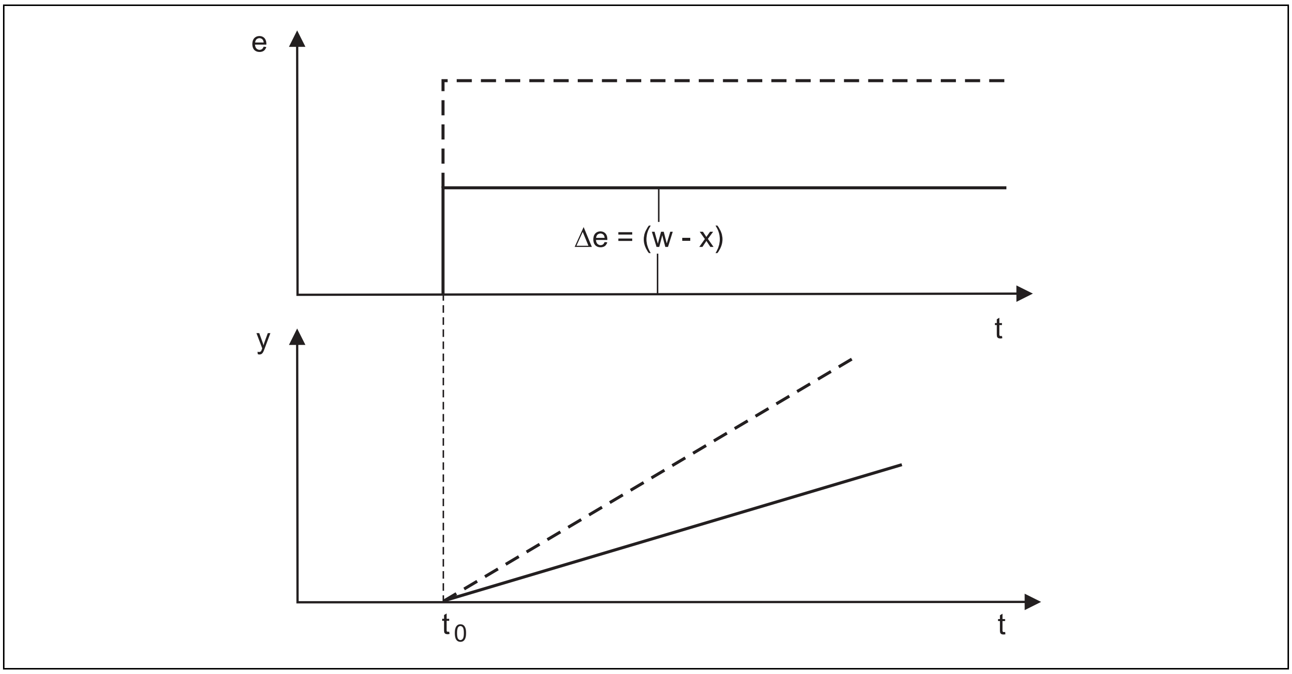


Figure 38: Step response of an I controller

Figure 38 shows the step response of an I controller: the control deviation is 0 before the step change, and in this case the I controller retains its current output level. If the output level was previously 0 %, it remains at this value. If the control deviation is suddenly set to a positive value, the controller forms the aforementioned areas and provides these with its output level. In other words, the controller increases its output level as soon as there is a positive control deviation. If the control deviation is constant, the output level is ramped up to 100 % and remains at this value. If the control deviation on offer is twice as large, the controller builds up the output level twice as fast (see the dotted lines in Figure 38). If the actual value is greater than the setpoint value (a negative control deviation), the output level will be reduced accordingly.

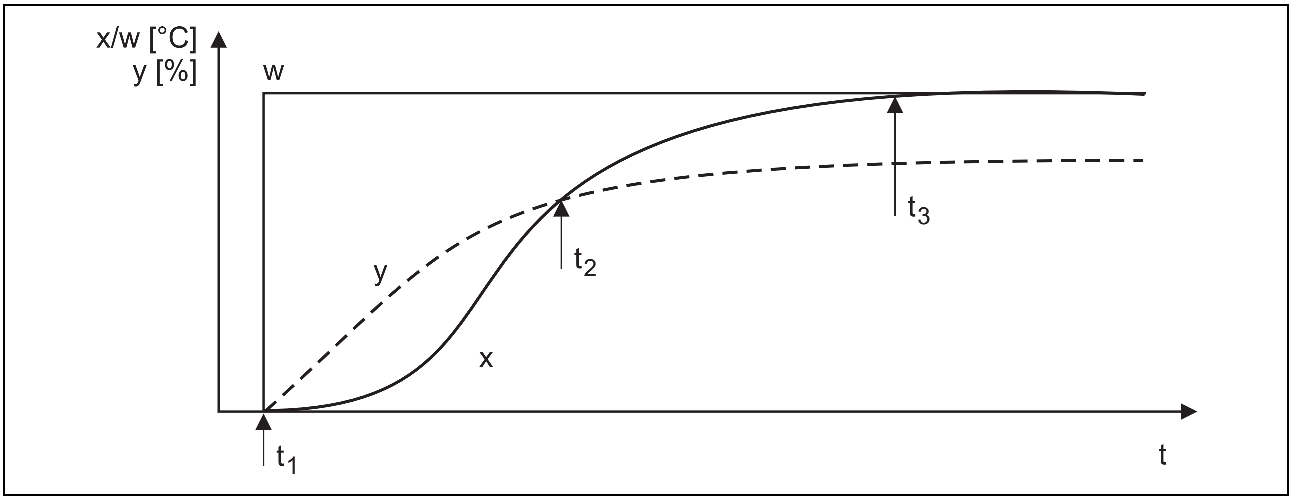


Figure 39: The I controller in a closed control loop

Figure 39 shows the setpoint value, actual value, and course of the output level for an I controller in a closed control loop:

t_1 The setpoint value is suddenly changed, the output level is immediately increased by the I controller, and the actual value is changed with a delay.

t_2 The actual value becomes ever greater and the control deviation ever smaller.
The controller builds up its output level ever-more slowly and the actual value increases at a slower rate in the direction of the configured setpoint value.

t_3 The controller has performed adjustment and the control deviation is 0.
The I controller retains the output level it has built up.

Generally speaking the controller offers the advantage that it eliminates the control deviation. However, its slow response is a disadvantage.

The integral-action time (T_I)

The integral-action time is used to change the speed of the I controller. In the case of a constant control deviation, the controller equation is:

$$y = \frac{1}{T_I} \bullet \Delta e \bullet t + y_{t_0} \qquad (14)$$

y_{t_0} Output level at beginning of analysis

The smaller T_I is, the faster the I controller will build up its output level. It is apparent from the formula that, once the time T_I has elapsed, the controller has increased the output level by the available control deviation (without taking the dimension into account).

Example:

If T_I has been set to 60 s and the control deviation is 2 K, the output level increases by 2 % over 60 s. In the case of a changing control deviation, the output level is formed according to the following equation:

$$y = \frac{1}{T_I} \bullet \int_{t_0}^{t} e \bullet dt + y_{t_0} \qquad (15)$$

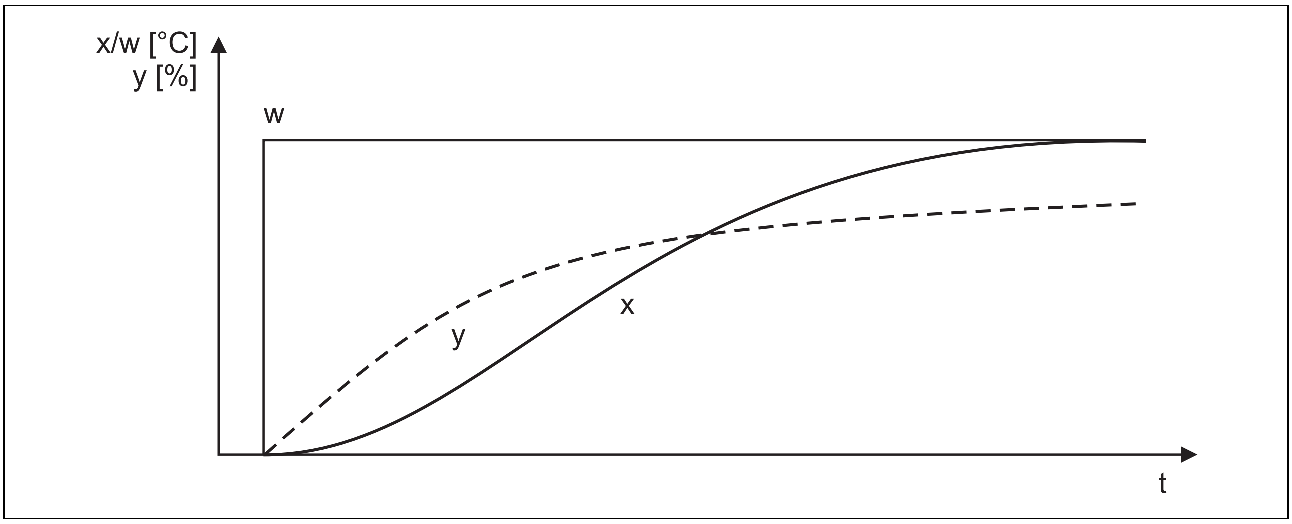


Figure 40: I controller with a large T_I

An I controller with a relatively large integral-action time with respect to the process responds slowly (Figure 40). The controller builds up the output level slowly. The actual value moves very slowly in the direction of the setpoint value (Figure 40).

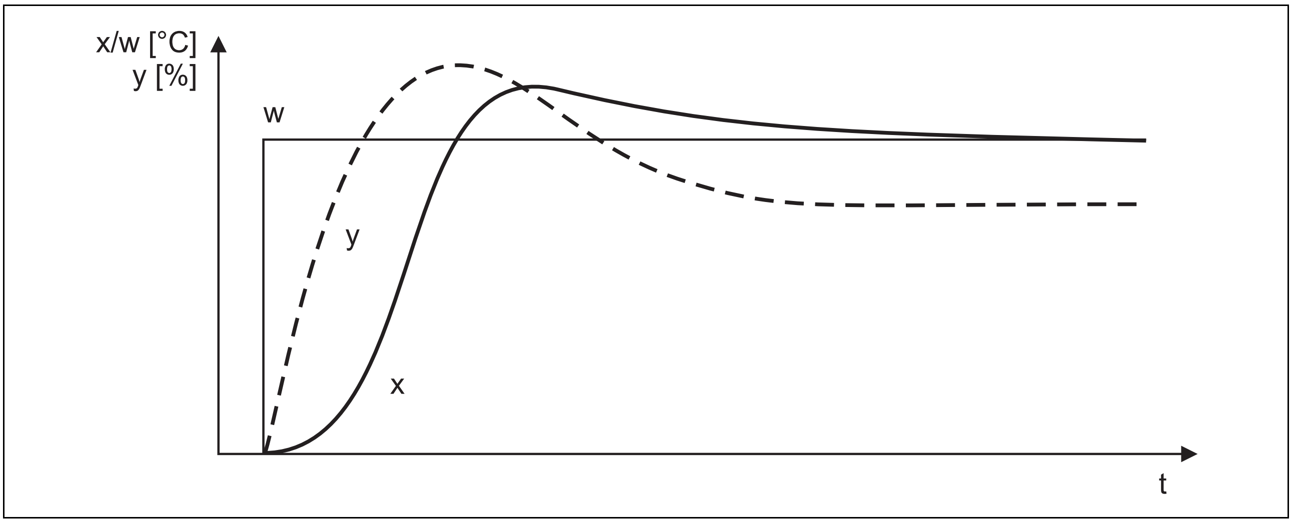


Figure 41: I controller with small T_I

An I controller with an integral-action time that is too small with respect to the process (Figure 41) builds up the output level too quickly. If the actual value reaches the level of the setpoint value, the output level of the controller has taken on an excessively high value. The amount of power supplied in the process is too high and the actual value exceeds the setpoint value.

Use of I controllers

I controllers are used relatively rarely: they are deployed for pulsating measurands (pressure control) and for paths with a relatively small compensation time in relation to the delay time ($T_g/T_u < 3$). To allow the controller to respond quickly, the integral-action time is set to low values for paths with a fast response.

3.3 PI controllers

PI controllers combine the benefits of both components: speed (P) and lack of a control deviation (I). If a control deviation occurs with a PI controller, the P component increases this and provides a relatively large output level. The I component increases its output level for the duration of a positive control deviation and ensures that the control deviation is brought to 0.

When combining the I component with a P component, the parameter for the integral-action behavior is known as the reset time (r_t). On I controllers this was called the integral-action time (T_I). In the case of I, PI, or PID controllers, only one parameter should be available to the I component. For this reason, the integral-action behavior of JUMO controllers with an I structure is also defined using the reset time parameter (r_t).

Figure 42 shows the step response of a PI controller:

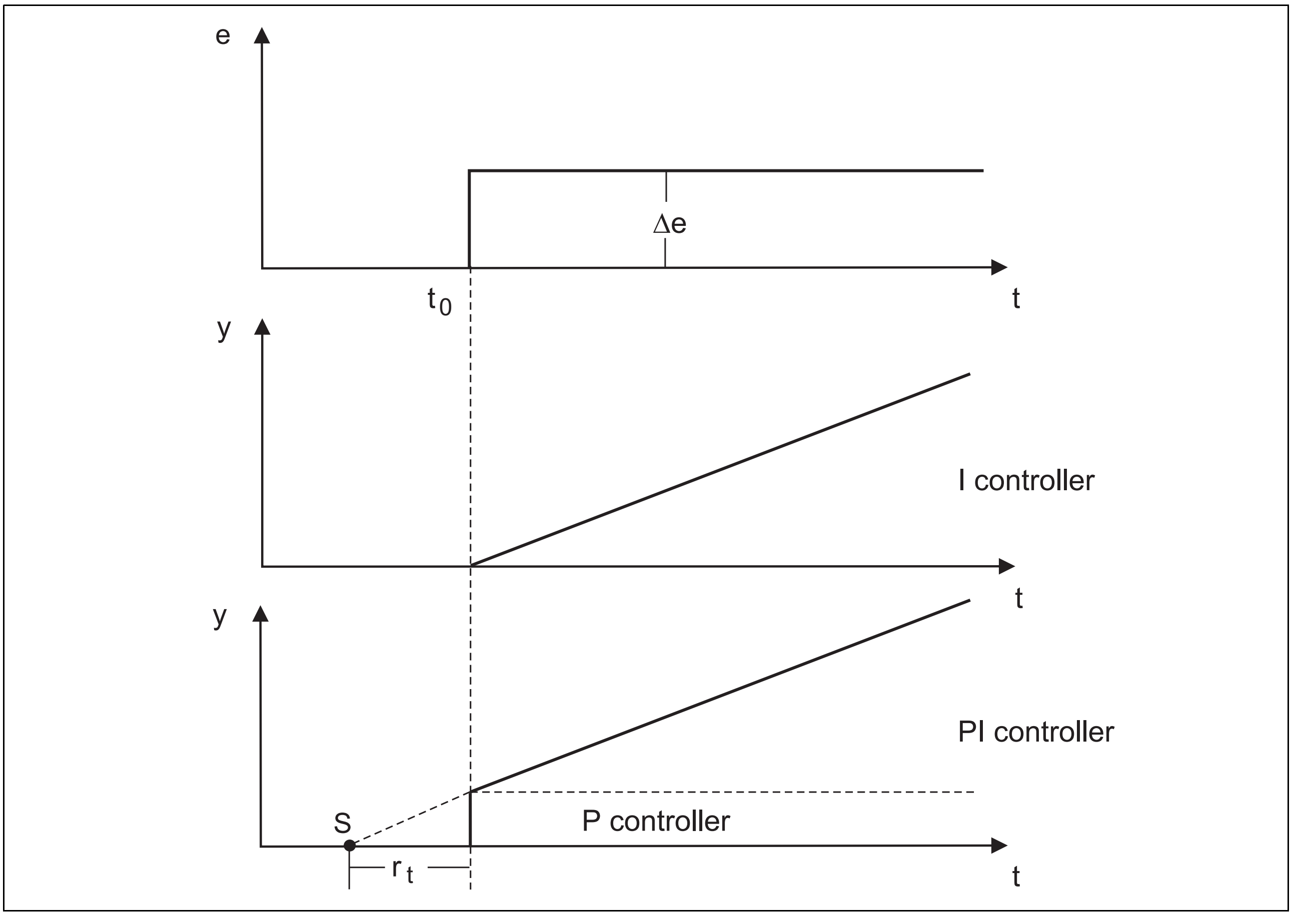


Figure 42: Step response of a PI controller

The two control parameters P_b and r_t are used for PI controllers: the smaller the value set for P_b, the harder the P component works. The smaller the value set for r_t, the faster the I component will form its output level.

The r_t set on the controller can be calculated on the basis of the step response from the PI controller (Figure 42): the ramp of the output level is extended to the left. The time from the intersection with the time axis until specification of the step change is the reset time. In the case of a constant control deviation, the output level is formed according to the following equation:

$$\Delta y = \frac{1}{P_b} \bullet 100\,\% \bullet \left(\Delta e + \frac{1}{r_t} \bullet \Delta e \bullet t\right) \qquad (16)$$

or when rearranged:

$$\Delta y = \underbrace{\frac{100\%}{P_b} \bullet \Delta e}_{\text{P component}} + \underbrace{\frac{100\%}{P_b} \bullet \frac{1}{r_t} \bullet \Delta e \bullet t}_{\text{I component}} \qquad (17)$$

It is evident from the equation that the configured P_b is also included in the integral-action behavior: if P_b is reduced, the I component works faster, for instance.

Detailed information on this topic is provided in Chapter 3.5.1 "*Block diagram of a PID controller*".

In the case of a non-constant control deviation, the controller operates according to the following equation:

$$\Delta y = \frac{100\%}{P_b} \bullet \left(e + \frac{1}{r_t} \bullet \int_{t_0}^{t} e \bullet dt\right) \qquad (18)$$

The PI controller in a closed control loop

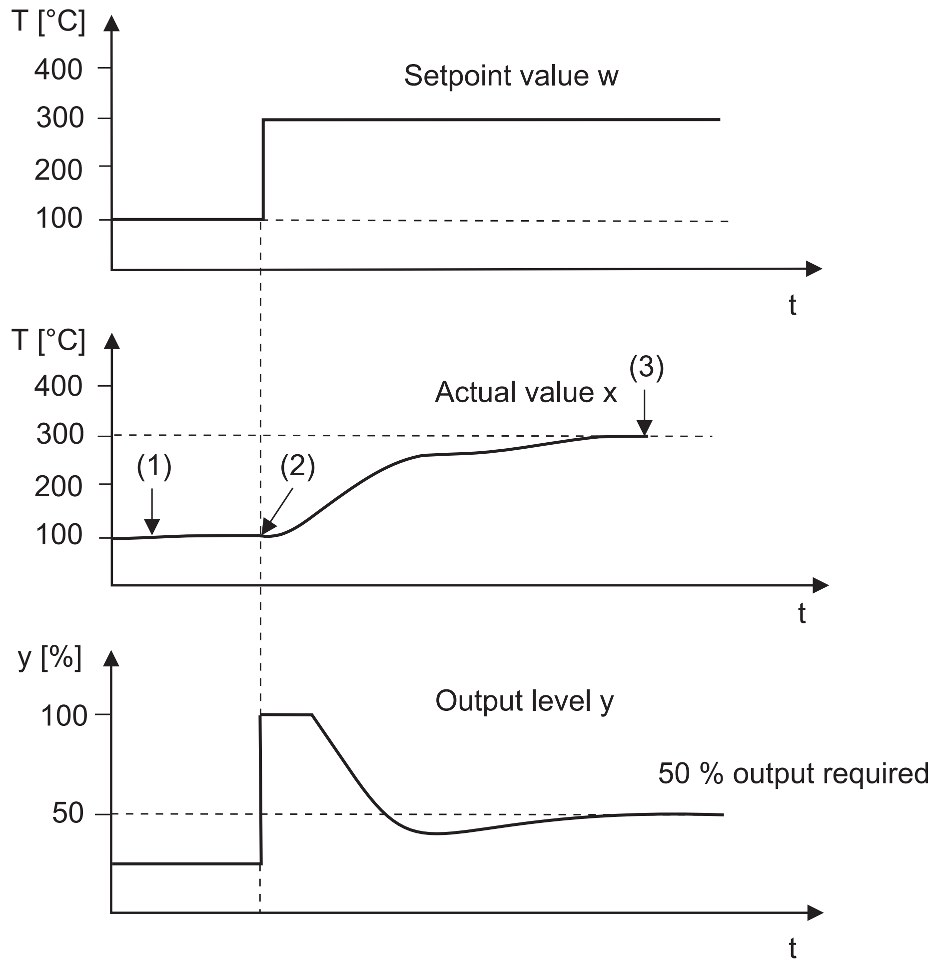


Figure 43: PI controller in a closed control loop

Figure 43 shows the behavior of a PI controller in a closed control loop: the setpoint value, actual value, and output level before and after a change to the setpoint value are depicted.

(1) The setpoint value is 100 °C, the controller has performed adjustment, and an output level of 25 % is provided. If the control deviation is 0, the P component does not provide an output level and the output signal will be supplied by the I component only.

(2) After the setpoint value has been changed to 300 °C, the actual value is outside of the proportional band. The output level of the P controller is 100 %. As a result of this change, the output level provided by the I component is set to 0 %. On account of the high output level, the actual value enters the proportional band. The P component falls below 100 % and the I component builds up the output level. The P component is reduced as a result of the declining control deviation. The I component increases and adjusts the actual value to the setpoint value.

(3) In adjusted state, the I component supplies the entire output level again (50 % in the example shown).

3.4 PD controllers

The D component (derivative component) responds to and counteracts changes to the control variable. With an increasing actual value, the D component of a controller with an inverse control direction provides a negative output level. Accordingly, a positive output level is provided for a declining actual value.

Figure 44 shows the behavior of a PD controller after an increase to the setpoint value:

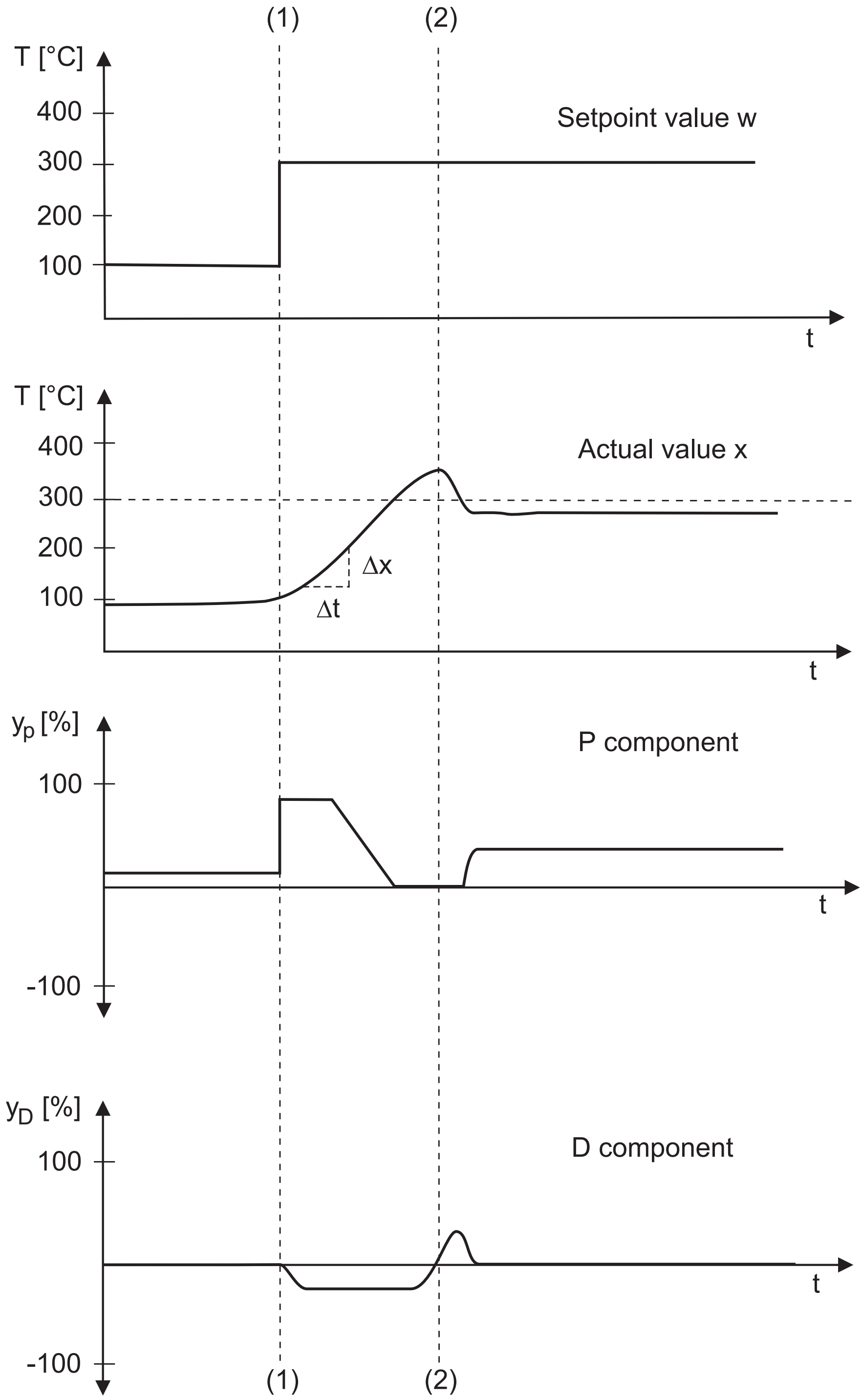


Figure 44: The PD controller in a closed control loop

3 Controller components PID and control parameters

P component

At the beginning the setpoint value is 100 °C and the actual value is slightly below 100 °C. The control deviation results from the lack of an I component, and only an output level that is proportional to the control deviation is provided. The setpoint value is then increased to 300 °C (1), the control deviation is greater than the proportional band, and the P component provides an output level of 100 %. The control deviation becomes smaller and the output level that was provided is reduced once the actual value has entered the proportional band. If the actual value exceeds the setpoint value, then the P component is 0 %. If, after a while, the actual value is below the setpoint value, a P component greater than 0% is set again.

D component

At the beginning the actual value stagnates and the D component does not form an output level. The actual value increases (1) and the D component provides a negative output level in proportion to the slope of the actual value. The output level reduces the overall output level and the rate at which the actual value is increasing is slowed down. In the case of a progressively flatter course for the actual value, the output level of the D component is progressively reduced. If the actual value has no slope, the output level of the D component is 0 %. While the actual value is declining [after (2)], the D component counteracts the movement of the actual value using a positive output level.

Users can influence the intensity of the D component with the derivative time d_t . The larger the parameter dimensioning, the stronger the described impact will be.

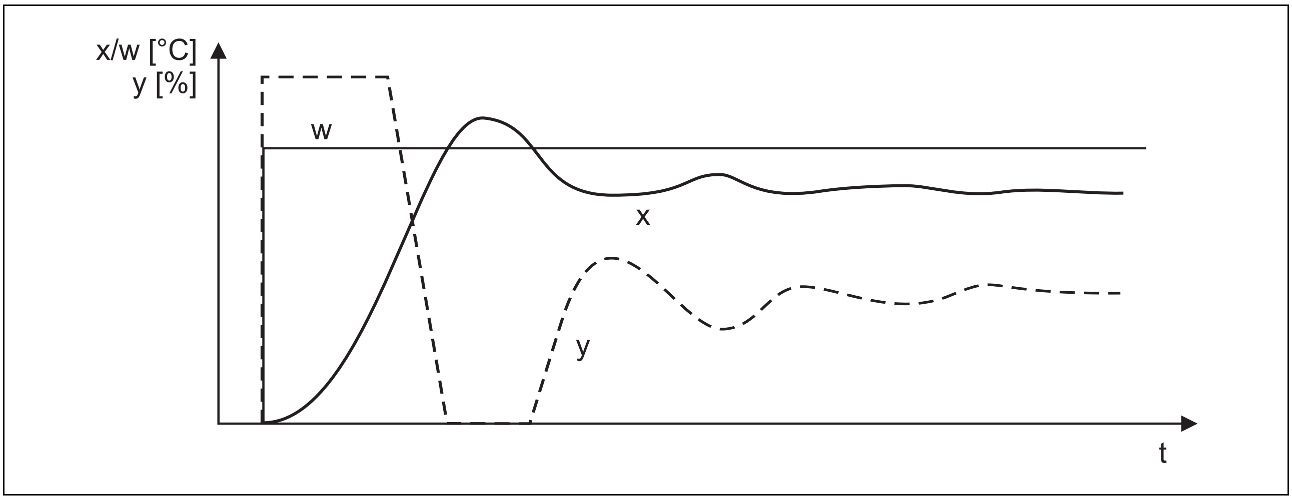


Figure 45: PD controller with d_t = 0 s (D component is ineffective), P controller

Figure 45 shows the control response of a PD controller with a derivative time of d_t = 0 s – the D component is ineffective. Due to the relatively small proportional band, the actual value tends to oscillate as it moves toward the end value.

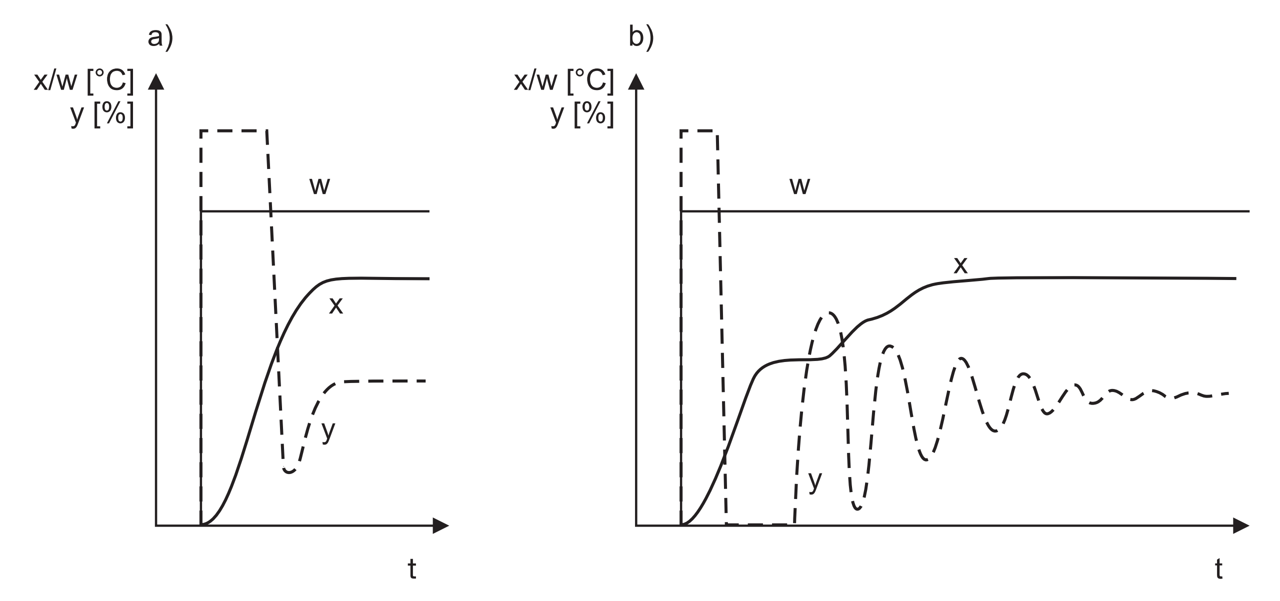


Figure 46: **PD controller with a) optimal setting for d_t and b) too large a setting for d_t**

Figure 46 a) demonstrates the control response for an optimally configured d_t : if the actual value increases, the D component reduces the overall output level; if the actual value is declining, the component increases the overall output level.
Thanks to this attenuation the controller can be operated with a relatively small proportional band: the tendency to oscillate that results from the high gain is suppressed by the D component.

A d_t that has been set too large will cause the control response shown in Figure 46 b): after the change to the setpoint value the P component will provide an output level of 100 %. As a result of the increasing actual value and the d_t that has been set too large, the D component reduces the overall output level to 0 % and the course of the actual value flattens out. Due to the smaller slope of the actual value, the D component withdraws its negative output level, which causes the actual value to increase again at a faster rate. As a result of the faster increase in the actual value, the D component reduces the overall output level again, and so on.

3 Controller components PID and control parameters

In a closed control loop, changes to disturbances will result in a temporary control deviation. The D component reduces the maximum control deviation that occurs.

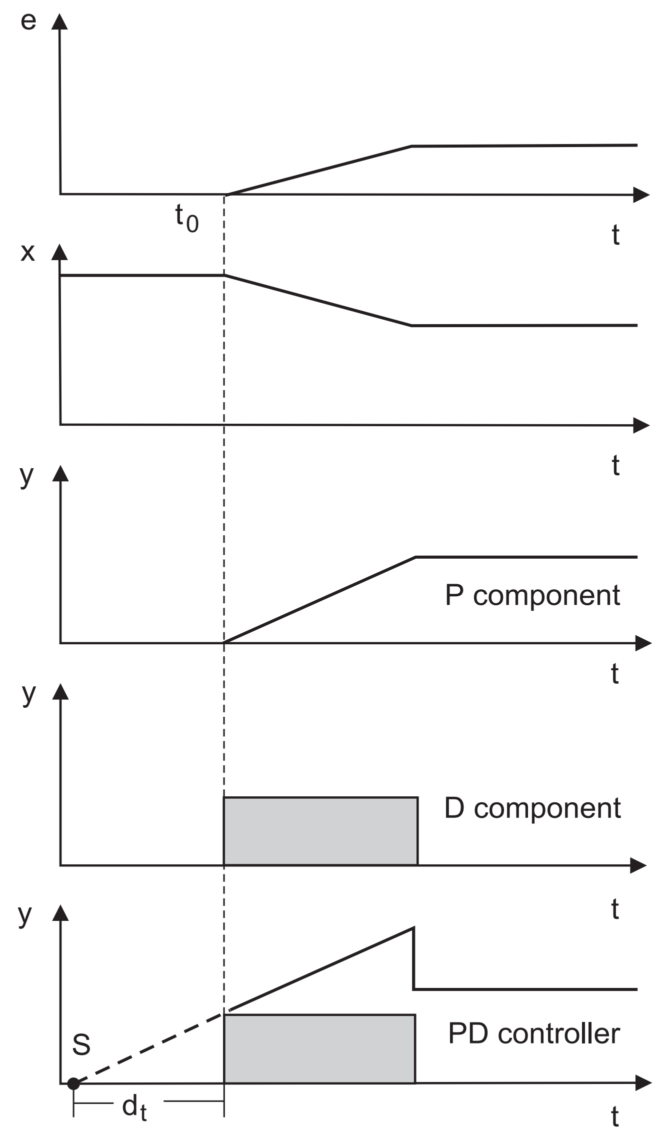


Figure 47: Ramp response of a PD controller

In Figure 47, the actual value decreases due to a changing disturbance. The control deviation increases and the P component forms its output level in proportion to the deviation. In the case of small control deviations, this output level is very low and influences the actual value to a correspondingly minor extent. When the actual value decreases the D component acts immediately in proportion to the rate of change, and influences the actual value immediately at high intensity.

If the slope of the actual value is constant, PD controllers with an inverse control direction form the output level according to the following equation:

$$y = \frac{1}{P_b} \bullet 100\% \bullet \left(e - d_t \bullet \frac{\Delta x}{\Delta t}\right) \qquad (19)$$

If the slope of the actual value changes, the output level is formed as follows:

$$y = \frac{1}{P_b} \bullet 100\% \bullet \left(e - d_t \bullet \frac{dx}{dt}\right) \qquad (20)$$

$\frac{dx}{dt}$ Slope of actual value (for temperature control, for example in K/s)

3.4.1 The practical D component – the DT_1 element

In principle the step response of a PD controller can also be analyzed. However, the rate of change for a step change is infinite. As a result, the D component output level derived from a step change would have an infinitely high value for a theoretically infinitely brief period of time (Figure 48).

In practice, sudden changes to the actual value tend to be an exception. However, sudden changes for the entered value, caused by the sampling rate of the control devices, are also caused in the case of a constantly changing signal.

In practice, the described behavior is attenuated through the use of a T_1 element.

Figure 48 shows the step response of the "practical D component". T_1 is the time constant of the T_1 element. In practice, the time constant $d_t/4$ is automatically selected and cannot be directly configured by users. Using the step response of the "practical D component", the derivative time d_t can be calculated from T_1 on the basis of the ratio $T_1 = d_t/4$.

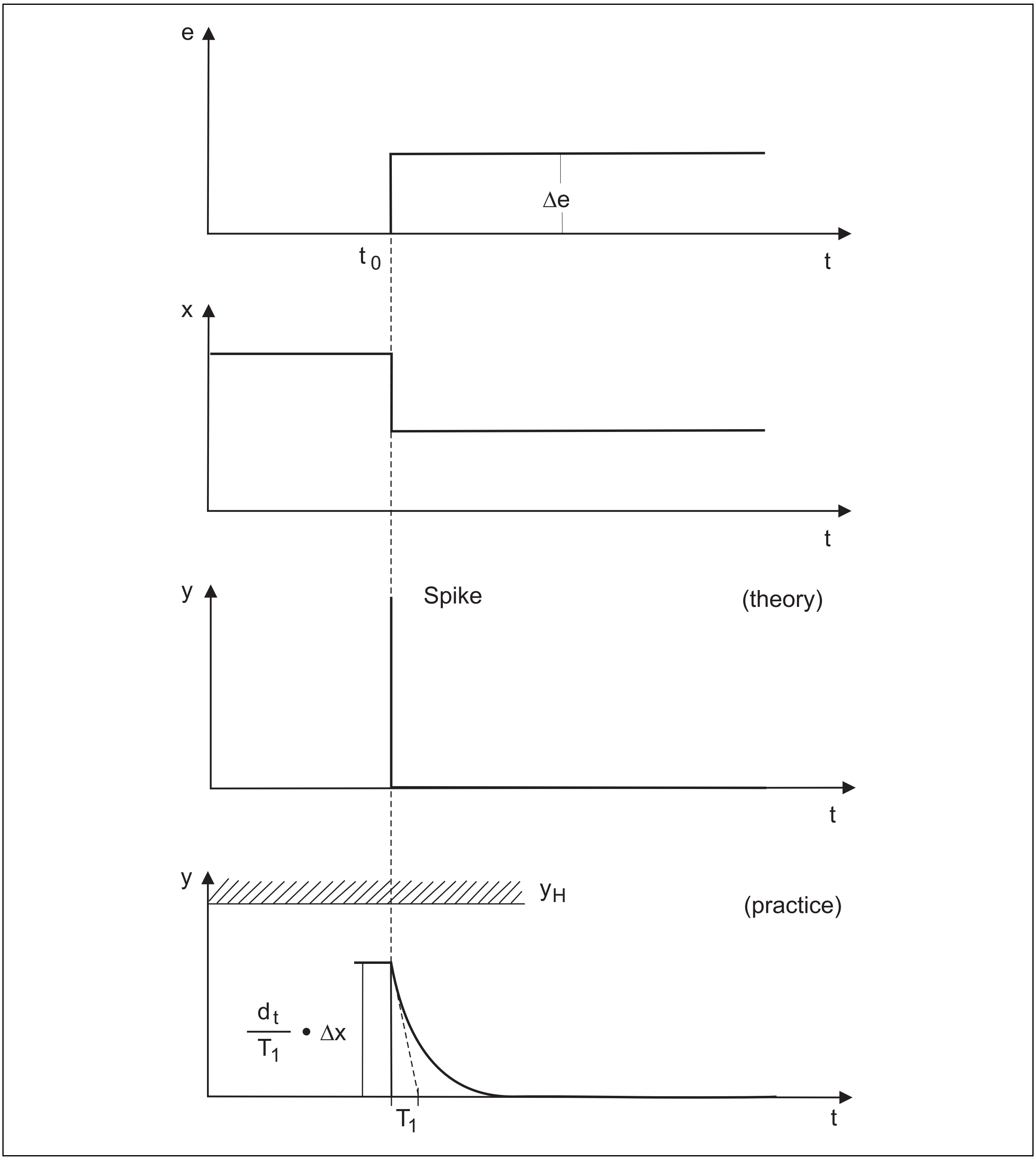


Figure 48: Step response of a DT_1 element

3.5 PID controllers

PID controllers are used in the majority of applications. The parameters X_P, T_n, and T_v must be set for these controllers. The parameters set in the controller can also be determined from the step response (Figure 49).

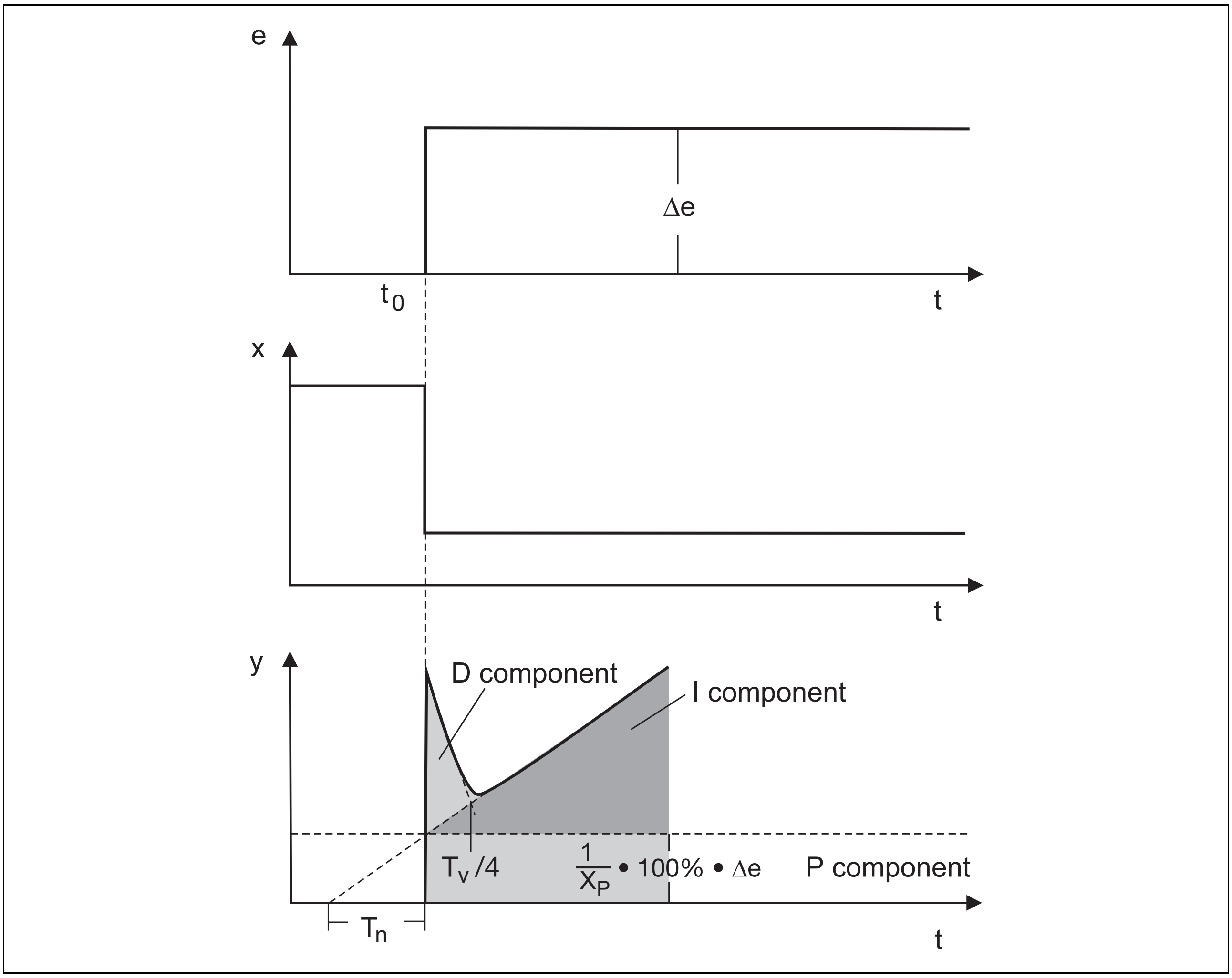


Figure 49: Step response of a PID controller

The D component responds exclusively to the change to the actual value; the changed control deviation in Figure 49 is therefore the result of a change to the actual value.

In the case of a sudden reduction in the actual value, the D component immediately provides a positive output level and thus counteracts the movement of the actual value. As a result of the control deviation, the P component also forms a positive output level in proportion to the control difference. In addition, the I component increases its output level, but the ramp of the I component is not evident until the I component is at the same level as the D component.

The equation for the PID controller becomes:

$$\Delta y = \frac{1}{X_P} \bullet 100\% \bullet \left(e + \frac{1}{T_n} \bullet \int e \bullet dt - T_v \bullet \frac{dx}{dt} \right) \quad (21)$$

3 Controller components PID and control parameters

Changing the control parameters will have the effects that were described previously:

Larger P_b corresponds to smaller P component

- Smaller gain, resulting in more stable but also slower response

Larger r_t corresponds to smaller I component

- I component integral action is slower, resulting in more stable but also slower response

Larger d_t corresponds to larger D component

- More strongly counteracts the change to the actual value, resulting in more stable response; d_t must not be too large

3.5.1 Block diagram of a PID controller

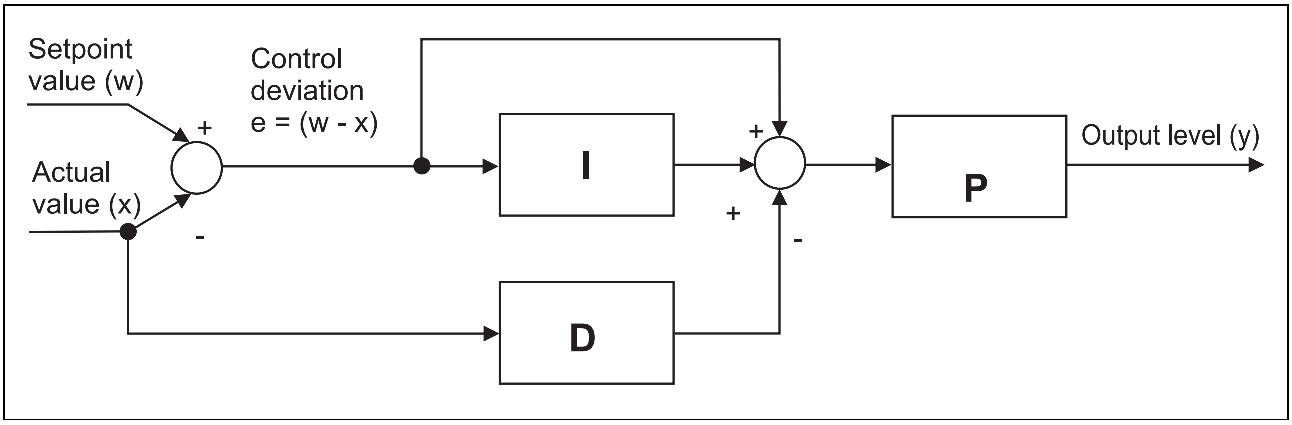


Figure 50: Block diagram of a PID controller

As can be seen from the equation for a PID controller, the P component also influences the I and D behavior. Figure 50 shows this chain structure.

If the proportional gain is doubled (by halving P_b), components I and D also work at double the intensity.

Example:
The PID controller shown in Figure 50 is set to r_t = 10 s and P_b = 100 K (the D component should be excluded from this example). The control deviation is 2.

When considered in dimensionless terms, the P component has a gain of $1\left(K_P = \frac{1}{P_b} \bullet 100\ \%\right)$.

The I component needs exactly the time r_t to reproduce the input signal at its output in a dimensionless manner. The output level is increased by 2 % within 10 s. Halving the proportional band or doubling the gain will also double the I component.

Therefore, increasing the proportional band, for example, will slow down the I component and reduce the intensity of the D component, and the two components are "moved in the right direction". If retuning is required, it is therefore often sufficient to change the proportional band, with no modifications required to the other control parameters.

For a PID controller, the I and D behavior is also influenced when the proportional band is changed.

4 Tuning controllers/selecting the controller structure

4.1 General information

This chapter describes various tuning methods and the autotuning function available in JUMO controllers. At the end of the chapter there is a guide to help you select the right controller structure for various control variables.

4.2 Transient behavior/disturbance behavior

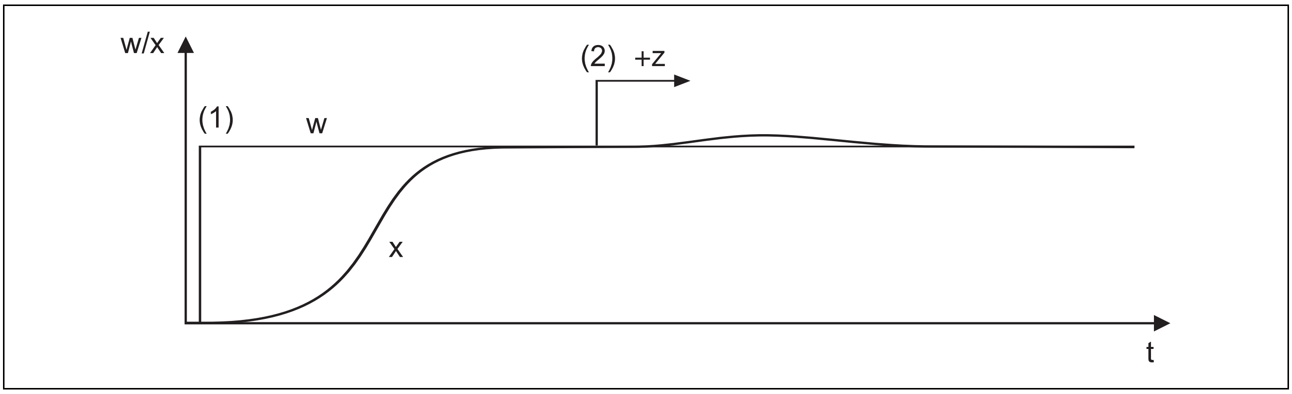


Figure 51: Transient behavior and disturbance behavior of a control loop

Controllers are typically tuned in terms of their transient behavior (1), which examines the control response after a new setpoint value has been specified.

Non-constant disturbances result in a temporary control deviation. The disturbance behavior examines how this control deviation can be eliminated (2).

Tuning controllers in terms of their transient behavior tends to result in high values for the control parameters (P_b, r_t, and d_t), and the resulting disturbance behavior is usually accepted. The disturbance behavior can be tuned further by reducing the control parameters. In the unusual event that controllers are tuned in terms of their disturbance behavior, the parameters calculated in this process, in turn, result in an overshoot of the actual value beyond the setpoint value for the transient behavior.

Parameter blocks and parameter block switching

In JUMO controllers, the control parameters can be stored multiple times in different parameter blocks. For example, parameters for the transient behavior can be stored in the first parameter block, and parameters for the disturbance behavior can be stored in the second parameter block. The limit value monitoring function monitors the control deviation. If a defined control deviation is not reached, the controller switches from parameter block 1 to parameter block 2 and the disturbance behavior parameters take effect.

4.3 Tuning methods

We recommend the following procedure to tune a controller:

If comparable plants/control loops exist, the control parameters of the controllers used in these systems can be used on a trial basis. Alternatively, the autotuning function included in JUMO controllers can be used. Both autotuning methods are described in Chapter 4.4 "*Autotuning in JUMO compact controllers*".

If neither of the aforementioned options leads to the desired result, one of the tuning methods described in this chapter may be used.

The response by control paths depends on the working point. Before tuning, the plant must be set to an operating status for which optimized control parameters are expected later on. For example, a furnace should be loaded before tuning, or a demand must be generated for a flow-type heater. If a setpoint value needs to be specified during tuning, this should lie within the subsequent working range.

4.3.1 The oscillation method according to Ziegler and Nichols

The method is used for relatively fast control paths. To prepare for the method, the parameters of the P structure are configured and a relatively large P_b is set. A setpoint value lying within the subsequent working range is defined (Figure 52).

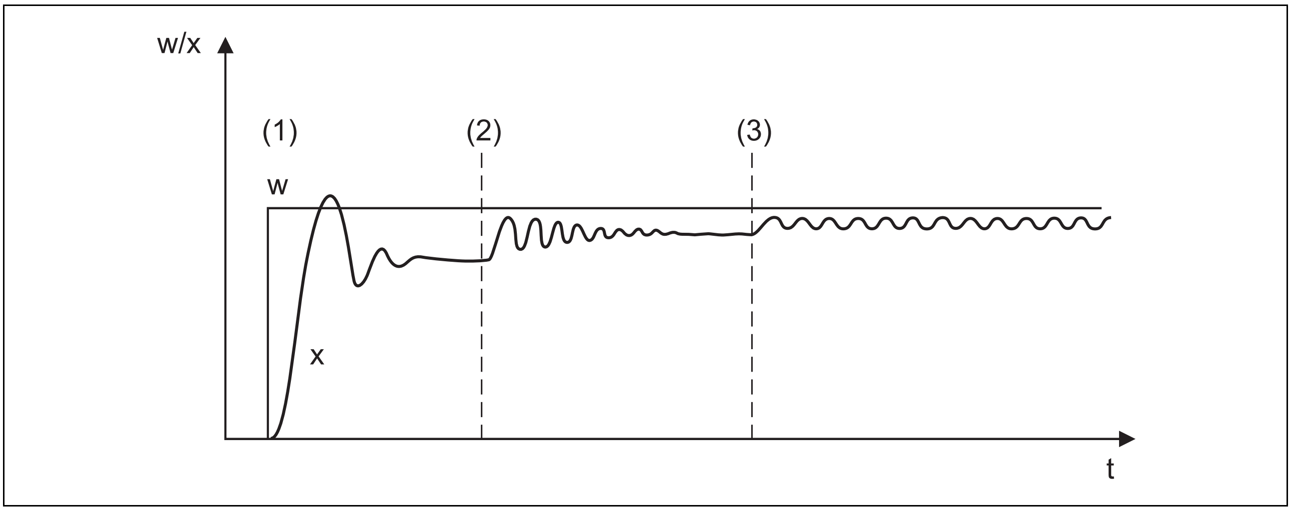


Figure 52: Setpoint value and actual value as part of the oscillation method

With the relatively large proportional band, the actual value tends to oscillate little as it moves toward the end value [Figure 52 (1)]. There is a permanent control deviation due to the lack of an I structure.

P_b is reduced [Figure 52 (2)]: the actual value increases and tends to oscillate more as it moves toward the end value. In certain circumstances the proportional band is reduced several times until the actual value is permanently oscillating [Figure 52 (3)]. The proportional band required for this method is called P_{bc} (critical P_b) and must be determined as accurately as possible (do not reduce $P_b$in excessively large intervals).

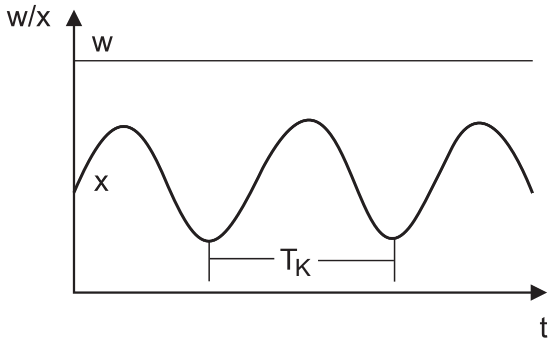


Figure 53: Critical pulse period

Based on the permanent oscillation of the actual value (Figure 53), the critical pulse period T_K represents the second parameter to be determined for the method. The critical pulse period T_K (in seconds) is calculated from the time interval between two minimum values, for example.

P_{bc} and T_K are used in the following table for the desired controller structure:

Controller structure	Control parameter
P	$P_b = P_{bc} /0.5$
PI	$P_b = P_{bc} /0.45$ $r_t = 0.83 \cdot T_K$
PID	$P_b = P_{bc}/0.6$ $r_t = 0.5 \cdot T_K$ $d_t = 0.125 \cdot T_K$

Table 1: Formulas for configuration according to the oscillation method

4.3.2 Method on the basis of the path step response according to Chien, Hrones, and Reswick

In this method the control parameters are calculated relatively quickly, even for slow control paths. The method is applied for paths as from the second order and is characterized by the fact that it distinguishes between the formulas for transient behavior and disturbance behavior.

For the rules of thumb, the transfer coefficient of the control path, the delay time, and the compensation time are calculated on the basis of the step response. Chapter 2.4 "*Recording the step response for paths with at least two delays and dead time*" describes the process in detail.

Controller structure	Transient	Disturbance
P	$P_b = 3.3 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$	$P_b = 3.3 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$
PI	$P_b = 2.86 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$ $r_t = 1.2 \cdot T_g$	$P_b = 1.66 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$ $r_t = 4 \cdot T_u$
PID	$P_b = 1.66 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$ $r_t = 1 \cdot T_g$ $d_t = 0.5 \cdot T_u$	**$P_b = 1.05 \cdot K_S \cdot (T_u / T_g) \cdot 100\ \%$** **$r_t = 2.4 \cdot T_u$** **$d_t = 0.42 \cdot T_u$**

Table 2: Formulas for configuration on the basis of the path step response

Example:
A controller with a PID structure is to be used for a laboratory furnace.
The aim is to achieve good disturbance behavior, and the typical setpoint values are 200 °C.

The output level is gradually increased in manual mode until the actual value is slightly below the future setpoint value (wait for the respective compensation process). For example, a temperature of 180 °C is reached with an output level of 60 %. Starting from 60 %, the output level is suddenly increased to 80 % and the actual value is recorded.

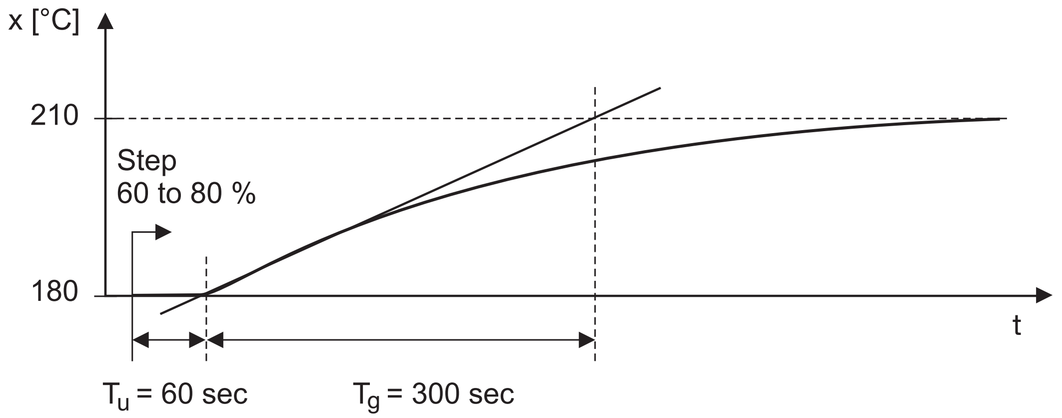


Figure 54: Step response of the laboratory furnace

Based on the step response (Figure 54), the following are calculated with the aid of the inflectional tangent:

Delay time T_u = 60 s, compensation time T_g = 300 s

The transfer coefficient of the control path is calculated by dividing the change to the actual value by the step change in the output level:

$$K_S = \frac{\Delta x}{\Delta y} = \frac{210\ °C - 180\ °C}{80\ \% - 60\ \%} = \frac{30\ K}{20\ \%} = 1{,}5\ K/\% \qquad (22)$$

Using the rules of thumb, this results in the following parameters for the disturbance behavior:

$$X_P = 1{,}05 \bullet K_S \bullet \frac{T_u}{T_g} \bullet 100\% = 1{,}05 \bullet 1{,}5\frac{K}{\%} \bullet \frac{60s}{300s} \bullet 100\ \% = 31{,}5K \qquad (23)$$

$$r_t = 2{,}4 \bullet T_u = 2{,}4 \bullet 60s = 144\ s \qquad (24)$$

$$d_t = 0{,}42 \bullet T_u = 0{,}42 \bullet 60s \approx 25s \qquad (25)$$

The step change to the output level must be performed in the area of the subsequent working point. Additionally, the step size must be set high enough to enable analysis of the course of the actual value.

Once the step change to the output level has been specified, it is necessary to wait for the end value of the actual value. A time-saving alternative is the method according to the rate of rise:

4.3.3 Method according to the rate of rise

In terms of the step change specification, the procedure is the same as that for the method on the basis of the path step response: prior to the step change an output level is specified that results in an actual value that is less than the setpoint value used later on.

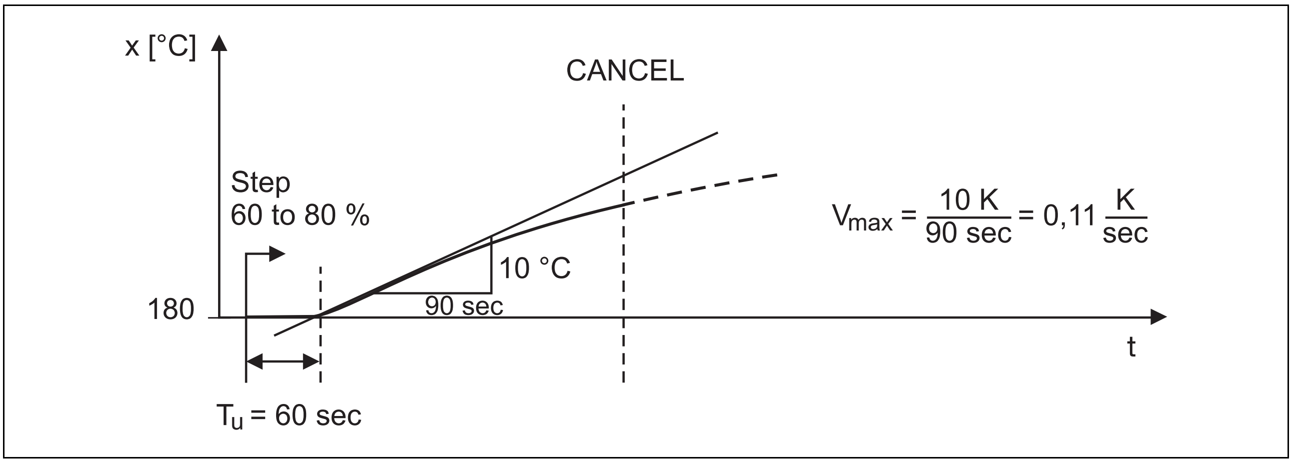


Figure 55: Course of the actual value for the method according to the rate of rise

The step change is specified for the laboratory furnace from Chapter 4.3.2 "*Method on the basis of the path step response according to Chien, Hrones, and Reswick*", whereby the subsequent working point is also 200 °C. Specifying an output level of 60 % in manual mode results in an actual value of 180 °C. The output level is suddenly increased to 80 %.

After specifying the step change, the actual value increases after a while. The recording continues until the actual value reaches its maximum slope. The inflectional tangent is also plotted and the delay time calculated for this method as well. The second parameter is the maximum rate of rise, which corresponds to the slope of the inflectional tangent. The maximum rate of rise can be determined by applying a slope triangle to the inflectional tangent:

$$V_{max} = \frac{\Delta x}{\Delta t} \qquad (26)$$

The calculated values V_{max} (0.11 K/s) and T_u (60 s) are used in the following formulas:

Controller structure	Control parameter	
P	$P_b = V_{max} \cdot T_u \cdot y_H / \Delta y$	y_H = maximum adjustment range (usually 100 %) Δy = specified step change to output level (20 % in the example shown)
PI	$P_b = 1.2 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$ $r_t = 3.3 \cdot T_u$	
PD	$P_b = 0.83 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$ $d_t = 0.25 \cdot T_u$	
PID	$P_b = 0.83 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$ $r_t = 2 \cdot T_u$ $d_t = 0.5 \cdot T_u$	

Table 3: Formulas for configuration according to the rate of rise

This results in the following values for a PID controller:

$$P_b = 0{,}83 \bullet V_{max} \bullet T_u \bullet \frac{y_H}{\Delta y} = 0{,}83 \bullet 0{,}11\frac{K}{s} \bullet 60\ s \bullet \frac{100\ \%}{20\ \%} \approx 27{,}4\ K \qquad (27)$$

$$r_t = 2 \bullet T_u = 2 \bullet 60\ s = 120\ s \qquad (28)$$

$$d_t = 0{,}5 \bullet T_u = 0{,}5 \bullet 60\ s = 30\ s \qquad (29)$$

4.3.4 Empirical method for calculating control parameters

This method is used to successively calculate optimal settings for the P, D, and I components. Starting from the original state (an output level of 0 %), the typical setpoint value is specified each time; the method is therefore only suitable for relatively fast control paths (such as fast temperature control paths or control variables such as speed or flow).

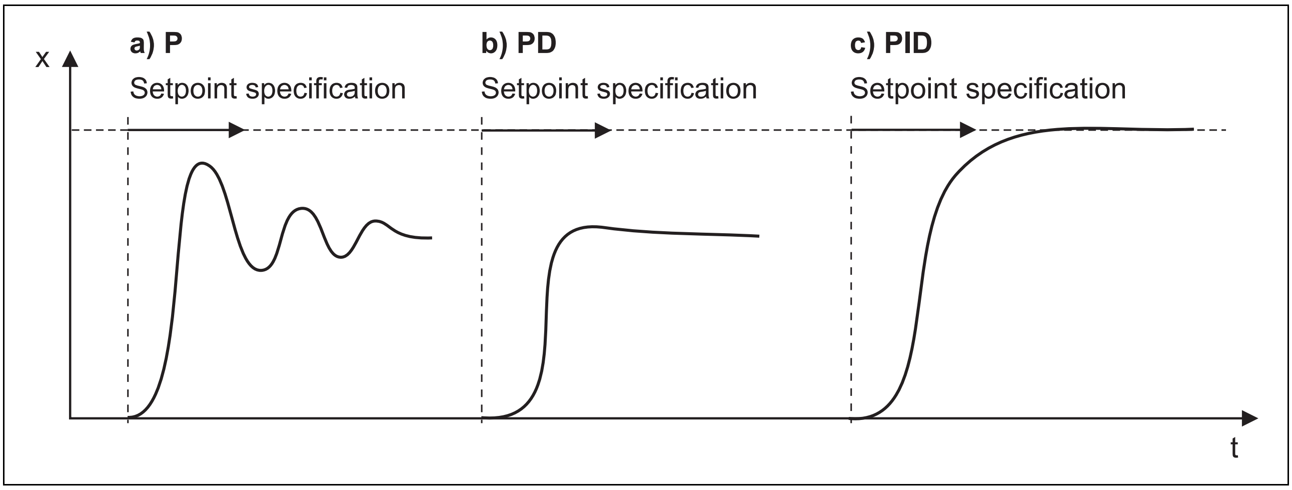


Figure 56: Configuring a PID controller according to the empirical method

The P structure is activated for the controller. The proportional band is set relatively large (the dimensioning depends on the control path) and the setpoint value in the subsequent working range is specified. The actual value will move slowly toward the end value and a relatively large control deviation is produced. The setpoint value is then specified with an increasingly small proportional band P_b. The aim is to achieve an P_b with which the actual value reaches its stable end value after two to three complete oscillations [Figure 56 (a)].

For a smooth start-up, the structure needs to be switched from P to PD. Starting with a small setting for the derivative time, the setpoint is specified with an increasingly large d_t. If the actual value reaches its end value with as small an oscillation as possible, d_t is at its optimal setting [Figure 56 (b)].

Note: as soon as the controller sets the output level to 0 % even just once during start-up, this means that d_t is too large.

The I component is activated when the structure is switched to PID. An optimal reset time r_t is generally set at four times the value of the previously calculated d_t. Figure 56 c) shows the response for a setting of $r_t = 4 \times d_t$.

On some paths it is not possible to activate all components. If, with a P structure, an unsettled response is already produced with a large P_b, it will not be possible to use the P or the D structure. The I controller needs to be used instead.

If the P controller was successfully tuned, but the introduction of the D component makes the control loop unstable, the PI structure should be used.

4.4 Autotuning in JUMO compact controllers

Autotuning finds optimal control parameters (P_b , r_t, and d_t) for many applications. As for the previous tuning methods, the operating conditions that will exist later on must be established for the plant (for example, a furnace must be loaded or a demand must be generated for a flow-type heater).

The standard method is the oscillation method:

4.4.1 The oscillation method

During autotuning, the controller calculates a switching level. If the actual value reaches this level, the output level is changed from 100 % to 0 % (or vice versa). The controller calculates the control parameters based on the course of the actual value:

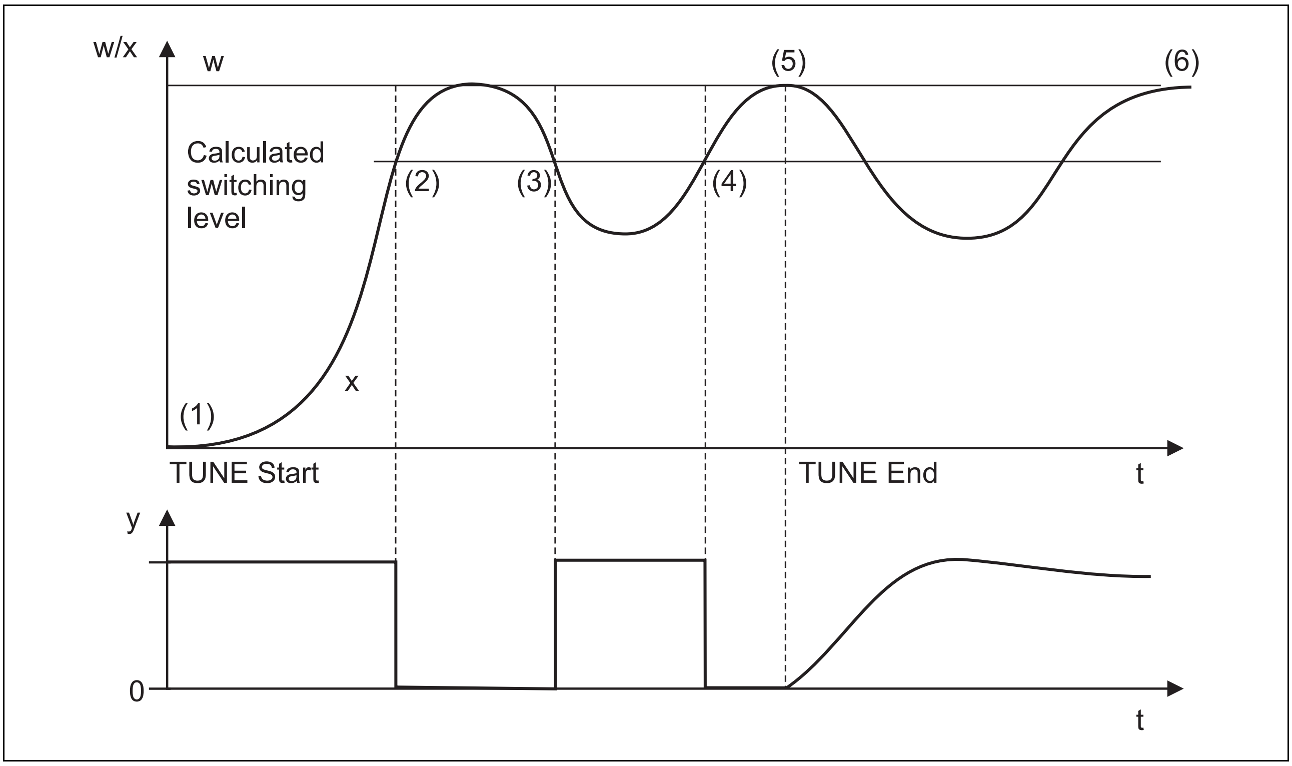


Figure 57: Course of the setpoint value, actual value, and output level during autotuning according to the oscillation method

In the example shown (Figure 57), autotuning is started once the setpoint value has been specified (1). The controller sets its output signal to 100 % and the actual value increases. During start-up, the controller calculates the aforementioned switching level. If the actual value reaches this level, the controller sets its output signal to 0 % (2). In the case of paths with a delay, the actual value also increases with an output signal of 0 %. Ideally, the actual value will reach the setpoint value and then change direction. The actual value decreases and, upon reaching the switching levels again (3), the power is set to 100 % again. As a result of the delays, the actual value only changes direction after a while. After the controller output has been switched off (4), the actual value reaches its maximum level for a second time (5). It is at this point that the controller has determined its control parameters, which it then uses to adjust the value to the setpoint value (6).

The method can generally be started with any actual value.

As can be seen in Figure 57, the controller alternately outputs an output level of 0 and 100 %. If tuning takes place during start-up, the maximum output level is also supplied for a prolonged period of time. Due to the behavior, in isolated cases the material to be processed or even the plant itself may be damaged. Examples include plastics processing machinery or large industrial furnaces. Additionally, use of the oscillation method for slowly cooling control paths is fraught with difficulties. It is extremely difficult to generate oscillations with these paths.

In the cases described above the alternative method based on the step response is used:

4.4.2 Step response method

In this method the controller provides a standby output when autotuning starts and waits for the actual value to stabilize (Figure 58). The controller suddenly increases the output level and the actual value increases with a rising slope. When the actual value reaches its maximum slope the control parameters have been determined and autotuning is complete:

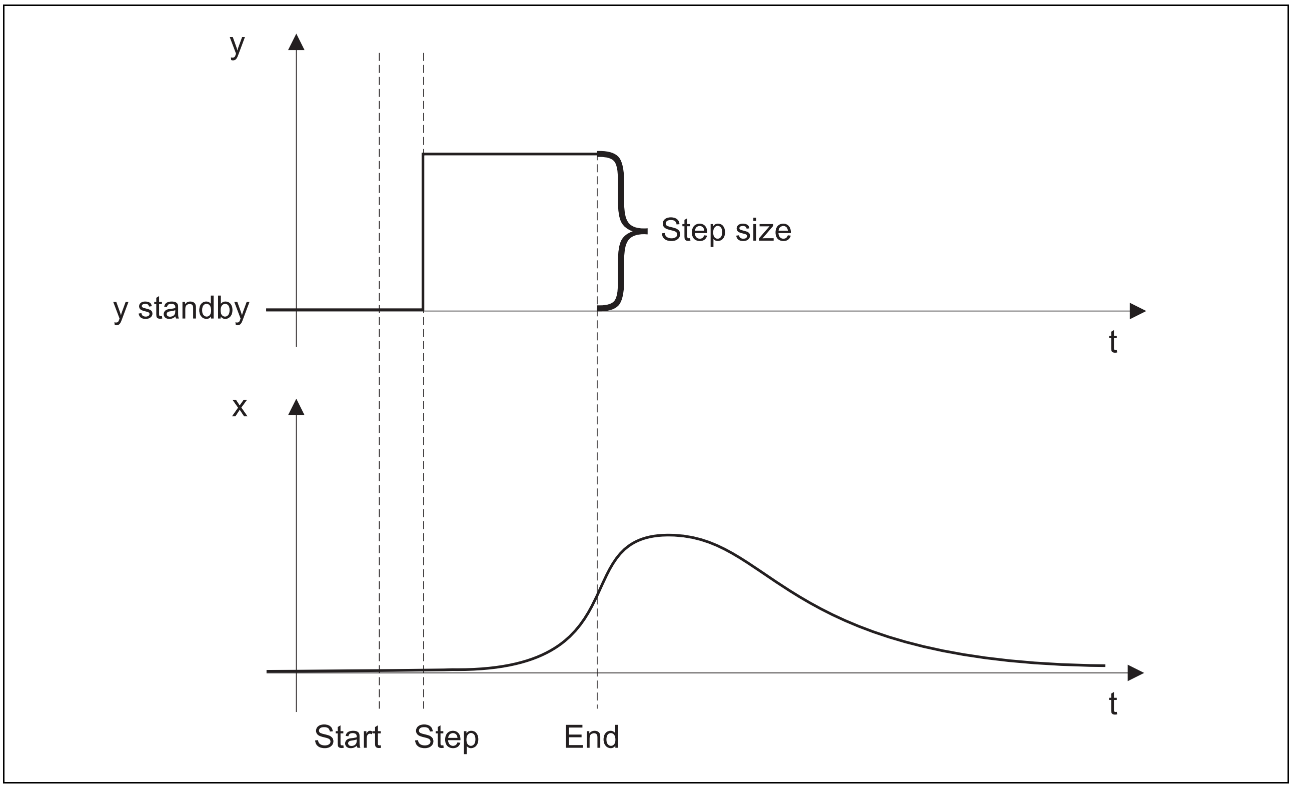


Figure 58: Course of the actual value and output level during autotuning according to the step response method

This method could be used before the plant is started up for the first time, for example (Figure 58). Autotuning is started and the standby output (0 % per default) is provided. If the controller detects that the actual value is stable, the output level is increased by the step change for the output level (30 % per default). The actual value increases with a rising slope. When the maximum slope for the actual value has been reached, the control parameters have been calculated and autotuning is complete. Once autotuning is complete, the user configures the setpoint value and the identified parameters are used to adjust the value to the setpoint value.

Tips for using this method: before starting autotuning, set a proportional band > 0 for the controller. Additionally, the controller draws on the reset time in order to calculate the time from the start of autotuning until specification of the step change. If the time until specification of the step change appears to be too long for a relatively fast control path, autotuning can be interrupted, a smaller reset time set (such as 40 s), and autotuning restarted.

4 Tuning controllers/selecting the controller structure

When using two-state and three-state controllers, before starting autotuning the cycle time (sum of switch-on and switch-off time) must be set to a sufficiently small value that, with a constant output level, the actual value does not oscillate as a result of the switching on and off.

Control paths modify their response depending on the working point. The step change to the output level is therefore performed in the area of the subsequent working point:

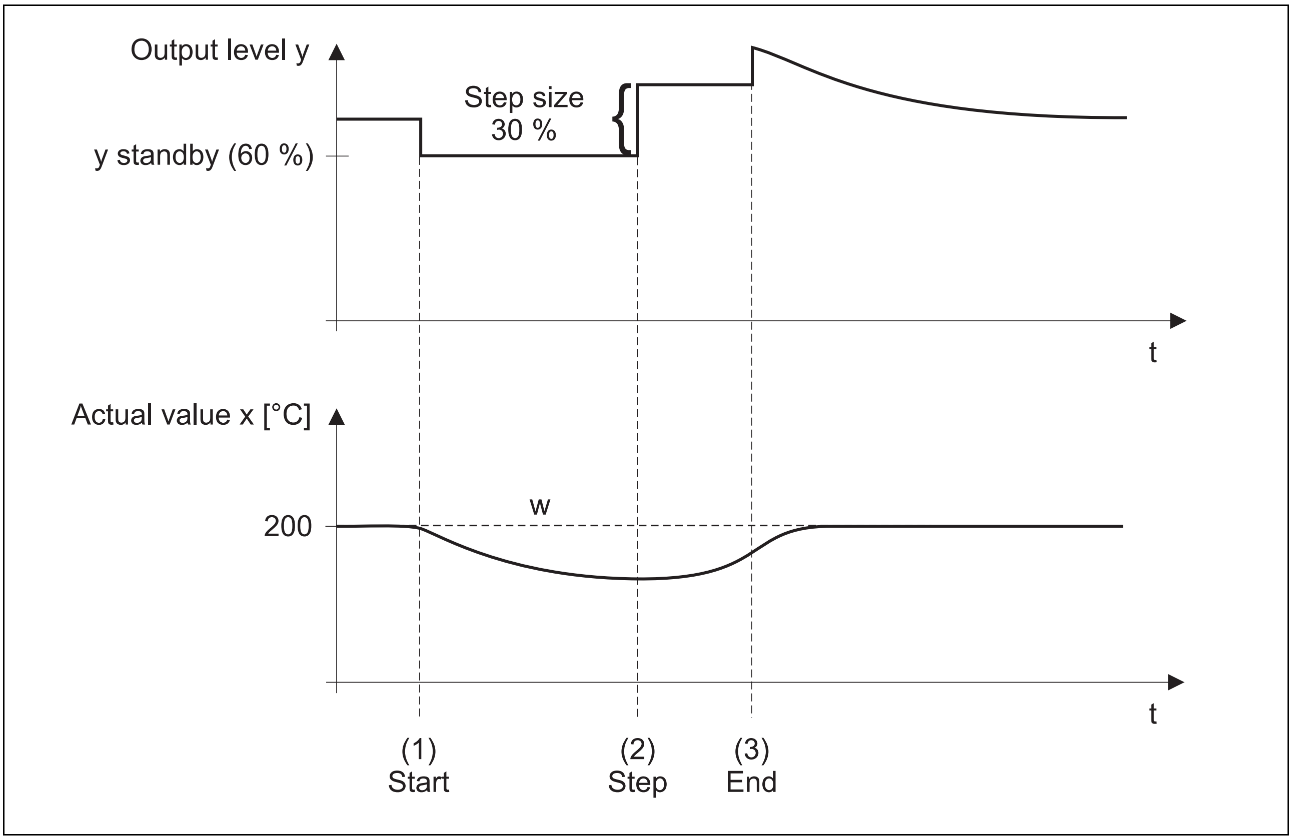


Figure 59: Performing a step change to the output level in the area of the working point

For example: the typical working point in an application is 200 °C. In order to use the method, the approximate output level for the working point must be known. In the example, the aforementioned 200 °C is reached with an output level of 60 %, whereby the output level can be determined in manual mode, for example. The step change to the output level is defined around the working point (standby output of 45 %, step size of 30 %):

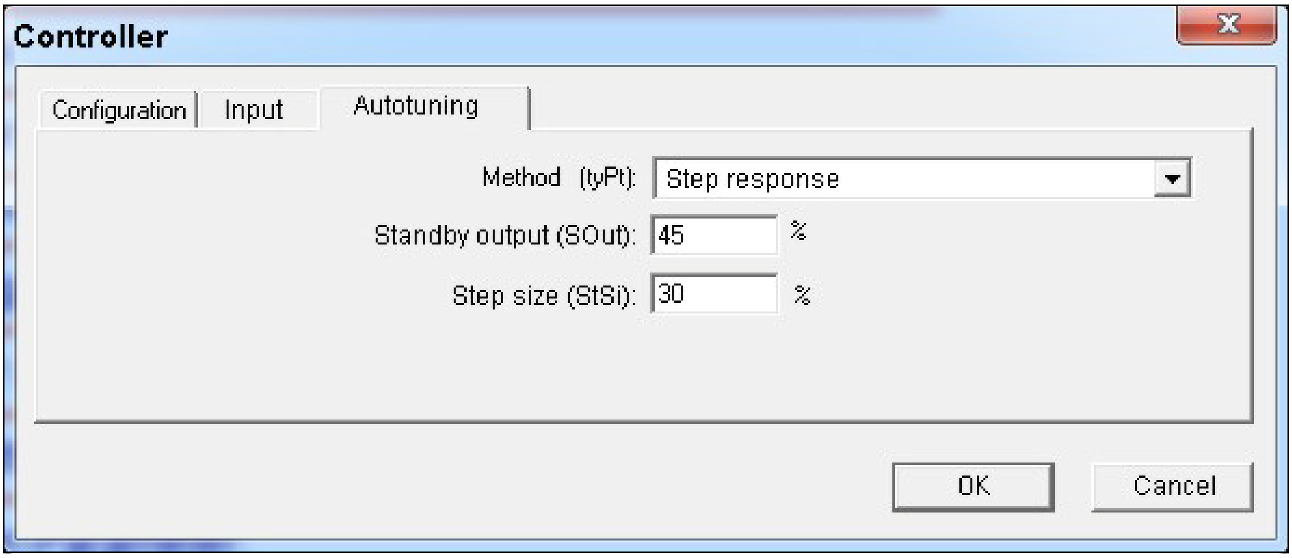


Figure 60: Autotuning settings in the configuration program of a JUMO controller

Autotuning takes place when the controller is in automatic mode. When autotuning starts, the controller provides a standby output of 45 % (Figure 59) and cooling takes place. If the controller detects that the actual value is stable, the output level is increased by 30 %. When the maximum slope for the actual value is reached, autotuning is complete.

4.4.3 Further information on tuning methods

Both methods can only be used for paths with compensation.

The oscillation method can be used for any configurable controller (continuous, two-state, three-state, modulating, and position controllers).

The same applies to the step response method, but in the case of modulating controllers this method is only used for a standby output of 0 % and a step size of 100 %. This is due to the fact that modulating controllers have no knowledge of the actual position of the actuator; see Chapter 5.3.2 "*Modulating controllers*".

For both methods, the structure is automatically set to PID after autotuning and the parameters P_b , r_t, and d_t are calculated. There are two exceptions in this context:

For various control paths, use of the D component results in an unstable response. Examples include pressure and flow control paths. In these cases, the PI structure is set before autotuning is used. Tuning is then carried out for a PI controller and the autotuning does not change the structure.

If a path of the first order is detected during autotuning, the structure is changed to the PI structure.

In the case of two-state and three-state controllers, the controller also calculates the cycle time of the digital outputs (sum of switch-on and switch-off time) in addition to the control parameters for the PID response.

In order to successfully determine the cycle time, the type of output must be configured:

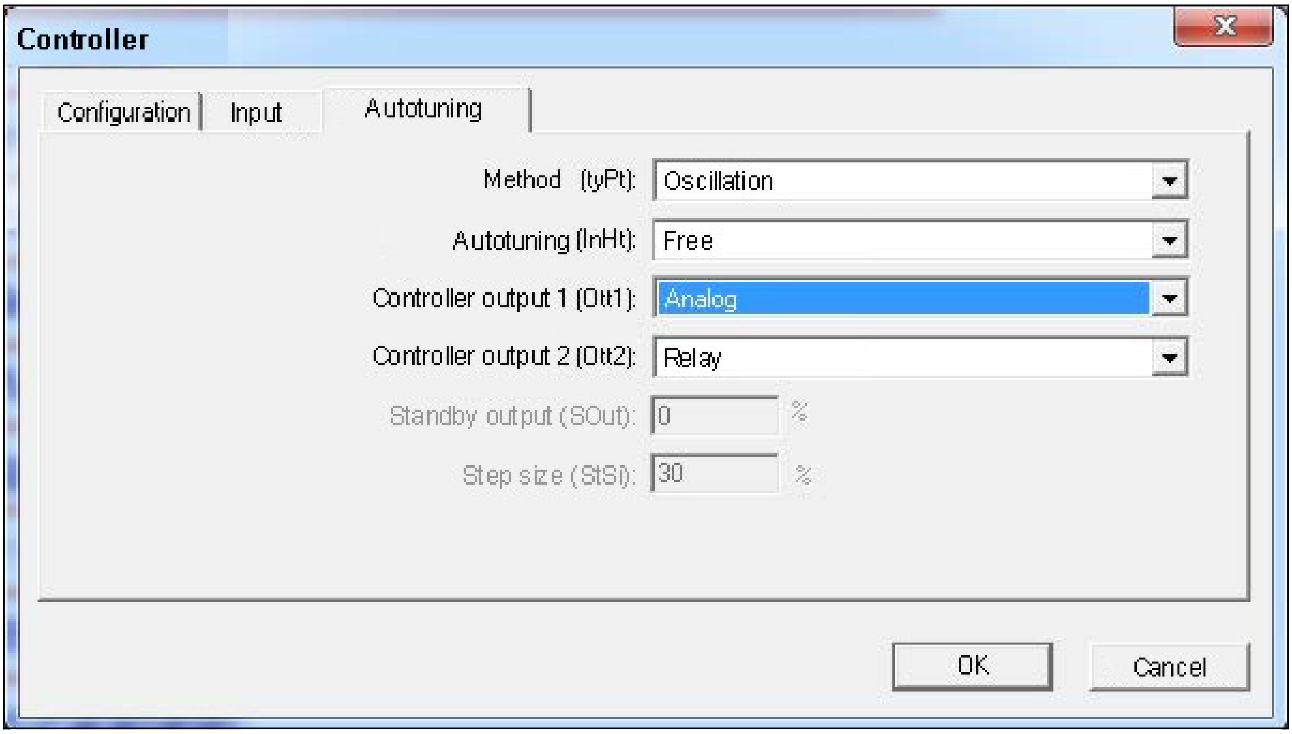


Figure 61: Type of outputs for autotuning

In the case of a continuous controller, "Analog" must be set for controller output 1.
For a two-state controller, the settings "Relay" and "Semiconductor + Logic" are possible under "Controller output 1".
For a three-point controller, the output type must be set for controller output 1 and controller output 2. Possible types are "Relay" and "Semiconductor + Logic" as well as "Analog".

Differentiating between the "Relay" and "Semiconductor + Logic" settings

In the "Relay" setting, autotuning calculates as short a cycle time as is necessary. The relay and downstream mechanics are protected as far as possible.
In the "Semiconductor + Logic" setting, as small a cycle time as possible is calculated (the output will switch very frequently).

4.5 Checking the controller setting for the PID structure

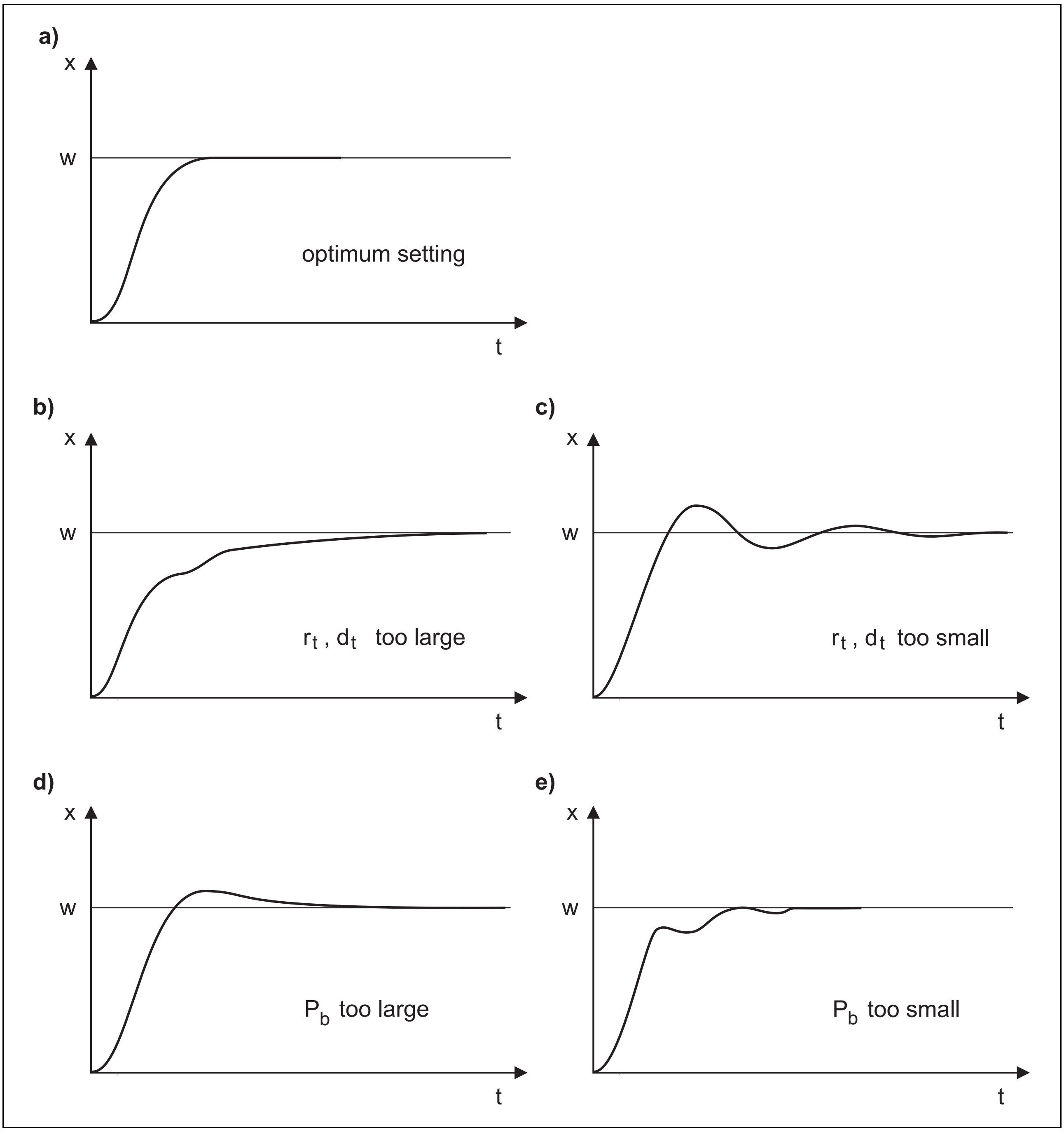


Figure 62: Indications of potentially incorrect settings

Figure 62 shows the control response of PID controllers with indications of necessary post-tuning.

a) The diagram shows an optimal response from a PID controller

b) After specification of the setpoint value, the actual value increases steeply until it reaches the proportional band. If the actual value enters the proportional band, the P component is reduced and the I component ensures the value is adjusted to the setpoint value. The increase of the I component takes place slowly on account of the relatively large r_t and the control deviation is slowly eliminated. d_t needs to be reduced according to the ratio $d_t / r_t = 1/4$.

c) When the actual value enters the proportional band, the I component increases the output level. The increase continues until the actual value reaches the setpoint value. In the example shown, the I component builds up an excessive output level until the elimination of the control deviation, and the actual value surpasses the setpoint value. If there is a negative control deviation, the output level is reduced too quickly and the actual value falls below the setpoint value, and so on. The symmetrical oscillation of the actual value around the setpoint value is indicative of too small a r_t. Too small a d_t is also being used according to the ratio $d_t / r_t = 1/4$.

d) The I component is formed from the time the actual value enters the proportional band until the elimination of the control deviation. Due to the large P_b, the I component already starts to build up its output level when there is a large control deviation. Due to the large control deviation at the start, the I component forms its output level relatively quickly. When the control deviation is eliminated the I component is too large and the actual value surpasses the setpoint value. With a smaller setting for P_b, if there are smaller control deviations the I component starts to build up its output level at a correspondingly slower rate. The one-off overshoot depicted becomes more improbable.

e) With a small P_b, the output level of the P component is reduced shortly before the setpoint value is reached. When the actual value enters the proportional band, the P component is sharply reduced and the actual value decreases. Due to the larger control deviation the output level becomes larger and the actual value increases. The response oscillates in the proportional band.

4.6 Guide for selecting the right controller structure for various control variables

The PID structure demonstrates the best control response for the majority of applications. However, a number of control variables exist for which certain components need to be deactivated:

Paths with a small T_g/T_u ratio become unstable if the D component is used; the PI structure is recommended.

If the T_g/T_u ratio is very small, even the P component will cause instability; the I controller should be used instead. The most extreme example is a control path with only dead time with a ratio of $T_g / T_u = 0$.

The D component is generally disruptive for pulsating control variables since it continuously counteracts the change to the actual value.

Paths without compensation necessitate the use of the P or PD structure. The PID structure may also be used if disturbances are taken into account.

Control variable	**In most cases (!) the following controller structure leads to the best result**
Temperature	PID
Pressure	I
pH-value	Throughput control: PID; stand-alone basin: P or PD
Speed	PI
Flow	I
Level	P or PD (PID in certain circumstances)
Transport (bulk material)	I
Positioning	P or PD

Table 4: Selecting the controller structure for the most important control variables

5 Controllers with digital outputs

This chapter covers two-state, three-state, modulating, and position controllers. Apart from one exception for three-state controllers, these controllers exclusively feature digital outputs. The outputs can be relay, logic, solid state, or PhotoMOS® outputs.

The controllers are used to control digital actuators such as relays, SCR power switches, or solenoid valves.

5.1 Two-state controllers

Two-state controllers supply two statuses: 1 and 0 or on and off. They enable control of a binary actuator in relatively slow processes.

The controller can be described as a combination of a continuous controller and a downstream switching step. The switching step implements pulse width or pulse frequency modulation:

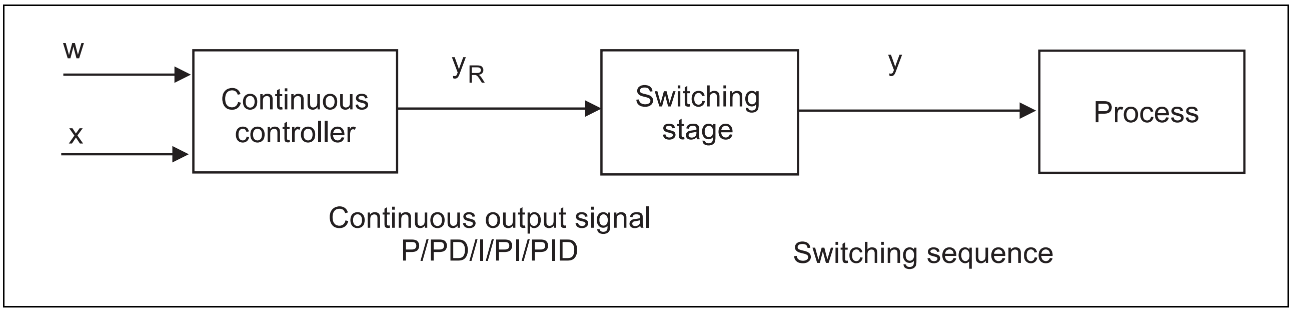


Figure 63: Two-state controller as a continuous controller with downstream switching step

5.1.1 Two-state controllers with pulse length output

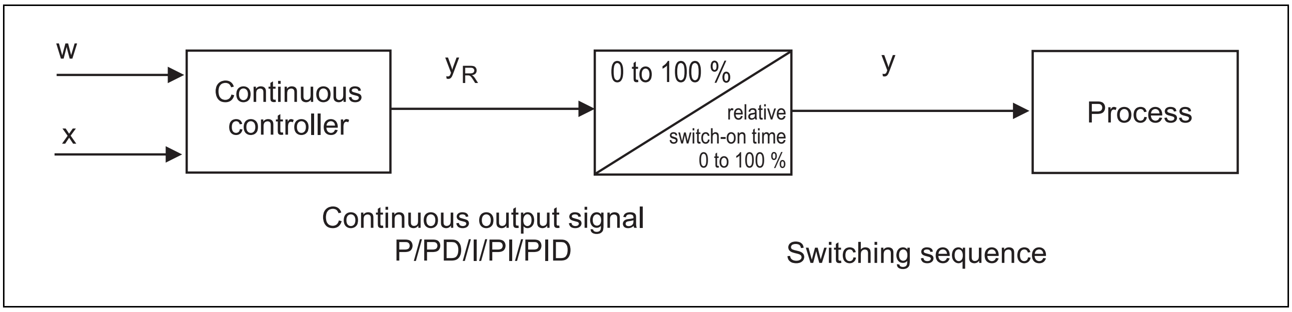


Figure 64: Two-state controller with pulse length output

Two-state controllers with pulse length output vary the relative duty cycle of the output in proportion to the continuous controller output level y_R:

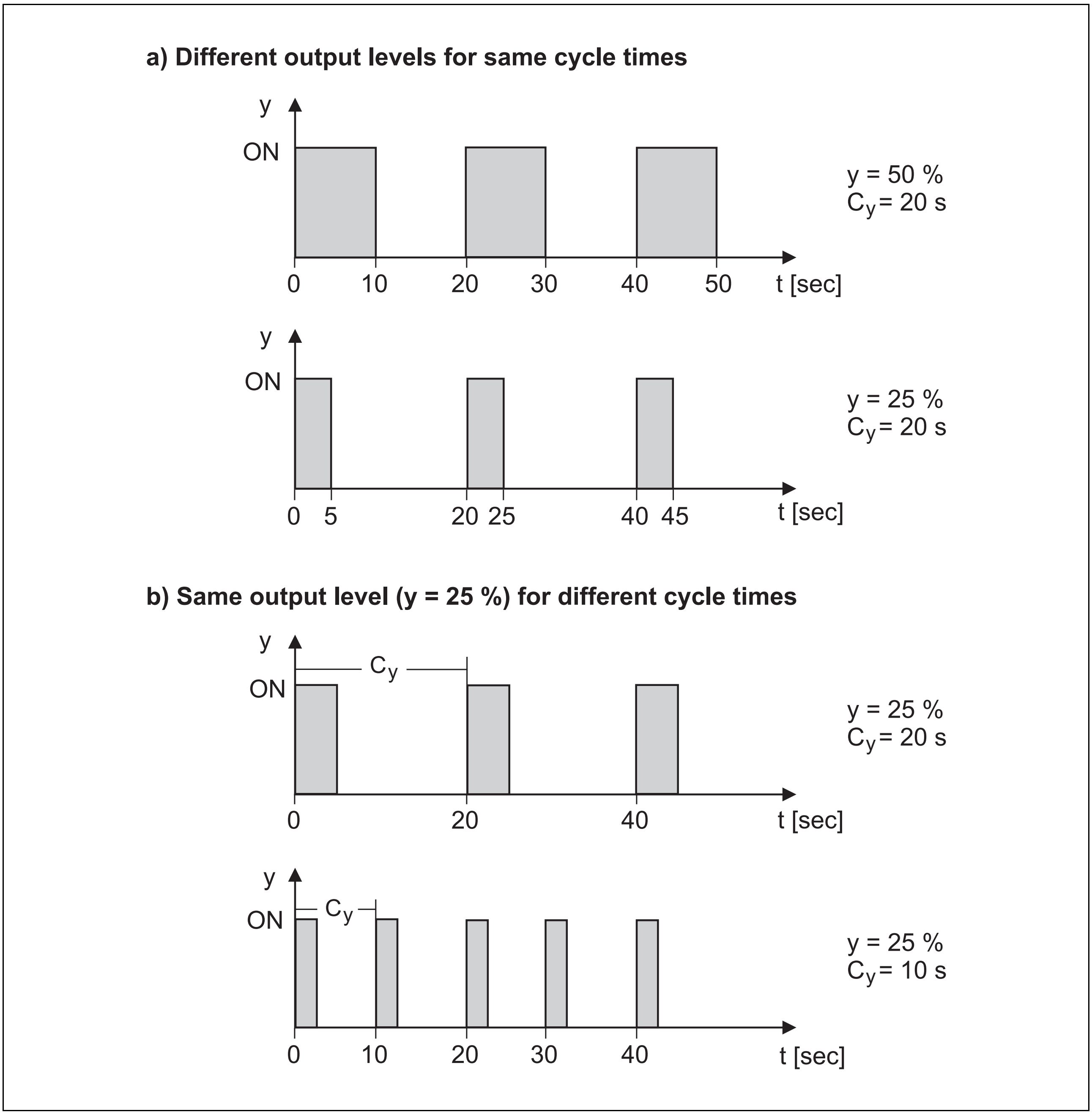


Figure 65: Two-state controller with pulse length output

Figure 65 a) shows the output signal of the controller with an output level of 50 % and 25 %. Accordingly, the controller activates its output for 50 % and 25 % of the time, and the output level corresponds to the relative duty cycle.

For the pulse length output, the cycle time C_y needs to be defined. The output switches on and off once within the cycle time; in the example shown it is 20 s.

If the cycle time has been set too large for the process, then the actual value will fluctuate even if the output level remains the same. Figure 65 b) shows a constant output level (25 %) with different cycle times. In the second case, a smaller cycle time has been set (10 s). The energy is more finely dosed and this results in smaller fluctuations of the actual value. The setting for the cycle time must be so small that it results in no, or acceptable, fluctuations of the actual value.

If mechanics need to be controlled, the cycle time C_y should only be set as small as is required. A small C_y negatively affects the operating life of items such as relays or contactors. In the case of electronic outputs (logic, solid state, or PhotoMOS® outputs) the C_y can be set as small as possible to maximize the control quality.

5.1.2 Two-state controllers with pulse frequency output

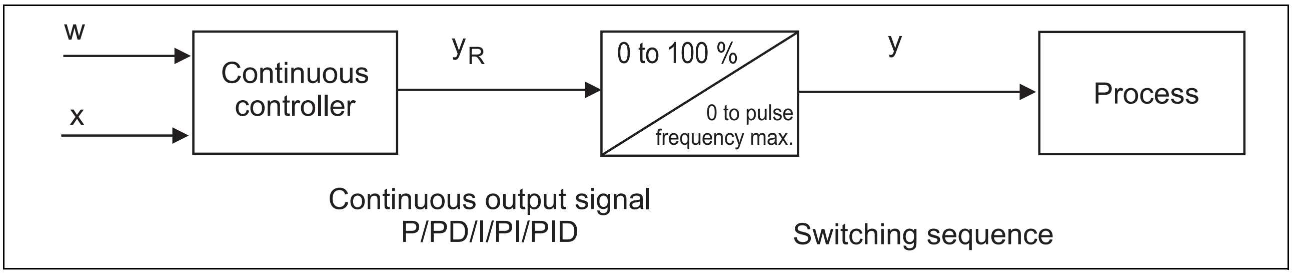


Figure 66: Two-state controller with pulse frequency output

Two-state controllers with pulse frequency output vary the pulse frequency of the output in proportion to the continuous controller output level y_R. For the switching step, the maximum pulse frequency is defined on the controller. The frequency at the digital output (0 to maximum pulse frequency) is varied in proportion to the controller output level (0 to 100 %). Two-state controllers with pulse frequency output are used to control dosing pumps.

5.1.3 Minimum ON period for two-state controller with pulse length output or pulse frequency output

Some actuators that are controlled with pulse length output need to be activated and deactivated for a minimum period of time. In addition to the cycle time (C_y), many JUMO controllers therefore also allow the aforementioned minimum ON and OFF period (T_k) to be specified.

Figure 67 shows the status of the digital output for a two-state controller with pulse length output. The minimum ON period is 20 s and the cycle time is 100 s.

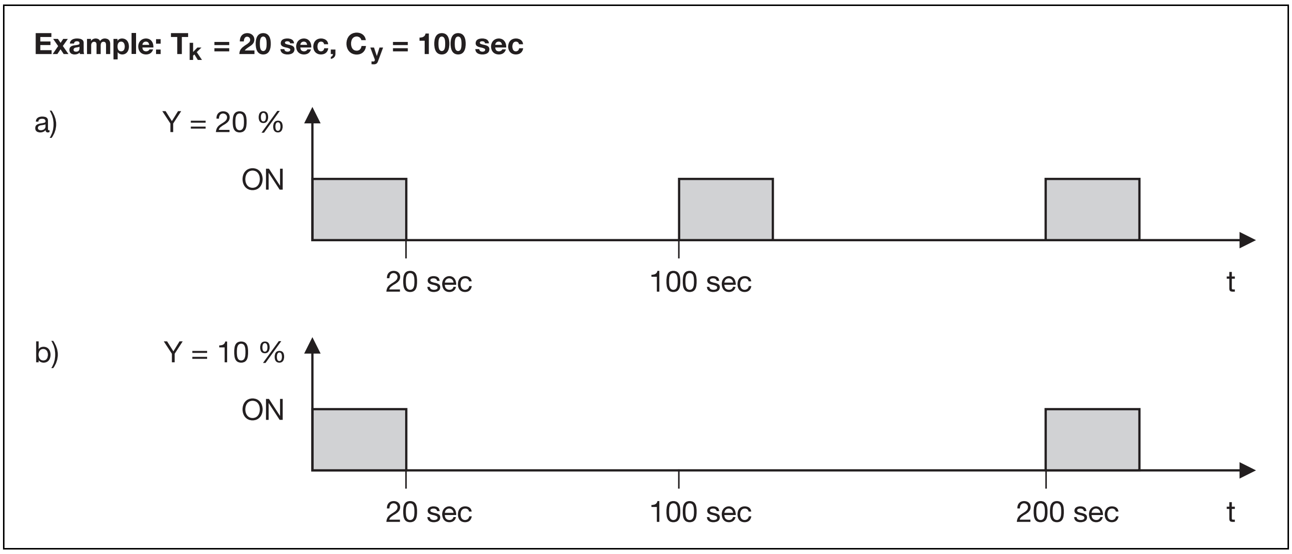


Figure 67: Output signal of a two-state controller, T_k = 20 s

In Figure 67 a), the controller provides an output level of 20 %: it closes the output for 20 s and opens it for 80 s (the cycle time of 100 s is adhered to with this output level).

In Figure 67 b), the controller provides an output level of 10 %: the output is also activated for 20 s in this case. For 10 % of maximum power, nine times the deactivation time for the output is required. For the stated output level, the controller extends the actual cycle time to 200 s.

If a dosing pump (controlled with a pulse frequency output) requires a minimum control period, this is also set using T_k.

5.1.4 Exception: discontinuous two-state controllers

If the controllers described in Chapter 5.1.1 "*Two-state controllers with pulse length output*" and Chapter 5.1.2 "*Two-state controllers with pulse frequency output*" are operated with a proportional band (P_b) of 0, the controller will display discontinuous behavior:

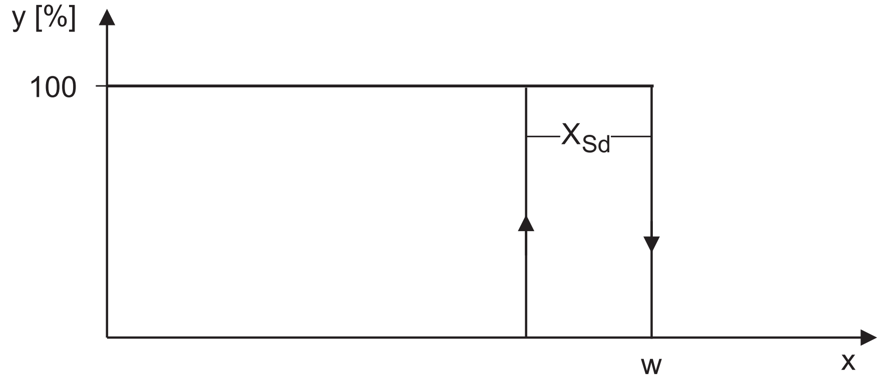


Figure 68: Characteristic line of a discontinuous two-state controller

The controller provides an output level of 100 % until the setpoint value is reached with a rising actual value. If the actual value is above the setpoint value, the output level is 0 %.

At an output level of 100 %, the controller with pulse length output permanently closes the digital output, and the controller with pulse frequency output switches the output with maximum frequency. At a level of 0 %, the outputs of both controllers remain switched off.

By setting a proportional band (P_b) = 0, JUMO controllers operate with the switching differential parameter (X_{Sd}).
If the actual value is declining, the controller switches on its output at $x < (w - X_{Sd})$.

Control response of a discontinuous two-state controller on paths of first and higher orders

Response when operating paths of the first order using the example of a thermal plant

When the cooled plant is switched on, the heating is activated immediately. The temperature increases immediately as there is only one energy store (Figure 69). Upon reaching the setpoint value, the power is reduced to 0 % and the actual value does not surpass the setpoint value. Theoretically, the actual value falls immediately and reaches the lower switching point after a while (setpoint value switching differential). The heating is switched on again and the actual value rises again. On a path of the first order, the actual value moves in the switching differential band. The smaller the switching differential and the faster the control path, the higher the switching frequency.

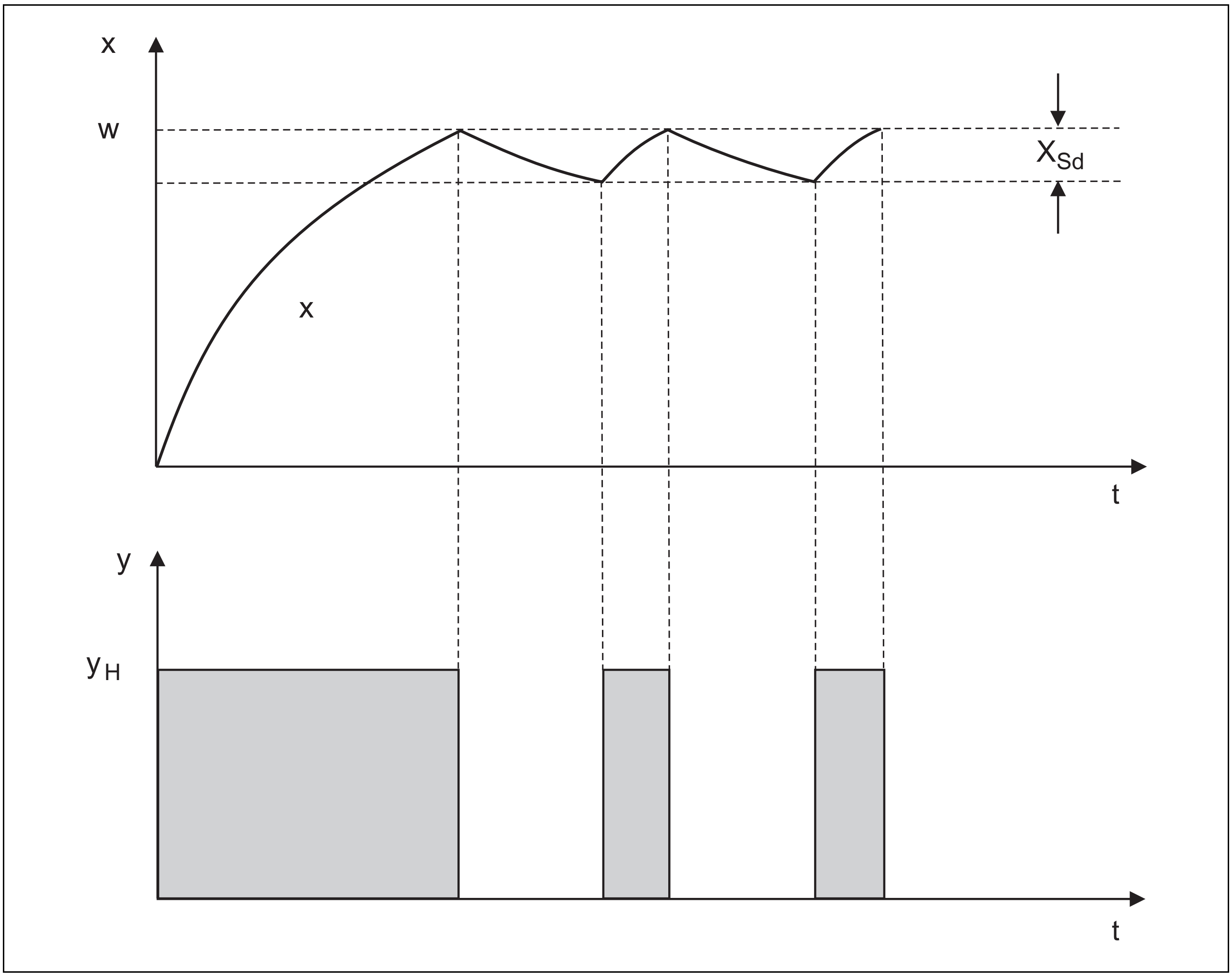


Figure 69: Discontinuous two-state controller on a path of the first order

Response when operating paths of a higher order using the example of a thermal plant

When a cooled plant is switched on, the heating is also switched on immediately (Figure 70). As there are several energy stores, the control variable does not increase until after a while (the energy stores first need to be charged). Upon reaching the setpoint value, the power is reduced to 0 %. Due to the delay time T_u, the actual value exceeds the setpoint value. The actual value falls after a while and reaches the lower switching point. The heating is switched on and the actual value rises with a delay.

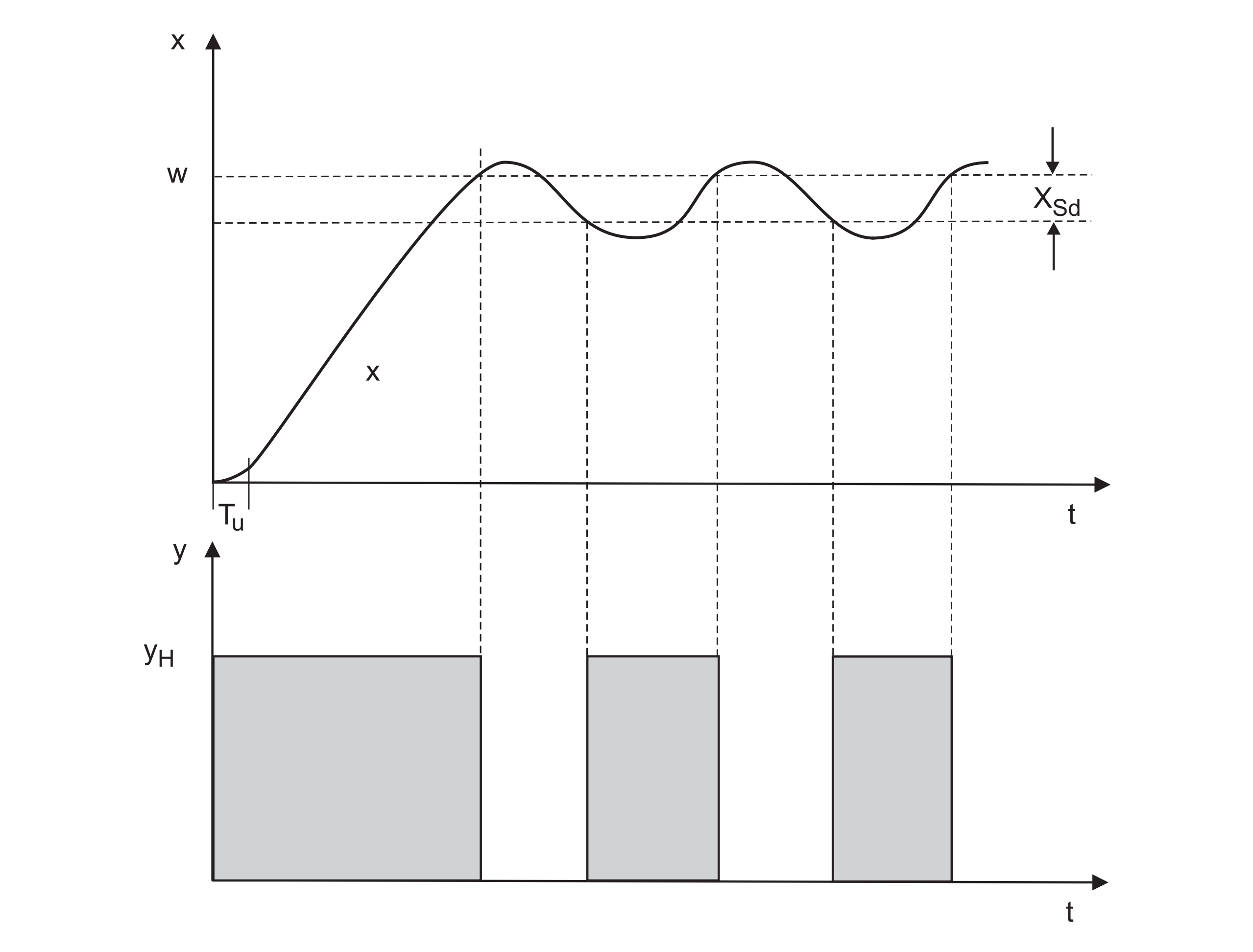


Figure 70: Discontinuous two-state controller on a path of a higher order

On paths of a higher order, the oscillations of the actual value are larger than the switching differential. For a thermostat, for example, the switching differential is 5 K, but the actual value may oscillate over a range of 10 K.

Summary:
Cost-effective control with a discontinuous controller is possible in the form of a thermostat, for example. This type of control is advisable if the resulting fluctuations in the actual value are not disruptive. However, two-state controllers are usually operated with a proportional band > 0 in compact controllers. On relatively slow control paths, the result of the control by the controllers corresponds to that of continuous controllers.

5.2 Three-state controllers

Three-state controllers influence the actual value in two directions. Typical examples include heating/cooling or humidification/dehumidification. In general a three-state controller can be described as a combination of two continuous controllers with switching steps that are usually located downstream.

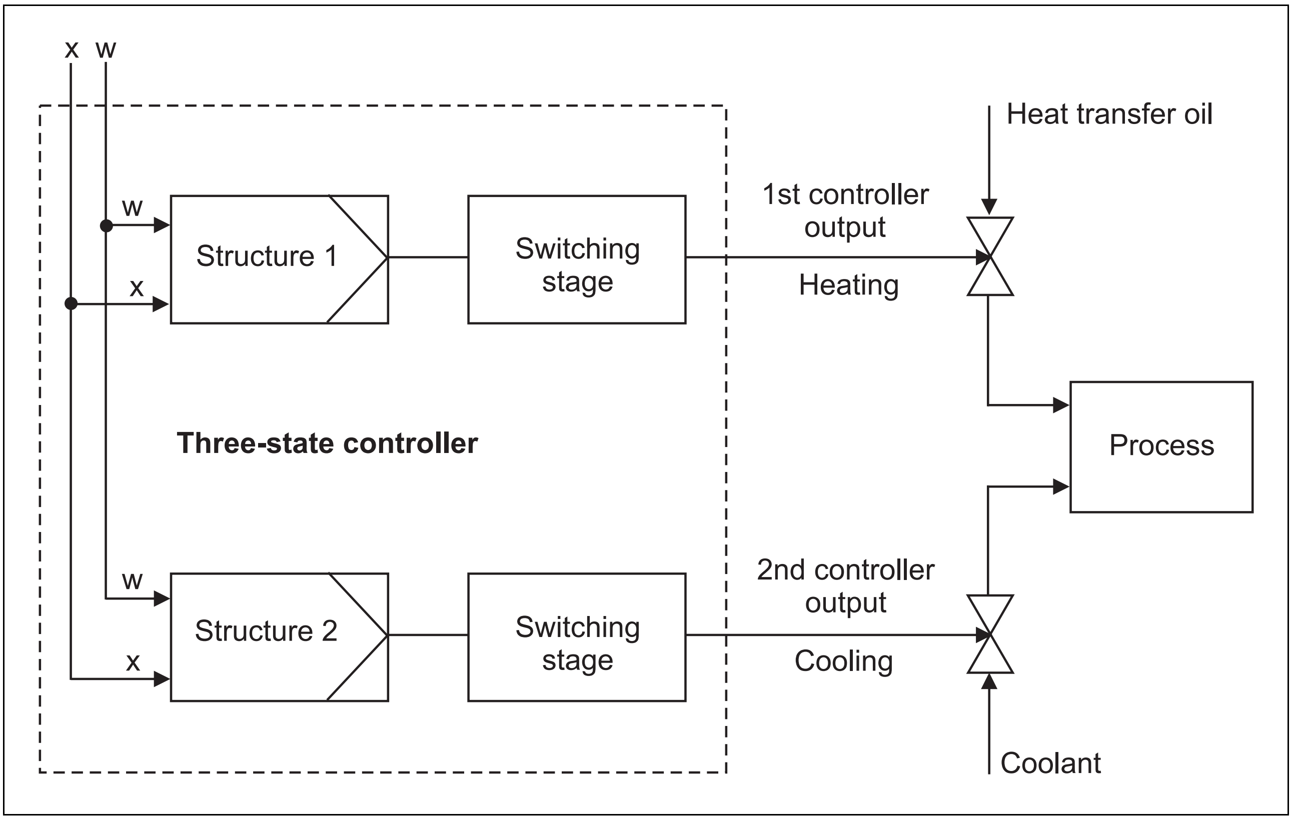


Figure 71: Design of a three-state controller

Three-state controllers involve two controller structures. For a thermal process, for instance, structure 1 provides a positive output level in the range 0 to 100 %. The output level is supplied to a switching step (pulse length or pulse frequency output) or provided directly with a continuous output.

Accordingly, if cooling is required structure 2 provides an output level of 0 to -100 %. The output level is provided directly with a continuous output or, if necessary, supplied via a switching step in the form of a pulse length or pulse frequency output.

The outputs of the two structures are referred to as the first and second controller output.

Both structures can be adjusted independently of one another (P, PD, I, PI, and PID). An index identifies the structure to which the control parameters belong: structure 1 (P_{b1}, r_{t1}, d_{t1}, etc.) or structure 2 (P_{b2}, r_{t2}, d_{t2}, etc.).

5.2.1 Contact spacing

On three-state controllers, undesired alternate switching of the first and second controller output may occur (heating and cooling, for instance). It may be the case that heat is generally required in an application and the actual value fluctuates around the setpoint value. The alternating actuation of the outputs for heating and cooling results in ineffective operation of the plant. The contact spacing (X_{SH}) can provide a solution here:

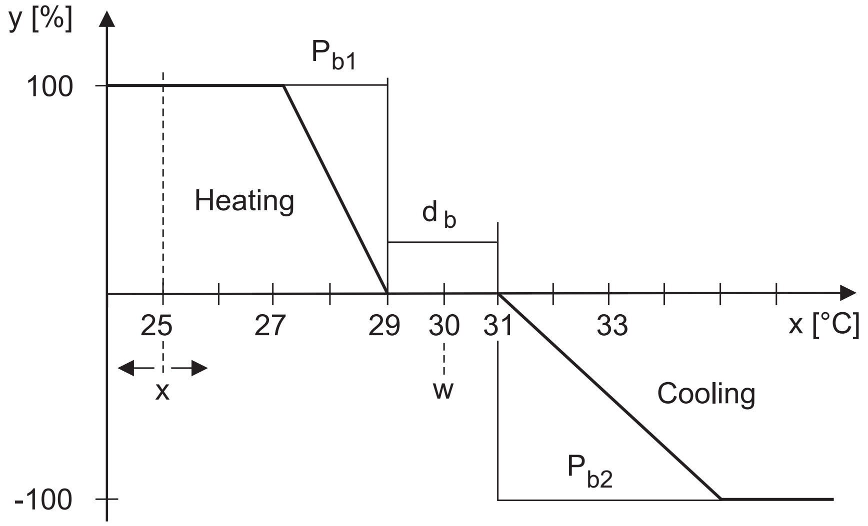


Figure 72: Three-state controller with contact spacing and P response for structure 1 and 2

Figure 72 shows the diagram for a three-state controller. A P response exists for both structures. P_{b1} is 2 K andP_{b2} is 4 K. The contact spacing has been set to 2 K.

When heating is started (actual value is at 25 °C, for example) the output level is 100 % and the first controller output provides the maximum possible power. The output level is reduced as from an actual value of 27 °C until it ultimately reaches 0 % at 29 °C. On paths of a higher order, the actual value may exceed 29 °C and enter the contact spacing (X_{SH}). Neither of the two controller outputs is active in the contact spacing area. The contact spacing "pushes" the proportional bands of the two controller structures away from each other. Without the contact spacing, the actual value would immediately enter the proportional band P_{b2} upon exceeding the setpoint value, and cooling would be initiated.

In the stationary state a steady-state control deviation is produced for the P structure: the actual value is ultimately located in proportional band P_{b1}. After the structure is switched from P to PI, the additional I component integrates the control deviation and adjusts the actual value to the setpoint value. The same applies if cooling is required.

Summary:
Appropriately configured contact spacing prevents undesired alternate actuation of the two actuators for heating and cooling, for instance. Larger dimensioning for the parameter will slow down the control response but has no impact on the control accuracy.

Control direction

In terms of the control direction, the overall output level of the controller needs to be considered. With a rising actual value, the controller from Figure 72 reduces the output level from 100 % (controller output 1 is actuated 100 %) to -100 % (controller output 2 is actuated 100 %). The control direction is inverse.

Both structures can output the relevant output level with continuous output, pulse length output, and pulse frequency output. The two structures also operate in a discontinuous manner with P_{b1} or P_{b2} = 0:

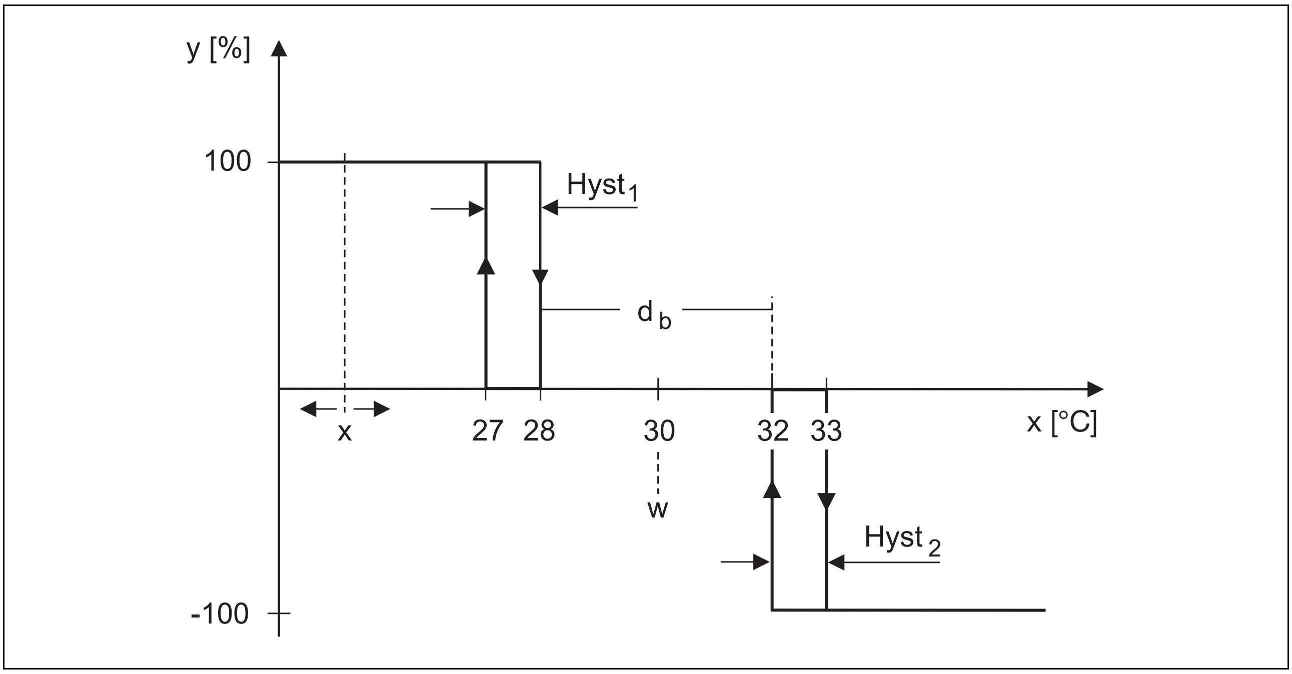


Figure 73: Three-state controller with discontinuous response

Figure 73 shows the control response for a three-state controller with P_{b1}, P_{b2} = 0 K, X_{Sd1}, X_{Sd2} = 1 K, and X_{Sh} = 4.

5 Controllers with digital outputs

5.3 Controller for actuating motor actuators

Motor actuators comprise a servomotor and an actuator. The actuators are often valves (gas, water) or flaps (air, etc.). The motor is switched to clockwise or counterclockwise operation by means of two supply lines, which opens or closes the actuator.

The voltage supply is normally provided to the aforementioned supply lines via two relay N/O contacts:

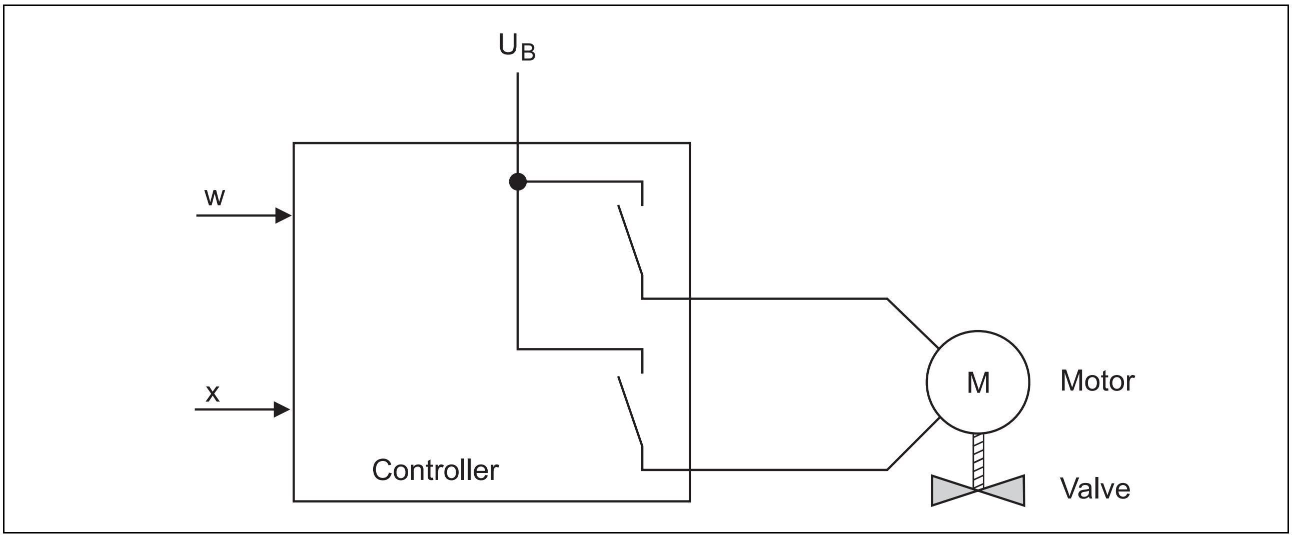


Figure 74: Actuating a motor actuator via two relay N/O contacts

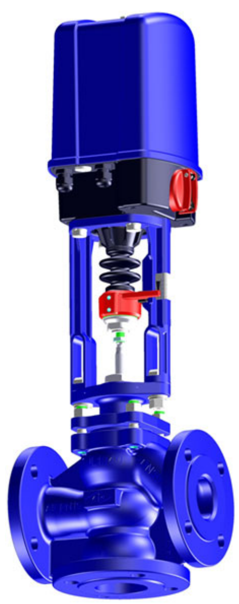


Figure 75: (Motor) actuator made by ARI-Armaturen Albert Richter & Co. KG

Position controllers and modulating controllers are used to actuate motor actuators.

5.3.1 Position controllers

The full description for a position controller is "continuous controller with an integrated position controller":

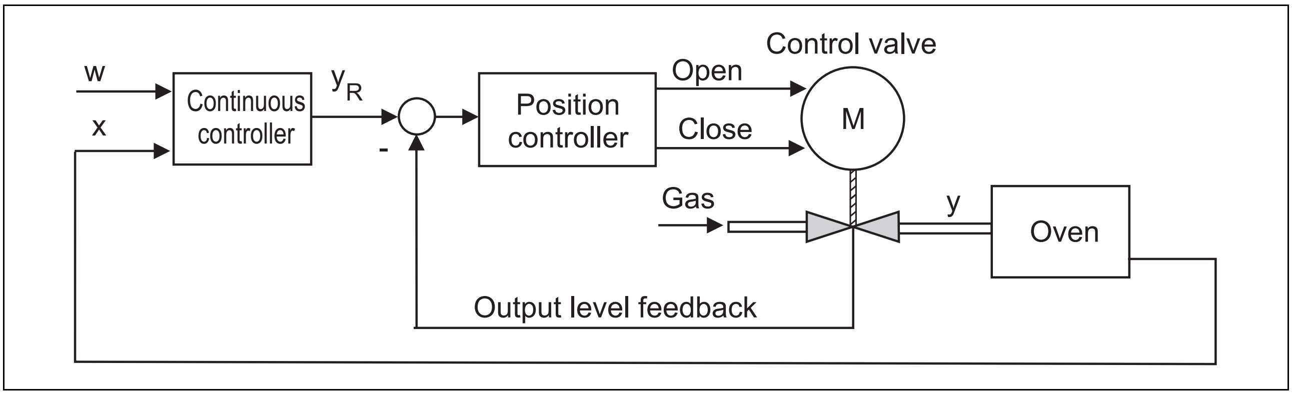


Figure 76: Continuous controller with an integrated position controller in the control loop

Due to the control parameters and the setpoint and actual values, the controller (Figure 76) supplies an output level in the range from 0 to 100 %. The subordinate position controller adjusts the position of the actuator in proportion to the output level. For this positioning, the output level feedback needs to be sent to the controller. This can be done using the resistance transmitters in the actuators, for example:

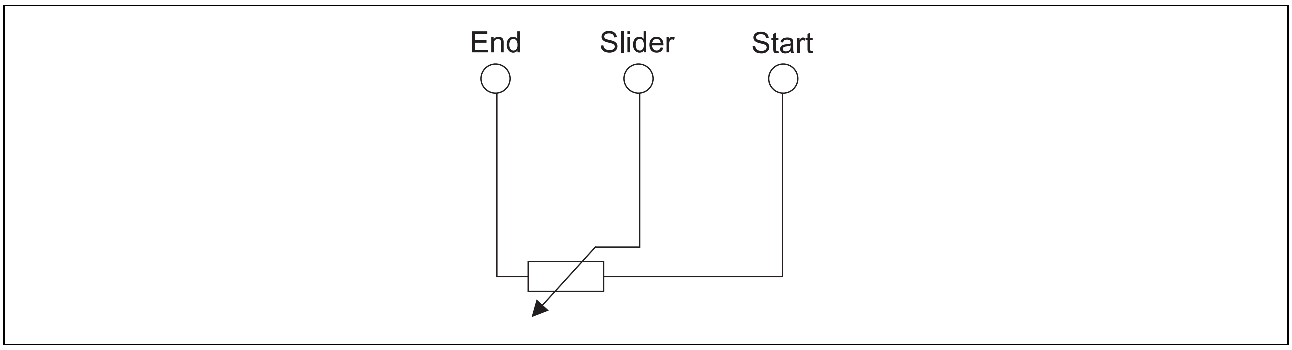


Figure 77: Principle of a resistance transmitter

The second analog input of the controller usually receives the output level feedback. The actual value (the furnace temperature in Figure 76) is supplied to the controller via analog input 1.

It is not necessary to tune the subordinate position controller; only the actuator time (TT) needs to be set on the controller. The actuator moves from fully open to closed (and vice versa) within this actuator time. Typical values for TT are 30 or 60 seconds.

5.3.2 Modulating controllers

In comparison with position controllers, modulating controllers have no output level feedback. The controller cannot move toward defined positions, rather it merely opens and closes the actuator:

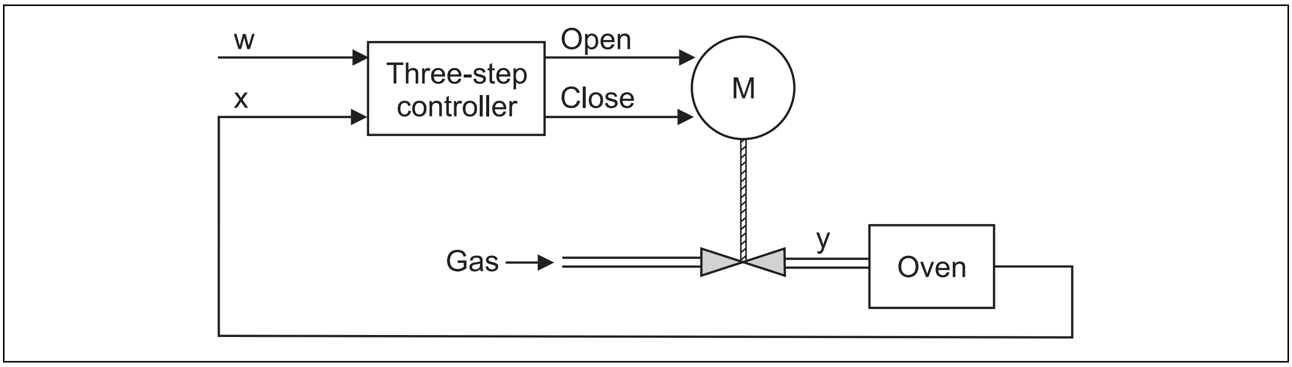


Figure 78: A modulating controller with motor actuator in a closed control loop

As there is no output level feedback, it is not possible to move toward a defined output level, even in manual mode; the only action is manual opening and closing. Furthermore, only controller structures with an I component are possible (PI and PID).

Example:
For a modulating controller with the PI structure (P_b = 25 K, r_t = 120 s) and an actuator time (TT) of 60 s, the actual value = setpoint value = 0 °C. After increasing the setpoint value, the control deviation is 10 K (Figure 79).

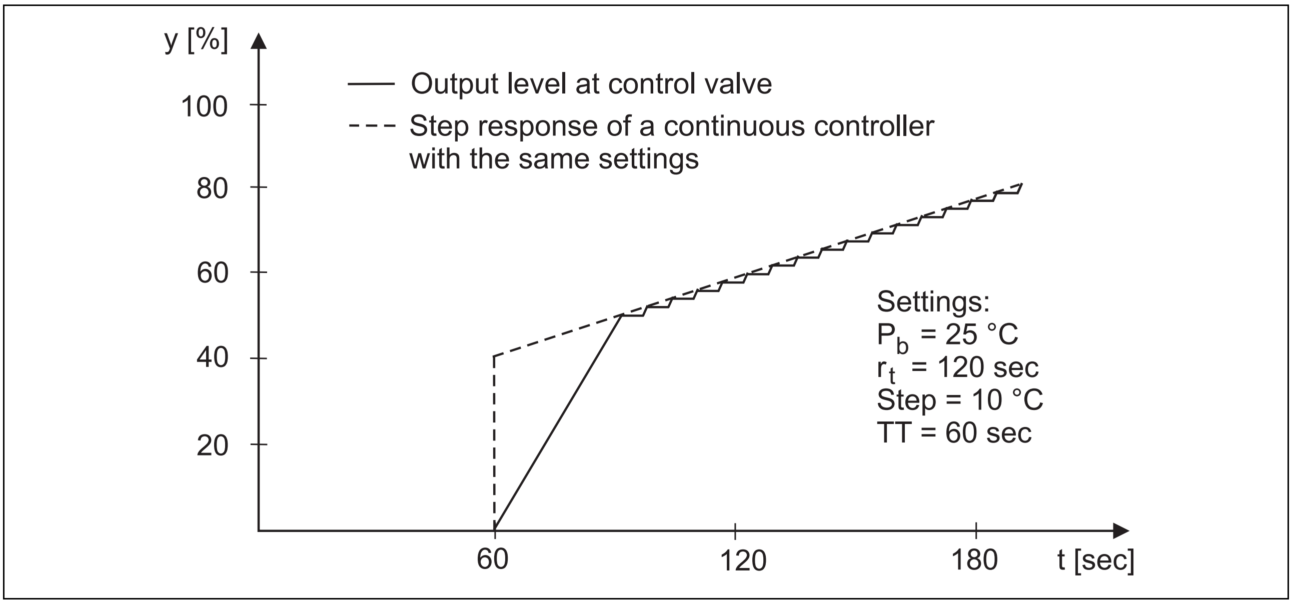


Figure 79: Step response of the system comprising a modulating controller and adjustment valve

A P component of 40 % is produced from the configured P_b of 25 K and the suddenly occurring control deviation of 10 K. The modulating controller actuates the relay for 24 s and therefore increases the output level by 40 %:

$$\frac{40\ \%}{100\ \%} \bullet \text{Actuator time} = 24\ \text{s} \quad (30)$$

On account of the control deviation of 10 K and the dimensioning of P_b = 25 K and r_t = 120 s, the I component is increased at a speed of $\frac{1\ \%}{3\ s}$.

The aforementioned output level increase at the actuator with a runtime of 60 s is performed with a relay relative duty cycle of 20 %.

While the control deviation is present, the controller opens the actuator ever further. With modulating controllers it may be the case that the actuator is already open, but the controller continues its attempts to open. As such end switches are required in the actuators.

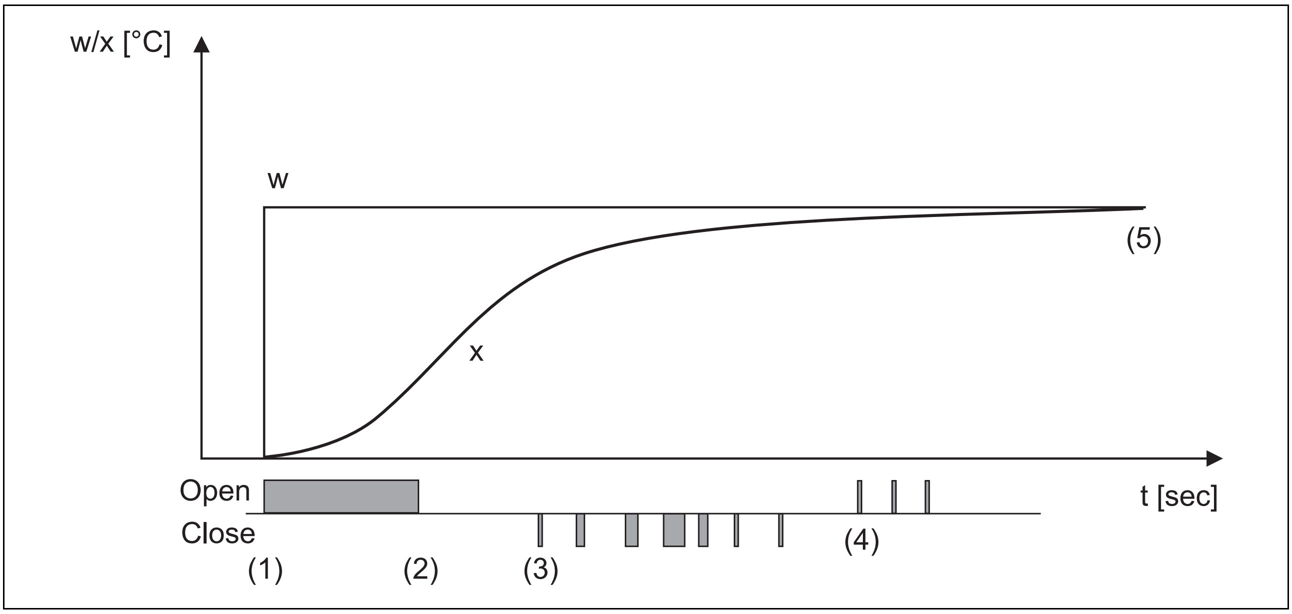


Figure 80: Transient behavior of a modulating controller

Figure 80 shows the setpoint value, actual value, and the two outputs of the modulating controller: at (1), a new setpoint value is specified. The actual value lies outside the proportional band and the controller uses the first controller output to open the valve for at least the actuator time [until (2)]. If the actual value enters the proportional band (3), the P component will be reduced and the I component will simultaneously increase. From (3) onward, the reduction of the P component predominates and the actuator is closed. From (4) onward, the increase in the I component predominates and the overall output level increases. The modulating controller closes and later opens the valve with the two controller outputs in accordance with the change to the output level and the actuator time. From (5) onward, adjustment is complete, the controller outputs are no longer actuated, and the valve remains in its position.

Manual mode

As has been mentioned above at several points, the modulating controller has no knowledge of the actual position of the actuator, and it cannot move the actuator to an output level that was defined in manual mode. After activating manual mode, the actuator is moved manually (jog mode).

5.3.3 Further information on position controllers and modulating controllers

Contact spacing

The controllers always actuate their outputs for at least the sampling rate, which is between 50 and 250 ms on JUMO controllers. Against this background, modulating controllers and position controllers are never able to fully eliminate the control deviation.
For example, an actuator time of 60 s and an actuation of longer than 250 ms result in a theoretical change to the output level of approx. 0.4 %. Based on the change to the output level, this results in a change to the actual value of possibly several Kelvin. The actual value will fluctuate around the setpoint value and the actuator will be opened and closed. The contact spacing parameter (X_{Sh}) defines a band around the setpoint value in which the controller outputs are not actuated. The control accuracy will adjust to a range of w ± 1/2 X_{Sh}.

Practical setting for the contact spacing

If the actuator is alternately opened and closed in the area of the setpoint value after having tuned the controller, a setting of greater than 0 is required for the contact spacing. The parameter is increased until there is no alternating opening and closing in the area of the setpoint value. This prevents unnecessary strain on the actuator.

Comparison of position controller with modulating controller

Advantages of position controllers

The position controller implements the output level required by the continuous controller in both automatic and manual mode. This leads to a slightly higher control quality and other benefits during servicing.

Position controllers enable Split-Range control to be established relatively easily.

Advantages of modulating controllers

Thanks to control that does not depend on the output level feedback, modulating controllers offer higher operational reliability.

Modulating controllers enable the control to be established more cost-effectively and this is sufficient for many applications.

The controller circuits presented in this chapter pursue the following goals for the plant:

- Cost-optimized set-up
- Simpler control
- Resource-optimized and cost-optimized operation
- Ability to keep disturbances stable
- Reduction of impact of disturbances
- Limitation of the flow of energy

6.1 Base load

When operating plants with base load settings, a part of the power is always supplied to the plant as a basic principle. The controller only controls a part of the overall power.

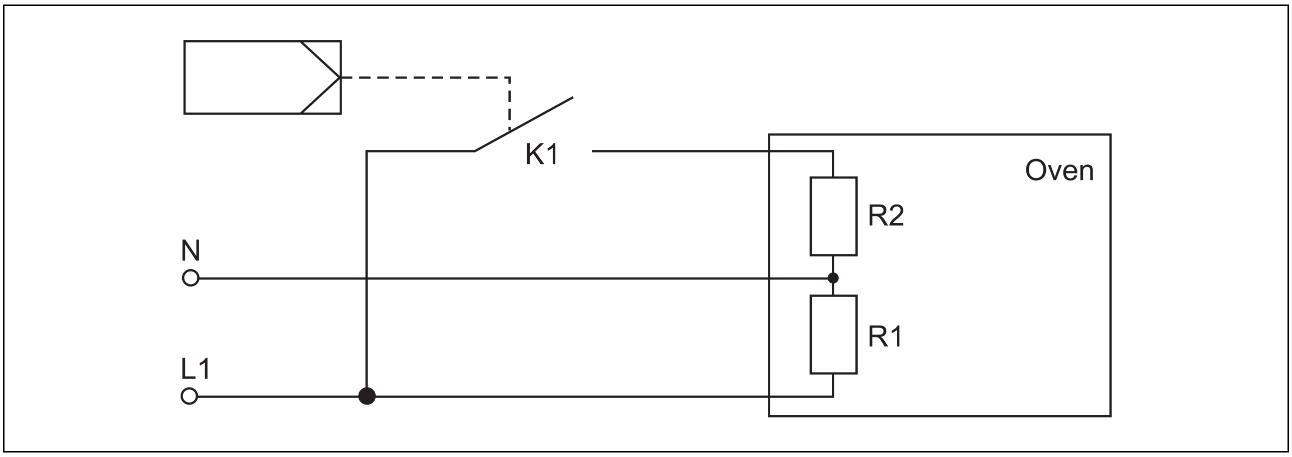


Figure 81: Base load settings

In the example shown (Figure 81), heating 1 is constantly switched on and the controller only controls heating 2. Thanks to the base load settings, the dimensioning for the actuator can be reduced. Furthermore, if electrical heating is involved and two-state controllers are being used, the alternating load on the network is also lower. In the case of a controller malfunction, the process is continued with the base load.

6.2 Two-stage control of actuators

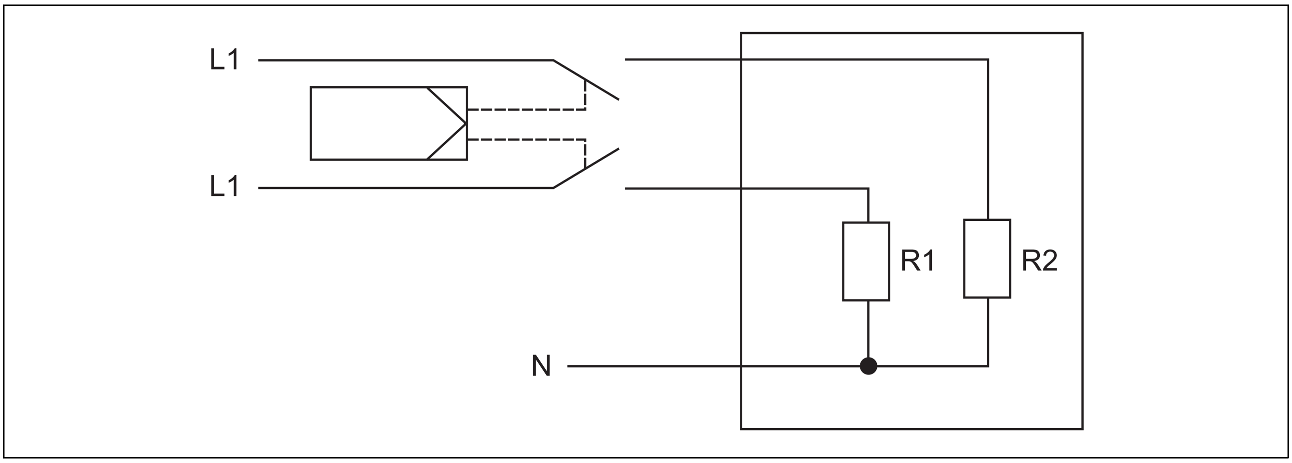


Figure 82: Two-stage control of actuators

The example (Figure 82) shows two-stage control of actuators: heating 1 + 2 are used to heat up the furnace shown in the schematic diagram. If the furnace temperature approaches the defined setpoint value, heating 1 is switched off and heating 2 is used to adjust to the setpoint value. For actuator 1, only discontinuous control is generally provided for (switch-off if the control deviation lies below a defined value). Continuous actuators (such as SCR power controllers) or binary actuators (such as SCR power switches) are used for actuator 2. In conjunction with gas firing plants, motor actuators can also be used.

This structure can be used if actuator 2 provides sufficient heating power for adjustment purposes.

In the case of comparatively small setpoint values, the power required by the plants is generally low. Accordingly, a relatively low amount of power is required from the actuator. Two-state controllers vary the power provided with a binary actuator using cycles. The actuator alternately provides full and no heating power to the system. It is difficult to approach the relatively small setpoint value without an overshoot and generally to reach a stable actual value. Using two actuators may represent a solution here (structure as in Figure 82). In the case of a relatively small setpoint value, only actuator 1 is actuated cyclically (Figure 83), and the amount of excess power is relatively low. If a defined setpoint value is exceeded, both actuators are actuated cyclically.

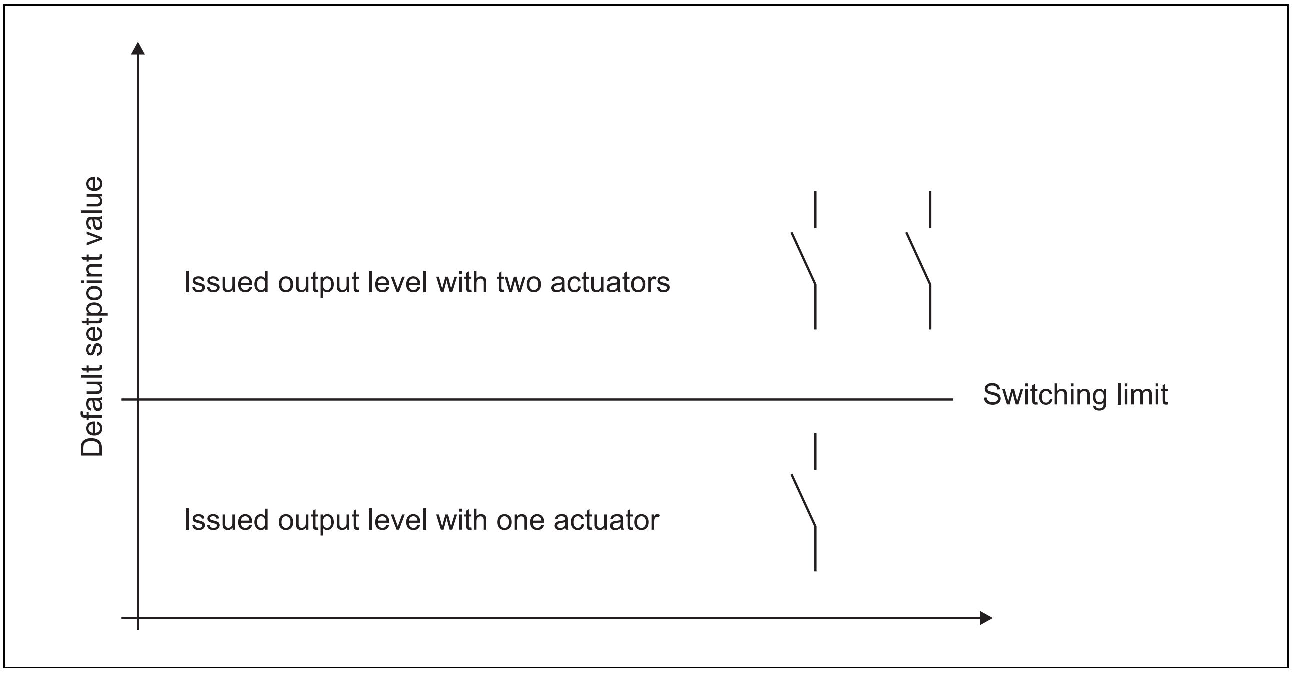


Figure 83: Actuation of one or two actuators depending on the configured setpoint value

The carry out this actuation, the controller monitors the configured setpoint value (in JUMO controllers this is done using limit value monitoring). If the setpoint value lies above a defined limit, the second actuator is also actuated (in JUMO controllers this is done using the logic function).

6.3 Split-Range operation

Split-Range operation refers to the distribution of the controller output level (generally 0 to 100 %) among several actuators. This distribution may be required if a large amount of power is required, for example. In the diagram shown, Split-Range operation enables energy-efficient operation of a cooling plant:

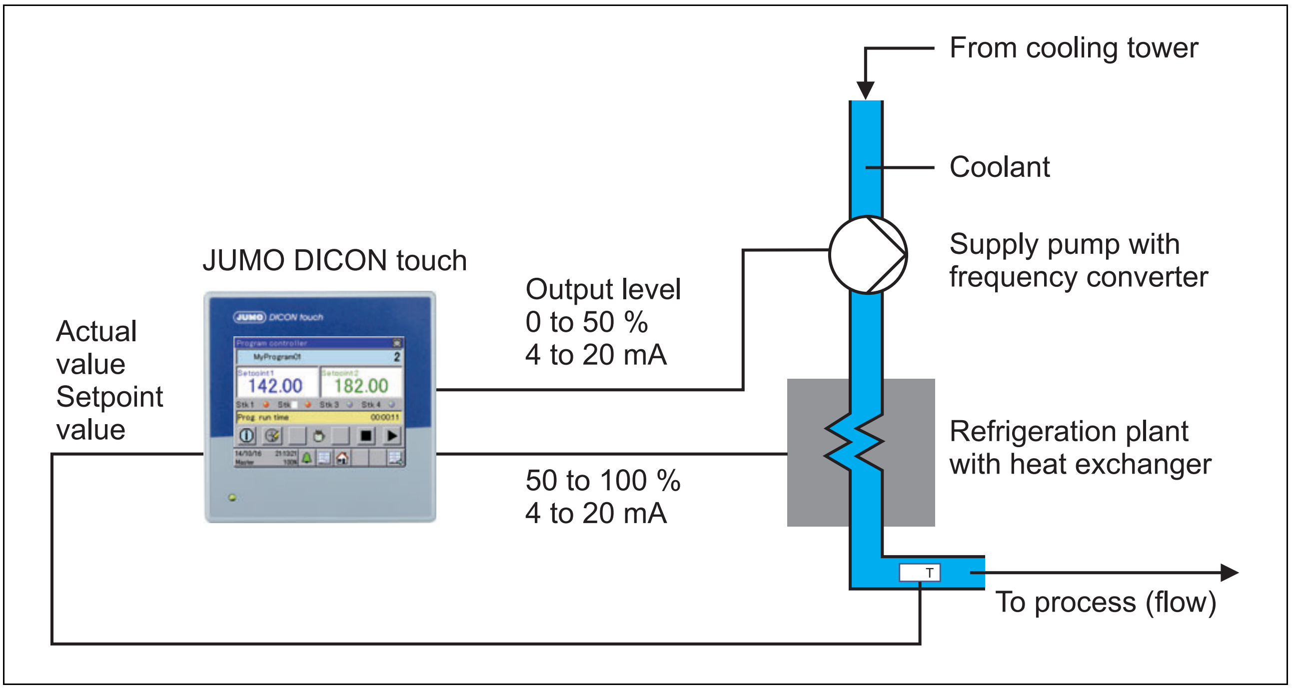


Figure 84: Split-Range operation of a cooling plant

The cooling plant provides coolant for a process at a required supply temperature. If the outdoor temperature is low, the cooling is provided by a cooling tower in a cost-effective manner that preserves resources. The supply pump increases the quantity of coolant up to a controller output level of 50 %. If the cooling provided by the cooling tower is no longer sufficient, the controller increases the output level to greater than 50 %. As from this output level, coolant after-cooling is performed. The power of the cooling machine is increased as the output level increases. At an output level of 100 %, the maximum cooling power at the maximum flow is achieved.

A continuous controller is used in the example shown. Split-Range operation is also possible with two-state controllers.

6.4 Keeping disturbances stable

If disturbances vary in a control loop, they will change the control variable and cause a temporary control deviation. As a result, the controller varies its output level and adjusts the actual value to the setpoint value again. This issue can lead to an unsatisfactory control result, in particular if changes to disturbances occur frequently. In the case shown below a disturbance is kept constant:

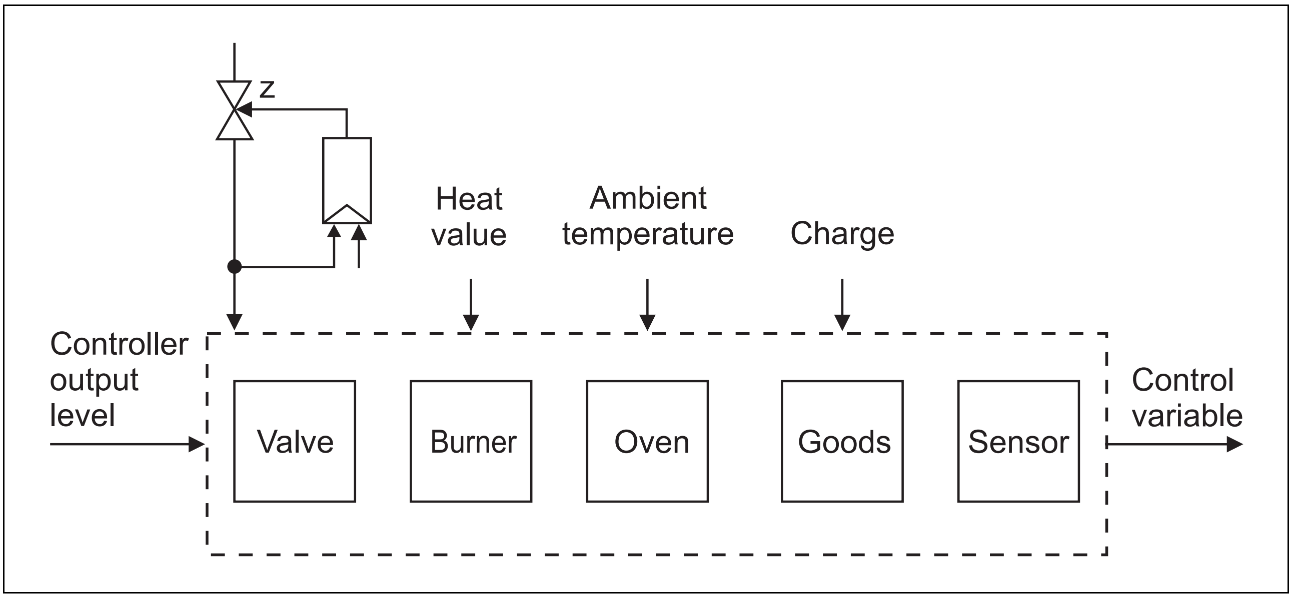


Figure 85: Keeping the 'gas pressure' disturbance constant in a gas-powered furnace

As described in Chapter 2.1 "*General information on the control path*", *page 19*, the gas pressure constitutes one of the disturbances in gas-powered furnaces (Figure 85). If the system is in a controlled state, a temperature deviation will arise after a change to the gas pressure. The controller will change the output level and in so doing eliminate the control deviation. The act of keeping the supply pressure for the valve constant eliminates the impact on the furnace temperature. This result can be achieved using a pressure regulator (shown in Figure 85 as a controller with a valve).

6.5 Disturbance feedforward control

As described above, changes to disturbances result in a temporary control deviation. The controller responds by changing the output level and adjusts the actual value to the setpoint value again.

It is also possible to influence the controller output level depending on the disturbance. This change to the output level reduces the control deviation that occurs in the event of a change to the disturbance. This disturbance feedforward control is possible if the disturbance has been recorded using measurement technology and the effect of disturbance changes on the actual value can be estimated.

6.5.1 Additive disturbance feedforward control

Additive disturbance feedforward control is used if an additional output level needs to be provided when the disturbance is changed.

Example of additive disturbance feedfoward control:

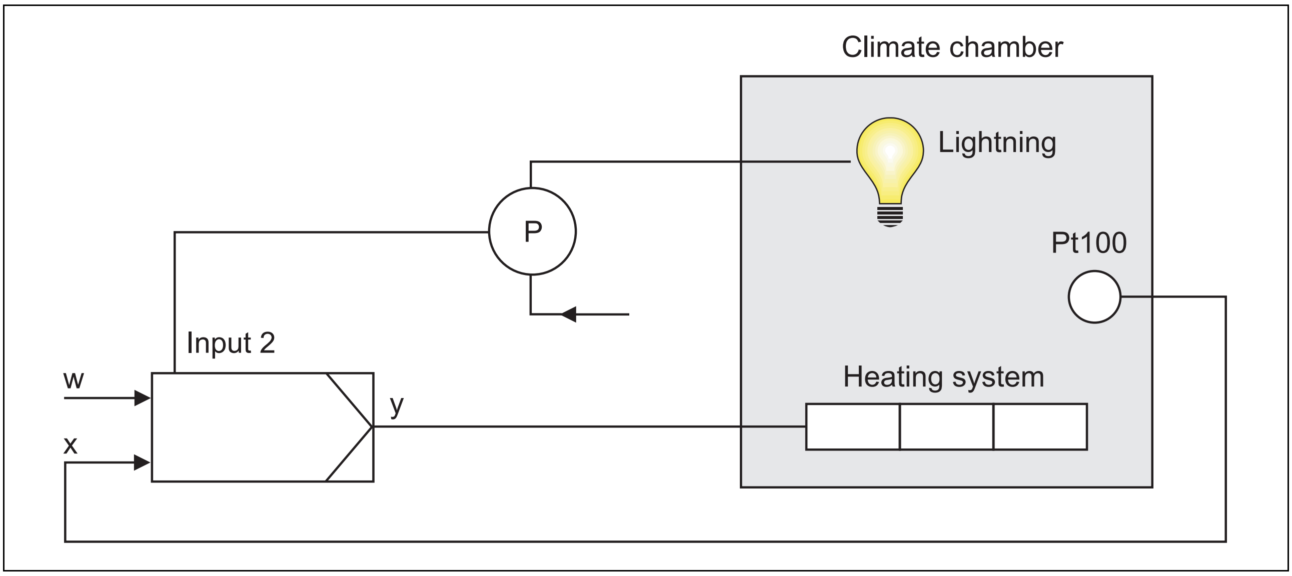


Figure 86: Example of additive disturbance feedforward control

Highly sensitive sensors are located in the climate chamber (Figure 86). The controller is used for highly accurate temperature control. Switching on the lighting results in additional heat input and the temperature rises. The controller responds to the control deviation by reducing the output level and adjusts the actual value to the setpoint value. Another control deviation is created as soon as the light intensity is changed again.

The heat input from the lighting is the disturbance, and a measure of this disturbance is the electrical power in the lighting.

For example, the measurement signal for the electrical power is provided to the controller via the second analog input in the form of additive disturbance feedforward control. At a maximum power of 50 W, the output level should be reduced by 10 %:

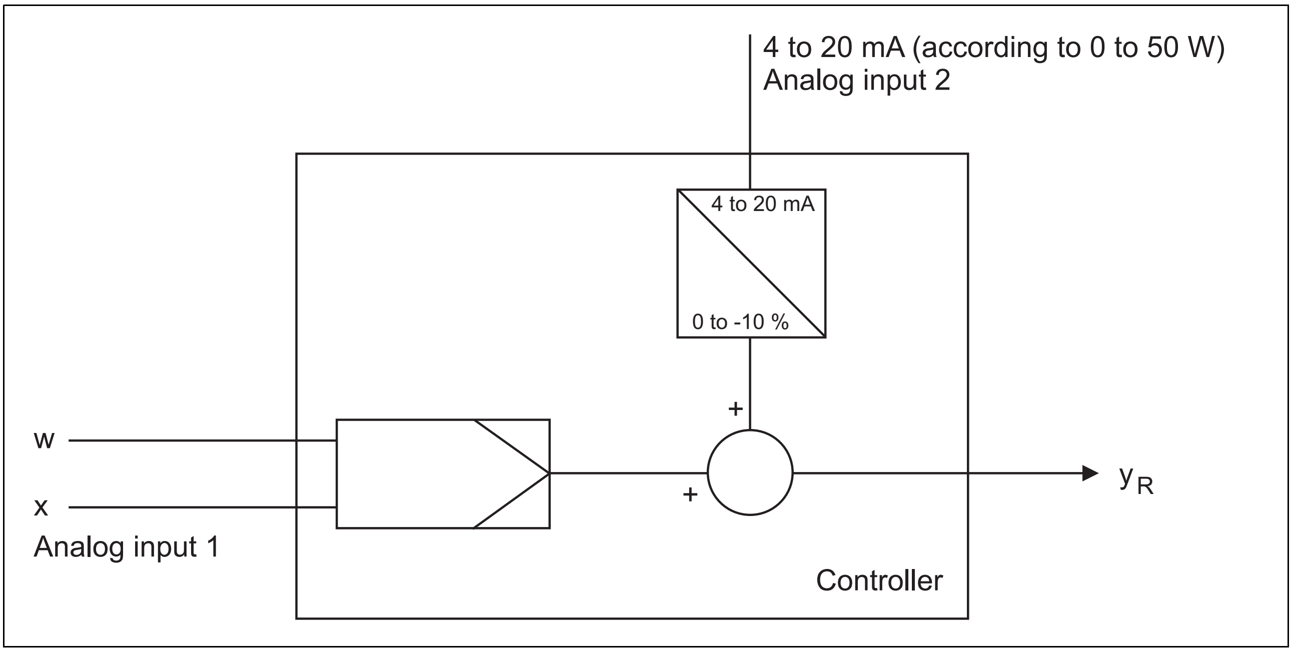


Figure 87: Using additive disturbance feedforward control

In the example shown (Figure 87), the actual value is provided to the controller via analog input 1. The power signal is used as additive disturbance feedforward control via analog input 2, whereby 4 to 20 mA corresponds to 0 to 50 W.
With a scaling of 4 to 20 mA (0 to 50 W) corresponding to 0 to -10 %, the controller output level is reduced by 10 % at a power of 50 W, for example. Increasing the lighting intensity will counteract the increase in the actual value.

Additive disturbance feedforward control implements an additional output level depending on the disturbance.

6.5.2 Multiplicative disturbance feedforward control

Multiplicative disturbance feedforward control changes the controller output level in proportion to the disturbance.

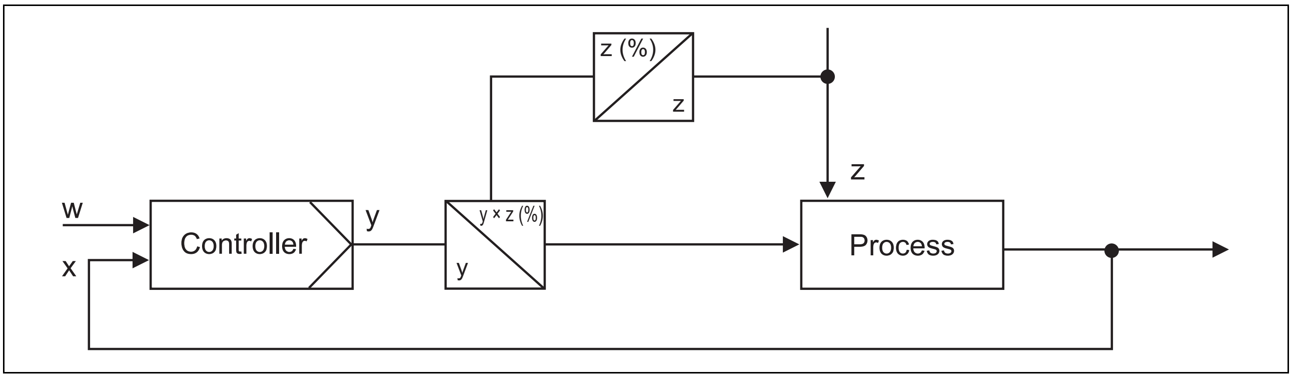


Figure 88: Schematic diagram of multiplicative disturbance feedforward control

A percentage is formed [z (%)] from the disturbance (z), see Figure 88. The controller output level is multiplied by z (%).

This method is used if the output level needs to be changed in proportion to the disturbance during a process.

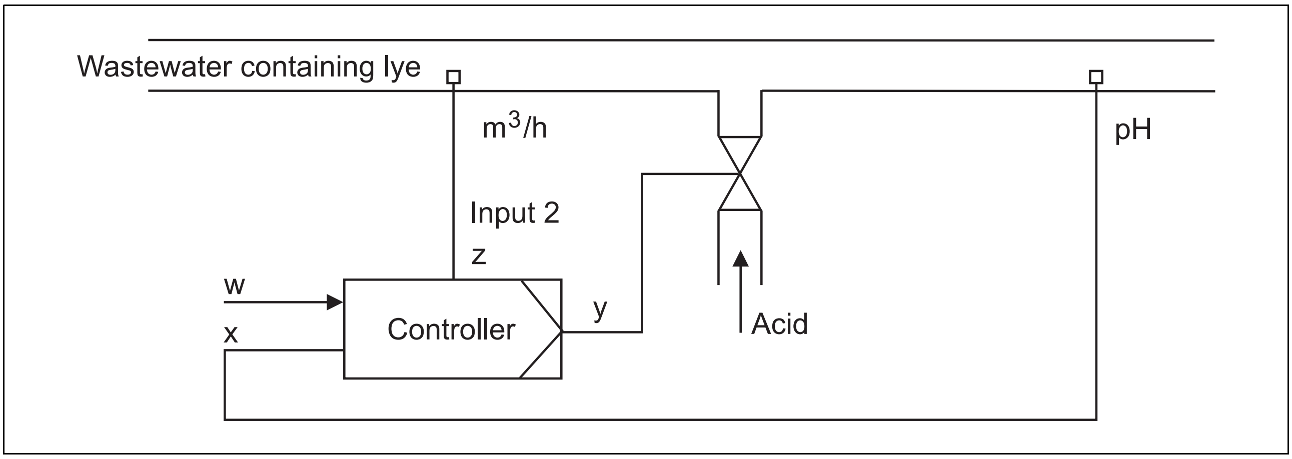


Figure 89: Neutralization plant

A neutralization plant will serve as an example (Figure 89). Acid is added to this plant to neutralize waste water containing lye. The aim is to achieve a setpoint value for the waste water of pH 7.

The disturbance is the flow; doubling the flow quantity will necessitate a doubling of the volume of acid. The flow is supplied in a multiplicative manner via input 2. The flow exists in the form of a 4 to 20 mA signal, which corresponds to a flow of 0 to "maximum flow". Input 2 is scaled to 4 to 20 mA/0 to 100 %, for example. The output level determined by the controller is multiplied by the disturbance in %. If, for instance, the flow increases to double the value, the controller output level will also be doubled before it is output. The disturbance feedforward control suppresses dynamic control deviations after changing the 'flow' disturbance.

In the example, the transfer coefficient of the control path is heavily influenced by the 'flow' disturbance: if a change to the output level heavily influences the control variable when the flow is low, then the influence is small when the flow is high. A high flow results in a small system gain; a low flow results in a high system gain. The overall gain of the controller and control path is calculated as follows:

$$K_p \bullet K_S \qquad (31)$$

K_p Proportional gain of the controller
K_S Transfer coefficient of the control path

If the controller has been tuned for a relatively high flow, there will be a relatively large K_p (with a relatively small K_S). If there is a smaller flow, the higher transfer coefficient will increase the overall gain and the control loop may become unstable. The disturbance feedforward control changes the proportional gain of the controller in proportion to the disturbance. If the transfer coefficient changes in inverse proportion to the disturbance, the overall gain $K_p \times K_S$ will remain constant for any disturbance, and the process will remain controllable in the case of a changed disturbance.

6.6 Cascade control

Cascade control distributes timing elements of a control path among at least two controllers. This structure can generally be used if an auxiliary actual value (x_H) needs to be recorded in a control path using measurement technology and adjusted in proportion to the controller output level.

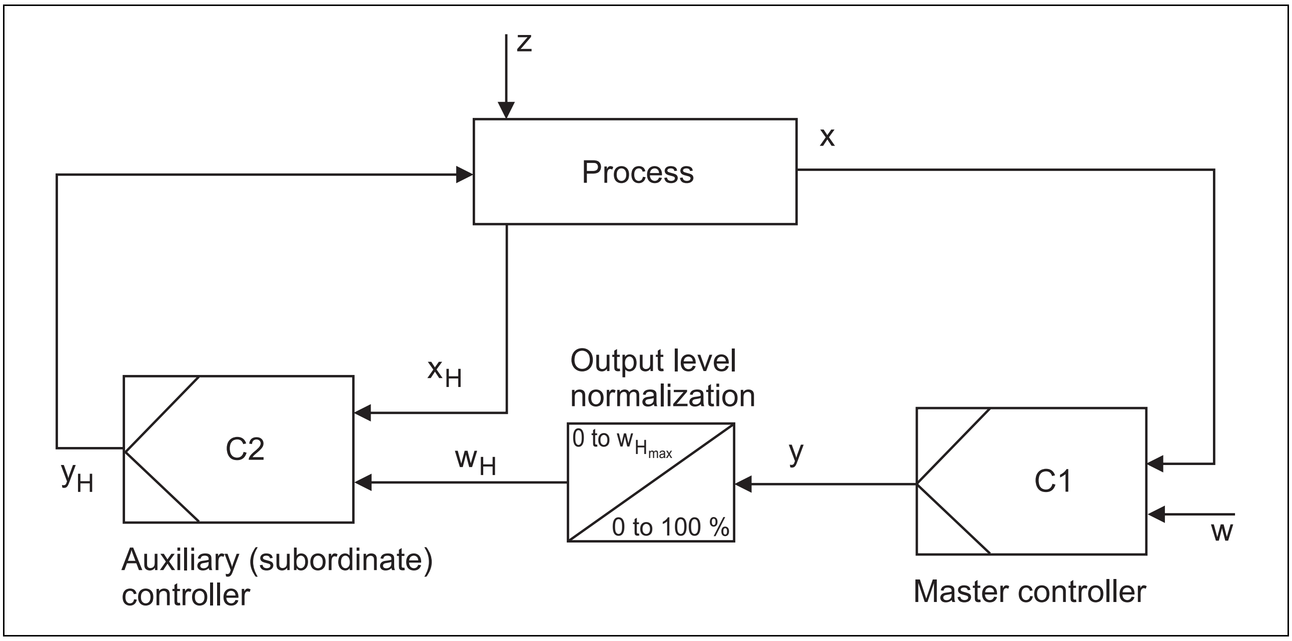


Figure 90: Cascade control

The actual setpoint value and the plant actual value are supplied to the master controller. Based on the output level determined by the master controller, the setpoint value for the slave controller is formed by the standardization of the output level. The slave controller adjusts the value to an auxiliary setpoint value (w_H) in proportion to the output level of the master controller.

Reasons for using cascade control:

- To control the process and achieve a higher control quality on paths of a higher order
- To limit the power in the control path and to limit the auxiliary actual value
- To compensate disturbances

Controlling the process and achieving a higher control quality on paths of a higher order

As a result of changes to the output level, the change to the power reaches the sensor via several timing elements (energy stores and elements with dead time). The higher the number of energy stores or the order of the control path, the more difficult it will be to control a process. The worst case scenario would be if the time constants of the control path are in the same order of magnitude (small T_g/T_u ratio). Distributing the timing elements among two control loops may offer a solution:

6 Special controller circuits

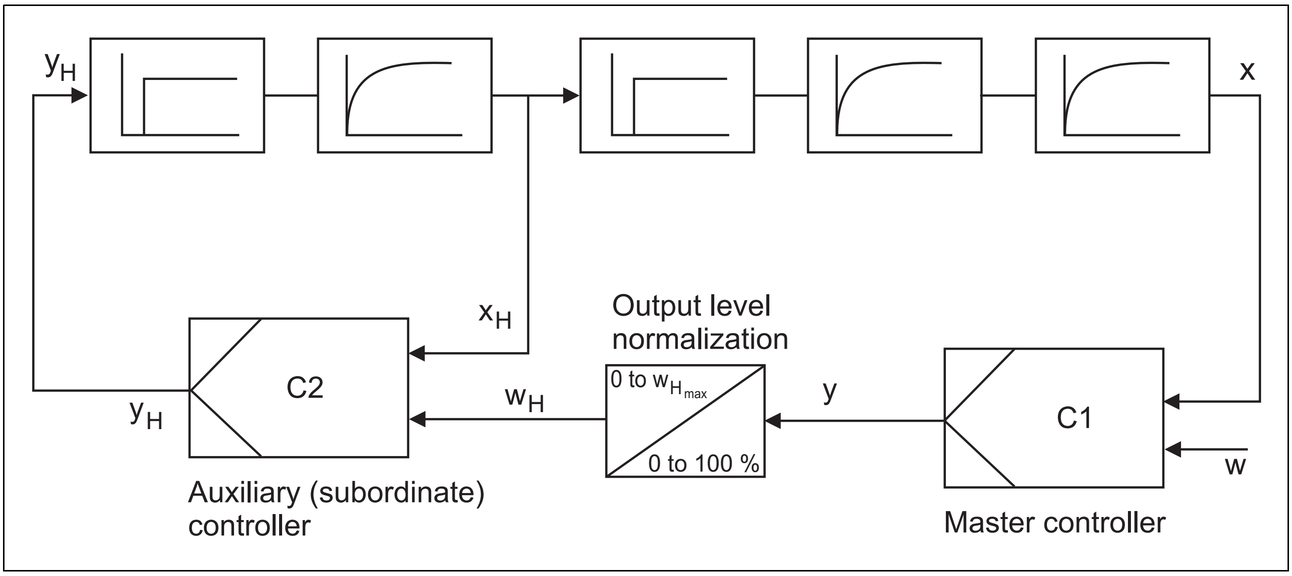


Figure 91: Distribution of timing elements among several control loops

Due to the distribution of the timing elements, the entire delay time will no longer elapse before a controller can respond to a malfunction at the path input. Following a change to the disturbance, the slave controller already responds once the delay time of the control path of the inner control loop has elapsed. The slave controller is able to compensate the malfunction much faster. The T_g/ T_u ratio of the two individual path sections is greater than that of the entire control path. The path sections, and therefore also the entire process, can be controlled more effectively as a result of the cascade structure.

Limiting the power in the control path and limiting the auxiliary actual value

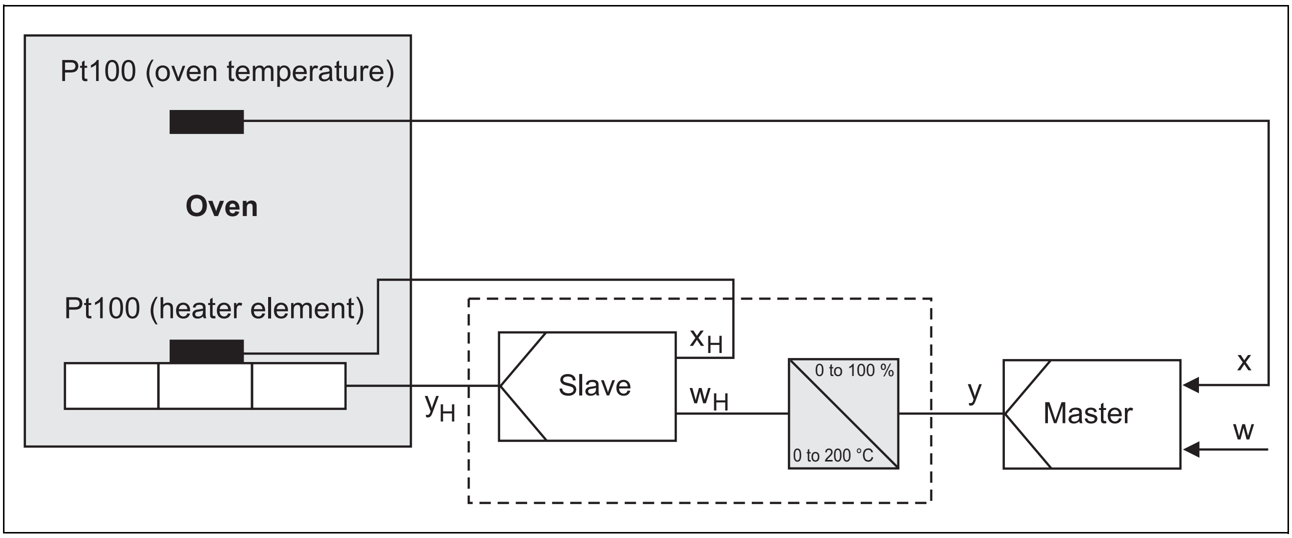


Figure 92: Cascade control on a furnace

In the example shown (Figure 92), the heating rod temperature is limited to 200 °C. The setpoint and actual values for the furnace are available at the master controller. The master controller determines an output level in the range from 0 to 100 %. Due to the standardization of the output level, this is converted into 0 to 200 °C. The slave controller adjusts a heating rod temperature of 0 to 200 °C in proportion to the output level of 0 to 100 %.

Compensating disturbances

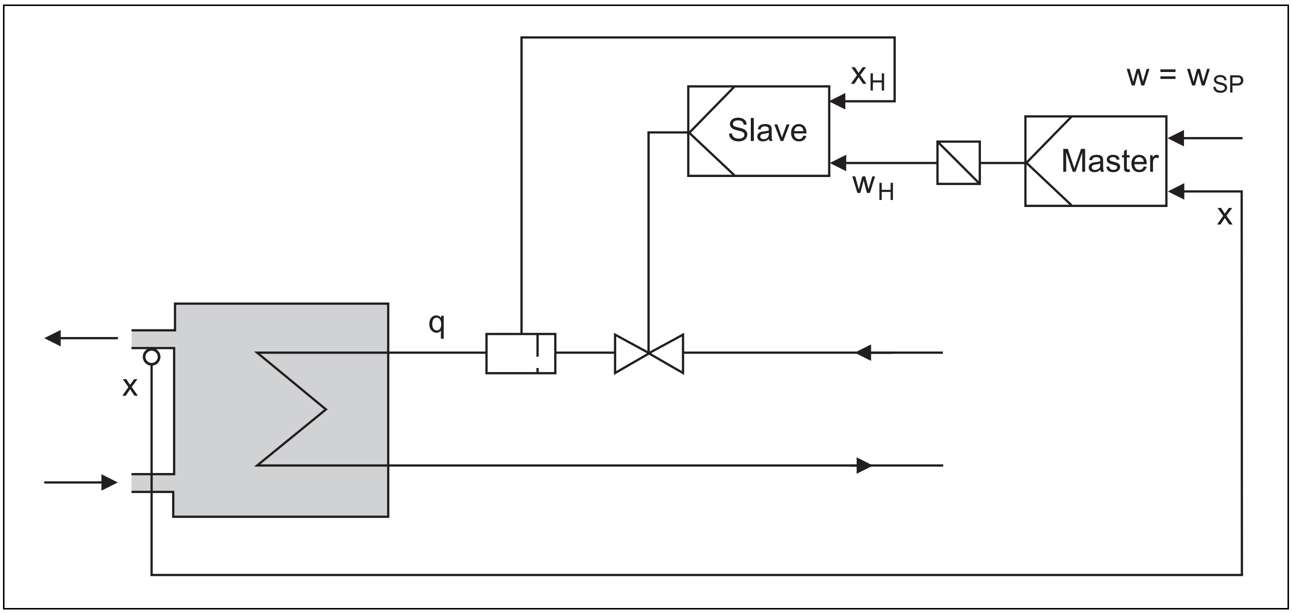


Figure 93: Cascade control on a steam-powered flow-type heater

In flow-type heaters (Figure 93), the fluid temperature is adjusted to a defined supply temperature (w) using steam. The temperature is controlled by the master controller. The slave controller controls the flow of steam for the flow-type heater in proportion to the output level of the master controller. The "master controller output level" is assigned to the "flow of steam" through the standardization of the output level. If the steam pressure fluctuates in the supply, the slave controller continues to keep the flow of steam constant. Changing the 'steam pressure' disturbance therefore has no impact on the supply temperature of the fluid.

Controller structures and tuning of master and slave controllers

When activating the I component for master and slave controllers, the overall system tends to oscillate. Against this background, the master controller uses the PID structure, and the slave controller uses the PD structure. For the slave controller, a control deviation will always arise, whereas the master controller ensures the adjustment of the actual value.

The tuning of the overall system takes place from the inside to the outside: the master controller is switched to manual mode and a typical output level is specified. Due to the standardization of the output level, this results in a typical setpoint value at the slave controller and tuning can start. After tuning the slave controller on the PD structure, the master controller is also switched to automatic mode and tuned.

6.7 Ratio control

Ratio controllers are used for burner control (control of the gas/air mixture ratio) in analytical measurement (mixture of reactants) and process engineering (manufacture of mixtures).

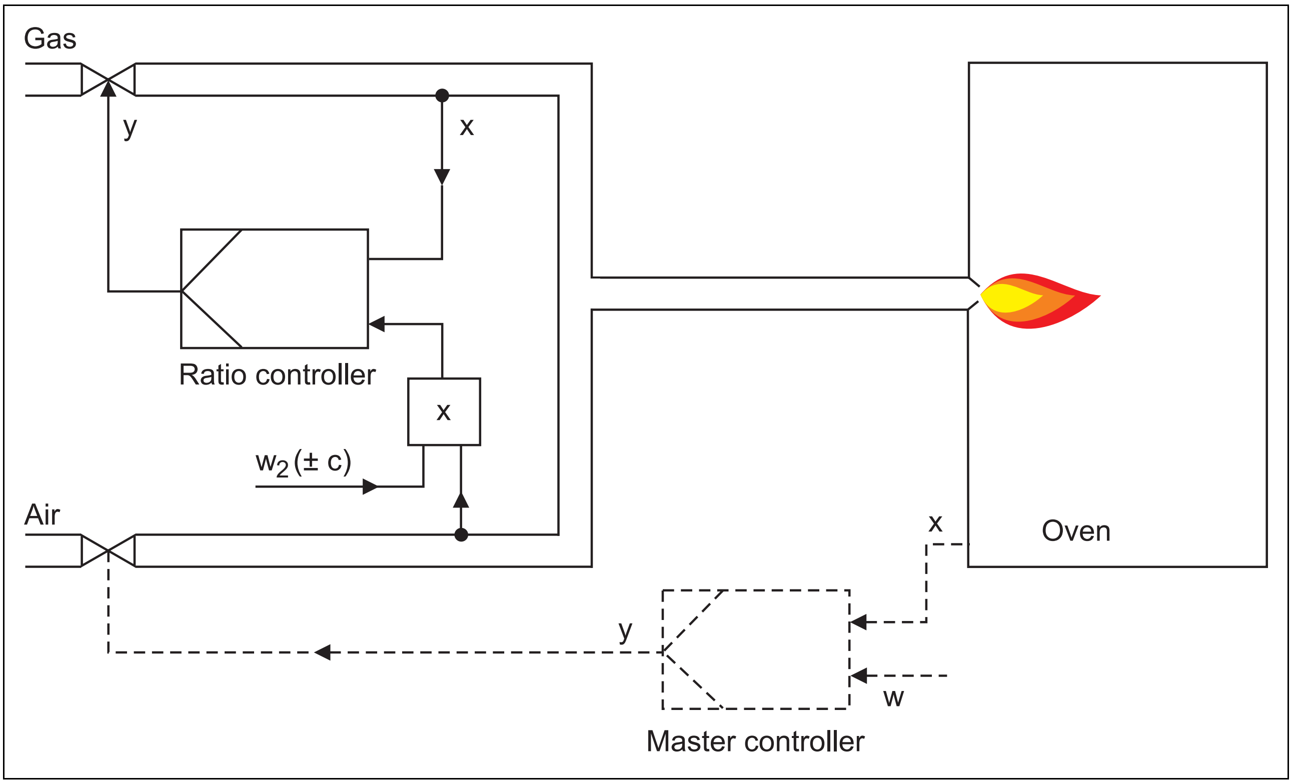


Figure 94: Ratio control for providing an air/gas mixture

In the example shown, the air flow is recorded using measurement technology and multiplied by a factor. The result is the required volume of gas, which represents the setpoint value for the ratio controller. The master controller, for its part, adjusts the required furnace temperature.

The overall system shown is tuned from the inside to the outside. The master controller is switched to manual mode and the ratio controller is tuned. Afterward, the master controller is also switched to automatic mode and tuned.

7 Additional functions on JUMO controllers

In addition to the control tasks themselves, JUMO controllers can also carry out a multitude of additional functions, thereby providing users with a range of benefits. This chapter describes some of these functions.

7.1 Additional settings for JUMO controllers for the controller function

In order to set up the controller function, the input needs to be set up for the sensor being used in the "Inputs" [Inputs] configuration menu (RTD temperature probe, thermocouple, 4 to 20 mA, etc.).

The controller type (two-state controller, continuous controller, etc.) and control direction then need to be specified in the "Controller" configuration menu. You can define the source for the actual value in the same menu (Figure 95):

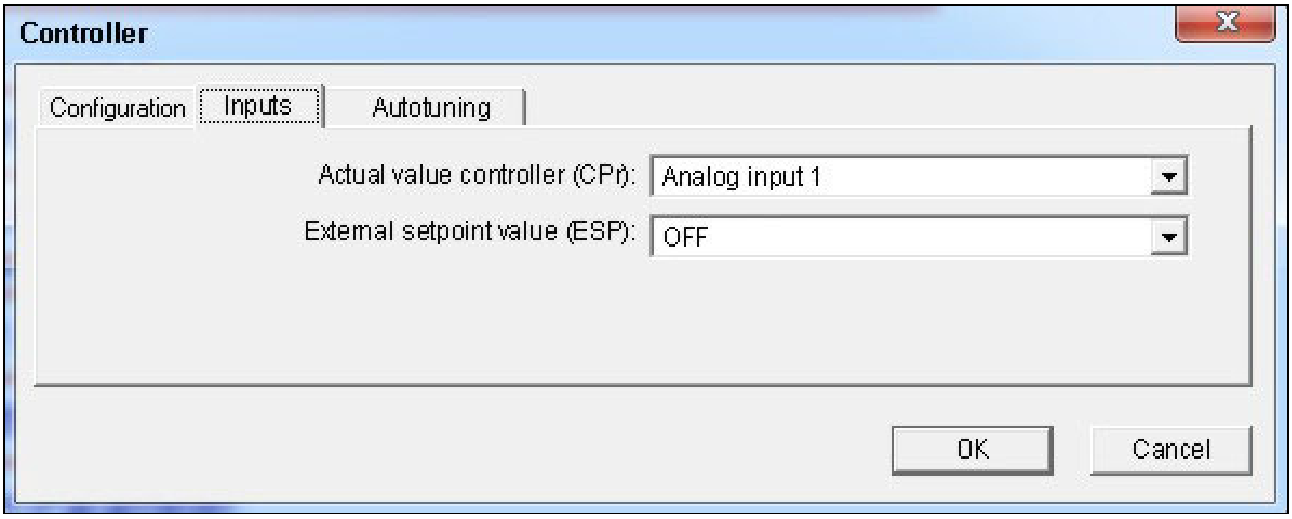


Figure 95: Sources for controller actual value and external setpoint value

The setpoint value is generally specified on the front of the device or using an interface.
Alternatively an analog signal can be used (analog input 2, for example) (Figure 95).

In the "Outputs" configuration menu, you can assign the first and, where appropriate, the second output to an analog or digital output.

Additional settings for the controller function can be configured in the "Controller" configuration menu:

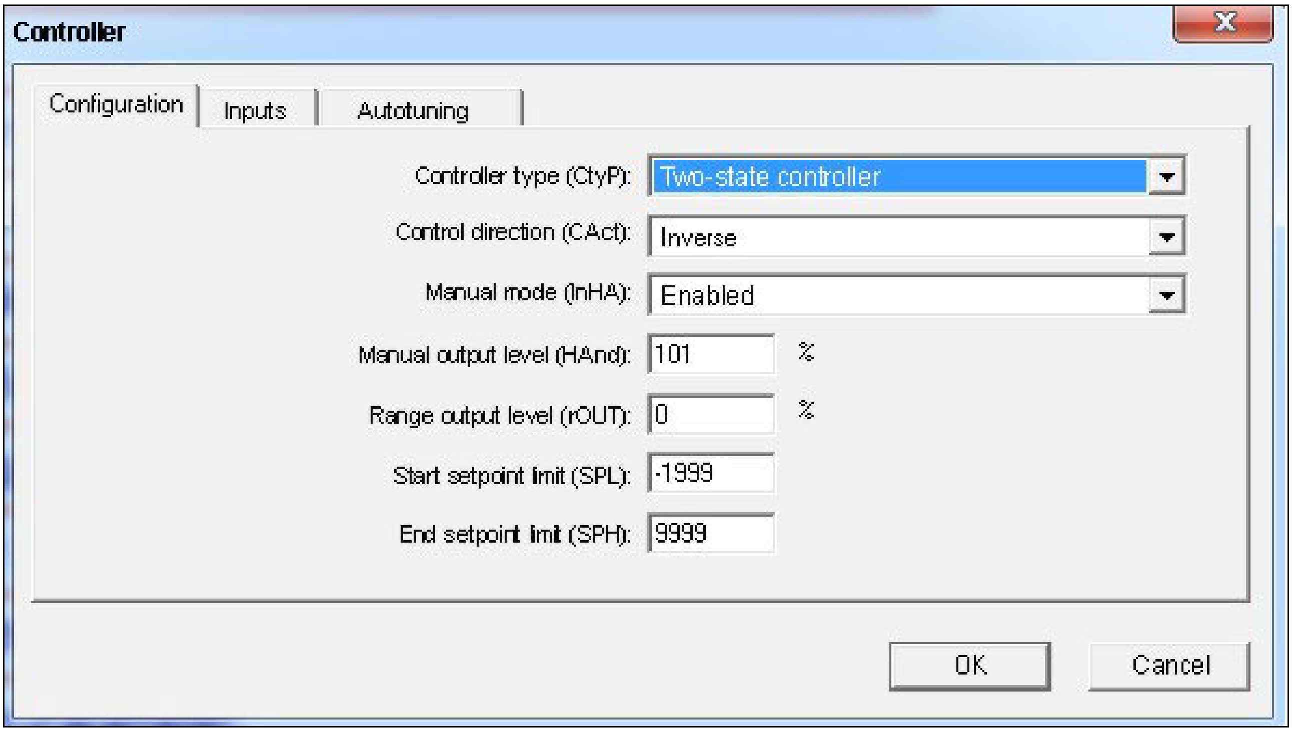


Figure 96: Settings in the "Controller" configuration menu

Manual mode can be activated by selecting the setting "Manual mode – enabled". If you select the setting "Manual output level 101 %", when in manual mode the controller takes the output level from automatic mode. In general the "Manual output level" parameter can also be used to define any output level for the switch to manual mode. Manual mode cannot be activated if the setting "Manual mode – blocked" is selected.

The "Range output level" setting is used to define an output level in the event that there is an invalid actual-value signal (RTD temperature probe cable break, signal < 4 mA at 4 to 20 mA).

The "Start of setpoint value limitation" and "End of setpoint value limitation" settings are used to define the setpoint value range that can be configured on the controller.

7.2 Ramp function

JUMO controllers are set to operate as fixed-setpoint controllers per default. The controller adjusts the value to the respective setpoint value until the user changes the setpoint value. The setpoint value is changed in step form. Various different processes require a ramp-type increase in the setpoint value. The ramp function available as standard in JUMO controllers fulfils this requirement:

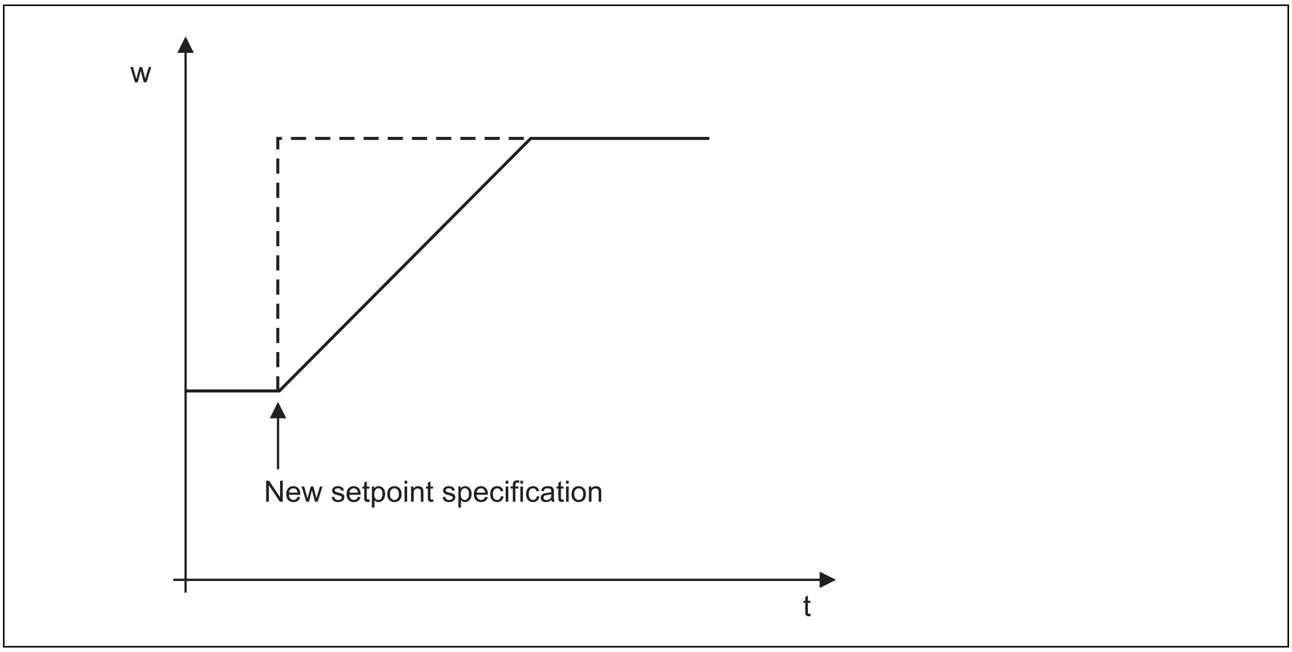


Figure 97: Ramp-type setpoint specification

When the ramp is activated, the slope is specified in Kelvin or minutes, for example.

7.3 Program generator function

Program generators allow setpoint value profiles to be specified. These setpoint value profiles are specified to the controller if required; the controller, for its part, adjusts the actual value to the applicable setpoint value.

Profiles are defined in sections. In the example shown, sections 1 and 2 each last an hour. Section 1 starts with 25 °C, section 2 with 50 °C (Figure 98).

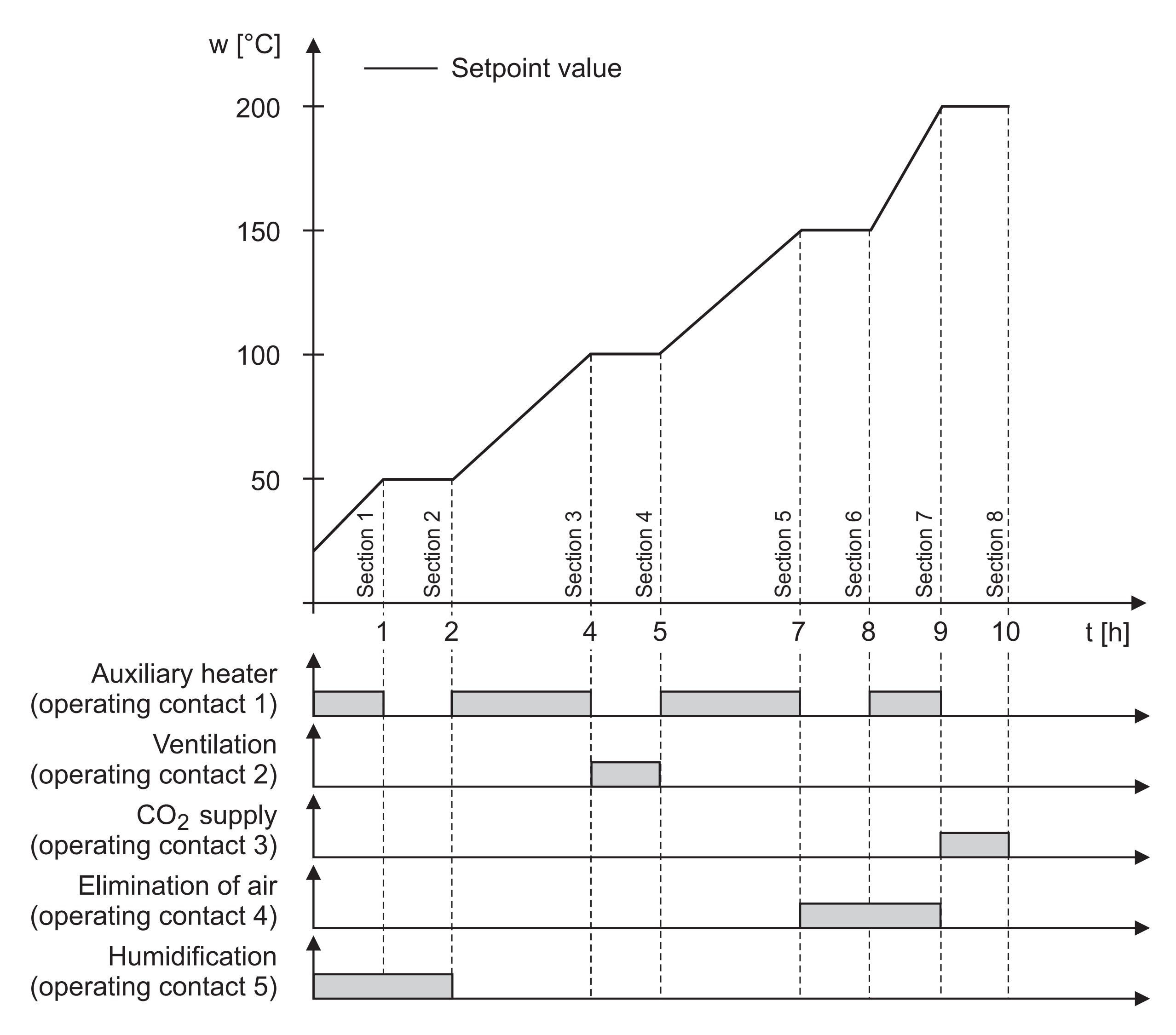


Figure 98: Program of a program controller

In many cases contacts are actuated in the sections; these contacts are used for additional heating, ventilation, etc. They are defined via operating contacts, which are assigned to the respective hardware (usually relays). The statuses of the operating contacts together with the setpoint value profile constitute a program. For an annealing furnace, various different programs are defined, for example. After loading the furnace, the relevant program is selected and started.

7.4 Limit value monitoring

The limit value monitoring function allows process measurands to be compared and analog measurands to be monitored for compliance with limit values.

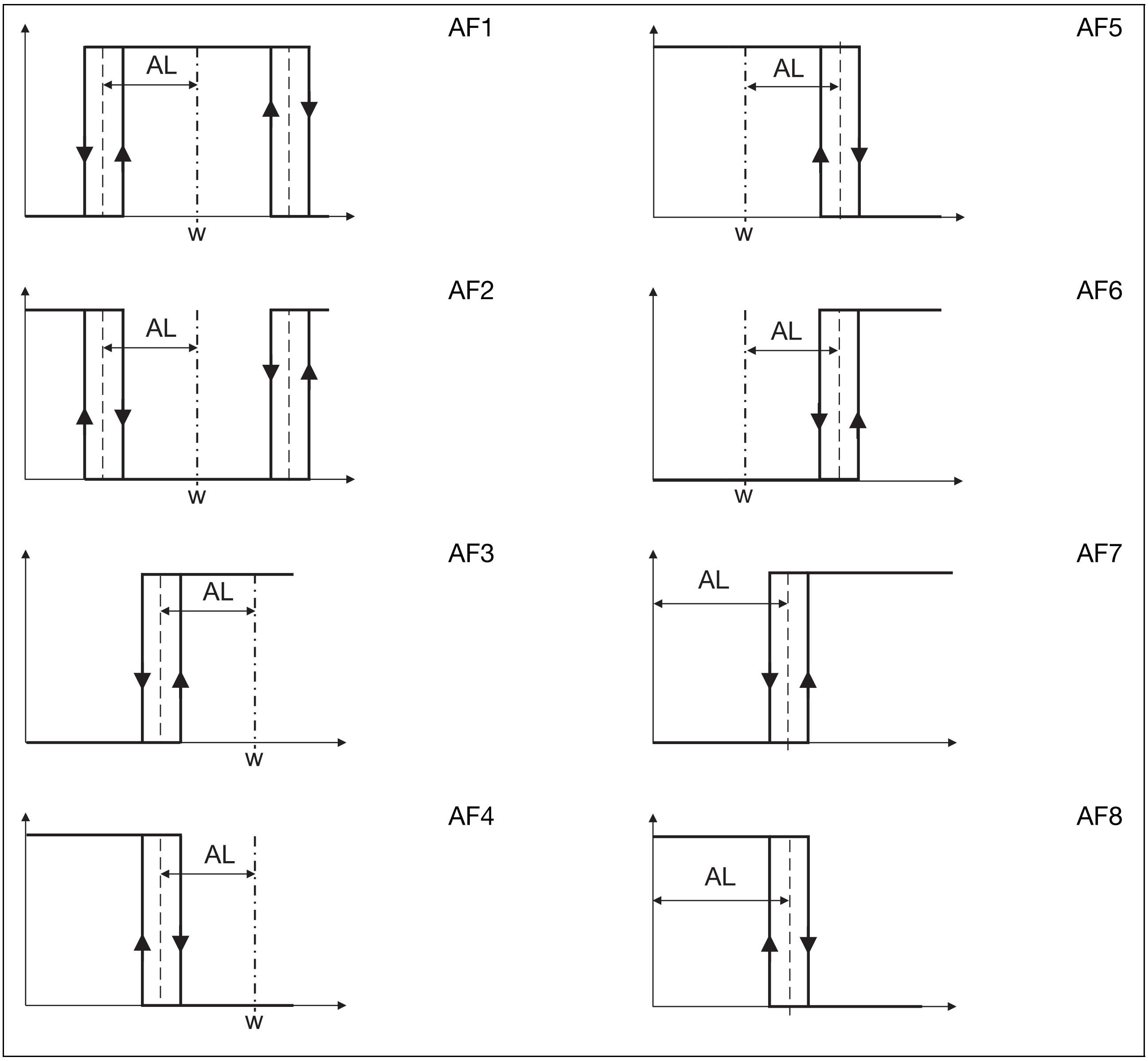


Figure 99: Alarm functions for limit value monitoring

Several limit value monitoring functions may be used in JUMO controllers. In turn, different alarm functions exist for these limit value monitoring functions (Figure 99). Four different alarm functions exist (AF1, AF3, AF5, AF7), and the subsequent alarm function in each case (AF2, AF4, AF6, AF8) represents the inverse function.

Alarm function 1 (AF1) defines a window around the setpoint value of the limit value monitoring (w). The window is defined by the limit value (AL) and the switching differential. The setpoint value (w) controls the window in terms of its position, and the signal source for the setpoint value can be freely defined. The actual value for the limit value monitoring can be found in the same diagram and moves toward the x-axis. If the actual value enters the window around the setpoint value, the limit value monitoring output will be activated. The source for the actual value of the limit value monitoring can also be freely selected.

As an example, the following settings are configured for monitoring that the control deviation is < 10:

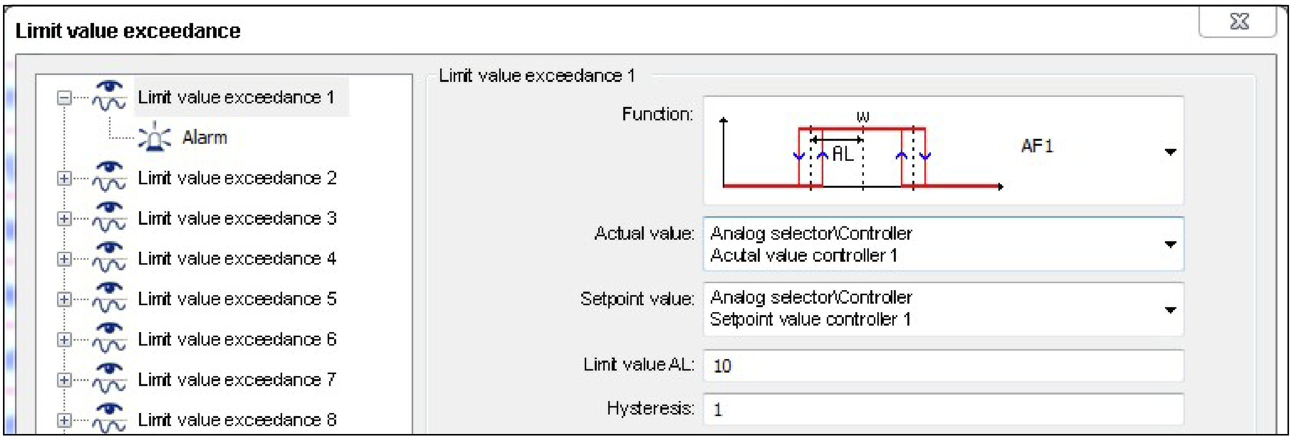


Figure 100: Settings for monitoring that the control deviation is < 10 (configuration program)

In the simplest scenario, the result of the limit value monitoring is output via a digital output.

AF2 is the inverse function of AF1 (Figure 99).

AF3 provides half the window of AF1 – if the rising actual value comes in the vicinity of the setpoint value, the limit value monitoring will switch on.

AF4 is the inverse function of AF3.

AF5 provides the right half of the window of AF1 – if the actual value exceeds the setpoint value by at least the value AL, the limit value monitoring will switch off.

AF6 is the inverse function of AF5.

AF7 provides monitoring of the actual value for a maximum value AL.

AF8 is the inverse function of AF7.

7.5 Binary functions

JUMO controllers include a range of binary signals, such as the status of digital inputs and the result of the limit value monitoring. Functions can be activated by changing the status of the respective binary signal. Using the configuration screen provided by way of example, the functions for digital input 1 can be set up:

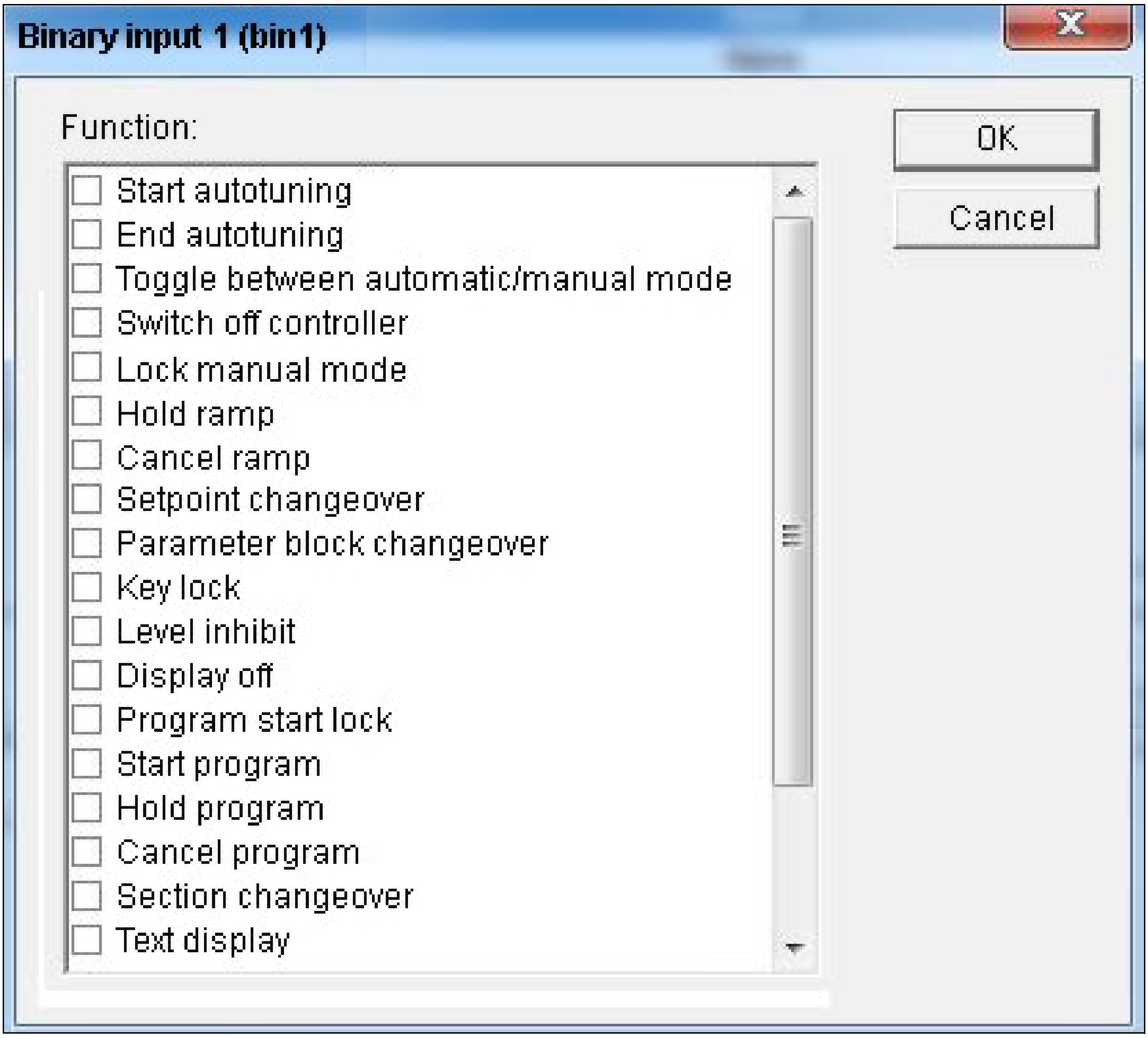


Figure 101: Binary functions for digital input 1 (configuration program)

In the example shown, selecting **"Start autotuning“** (edge-triggered) allows autotuning to be started via digital input 1. You can end it by selecting **"End autotuning"** (edge-triggered).

The controller is usually in automatic mode and adjusts the value to the configured setpoint value. If there is an active binary signal, selecting **"Toggle between automatic/manual mode"** switches the mode to manual mode. An output level can, in turn, be defined for manual mode, and this output level is adopted directly after the switchover.

Selecting **"Switch off controller"** deactivates the controller output signal if there is an active binary signal.

7 Additional functions on JUMO controllers

If the ramp function (Chapter 7.1 "*Additional settings for JUMO controllers for the controller function*") is active and the defined setpoint value has not yet been reached, the **"Hold ramp"** function allows the ramp setpoint value to be held. Selecting **"Cancel ramp"** allows a step-type setpoint specification, even if the ramp function is active.

JUMO controllers are set to operate as fixed-setpoint controllers per default. The controllers adjust the value to setpoint value 1. Setpoint value 2 can be defined if required, and selecting **Setpoint changeover** allows you to toggle between setpoint value 1 and 2. Most JUMO controllers also come with setpoint values 3 and 4. To toggle between the four defined setpoint values, **Setpoint changeover** needs to be selected for two digital inputs (B1 and B2), for example. The toggling is binary-coded.

The control parameters (P_b , r_t, d_t, etc.) can be found in parameter block 1 in the parameter level of the controller. In some cases, the conditions in the process change to such an extent that the parameters no longer allow a satisfactory control result to be achieved. As a result of this operating status, the control parameters need to be re-dimensioned. Parameter block 2 contains the same selection of control parameters as parameter block 1, and the required parameters can be configured here. Selecting **"Parameter block changeover"** allows you to toggle between parameter blocks 1 and 2.

Selecting **"Key lock"** blocks the keypad while a binary signal is activated.

Selecting **"Level inhibit"** locks the levels for configuration and parameter setting.

Selecting **"Display off"** blanks the display screen but otherwise leaves the control devices fully functional.

Selecting **"Program start lock"** prevents the program from starting when configuring the program controller function.

"Start program" and **"Cancel program"** are both edge-triggered and allow you to start and stop a program.

"Hold program" holds the program (the program setpoint is held for as long as the binary signal is active).

Selecting **"Section changeover"** (edge-triggered) switches the program to the next section.

"Text display" shows a definable text on the controller display while the binary signal is active.

7.6 Start-up and diagnosis function

In many cases, the process of tuning controllers requires important process measurands to be recorded, such as the actual value, setpoint value, and output level. Recording these measurands with a recorder is relatively complex: the recorder needs to be purchased, the process measurands need to be provided via analog output signals of the controller, or an additional probe may even need to be positioned.

The configuration program for JUMO controllers therefore includes the Startup software component, which is able to record important analog and binary signals. The PC must be connected with the JUMO controller while the measurands are being recorded.

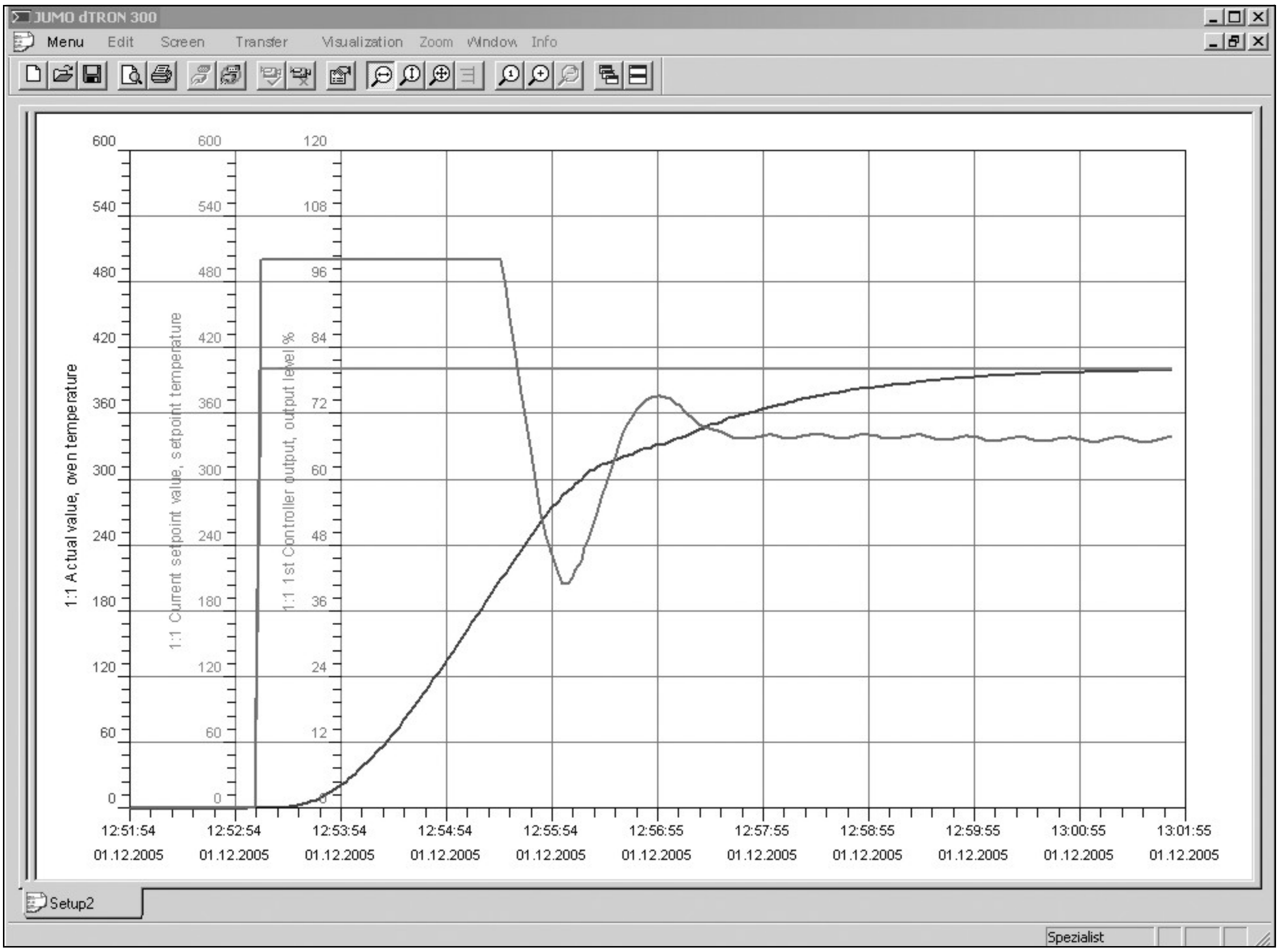


Figure 102: Data recorded online for a JUMO controller with Startup

The result of the recording can be printed out and saved (including in tabular format).

7 Additional functions on JUMO controllers

The **diagnosis function** shows the status of inputs and outputs and provides important information on the controller status:

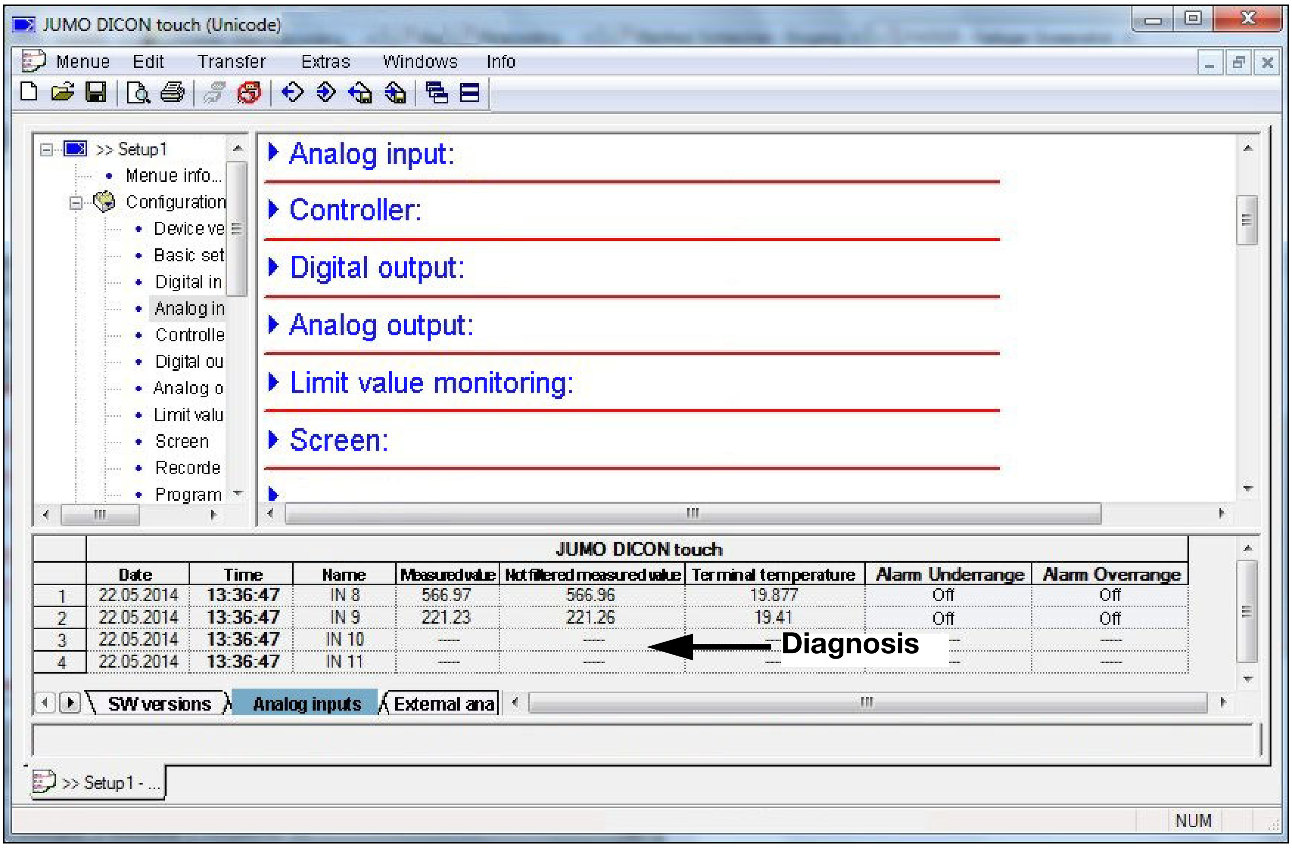


Figure 103: **Diagnosis for a JUMO DICON touch**

The function helps with troubleshooting and provides general assistance when carrying out maintenance work.

7.7 Recording

Selected JUMO controllers include the option to record process measurands in the device. The data is recorded in analog and binary channels and the signals to be recorded can be freely defined.

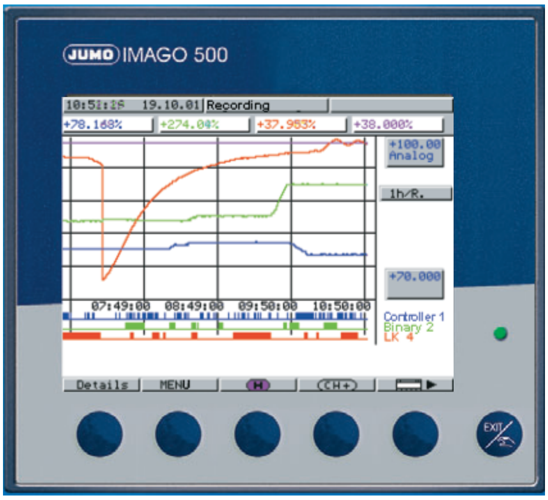


Figure 104: Recording data in the JUMO IMAGO 500

The data is stored in a ring buffer on the basis of a configurable memory cycle and can be viewed on the device in the history function.

The data can be transferred from the 'PCC' PC communication software to an archive file in a time-controlled manner. This process enables continuous data recording. The data is analyzed using the 'PCA3000' PC evaluation software.

7 Additional functions on JUMO controllers

7.8 Math and logic function

The math and logic function included in some JUMO controllers enables the use of mathematical calculations and Boolean operators. The formula editor is available to enter formulas:

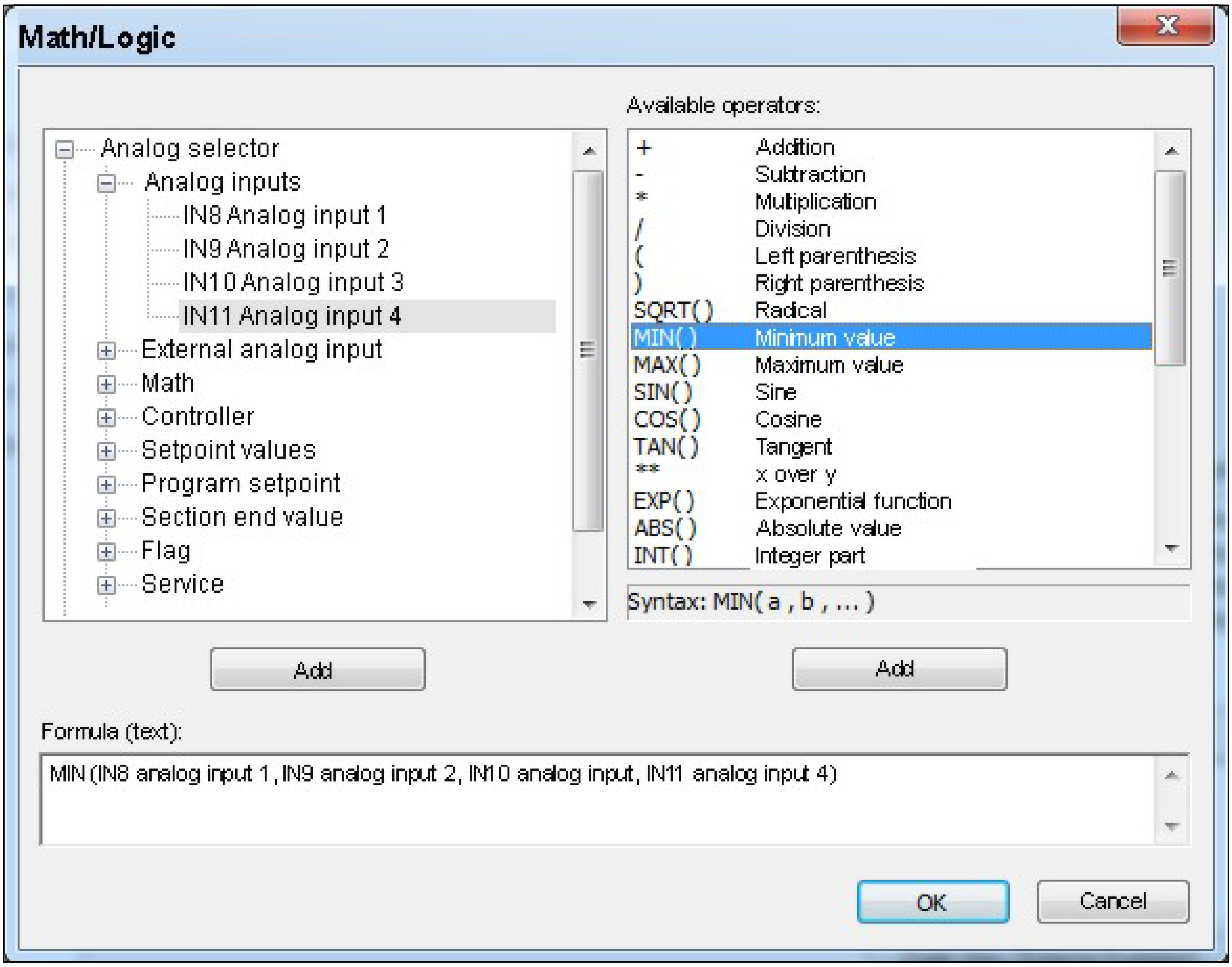


Figure 105: Math and logic function of the JUMO DICON touch

In the formula editor, the usable variables are located on the left and the admissible functions, including information on the syntax to be used, are located on the right. On the basis of these two windows, a formula has been defined for calculating the minimum value of analog inputs 1 to 4. The four process measurands could be four furnace temperatures, and the math function calculates their minimum value. In the furnace, steps must be taken to ensure that the temperature at all measurement points corresponds at least to the setpoint value. The result from the math function is defined as the source for the actual value in a subsequent step in the controller.

7.9 Interfaces

JUMO controllers come equipped with different interfaces: **configuration interfaces** (TTL or USB device), **serial interfaces**, **Ethernet interfaces**, and **PROFIBUS-DP interfaces** are all available depending on the model.

With the exception of PROFIBUS-DP, all interfaces allow the configuration and recorded measurement data to be transferred.

The USB/TTL converter PC interface is used to connect the **TTL interface** with a PC. Additionally, most JUMO controllers require an adapter socket between the PC interface and the TTL interface:

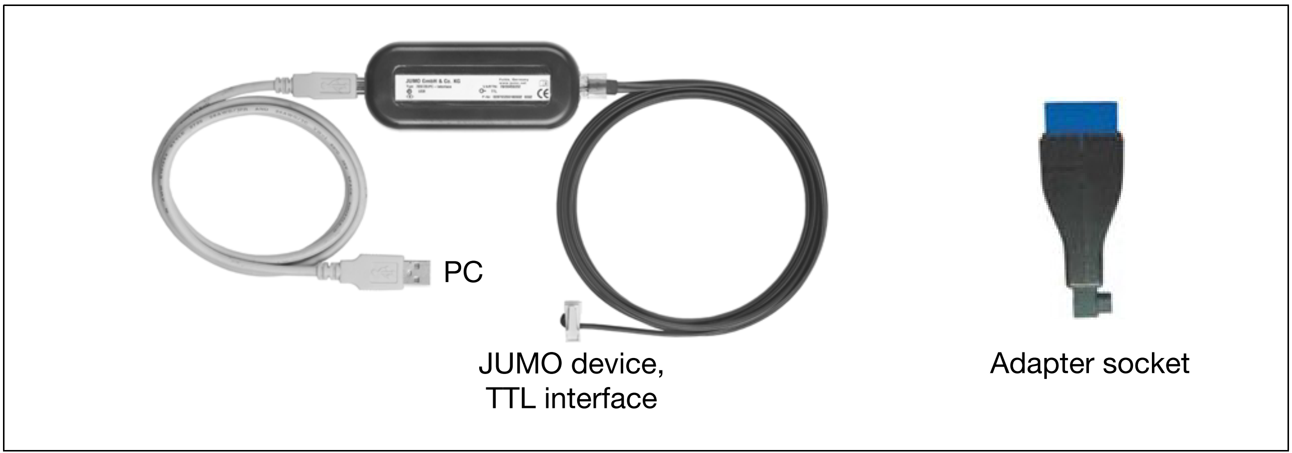


Figure 106: USB/TTL converter PC interface with socket

New products come with a **USB device interface** instead of the TTL interface. A standard USB cable is used for connection.

Figure 107: JUMO DICON touch with USB device and USB host interface

7 Additional functions on JUMO controllers

The **USB host interface** also shown in the figure is primarily used to save recorded data on a USB flash drive.

Virtually all JUMO controllers offer the option of at least one **serial interface**. Thanks to the two-wire RS485 interface, a maximum of 31 field devices can be connected to a PC. Alternatively the four-wire RS422 interface can be used. The Modbus RTU protocol is used for serial interfaces.

One typical application for serial interfaces is to connect controllers to SCADA systems. JUMO offers the easy-to-use SVS3000 visualization software, which can be used to select JUMO devices from a catalog and connect them without the need for programming.

Figure 108: Group image for the JUMO SVS3000

JUMO controllers can generally be connected to all systems with a Modbus master interface.

Relay modules extend the range of available hardware for JUMO controllers; they are also connected via a serial interface:

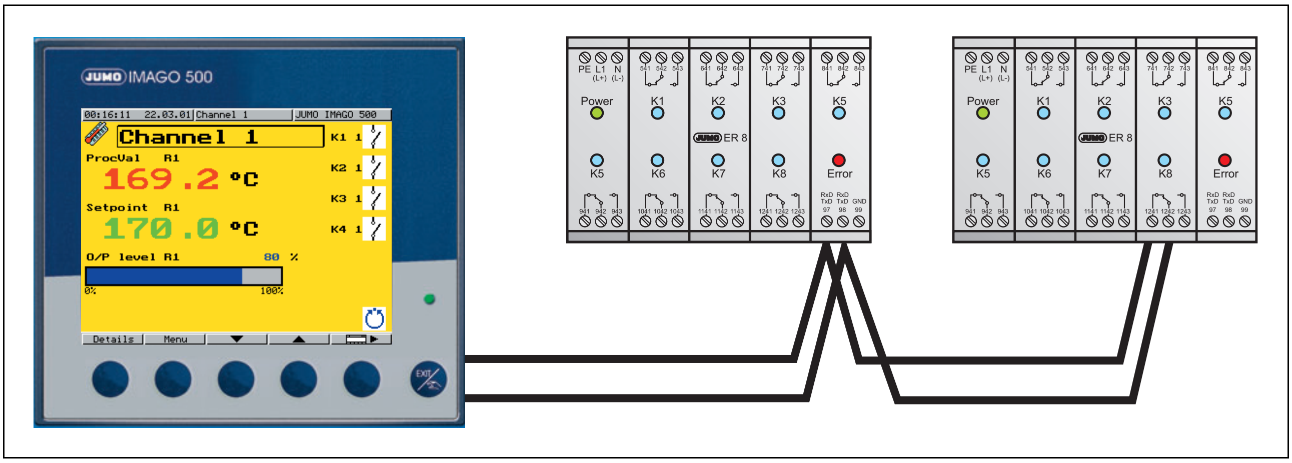


Figure 109: **JUMO IMAGO 500 with two external ER8 relay modules**

Serial interfaces are also used for modem transfers – they allow a connection to be established with a control cabinet modem, for example.

Serial interfaces generally operate as slaves – they respond to requests or follow instructions issued by a master. Due to the Modbus protocol that is used, they are referred to as Modbus slaves. Alternatively, the interfaces of selected JUMO controllers can operate as a master (Modbus master): field devices with a serial interface (usually RS485) and Modbus RTU protocol are connected to the respective JUMO controllers.

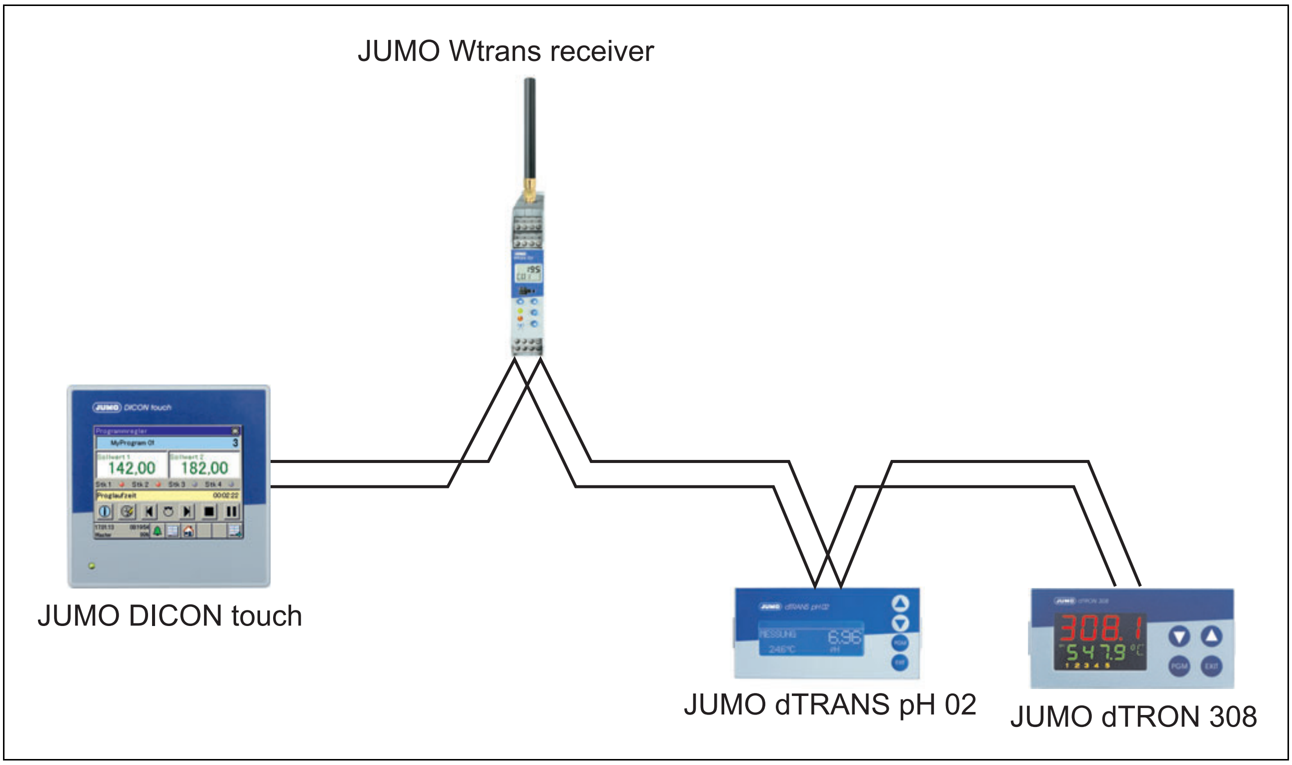


Figure 110: **JUMO DICON touch with Modbus master interface and field devices with Modbus slave interface**

7 Additional functions on JUMO controllers

The **Ethernet interface** connects JUMO controllers to a LAN (Local Area Network); this network can then be used to transfer the recorded data, for example. As described above, the configuration can also be transferred using this type of connection.

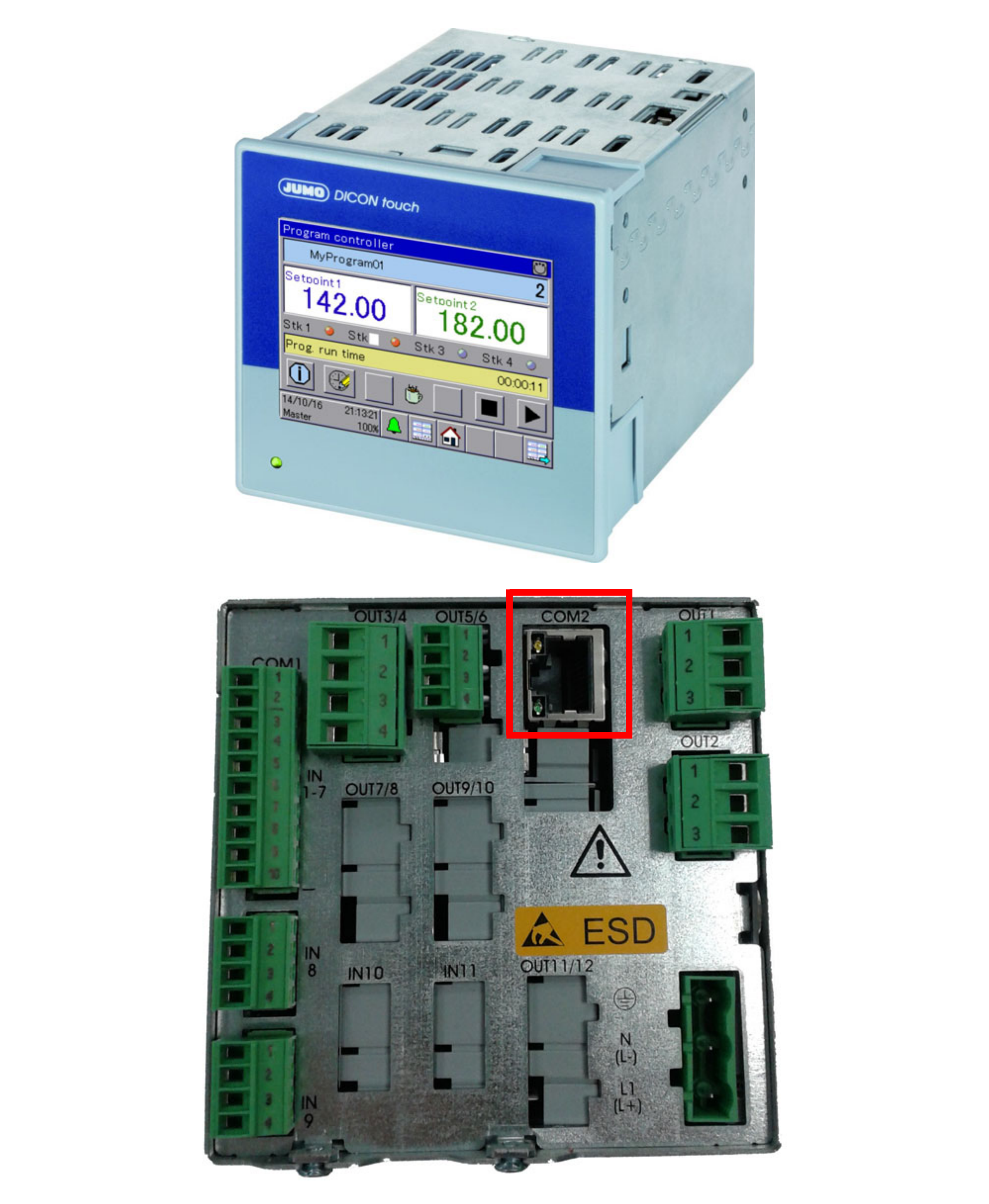


Figure 111: JUMO DICON touch with Ethernet interface

The protocol is Modbus/TCP, which is based on Ethernet. It is also used to send requests and instructions to the controller.

As an alternative to connecting slaves to the Modbus master via a serial interface (Figure 110), the connection can also be established via Ethernet. In this case, the interface functions as a Modbus/ TCP master and sends requests and instructions to field devices, which are also located in the Ethernet.

The **PROFIBUS-DP interface** is used for rapidly exchanging process data (actual values, setpoint values, output levels, etc.) using a PLC. The control, which is independent of the PLC, offers a number of advantages such as higher process reliability, on-site display, and simple modification of control parameters. To connect the controller, the PLC configuration tool requires a GSD file, which defines aspects including which process data needs to be transferred. To reduce the volume of data, the process data to be transferred is selected in a JUMO GSD generator.

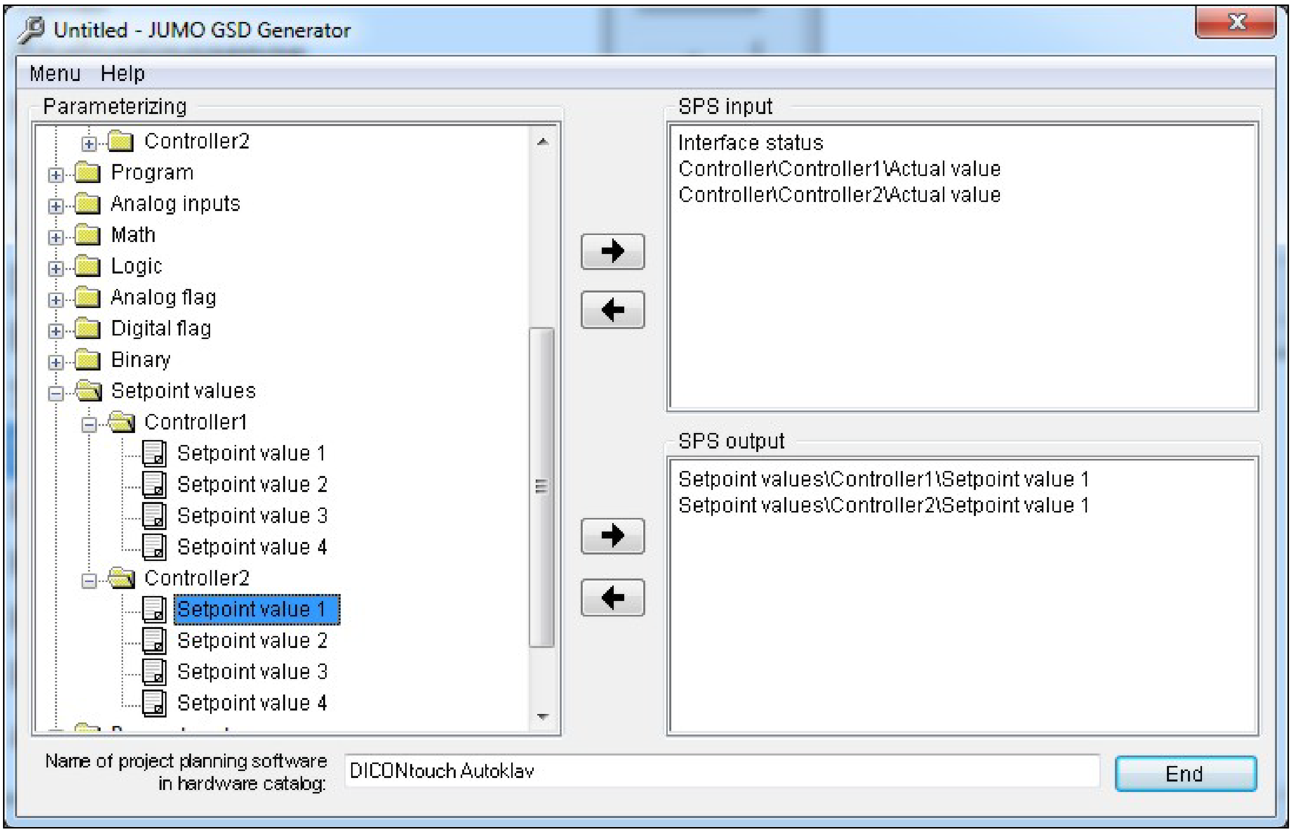


Figure 112: Creating a GSD file with the JUMO GSD generator

In the example shown, two controller actual values need to be imported into the PLC and two setpoint values need to be written to the controller.

Controller parameters

This chapter lists all parameters of JUMO controllers (ordered by function) that affect the actual controller function. They can be found in the JUMO controller in the parameter level, or in the setup program in the "Regelparameter" [Control parameters] menu.

PID behavior

P_b	Proportional band of the P component; Pb
r_t	Reset time of the I component; rt
d_t	Derivative time of the D component; dt

General parameters

Y1	Upper output level limit of the controller output signal (not used with modulating controllers)
Y2	Lower output level limit of the controller output signal (not used with modulating controllers)
Y0	Working point correction of a P controller (only worthwhile for P controllers)

Parameters for two-state, three-state, modulating, and position controllers

C_{y1}	Cycle time of the first digital output (effective for two-state and three-state controllers, $P_{b1} > 0$)
C_{y2}	Cycle time of the second digital output (effective for three-state controllers, $P_{b2} > 0$)
T_{k1}	Minimum ON period of the first digital controller output (effective for two-state and three-state controllers, $P_{b1} > 0$)
T_{k2}	Minimum ON period of the second digital controller output (effective for three-state controllers, $P_{b2} > 0$)
X_{Sd1}	Switching differential of the first digital output (effective for two-state and three-state controllers, $X_{P1} = 0$)
X_{Sd2}	Switching differential of the second digital output (effective for three-state controllers, $P_{b2} = 0$)
X_{Sh}	Contact spacing; db The contact spacing lies symmetrically around the setpoint value. In the case of three-state controllers, the P components are pushed apart by this spacing; in the case of modulating and position controllers, the motor actuator is not actuated in this area.
TT	Runtime of the motor actuator; setting for modulating and position controllers

List of abbreviations used

Other symbols

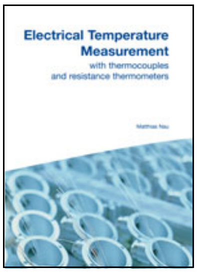
e	Control deviation (setpoint value - actual value)
K_{IS}	Transfer coefficient of a control path without compensation
K_P	Proportional coefficient of the controller
K_S	Transfer coefficient or gain of the control path with compensation
T_1, T_2	First and second time constant of a path of the second order
T_a	Settling time; in a control loop, once this time has elapsed the actual value is permanently within a defined band around the setpoint value
T_{an}	Rise time; in a control loop, once this time has elapsed the actual value reaches the setpoint value for the first time
T_g	Compensation time of a control path
T_I	Integral-action time of an I controller
T_K	Duration of oscillation for the actual value at P_{bc} (tuning method according to Ziegler/Nichols)
T_S	Time constant of a path of the first order
T_t	Dead time of a control path
T_u	Delay time of a control path
V_{max}	Maximum rate of rise (tuning method according to the rate of rise)
w	Setpoint value, reference variable
x	Actual value, control variable
X_{max}	Overshoot
P_{bc}	Critical P_b at which the control variable permanently oscillates (tuning method according to Ziegler/Nichols)
y	Output level, actuating variable
y_H	Adjustment range of a controller, usually 100 %
y_R	Output level of a controller
z	Disturbance

Informative material from JUMO –
for beginners and those with some practical experience

Know-how is not just needed to create JUMO products, but also for their later application.
That is why we offer several publications on aspects of measurement and control engineering for our users.

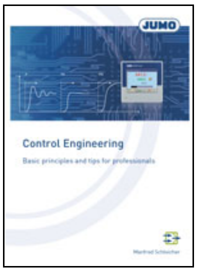
The publications are intended to provide step-by-step familiarization with a wide range of applications, for both beginners and those with some practical experience. They primarily illustrate general topics with JUMO-specific applications to some extent.

In addition to JUMO technical literature and our new software downloads we also offer the possibility to order our brochures and CD-ROM catalogs online.



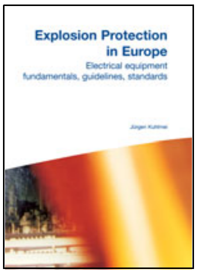
Electrical Temperature Measurement
with thermocouples
and resistance thermometers
Matthias Nau

FAS 146
Sales no.: 00085081
ISBN: 978-3-935742-07-X
Free of charge



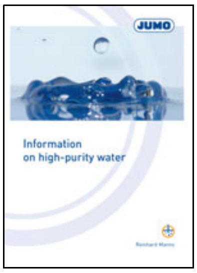
Control Engineering
Basic principles and tips for practitioners
Manfred Schleicher

FAS 525
Sales no.: 00323761
ISBN: 978-935742-01-6
Free of charge



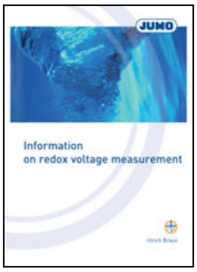
Explosion Protection in Europe
Electrical equipment
fundamentals, guidelines, standards
Jürgen Kuhlmei

FAS 547
Sales no.: 000414312
ISBN: 978-3-935742-10-X
Free of charge



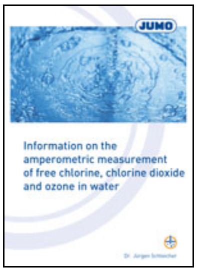
Information
on high-purity water
Reinhard Manns

FAS 614
Sales no.: 00403834
Free of charge



Information
on redox voltage measurement
Ulrich Braun

FAS 615
Sales no.: 00398237
Free of charge

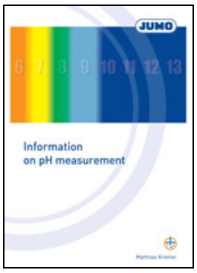


Information on the amperometric measurement of free chlorine, chlorine dioxide and ozone in water
Dr. Jürgen Schleicher

FAS 619
Sales no.: 00398147
Free of charge

SCR Power Controllers
Basic principles and tips for professionals
Manfred Schleicher, Winfried Schneider

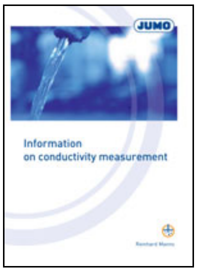
FAS 620
Sales no.: 00400481
ISBN: 978-3-935742-05-4
Free of charge



Information
on pH measurement
Matthias Kremer

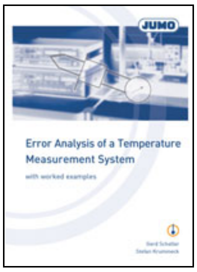
FAS 622
Sales no.: 00403233
Free of charge

Informative material from JUMO –
for beginners and those with some practical experience



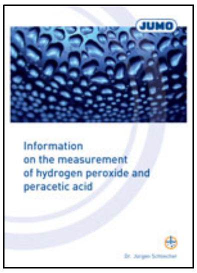
Information
on Conductivity Measurement
Reinhard Manns

FAS 624
Sales no.: 00411341
Free of charge



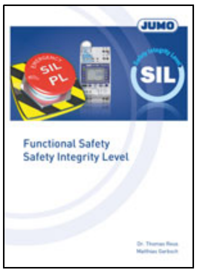
Error Analysis of a
Temperature Measurement System
with worked examples
Gerd Scheller, Stefan Krummeck

FAS 625
Sales no.: 00415704
ISBN-13: 978-3-935742-13-4
Free of charge



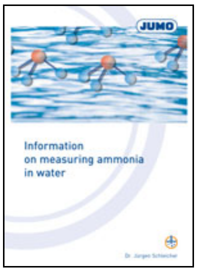
Information on the Measurement
of Hydrogen Peroxide
and Peracetic Acid
Dr. Jürgen Schleicher

FAS 628
Sales no.: 00420697
Free of charge



Functional Safety
Safety Integrity Level
Dr. Thomas Reus, Matthias Garbsch

FAS 630
Sales no.: 00476107
Free of charge



Information
on measuring ammonia in water
Dr. Jürgen Schleicher

FAS 631
Sales no.: 00485097
Free of charge

Please visit our website **www.jumo.net** and familiarize yourselves with the wide variety of JUMO products for different application fields. Our website provides you with more details and information concerning the contact persons for your requirements, questions, and orders.

JUMO

More than sensors + automation

ISBN: 978-3-935742-01-6

www.jumo.net