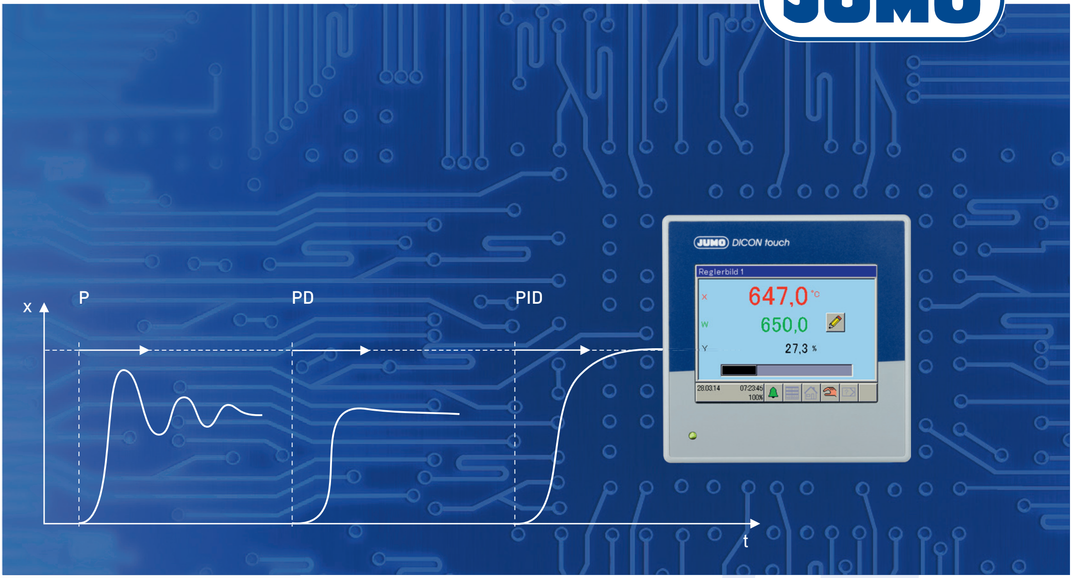

Control Engineering

Basic principles and tips for practitioners

Manfred Schleicher

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Part no.: 00323761
Book number: FAS 525
Print date: 2024
ISBN: 978-3-935742-01-6

Preface

Control technology is a key component in modern automation technology and is a central pillar within industry. However, it is often considered to be highly theoretical and based on math. This specialist book therefore concentrates very strongly on practical aspects of control technology.

As simple as possible, the book shows users how to define controlled processes and determine suitable control parameters. This specialist book is based on the author's experience as a lecturer in measurement and control technology, 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 specialist book 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 portfolio stretches from one-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 specialist book “Control technology – 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.

JUMO offers practical control technology seminars that include a high proportion of practical work (https://en.jumo.de/web/services/jumo-campus/literature).

We hope that you enjoy reading this specialist book and that you will find it useful. We would be glad to receive any requests or suggestions that you might have for future issues.

Fulda, Germany, February 2024

Manfred Schleicher

Comment:

This specialist book has been prepared to the best of our knowledge and belief. We assume no liability for possible errors. The definitive source of information are always the operating manuals for the relevant devices.

1 Key terms and overview

1.1 The closed control loop

The closed control loop contains the control process, a controller, and an actuator:

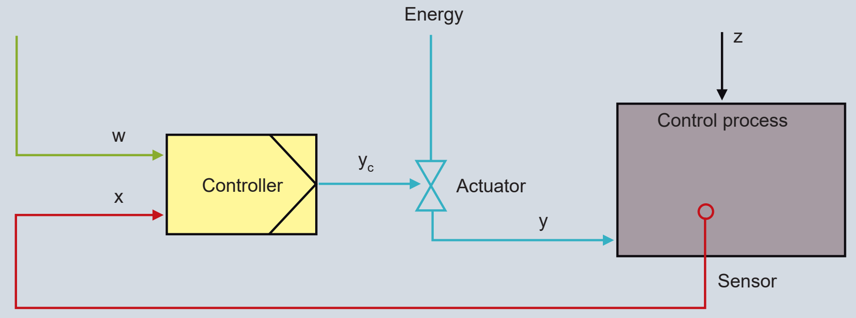


Fig. 1: The closed control loop

The control process 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. For the measurement of temperature in industrial processes usually RTD temperature probes or thermocouples are used. The electric thermometers can be directly connected to the controller, which determines the temperature on the basis of the measured resistance/respectively the voltage. The actual value is influenced by the **output level (y)**. In the shown 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 required. The actuator is driven by the controller output level (y_c), 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/time of gas enters the control process. Accordingly, if the controller output level is 50 % approximately half the amount of gas enters the process. The controller output level y_c indicates the approximate percentage of the maximum possible output and, when compared with the output level y, represents the more important of the 2 measurands for control engineers.

Controller

There is a **setpoint value** (w) adjusted on the controller. By varying its output signal, the controller regulates the actual value to this setpoint value. 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 actual value.

Further information on disturbances is provided in Chapter 2.

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

Fig. 2: Controller screen for JUMO DICON touch

1.2 Open-loop control in manual mode

In so-called automatic mode, the controller regulates the actual value to the setpoint as described above. Modern compact controllers also allow the actuator to be operated manually – in this manual mode, a defined controller output level can be specified by hand. The controller output level results in a power provided by the actuator and, ultimately depending on the plant, in a certain actual value. 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 to the respective control process through the dimensioning of the control parameters P_b (proportional band), r_t (reset time), and d_t (derivative time).

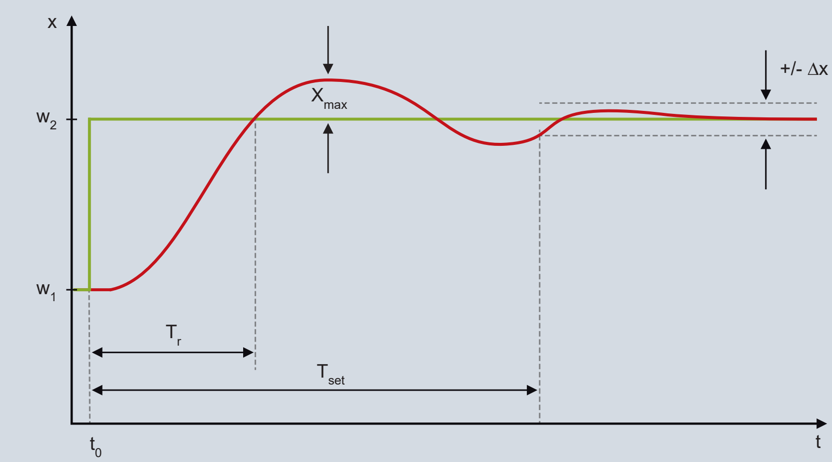


Fig. 3: Criteria for the control quality

Figure 3 shows the possible control behavior after a sudden change of the setpoint value. The following measurands can be used to assess the control quality. The rise time **(T_r)** indicates the time after which the actual value reaches the setpoint value for the first time after having specified the new setpoint. 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_{set})**.

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_r, T_{set}, and X_{max}, the higher the control quality.

1.4 Actual value processing

1.4.1 The sampling time

Modern compact controllers operate on the basis of microprocessors that require a certain computing time. The actual value is measured via the sensor, processed internally, and the output level is provided. Once the output has been updated, the input signal is read again. The time between 2 read processes of the input signal is called the sampling time.

The sampling time 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 sensors e.g. for measuring the actual value are connected.

In measurement and control technology, the transfer of measurement values take place using so-called **standard signals**. The 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. The universal inputs can evaluate standard signals, as shown in Figure 4 for a pressure transmitter.

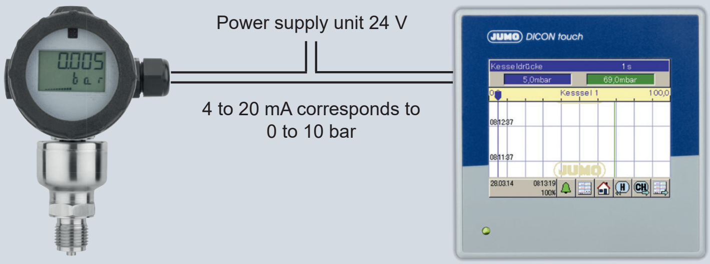


Fig. 4: Example of signal transfer using a standard signal of 4 to 20 mA

The pressure transmitter shown has measured a relative pressure of 0 to 10 bar and outputs this value 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 measured pressure is available in the controller and all settings refer to the scaled unit (in 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:

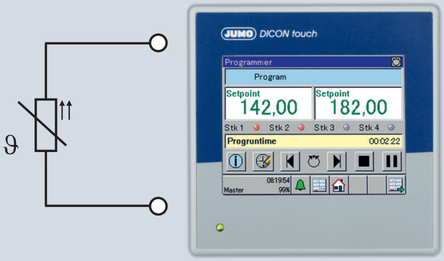


Fig. 5: RTD temperature probe on JUMO DICON touch compact controller

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 selected. 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.

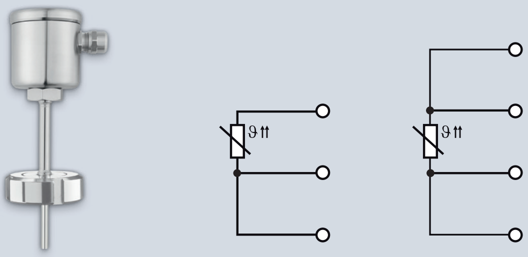


Fig. 6: RTD temperature probe for the food industry and schematic diagram of three-wire and four-wire connection concept

The main reason for the use of thermocouples is a relatively high temperature (typically greater than 600 °C). The universal inputs on JUMO compact controllers also allow this type of thermometer to be connected, see Figure 7.

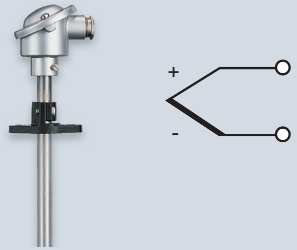


Fig. 7: Push-in thermocouple and symbol

The universal input of the controller must be configured for the "thermocouple" setting and the relevant linearization [such as NiCr-Ni (type K)] must be selected. 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:

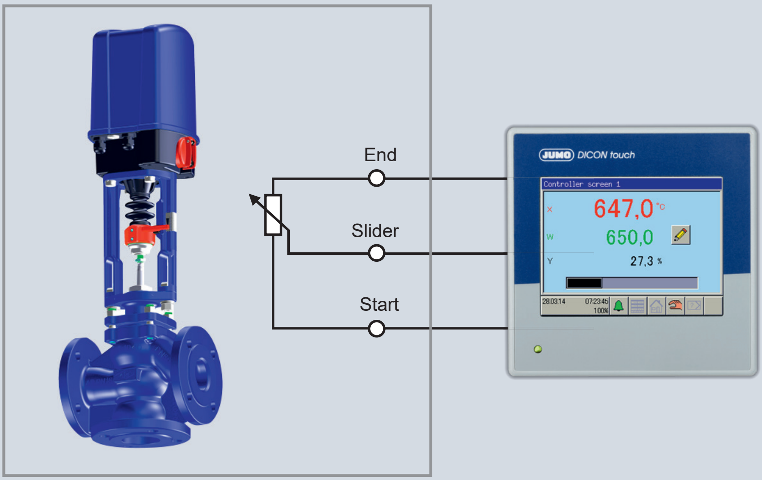


Fig. 8: Actuator made by ARI Armaturen including the connection of the output level feedback to the JUMO DICON touch compact controller

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

1.4.3 Connection of sensors for liquid analysis

JUMO has decades of experience in the production of sensors for liquid analysis. Sensors to measure the pH value, redox potential, and conductive and inductive conductivity etc., can be directly connected to JUMO transmitters and controllers used in analytical measurement.

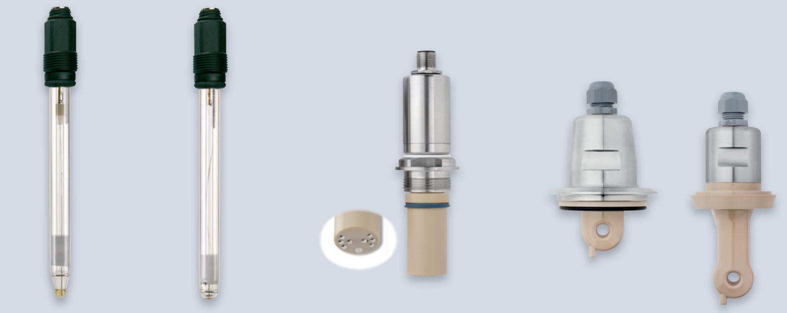


Fig. 9: Sensors for liquid analysis

1.5 Types of outputs on JUMO compact controllers

The respective control process, the required control quality, and the availability are key criteria when selecting the most suitable actuator. The actuator, in turn, requires a certain operate 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 are:

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

The actuators are operated with standard signals (Chapter 1.4.2) via a continuous output.

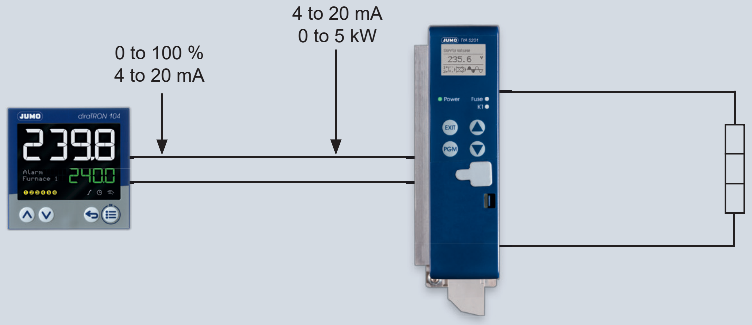


Fig. 10: JUMO diraTRON 104 compact controller, JUMO TYA 201 thyristor power controller, and heating element

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

1.5.2 Binary outputs

JUMO compact controllers are ideally suited to control a wide range of physical measurands. The components are used widely for temperature control in particular. Binary outputs are often used to control this measurand. This output type can be used for sluggish processes - with these, the controlled variable does not fluctuate, even though the energy is supplied intermittently.

The classic binary 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 require a low switching frequency (power contactors, solenoid valves, etc.).

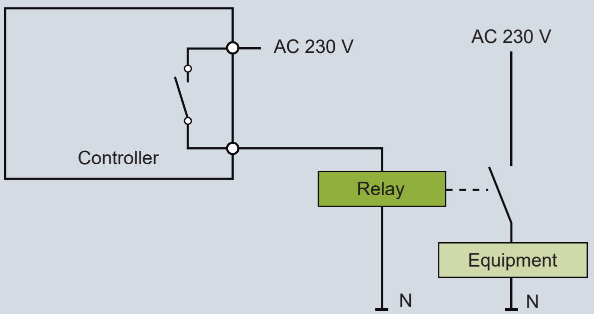


Fig. 11: Normally open contact for controlling a relay

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 the process is, the higher the required switching frequency.

Solid state relays or **Triacs** are used for higher switching frequencies and to switch an alternating (!) voltage, see Figure 12.

The elements contain 2 thyristors connected in an antiparallel manner and switch the alternating voltage with virtually no wear at all.

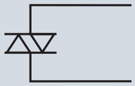


Fig. 12: Schematic diagram of a solid state relay or Triac

Binary outputs (for example 0 or 12 V) are used for controlling actuators with a direct voltage and low power requirements. A typical application is the control of thyristor power switches for supplying electrical power to heating elements:

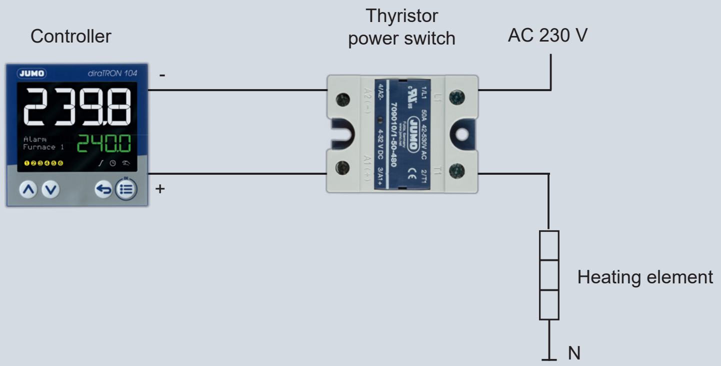


Fig. 13: Operating a thyristor power switch via the logic output of a controller

Dosing pumps are used to add acids, lyes, or chlorine, for example. The actuators often feature a pulse input that can generally be operated with a relay output. Due to the high switching frequency, so-called PhotoMOS® relays are used, see Figure 14.

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

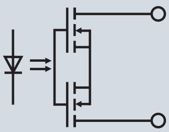


Fig. 14: Symbolic diagram of a PhotoMOS® relay

1.6 Overview of controller types

JUMO controllers can be used to implemented the following controller types:

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

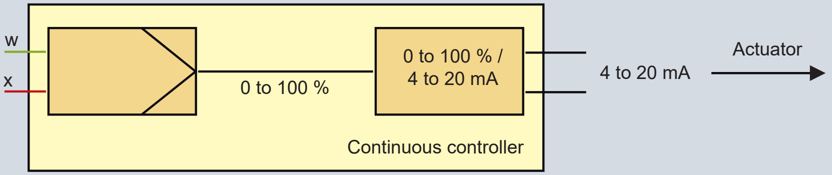


Fig. 15: Schematic diagram of a continuous controller

Two-state controllers feature a binary output for operating the actuator. In addition to a relay output, the binary outputs described in Chapter 1.5.2 are also possible. The controllers vary the relative switch-on time in proportion to the calculated output level.

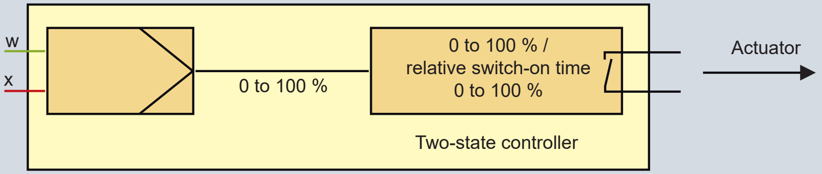


Fig. 16: Schematic diagram of a two-state controller

In order to control dosing pumps, controllers used for analytical measurement can also be operated with a pulse frequency output. In this case, the binary output is operated with a frequency that rises in proportion to the output level.

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

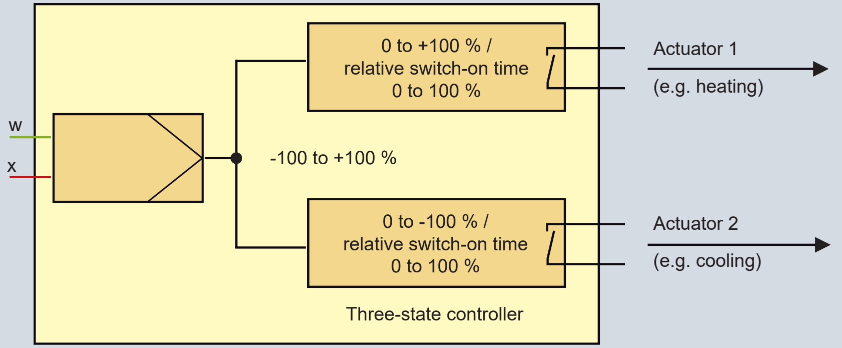


Fig. 17: Schematic diagram of a three-state controller

All binary outputs described in Chapter 1.5.2 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 binary outputs, continuous outputs can also be used.

Modulating controllers and **position controllers** operates motor actuators. The 2 outputs of the controllers open and close an actuator via the motor. The position controller requires feedback on the position of the actuator. The modulating controller does not require this output level feedback.

2 The control process

2.1 General information on the control process

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

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

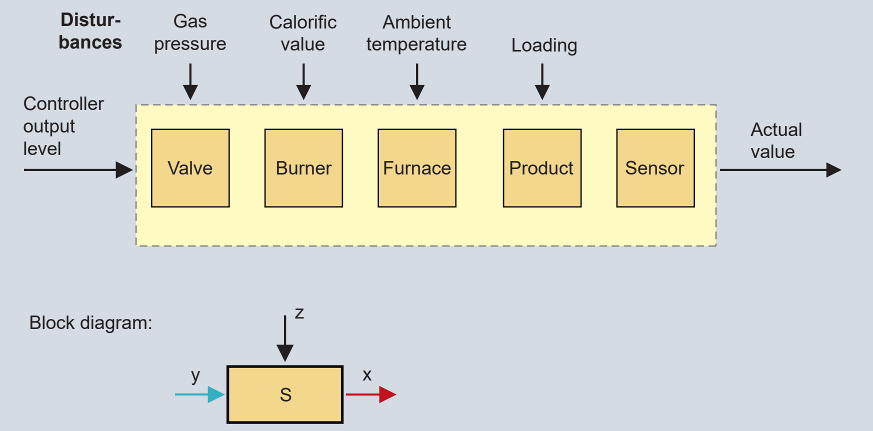


Fig. 18: Example of a control process

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

The control process includes timing elements and energy storages, 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. 1 disturbance in the system is the gas supply pressure. After the actual value is regulated to the setpoint, 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 Processes with and without compensation

2.2.1 Processes with compensation

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

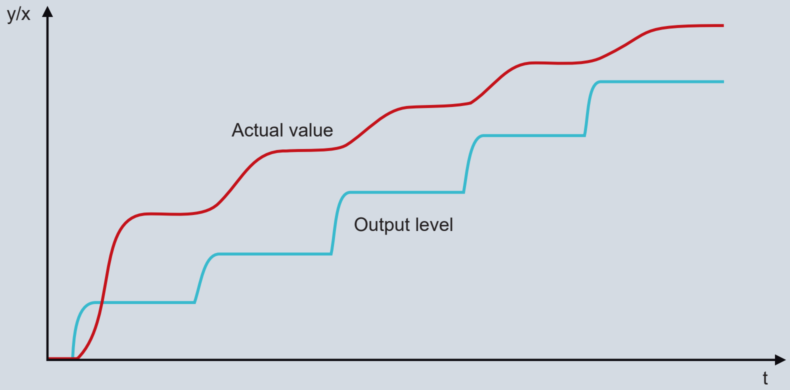


Fig. 19: Course of the actual value for a non-linear control process with compensation in the case of stepped increases in the output level

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 process with compensation behaves in a non-linear manner.

The transfer coefficient for the controlled system is the ratio of the actual value change to the change of the output level. Non-linear control processes change the transfer coefficient according to the working point. This may require changing the control parameters for different setpoints.

2.2.2 Processes without compensation

Processes without compensation respond to a step change in the output level with a continuous change to the actual value. The slope of the actual value depends on the process characteristics and is proportional to the specified output level.

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

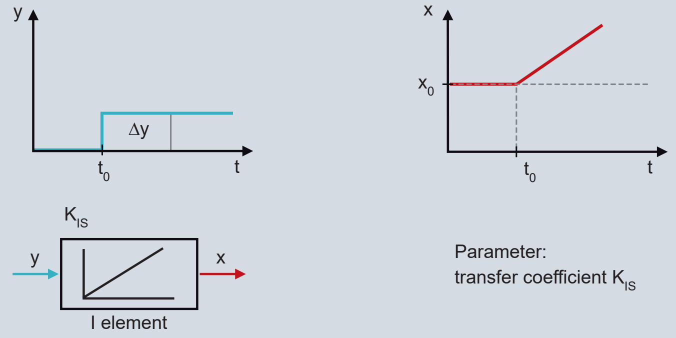


Fig. 20: Step response of a process without compensation and block symbol

If the output level for the process 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 designation "I element" (integral element) is derived from the integral-action behavior.

The following applies to the specification of an output step:

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

K_{IS}: Transfer coefficient of the control process without compensation

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

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

Examples of processes without compensation include:

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

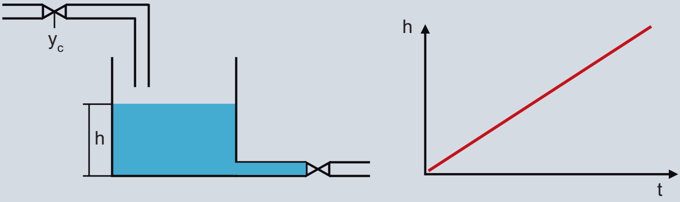


Fig. 21: Level control process

Figure 21 shows the classic example of a process without compensation. The level in a fluid container is controlled via a supply valve and applicable sensor technology. The container also features a drain valve, which is closed for this consideration. 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 process with compensation, an equilibrium state for the actual value does not occur if the output ratio is not 0 % (except if drain = supply).

2.3 Processes (process sections) with proportional response, dead time, and delay

All of the following observations apply to processes with compensation.

2.3.1 Processes with proportional response

Proportional control processes amplify the specified output level with transfer coefficient K_S with no delay:

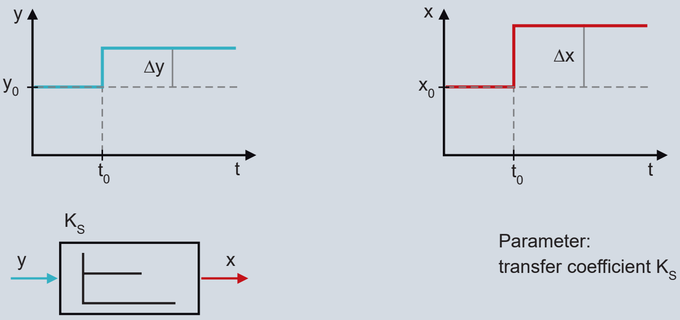


Fig. 22: P control process – step response and block symbol

If there is a sudden increase in the output level, the actual value increases in proportion. For the relationship of the actual value change Δx with respect to an output change Δy, the equation already described applies:

$$\Delta x = K_S \times \Delta y \qquad (3)$$

The described proportional behavior is usually present in combination with the following time elements.

2.3.2 Processes with dead time

P processes often occur in conjunction with dead-time elements. These so-called PT_d processes are defined by the transfer coefficient and the dead time:

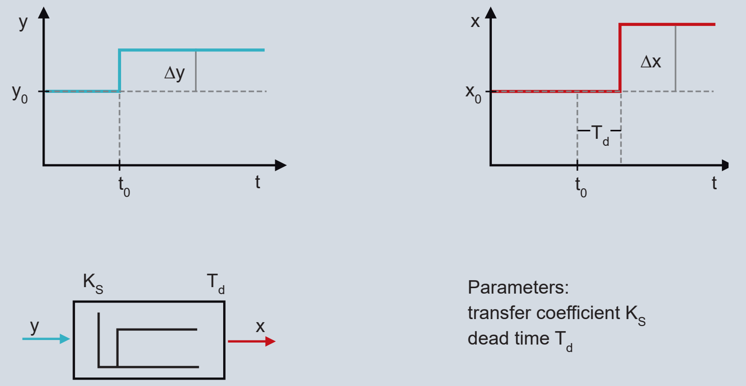


Fig. 23: PT_d process – step response and block symbol

The process responds like a P control process, 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 formula demonstrates the relationship between the actual value change and the output level change:

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

One example of a PT_d process would be a conveyor belt where a constant quantity of bulk material needs to be controlled:

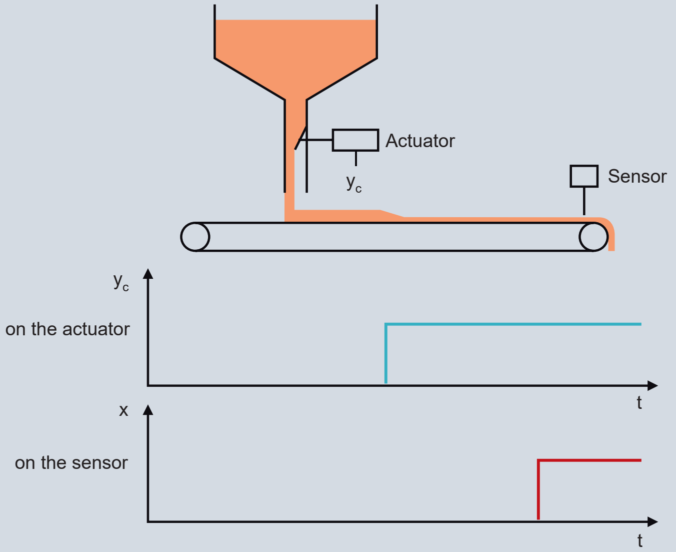


Fig. 24: Control of bulk material quantity on a conveyor belt

A controller actuates a flap with its degree of operation. 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 characterizing parameters:
An output level specified at 50 % results in an actual value of 100 t/h. If there is a sudden 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:

$$K_S = \frac{\Delta x}{\Delta y} = \frac{150\,\frac{t}{h} - 100\,\frac{t}{h}}{75\,\% - 50\,\%} = \frac{50\,\frac{t}{h}}{25\,\%} = 2\,\frac{t}{h \times \%} \tag{5}$$

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

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

2.3.3 Processes with delay

For processes with delay, after a change in the output level, the new actual value is obtained with delay. The delay results from the required charging of energy storages. The process is comparable to that for charging capacitors.

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

Control processes with a delay resp. an energy storage change the actual value immediately after having specified the step change. Directly after activation of the step the rate of change of the actual value is the highest. The actual value then moves more and more slowly towards its final value (Figure 25).

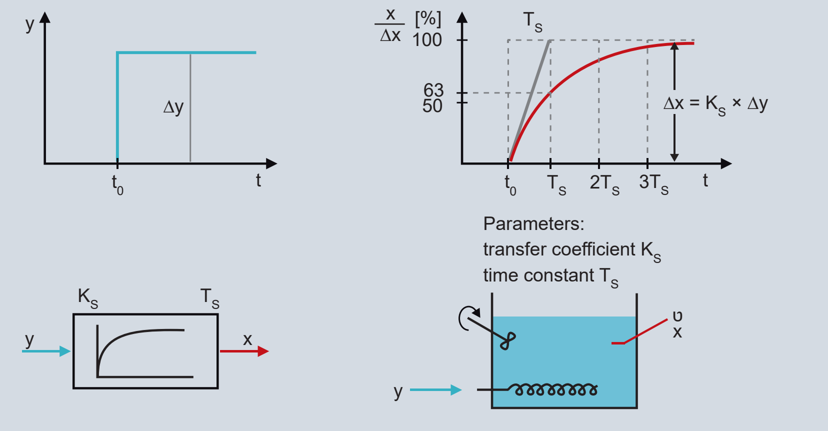


Fig. 25: Process of the first order; PT_1 process

Figure 25 shows an example of a process of 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:

$$\Delta x = K_S \times \Delta y \times \left(1 - e^{\frac{-t}{T_s}}\right) \qquad (6)$$

The characterizing parameters for the process of the first order are the transfer coefficient K_S and the process time constant T_S. The 2 measurands can be determined from the step response of the process. For this purpose, an electrical power of 5 kW is applied to the heating element as an example and the actual value (the water temperature) is recorded.

The following figure shows the course of the actual value after specifying the output step.

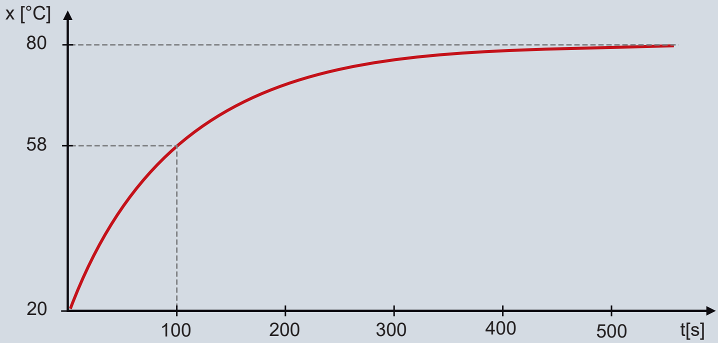


Fig. 26: Example diagram of the step response of a process of the first order

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 process is given by:

$$K_S = \frac{\text{Actual value change}}{\text{Output-level change}} = \frac{60\text{ K}}{5\text{ kW}} = 12\,\frac{\text{K}}{\text{kW}} \qquad (7)$$

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

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

$$20\ °C + 60\ K \times 63\ \% \approx 58\ °C \qquad (8)$$

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

With the 2 characterizing parameters for the process of the first order (K_S and T_S), the formula for the process step response is as follows:

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

Or:

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

Processes with 2 delays

Processes with 2 delays (second order) have 2 energy storages.

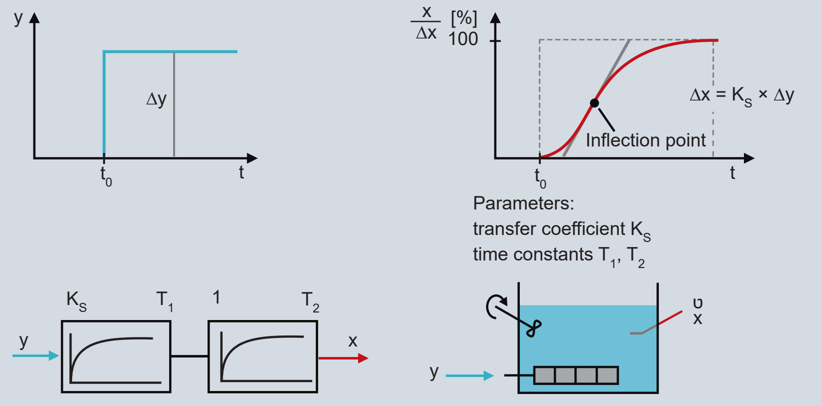


Fig. 27: Process of second order; Pt_2 process

A heating rod with a relatively large mass is used to heat the water bath. The heating rod is the second energy storage. If there is a sudden increase of the heating power, this is used at the beginning to heat the heating rod. As the heater rod heats up, the water temperature rises more and more steeply. The water temperature becomes more and more equal to the heater temperature and thus the course of the water temperature becomes flatter and flatter. At the end the water temperature runs to its final value. Figure 27 shows the tangent applied at the steepest point.

The PT_2 process is defined by the 2 time constants and the transfer coefficient. The step response is calculated according to the following equation:

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

It is not practicable to determine the 2 process time constants from the step response. The time behavior of second and higher order processes is characterized in practice by substitute parameters.

Processes of a higher order
In practice, control processes usually consist of more than 2 energy storages. However, the character of the step response of such processes is the same as that of the processes of second order previously described.

2.4 Recording of the step response for control processes

Control processes usually consist of several elements with delays and dead time:

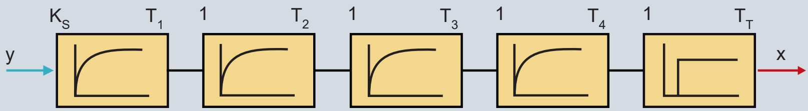


Fig. 28: Block diagram of a control process with several delays and dead time

The block diagram in Figure 28 shows 4 energy storages and a dead-time element. With real processes, the practitioners do not know the order of the process or its time constants. They also have no knowledge of how many dead-time elements are present.

Processes of 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 later. The substitute variables are the transfer coefficient (K_S) (discussed above), the delay time (T_u), and the compensation time (T_g).

The characterizing parameters are determined by recording the step response:

A step change to the output level is supplied to the control process and the course of the actual value is recorded (see Figure 29). The recording is ended when the actual value has reached the end value. A line is plotted parallel to the time axis at the level of the final actual value. By creating 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 until the intersection of the inflectional tangent with the time axis is the delay time (T_u); the time from this intersection until the intersection of the inflectional tangent with the max. line corresponds to the compensation time (T_g). The transfer coefficient results from the change in the actual value divided by the output step change.

Example:
K_S, T_u, and T_g are calculated for an industrial furnace. The furnace has cooled down and the temperature inside 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:

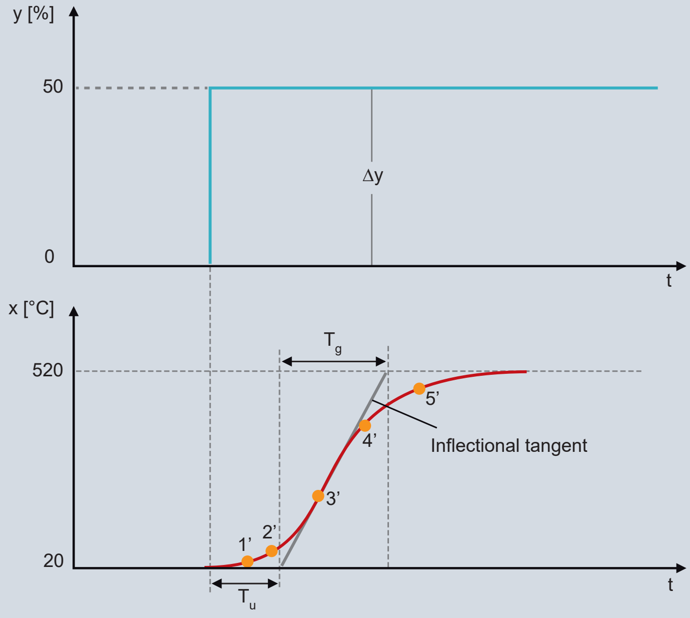


Fig. 29: Calculating the delay time and compensation time

A straight line is plotted parallel to the time axis at the level of the maximum actual value (520 °C). The transfer coefficient can therefore already be calculated. To determine the inflectional tangent, the tangents are created to imaginary points on the course of the actual value (from left to right: 1', 2', etc.). Starting at 1', the first tangent is created, 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 area is determined in this way. In Figure 29 the tangent at point 3' is the steepest. The inflectional tangent is used to determine the times mentioned.

The ratio T_g/T_u can be used as a measure for the controllability of a process:

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

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

Example:
A process of a higher order consists of many energy stores. 2 of the energy storages have relatively large time constants, however. The behavior of the process therefore corresponds to a process of second order and the ratio T_g/T_u will be relatively large.

If the characterizing parameters are used in the rules of thumb (Chapter 4.3.2), this usually results in suitable control parameters for a PID controller, for example.

3 Controller components PID and the 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) calculates the control deviation on the basis of the set-point and actual value, and amplifies this deviation with the proportional coefficient K_P. The result is output as the output level (Figure 30).

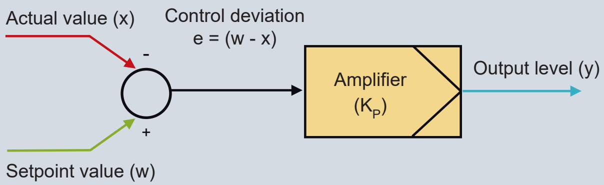


Fig. 30: Function principle of a P controller

The proportional coefficient is set on the controller by the user.

$$y = K_P \times (w - x) \qquad (12)$$

The controller operates with the dimensionless numerical value of the control deviation.

However, K_P is generally expressed by the unit %, divided by the unit of the actual value: %/Kelvin, %/bar, %/(rpm) etc.

Examples:

If the control deviation is 5 K, a P controller for a thermal process 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 %.

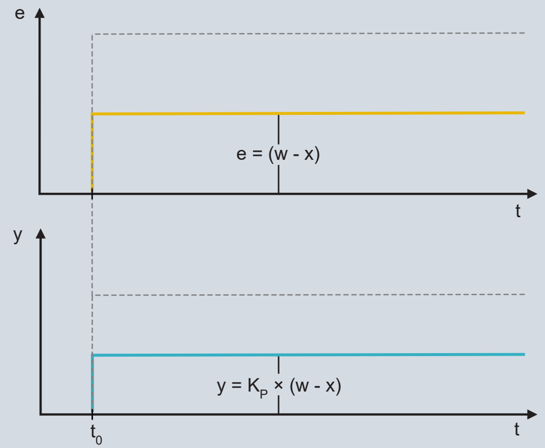


Fig. 31: Step response of a P controller

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

In JUMO controllers, the P component is defined by the proportional band and not by the proportional coefficient. The proportional band is explained in the following.

3.1.1 The proportional band

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

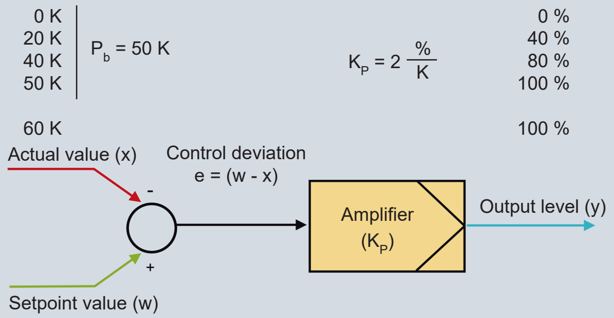


Fig. 32: Proportional coefficient K_P and proportional band P_b

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

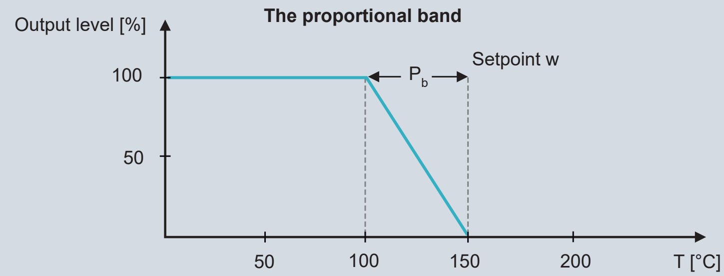


Fig. 33: Characteristic line of a proportional controller

The characteristic line (Figure 33) shows the behavior of a P controller. The output level is drawn 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 shown in Figure 34:

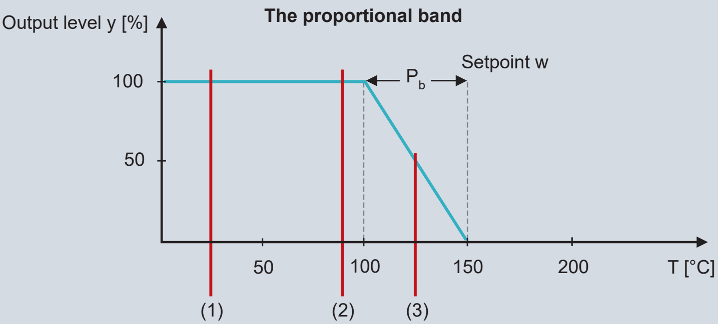


Fig. 34: Characteristic line of a proportional controller with plotted actual value

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 can be seen from the intersection with the graph line that the controller is output a 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 greater than/equal to 150 °C, the output level is 0 %.

Steady-state control deviation

If the actual value is above the setpoint value, heat output is no longer fed into the system. In the case of a furnace, the furnace will no longer be heated. In the example, the temperature will drop below 150 °C and the output level will increase. The process will reach a balanced state - if an actual value of 125 °C requires an output of 50 %, this is the case at this temperature.

The disadvantage of the P controller is the resulting control deviation. As a result, it is only used rarely. The P 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, the assumption was made that the actual value stagnates at 125 °C as an output level of 50 % is required for this temperature. If the proportional band is reduced to 25 K, the output level initially 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:

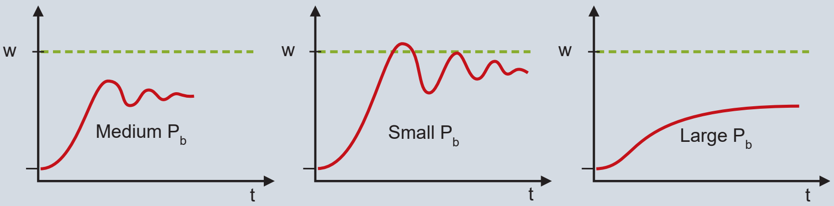


Fig. 35: Control response for different P_b

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 band and proportional coefficient

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

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

Inverse and direct control direction

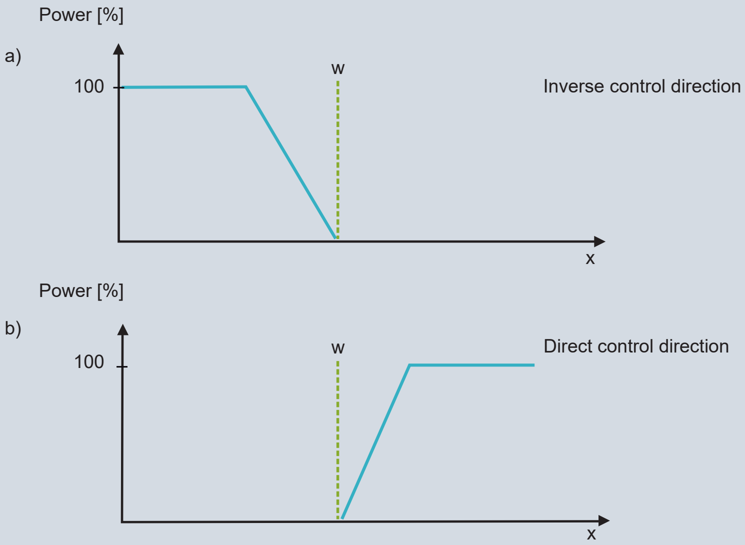


Fig. 36: Inverse and direct control direction

Depending on whether the operated actuator influences the actual value towards larger or smaller values the respective direction of action is defined at the controller.

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.).

When direct action b) is set, the output level is increased with an increase in the actual value. The increase of the output level starts when the actual value is at least equal to 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 value limit

Controllers with only 1 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:

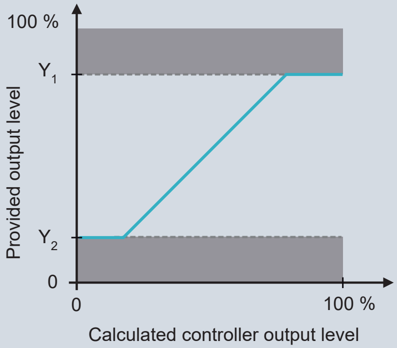


Fig. 37: Using the upper output value limit

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

A minimum output level is defined with Y_2 when using a continuous controller (Figure 37). This output level will be provided at the very least, regardless of the control deviation.

Three-state controllers (which are described later on) influence the actual value in 2 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 value limit (Y_2) (for instance, to 50 % if Y_2 is set to -50 %).

3.2 I controller

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

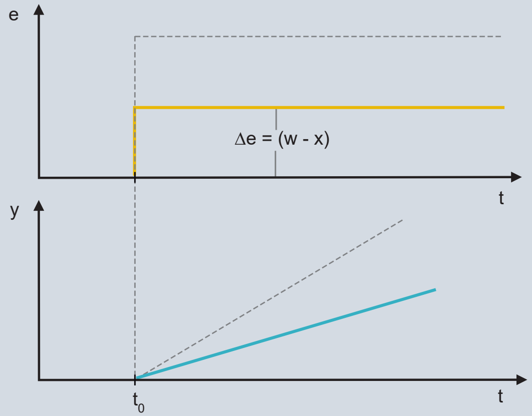


Fig. 38: Step response of an I controller

Figure 38 shows the step response of an I controller: before the step change the control deviation is 0, 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 determines the mentioned 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 %. If the control deviation offered 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.

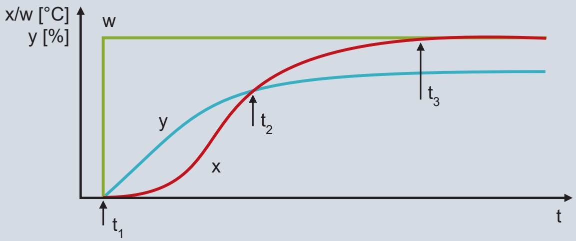


Fig. 39: The I controller in a closed control loop

Figure 39 shows the course of the setpoint value, actual value, and 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 greater and the control deviation smaller. The controller builds up its output level more and more slowly and the actual value increases at a slower rate in the direction of the 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 I controller offers the advantage that it eliminates the control deviation. However, its slow response is a disadvantage.

The integration time (T_I)
The integration time is used to change the speed of the I controller. In the case of a constant control deviation, the controller equation is:

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

y_{t_0} Output level at beginning of consideration

The smaller T_I is, the faster the I controller will build up its output level. The formula shows 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:

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

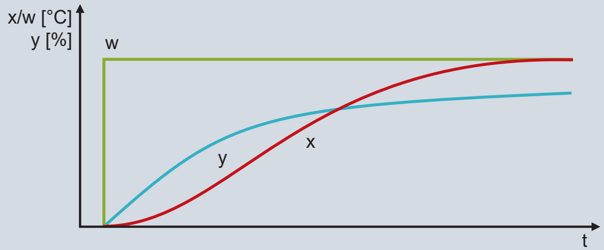


Fig. 40: I controller with a large T_I

An I controller with a relatively large integration 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.

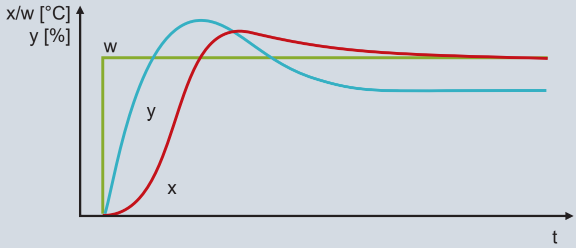


Fig. 41: I controller with small T_I

An I controller with an integration 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 power fed into the process is too high and the actual value rises above the setpoint.

Use of I controllers
I controllers are used relatively rarely, examples are strongly pulsating measurands (e.g. pressure control). They are still used for dead-time control processes and processes which have a relatively small compensation time in relation to the delay time ($T_g/T_u < 3$).

3.3 PI controller

PI controllers combine the benefits of the respective components: speed (P) and elimination of the control deviation (I). If a control deviation occurs with a PI controller, the P component amplifies 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 integration behavior is known as the reset time (r_t). On I controllers this was called the integration time (T_I). In the case of I, PI, or PID controllers, only 1 parameter should be used for the I component. For this reason, the integral behavior of JUMO controllers with only an I structure is also defined using the reset time (r_t).

Figure 42 shows the step response of a PI controller:

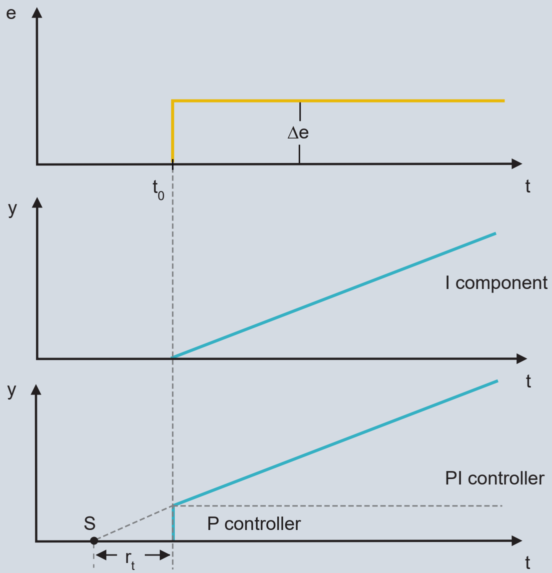


Fig. 42: Step response of a PI controller

The 2 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 determined 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:

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

or when rearranged:

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

It can be seen from the equation that the configured P_b is also included in the integral 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.

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

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

The PI controller in a closed control loop

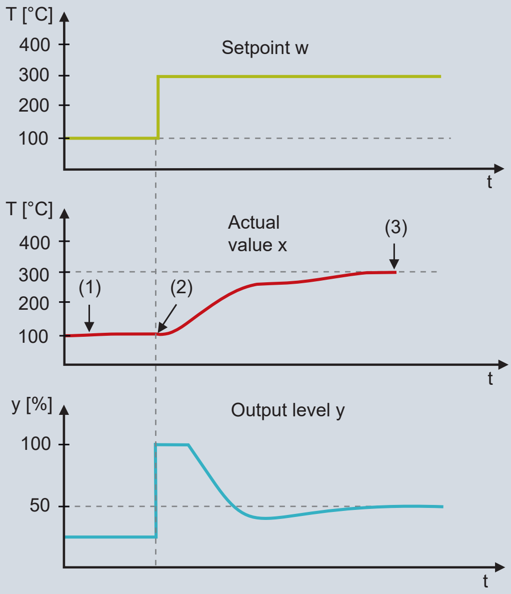


Fig. 43: PI controller in a closed control loop

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 shown.

(1) The setpoint value is 100 °C, the controller has performed adjustment, and an output level of 25 % is output. 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 decreasing control deviation. The I component increases and adjusts the actual value to the setpoint value.

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

3.4 PD controller

The D component (derivative component) reacts when the actual value changes and counteracts it. For a controller with an inverse control direction, it provides a negative output level with an increasing actual value. Accordingly, a positive output level is provided for a decreasing actual value.

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

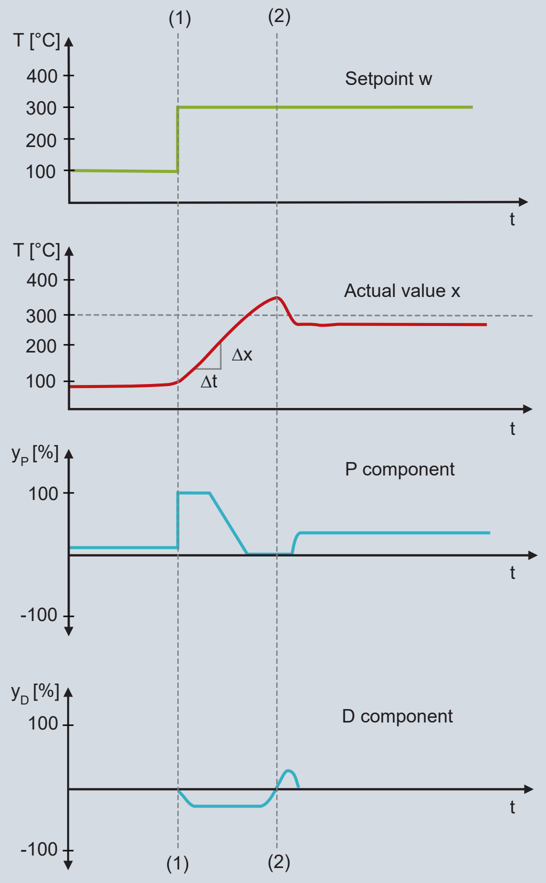


Fig. 44: The PD controller in a closed control loop

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 absence 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 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 output 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. This output level reduces the overall output level and the increase of the actual value is slowed down. With a flattening actual value curve, the output level of the D component is increasingly further reduced. If the actual value has no slope, the output level of the D component is 0 % (2). While the actual value is decreasing "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 is dimensioned, the stronger the described effect will be.

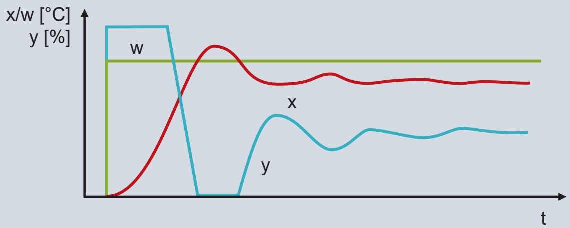


Fig. 45: PD controller with d_t = 0 s (D component is ineffective), P controller

Figure 45 shows the control behavior 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.

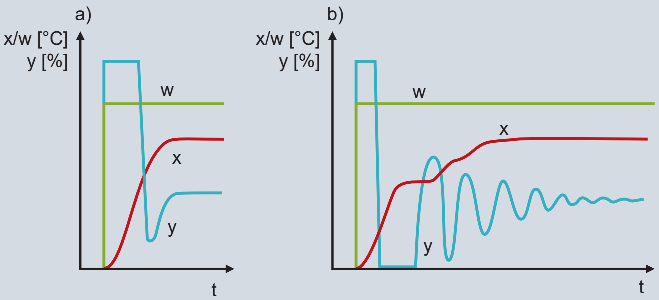


Fig. 46: PD controller with a) optimal setting for d_t and b) too large a setting for d_t

Figure 46 a) demonstrates the control behavior for a favorably set d_t: if the actual value increases, the D component reduces the overall output level; if the actual value is decreasing, the component increases the overall output level.

Thanks to this damping 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 too large d_t, the D component reduces the total output level to 0 % and the actual value curve becomes flatter. Due to the smaller slope of the actual value, the D component reduces 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 total output level again, and so on.

In a closed control loop, the actual value is influenced by changes to disturbances and moved away from the setpoint value. The D component counteracts the movement of the actual value (Figure 47), thereby reducing the maximum control deviation in the event of changes to disturbances.

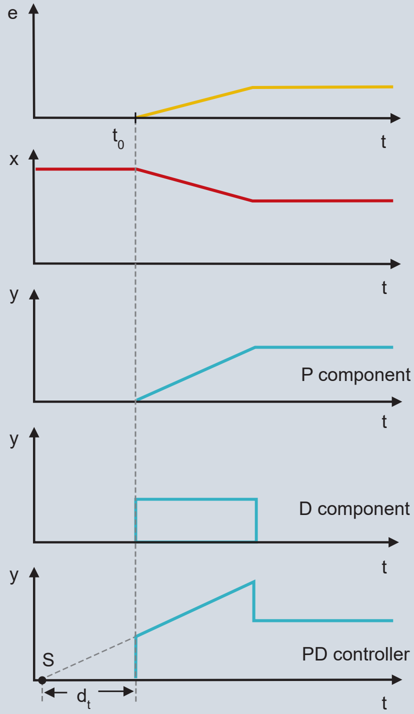


Fig. 47: Ramp response of a PD controller

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. The D component is effective from the moment in which the actual value changes. The intensity is proportional to the rate of change.

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:

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

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

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

$\frac{dx}{dt}$ Slope of the 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 "Theory").

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

In practice, the signal of the D component is damped by 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 is automatically dimensioned at $d_t/4$ and cannot be set 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 $T_1 = d_t/4$.

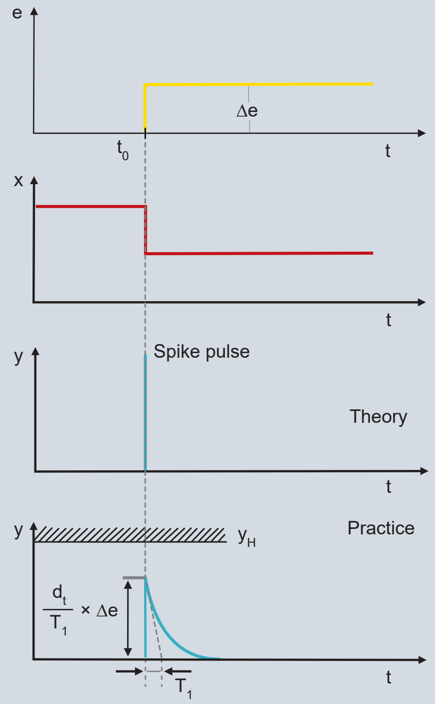


Fig. 48: Step response of a DT_1 element

3.5 PID controller

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

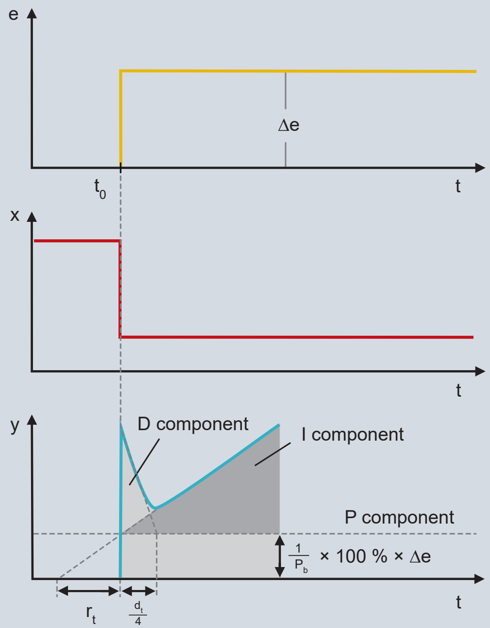


Fig. 49: Step response of a PID controller

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 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 can only be seen when the I component is at the same level as the D component.

The equation for the PID controller is:

$$\Delta y = \frac{1}{P_b} \times 100\,\% \times \left(e + \frac{1}{T_n} \times \int e \times dt - T_V \times \frac{dx}{dt} \right) \qquad (21)$$

Changing the control parameters has the effects already described:

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 integrates more slowly, resulting in more stable but also slower response.

Larger d_t corresponds to larger D component
Counteracts the change to the actual value more strongly, resulting in more stable response; d_t must not be too large.

3.5.1 Block diagram of a PID controller

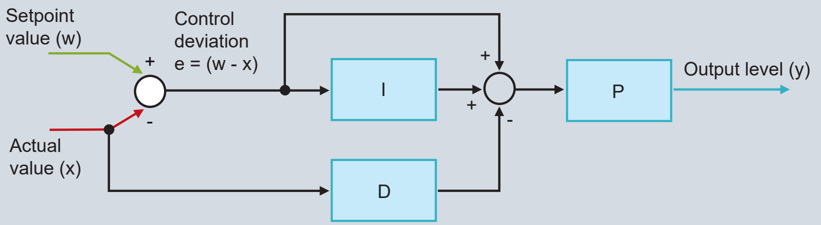


Fig. 50: Block diagram of a PID controller

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 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 ($K_P = 1/P_b \times 100$ %).

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. If doubling the proportional band or halving the gain, the I component is also reduced by half.

Therefore, increasing the proportional band, for example, will slow down the response of the I component and reduce the intensity of the D component, and the 2 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 and 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 selection aid to help you select the right controller structure for various control variables.

4.2 Transient behavior/disturbance behavior

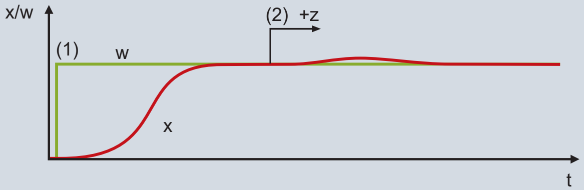


Fig. 51: Transient behavior and disturbance behavior of a control loop

Controllers are typically tuned in terms of their transient behavior (1). For this, the control behavior is considered after a new setpoint value has been specified.

Non-constant disturbances result in a temporary control deviation. The disturbance behavior shows how the control deviation is eliminated following the change to the disturbance (2).

Controller tuning is usually performed on transient behavior and the disturbance behavior is accepted. Optimization to changing setpoint values, tends to rather large values for the control parameters (P_b, r_t, and d_t). The disturbance behavior can be tuned further by reducing the control parameters. If a new setpoint value is specified with these parameters, an overshoot is very probable, however.

Parameter sets and parameter set switching
In JUMO controllers, the control parameters can be stored multiple times in different parameter sets. For example, parameters for optimal transient behavior can be stored in the first parameter set, and parameters for good disturbance behavior can be stored in the second parameter set. Switching between the parameter sets can, for example, be based on the control deviation. If there is a large control deviation, parameter set 1 (good transient behavior) is activated, for example. If the control deviation falls below a defined value, there is a switch to parameter set 2 (good disturbance behavior).

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.

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

The control process response 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 heater. If a setpoint value needs to be specified during tuning, this should lie within the later working range.

4.3.1 The oscillation method according to Ziegler and Nichols

The method is used for relatively fast control processes. To prepare for the method, the controller is set to P structure and a relatively large P_b is adjusted. A setpoint value lying within the subsequent working range is defined (Figure 52).

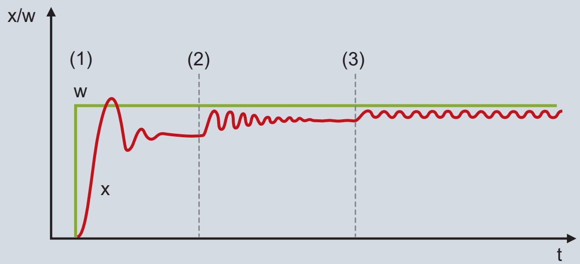


Fig. 52: Course of setpoint value and actual value with application of the oscillation method

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 absence of an I structure.

P_b is reduced (Figure 52 [2]): The actual value increases and runs with greater oscillation tendency to the final 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).

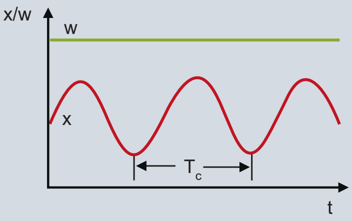


Fig. 53: Critical period duration

Based on the permanent oscillation of the actual value (Figure 53), the critical period duration T_c represents the second characterizing parameter to be determined for the method. The critical period duration T_c (in seconds) is determined from the time interval between 2 minimum values, for example.

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

Controller structure	Control parameters
P	$P_b = P_{bc} / 0.5$
PI	$P_b = P_{bc} / 0.45$ $r_t = 0.83 \times T_c$
PID	$P_b = P_{bc} / 0.6$ $r_t = 0.5 \times T_c$ $d_t = 0.125 \times T_c$

Table 1: Formulas for the parameters according to the oscillation method

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

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

For the rules of thumb, the transfer coefficient of the control process, the delay time, and the compensation time are determined on the basis of the step response. Chapter 2.4 describes the process in detail.

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

Table 2: Formulas for setting on the basis of the process 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 value is 200 °C.

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

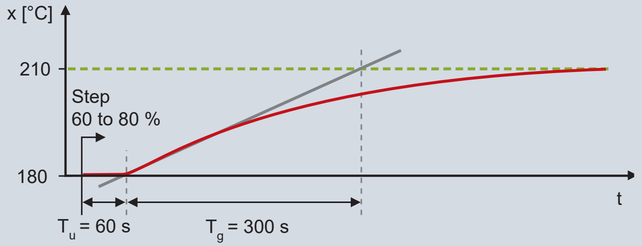


Fig. 54: Step response of the laboratory furnace

Based on the step response (Figure 54), the following is determined with the aid of the inflectional tangent: delay time T_u = 60 s, compensation time T_g = 300 s.

The transfer coefficient of the controlled system results from the change in the actual value divided by the output step:

$$K_S = \frac{\Delta x}{\Delta y} = \frac{210\ °C - 180\ °C}{80\ \% - 60\ \%} = \frac{30\ K}{20\ \%} = 1.5\ K / \% \qquad (22)$$

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

$$P_b = 1.05 \times K_S \times \frac{T_u}{T_g} \times 100\,\% = 1.05 \times 1.5\,\frac{K}{\%} \times \frac{60\,s}{300\,s} \times 100\,\% = 31.5\,K \qquad (23)$$

$$r_t = 2.4 \times T_u = 2.4 \times 60\,s = 144\,s \qquad (24)$$

$$d_t = 0.42 \times T_u = 0.42 \times 60\,s \approx 25\,s \qquad (25)$$

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 process step response: before the step change, an output level is specified that results in an actual value that is slightly less than the setpoint value used later on.

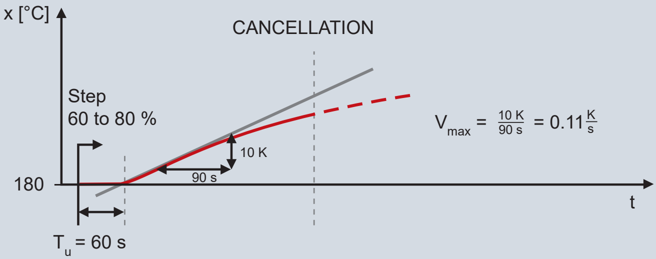


Fig. 55: Course of the actual value for the method according to the rate of rise

The step change is specified again for the laboratory furnace from Chapter 4.3.2, 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 drawn and the delay time calculated for this method as well. The second characterizing 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:

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

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

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

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

For a PID controller, the following values arise with the formulas:

$$P_b = 0.83 \times V_{max} \times T_u \times \frac{y_H}{\Delta y} = 0.83 \times 0.11 \frac{K}{s} \times 60\ s \times \frac{100\ \%}{20\ \%} \approx 27.4\ K \quad (27)$$

$$r_t = 2 \times T_u = 2 \times 60\ s = 120\ s \quad (28)$$

$$d_t = 0.5 \times T_u = 0.5 \times 60\ s = 30\ s \quad (29)$$

4.3.4 Empirical method for determining the control parameters

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

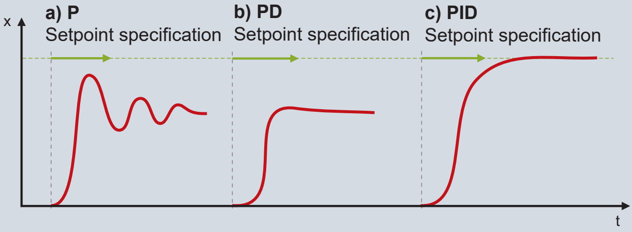


Fig. 56: Optimization of a PID controller according to the empirical method

The P structure is activated for the controller. The proportional band is set relatively large (the dimensioning depends on the control process) 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 a P_b with which the actual value reaches its final value after 2 to 3 complete oscillations (Figure 56a).

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 repeatedly specified with an increasingly large d_t. If the actual value reaches its final value with the smallest possible oscillation, d_t is at its optimal setting (Figure 56b).

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

The I component is activated by switching the structure to PID. A favorable reset time r_t is usually 4 times the previously determined d_t. Figure 56c) shows the behavior for a setting of $r_t = 4 \times d_t$.

On some processes it is not possible to activate all components. If P structure already shows an unstable behavior for large settings of 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 activation of the D component makes the control loop unstable, the PI structure should be used.

4.4 Autotuning in JUMO compact controllers

Autotuning finds practical 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 heater).

The standard method is the oscillation method.

4.4.1 The oscillation method

During autotuning, the controller calculates a switching line. If the actual value reaches this line, 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:

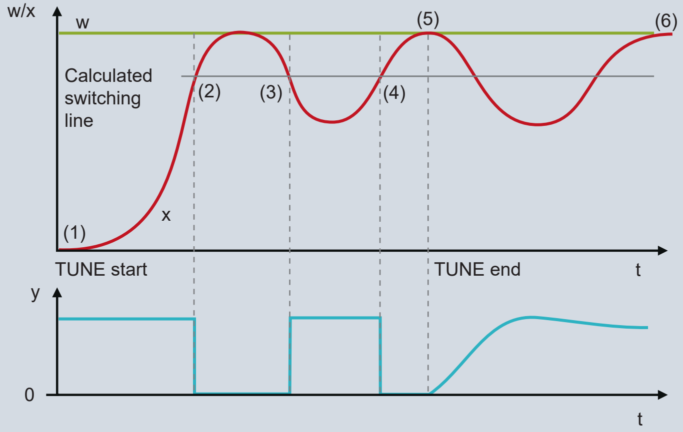


Fig. 57: Course of the setpoint value, actual value, and output level during autotuning according to the oscillation method

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 mentioned switching line. If the actual value reaches this line, the controller sets its output signal to 0 % (2). In the case of processes 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, with reaching the switching lines 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). At this moment 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 %. Furthermore, when optimizing during start-up, the maximum output level is activated for a long time. Due to this behavior, in special cases the material to be treated or even the plant itself may be damaged. Examples include plastics processing machinery or large industrial furnaces. Furthermore, the method according to the oscillation method is difficult to apply for systems that cool down only very slowly. It is extremely difficult to generate oscillations with these processes.

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

4.4.2 Step response method

With this method, the controller provides a standby output (0 % per default) when autotuning starts and waits for the actual value to stabilize (Figure 58). After this, the controller increases the output level in a step-like manner, and the actual value rises with increasing greater slope. When the actual value reaches its maximum slope the control parameters have been determined and autotuning is terminated:

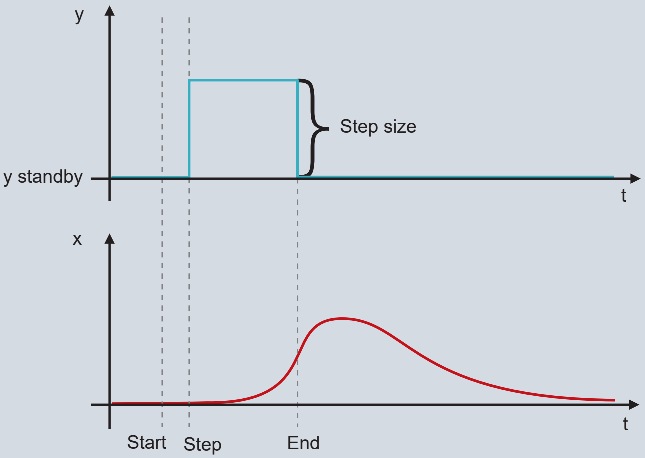


Fig. 58: Course of the actual value and output level during autotuning according to the step response method

Once autotuning has finished, the user defines the setpoint value and the identified parameters are used to adjust the actual value to the setpoint value.

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

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 constant output level no oscillation of the actual value results even with the pulse sequences.

Control processes 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:

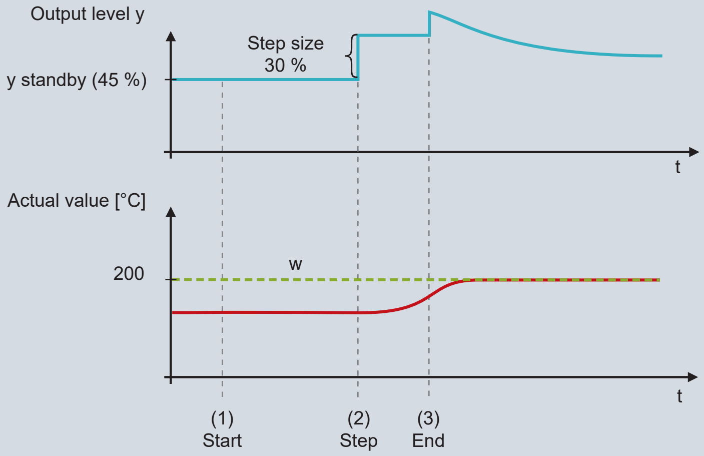


Fig. 59: Performing a step change to the output level in the area of the working point

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 mentioned 200 °C is reached with an output level of approx. 60 %, whereby the output level can be determined in manual mode, for example. The standby output is defined such that this enables the actual value to be below the subsequent working point. When autotuning is started (1) the standby output is provided (this has been defined at 45 % in the example). As soon as the actual value is stable, the output level is increased by the step change for the output level (for example 30 %) (2). The actual value increases and once it reaches the greatest slope (3) the control parameters were found and the controller uses them to adjust the value to the defined setpoint value.

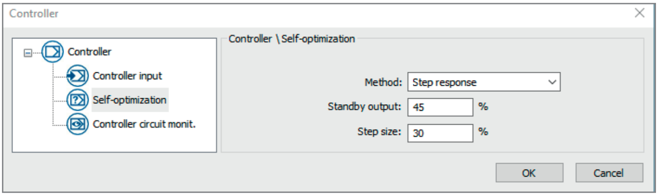


Fig. 60: Autotuning settings in the configuration program of a JUMO controller

To use the method, **Step response** is set under **Method** (Figure 60); the setting **Oscillation** is set per default. The standby output and step size are parameterized in the same menu.

4.4.3 Further information on autotuning

Both methods can only be used for processes 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 for a step size of 100 %. This is due to the fact that modulating controllers have no information of the actual position of the actuator; see Chapter 5.3.2.

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 2 exceptions in this context:

For various control processes, use of the D component results in an unstable response. Examples include pressure and flow control processes. 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 process of the first order is detected during autotuning, the structure is changed to PI.

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

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

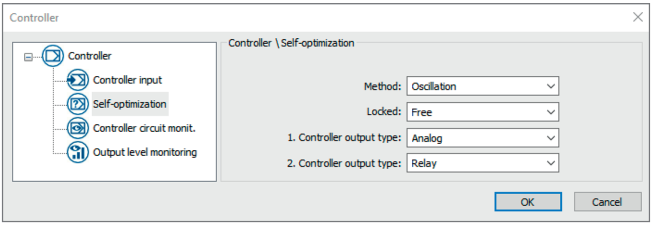


Fig. 61: Type of outputs for autotuning

In the case of a continuous controller, **Analog** must be set for **1.Controller output type**.

For a two-state controller, the settings **Relay** and **Semiconductor/Logic** are possible under **1. Controller output type**.

For a three-state 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 the Semiconductor/logic settings
With the setting **Relay**, autotuning calculates the cycle time only as short as necessary. The relay and downstream mechanics are protected as far as possible.

With the **Semiconductor/logic** setting, the cycle time is calculated as small as possible (the output will switch very frequently).

4.5 Manual retuning of a PID controller

Applying one of the tuning methods presented in this chapter, will most probably result in a stable, but not optimal control behavior.

The control result can be further improved by manual retuning. If the behavior of a PID controller can be assigned with one of the curves 62b to 62e, you will find information in this chapter for further tuning.

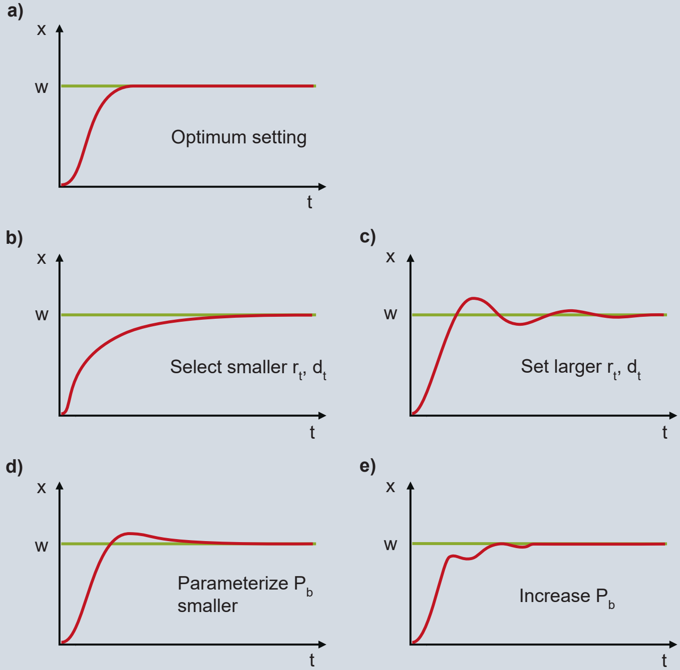


Fig. 62: Information for retuning a PID controller

a) The diagram shows an optimal behavior of 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. For faster integration, r_t must be set smaller; d_t is also 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 gets above 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 indicates that r_t is set too low. r_t must be made larger and d_t must also be increased 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 form 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 of P_b, the I component starts to build up its output level at smaller control deviations and therefore with smaller slope. The one-time overshoot shown becomes less likely.

e) With a P_b that is set too small, 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. In the proportional band, small changes in the actual value lead to large changes in the output level, resulting in a high tendency for oscillation. This can be calmed by increasing the proportional band.

4.6 Selection aid regarding the controller structure for different 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:

Processes 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 process with only dead time with a ratio of $T_g/T_u = 0$.

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

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

Control variable	Recommended controller structure
Temperature	PID
Pressure	I
pH value	Throughput control: PID; stand-alone basin: P or PD
Rotational speed of a motor	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 common control variables

5 Controllers with binary outputs

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

The controllers are used to operate digital actuators such as relays, thyristor power switches, or solenoid valves, for example.

5.1 Two-state controller

Two-state controllers provides 2 states: 1 and 0 or on and off. They enable control of a binary actuator in relatively slow processes.

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

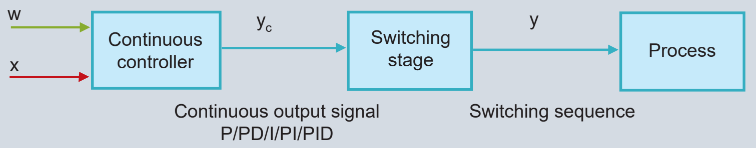


Fig. 63: Two-state controller as a continuous controller with downstream switching stage

5.1.1 Two-state controller with pulse length output

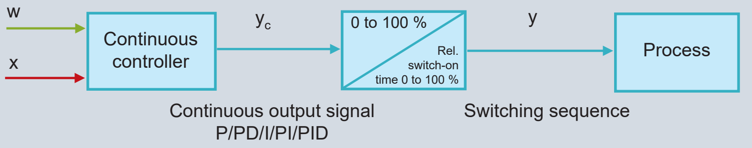


Fig. 64: Two-state controller with pulse length output

Two-state controllers with pulse length output vary the relative switch-on time of the output in proportion to the continuous controller output level y_c:

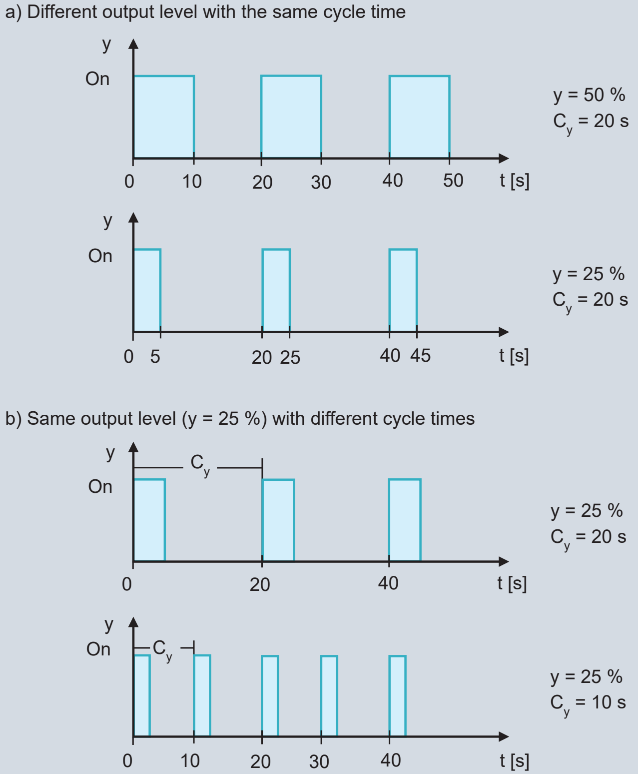


Fig. 65: Two-state controller with pulse length output

Figure 65a) 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 switch-on time.

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 C_y 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 65b) 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 operated, 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 controller with pulse frequency output

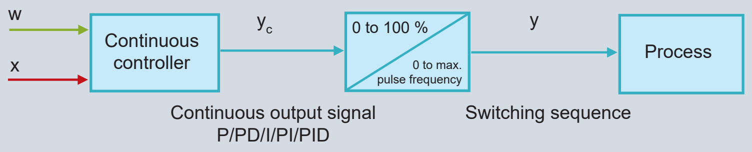


Fig. 66: Two-state controller with pulse frequency output

Two-state controllers with pulse frequency output vary the pulse frequency of the output in proportion to the continuous controller output level y_c. For the switching stage, 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 operate 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 minimum ON and OFF period (T_k) to be specified.

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

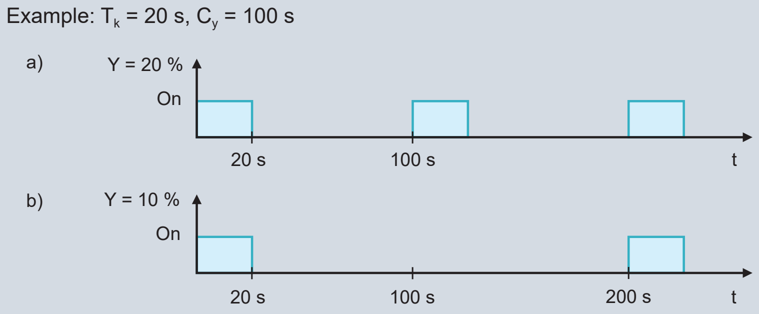


Fig. 67: Setting of $T_k \neq 0$ s

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

In Figure 67b), the controller provides an output level of 10 %: the output is also activated for 20 s in this case. For 10 % of maximum power, 9 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 pulse length, this is also set using T_k.

5.1.4 Exception: discontinuous two-state controller

If a two-state controller is operated with a proportional band (P_b) of 0, it shows discontinuous behavior. With this setting, the switching differential X_{Sd} is used and the output level is only 0 or 100 %:

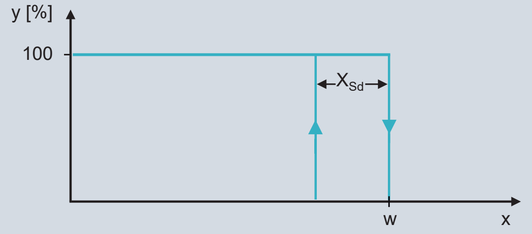


Fig. 68: Characteristic line of a discontinuous two-state controller

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 %. If the actual value falls to the setpoint value – reduced by the switching differential X_{Sd} – the output level is 100 % once again.

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

The discontinuous behavior, taking into account the switching differential, is achieved by the proportional band setting = 0.

Discontinuous two-state controllers such as thermostats and pressure switches are affordable and fulfill their control tasks in many applications. The components are to be assigned to controllers with pulse length output, where the output level is exclusively 0 or 100 %. With the control devices, the fluctuation range of the actual value is higher than the switching differential for some control processes – this applies to processes of higher order. The issue is outlined for thermal plants in the following:

Figure 69 shows the response for a **control process of first order**. The water bath operated via a heating coil from Chapter 2.3.3 can be taken as an example here.

When the cooled plant is switched on, the heating is activated immediately. The temperature increases immediately as there is only 1 energy storage (the heating coil cannot store any energy). 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. With a process of first order, the actual value moves in the switching differential band. The smaller the switching differential and the faster the control process, the higher the switching frequency.

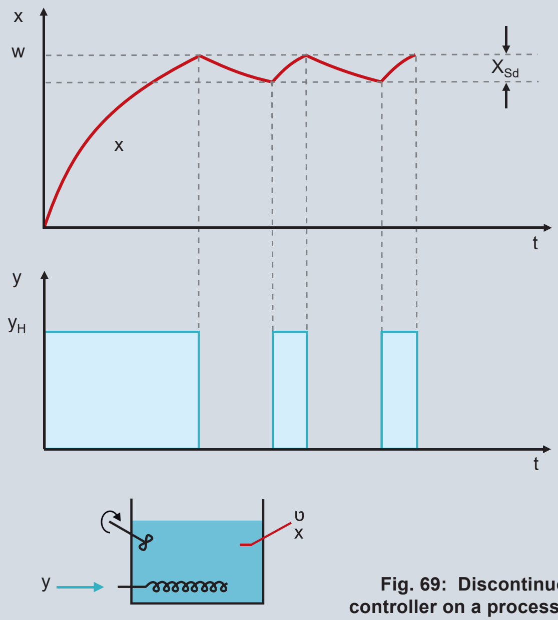


Fig. 69: Discontinuous two-state controller on a process of first order

Figure 70 shows the behavior for a **control process of second order**. In contrast to a heating coil, a heating rod with storage capacity is used.

When the cool plant is switched on, the heating is also switched on immediately. As there is a second energy storage, the actual value increases only after some time (the heating rod first needs to be heated up). 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 (at the point of switching off, the heating rod is warmer than the water – thermal energy is emitted). The actual value falls after a while and reaches the lower switching point. The heating switches on; the temperature of the water will continue to fall, until the heating rod temperature has increased noticeably. The actual value then rises again.

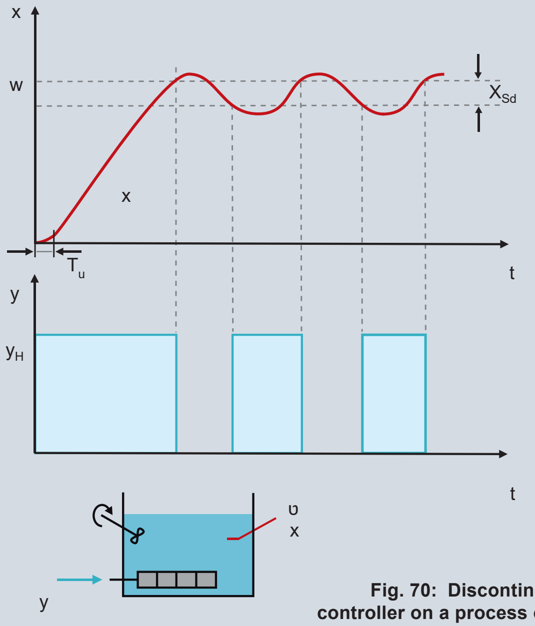


Fig. 70: Discontinuous two-state controller on a process of higher order

With processes of higher order, the fluctuations 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 fluctuate over a range of 10 K.

Summary for discontinuous and quasi-continuous controllers:
Discontinuous control systems are useful when the resulting fluctuations in the actual value are not disturbing.

The discontinuous control systems are formed using affordable components such as thermostats and pressure switches.

If the two-state controllers are realized using compact controllers, their operation is generally quasi-continuous. The quasi-continuous behavior is achieved by setting a proportional band greater than 0. The output then runs with the set cycle time and the relative switch-on time corresponds to the output level.

If the control processes are relatively slow and the cycle time is set sufficiently low, the control result of the quasi-continuous controllers with operated binary actuator corresponds to that of continuous controllers and a continuous actuator.

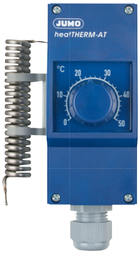


Fig. 71: JUMO heatTHERM-AT surface-mounted thermostat as a controller

5.2 Three-state controller

Three-state controllers influence the actual value in 2 directions. Typical examples include heating/cooling, humidification/dehumidification, or increasing/decreasing the pH value. In general a three-state controller can be described as a combination of 2 continuous controllers with switching stage that are located downstream.

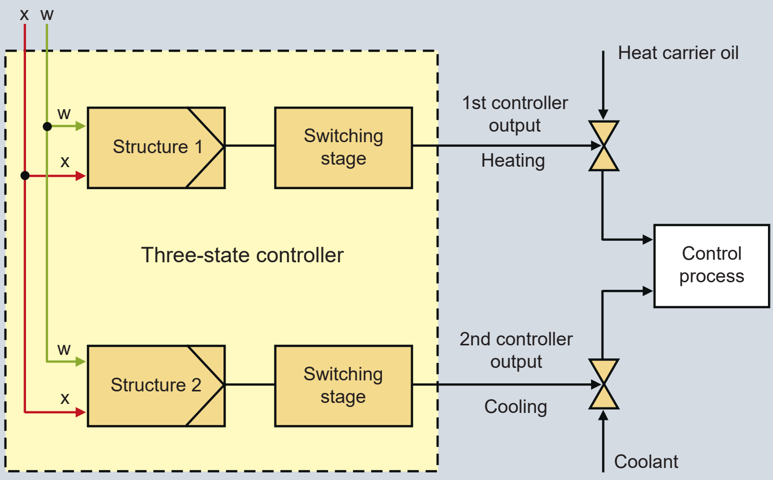


Fig. 72: Design of a three-state controller

With three-state controllers, we talk of 2 controller structures rather than 2 controllers. 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 stage (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 %. There are the same options for the output as with structure 1.

The outputs of the 2 structures are referred to as the first and second controller output.

Both structures can be adjusted independently of one another (P, PD, I, PI, or 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 but 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 (d_b) can provide a solution here:

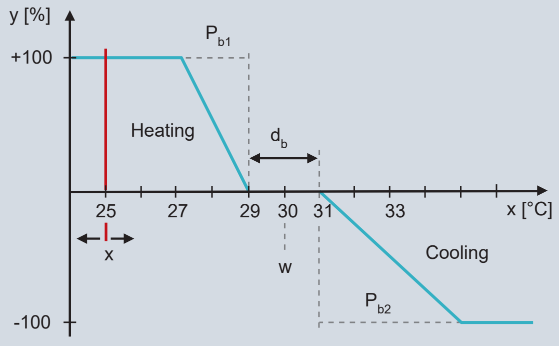


Fig. 73: Three-state controller with contact spacing and P behavior for structure 1 and 2

Figure 73 shows the diagram for a three-state controller. A P behavior exists for both structures. P_{b1} is 2 K, and P_{b2} is 4 K. The contact spacing is 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. With processes of higher order, the actual value may exceed 29 °C and the actual value is located in the contact spacing (d_b). Neither of the 2 controller outputs is active in the contact spacing area. The contact spacing "pushes" the proportional bands of the 2 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 permanent 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 2 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 73 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.

The 2 structures also operate in a discontinuous manner with the setting P_{b1} resp. P_{b2} = 0:

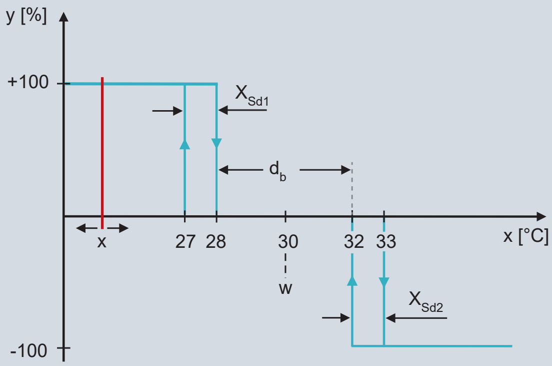


Fig. 74: Three-state controller with $P_{b1} = P_{b2} = 0$, $X_{Sd1} = X_{Sd2} = 1$ and $d_b = 4$

5.3 Controller for operation motor actuators

Motor actuators consist of a servomotor and an actuator. The actuators are often valves (gas, water) or flaps (air, etc.). The motor is switched to counterclockwise or clockwise rotation via 2 supply lines and the actuator is thus opened or closed.

The voltage supply is normally provided to the mentioned supply lines via 2 relay NO contacts:

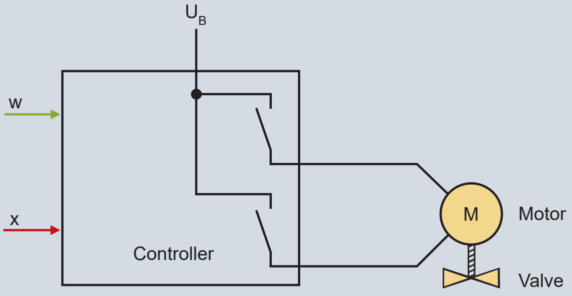


Fig. 75: Operation a motor actuator via 2 relay NO contacts

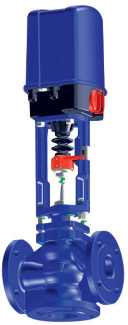


Fig. 76: Motor actuator made by ARI-Armaturen

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

5.3.1 Position controller

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

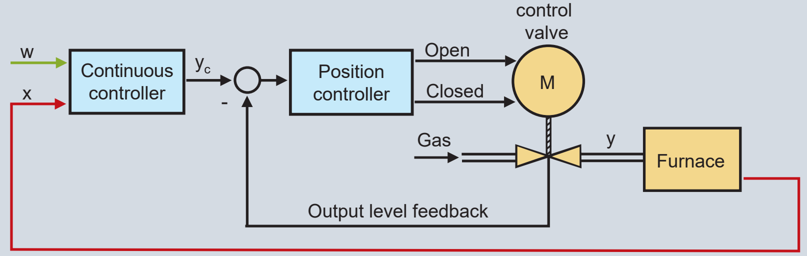


Fig. 77: Continuous controller with an integrated position controller in the control loop

Due to the control parameters, the setpoint and actual value, the continuous controller (Figure 77) 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 controller needs the output level feedback. This is performed, for example, by a potentiometer located in the actuator.

The second analog input of the controller usually receives the output level feedback. The actual value (the furnace temperature in Figure 77) is given 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.

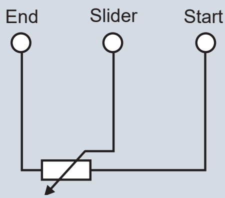


Fig. 78: Principle of a potentiometer

5.3.2 Modulating controller

In comparison with position controllers, modulating controllers have no output level feedback. The controller cannot move toward defined positions, but only moves the actuator further open and close.

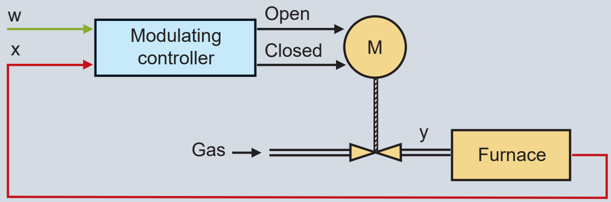


Fig. 79: A modulating controller with motor actuator in a closed control loop

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 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 80).

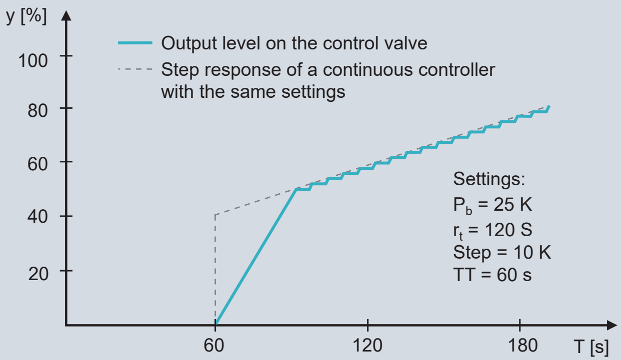


Fig. 80: Step response of the system consisting of a modulating controller and control valve

Due to the set P_b of 25 K and the suddenly occurring control deviation of 10 K this results in a P component of 40 % after the step change. The modulating controller actuates the relay for 24 s and therefore increases the output level by 40 %:

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

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 with a speed of 1 % per 3 s.

The mentioned output level increase at the actuator with a runtime of 60 s is performed with clocked control of the relay.

As long as the control deviation is present, the controller opens the actuator by clocking its output. With modulating controllers it may be the case that the actuator is already open, but the controller continues to open the actuator (for example, when the gas supply has been switched off). This fact requires end switches in the actuators.

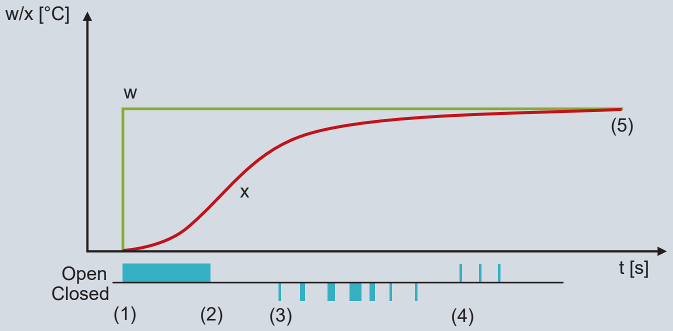


Fig. 81: Transient behavior of a modulating controller

Figure 81 shows the setpoint value, actual value, and the 2 controller outputs of the modulating controller: a new setpoint value is specified (1). 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, 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 total output level increases. From (5) onward, adjustment is complete; the controller outputs are no longer actuated, and the valve remains in its position.

Manual mode
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 operates their outputs minimally for the sampling time. For JUMO controllers, this is between 50 and 250 ms. Due to this property, it is not possible to finely adjust the output level as desired.

If, for example, an actuator with a stroke time of 60 s is actuated over 250 ms, the output level theoretically changes by 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 (d_b) defines a band around the setpoint value in which the controller outputs are not actuated. The control accuracy will be in the range of w ± 1/2 d_b.

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 longer alternating opening and closing. The actuator is therefore not unnecessarily stressed. It is particularly important to correctly dimension the contact spacing for actuators which are not designed for permanent operation.

Comparison of position controller with modulating controller

The **position controller** moves the actuator to the position required by the continuous controller in automatic or manual mode. This leads to a slightly higher control quality as well as other benefits during servicing.

Due to a control that is independent of the output level feedback, **modulating controllers** offer higher operational reliability. Modulating controllers enable the control to be established more cost-effectively (a potentiometer for the motor actuator and wiring are not required) and is sufficient for many applications.

6 Special controller circuits

So far this book has only considered single-loop control circles, where a controller operates an actuator based on its control parameters and the current actual value and setpoint value.

Alternative controller circuits can achieve the following goals:

- Cost-optimized construction
- Simpler controllability
- Resource-optimized and cost-optimized operation
- No impact from disturbances
- Reduction of impact of disturbances
- Limitation of the energy flow

6.1 Base load

When operating plants with base load, a part of the power is always supplied to the plant. The controller operates only a part of the total power.

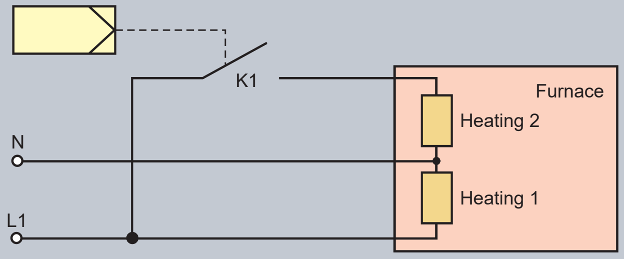


Fig. 82: Base load settings

In the example shown (Figure 82), heating 1 is constantly activated and the controller only operates heating 2. Thanks to the base load, the dimensioning for the actuator can be reduced. Furthermore, if two-state controllers are used for electrical heating, the alternating mains power is also lower. In the case of a controller malfunction, the process is continued with the base load. This results in greater process reliability.

6.2 Two-stage operation of actuators

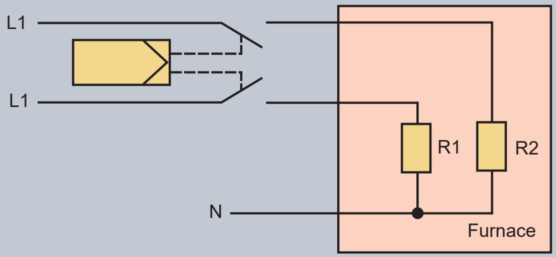


Fig. 83: Two-stage operation of actuators

The example (Figure 83) shows two-stage operation of actuators: heating 1 + 2 are used to heat up the furnace. If the furnace temperature comes close to 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 required for (switch-off if the control deviation lies below a defined value). For actuator 2, continuous actuators (for example thyristor power controllers) or binary actuators (such as thyristor power switches) are used. Motor actuators can also be used in conjunction with gas-fired plants.

This structure can be used if actuator 2 provides sufficient heat output for the adjustment to the setpoint and actuator 1 is only required for the heating up. The actuator for the adjustment may be smaller, and the load changes in the adjusted state are less intensive.

Thermal plants are occasionally operated in a large temperature range, and very high as well as low temperatures are specified as the setpoint value. With the small setpoints, only a small percentage of the available power is required, there is a high power excess. In the case of binary actuators, these can only provide the full power or no power in the moment. After a small setpoint value has been specified, even just brief activation of the actuator (with very high nominal power) may result in an overshoot.

A solution can be provided by the power being output via 2 actuators. With small setpoint values, only 1 actuator is operated, and from a certain higher setpoint value, 2 actuators are operated.

With small setpoint values, the maximum power output is lower and an overshoot is less likely.

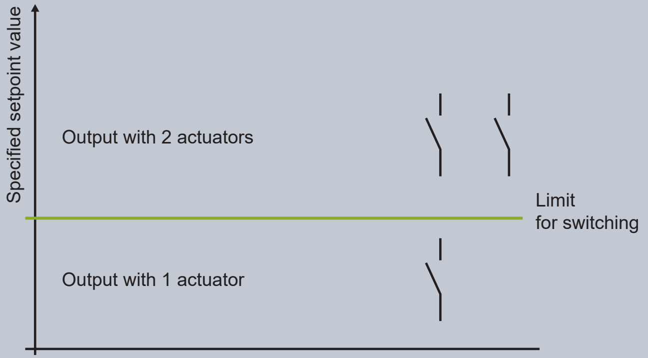


Fig. 84: Operation of 1 or 2 actuators depending on the current setpoint value

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

In a higher temperature range, thermal control processes have a smaller transfer coefficient than for smaller actual values. To achieve good control dynamics, the gain for the high temperatures can often be relatively high (the proportional band is set correspondingly small).

For smaller actual values, the high controller gain can be too large, however, and the control loop may become unstable. The instability results from too high overall gain. The overall gain results from the gain of the controller, multiplied by the transfer coefficient of the control process.

Due to the reduced power for the small setpoint values (see Figure 84), the transfer coefficient of the control process becomes smaller, and the closed-loop gain becomes similar to in the higher working range. The control will tend to remain stable even for small setpoint values.

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, which is distributed to several actuators. In the diagram shown, Split-Range operation enables energy-efficient operation of a cooling system:

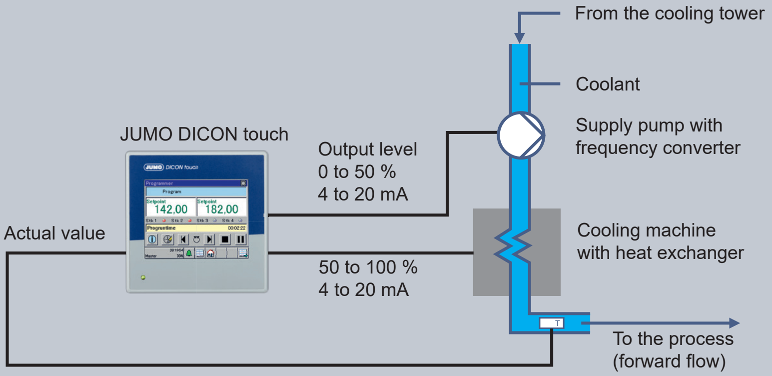


Fig. 85: Split-Range operation of a cooling system

The cooling system provides coolant for a process at a required 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 automatically 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, causing a temporary control deviation. With each change to a disturbance, 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.

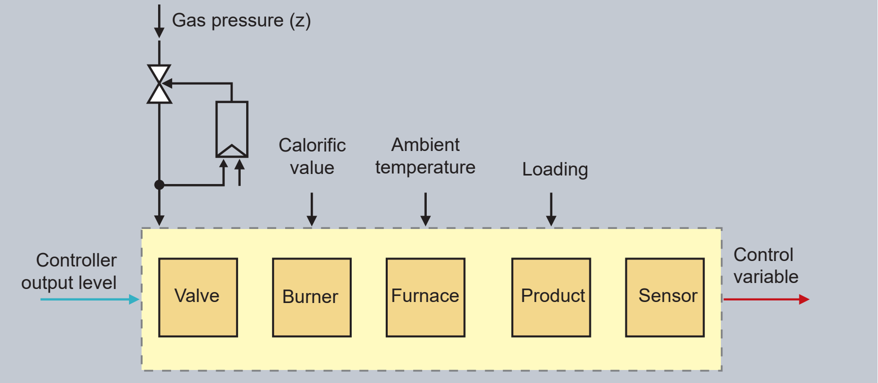


Fig. 86: Keeping the 'gas pressure' disturbance constant in a gas-powered furnace

As described in Chapter 2.1, the gas pressure is one of the disturbances in gas-powered furnaces (Figure 86). If the system is in an adjusted state, after a gas pressure change there will be a temperature deviation. The controller will change the output level and thus eliminate the control deviation. In the example, the gas pressure is kept constant, and the influence on the control variable is therefore avoided. This result can be achieved using a pressure reducer (shown in Figure 86 as a controller with a valve).

6.5 Disturbance feedforward control

Depending on the disturbances, the output level of the controller can be changed in such a way, that in the best case the influence on the actual value is completely compensated.

In JUMO controllers an additional output level can be given (additive feedforward control) or the output level can be changed in proportion to the disturbance (multiplicative feedforward control).

The controller output level is influenced depending on the disturbance. The output level change of the controller due to the influence of the disturbance reduces the control deviation that occurs in the event of a changing disturbance. This so-called disturbance feedforward control is possible if the disturbance can be measured 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 feedforward control:

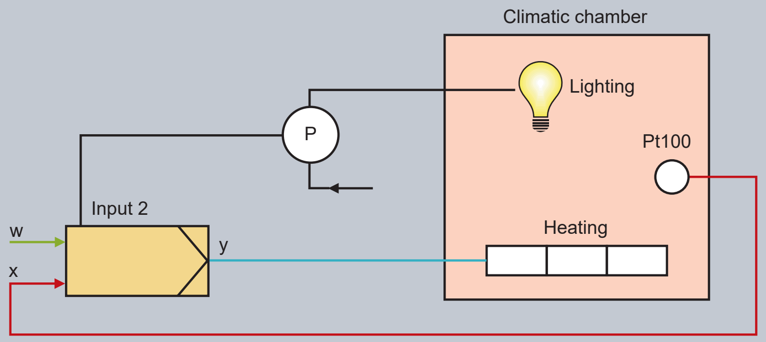


Fig. 87: Example of additive disturbance feedforward control

The incubator (Figure 87) contains highly sensitive samples. 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. As soon as the light intensity is changed again, a control deviation occurs again.

The heat entry 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 %:

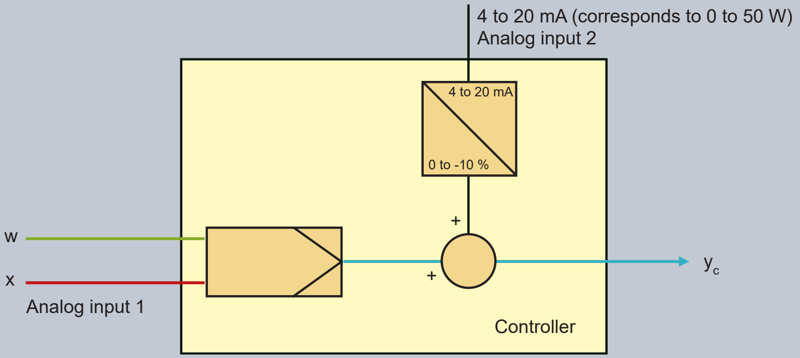


Fig. 88: Using additive disturbance feedforward control

In the example shown (Figure 88), 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 the 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 controller output 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.

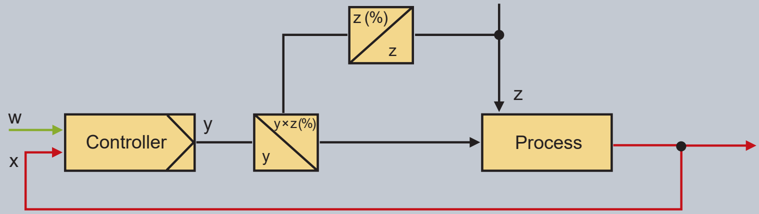


Fig. 89: Schematic diagram of multiplicative disturbance feedforward control

The value z (%) is formed from the disturbance (z), see Figure 89. The controller output level is multiplied by this percentage.

This method is used if the output level in processes needs to be changed in proportion to the disturbance variable.

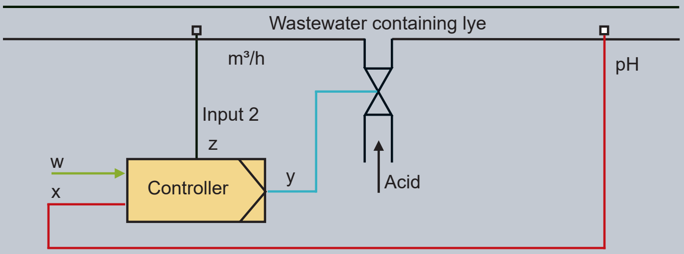


Fig. 90: Neutralization plant

A neutralization plant will serve as an example (Figure 90). Acid is added in this plant to neutralize wastewater containing lye. The aim is to achieve a setpoint value for the wastewater of pH 7.

The disturbance is the flow; doubling the flow rate needs a doubling of the amount of acid. The flow rate is fed to input 2 and the controller output is multiplicatively influenced. The flow is represented by a 4 to 20 mA signal, which corresponds to a flow of 0 to "maximum flow". By scaling the current signal at input 2, a value of 0 to 100 % is formed, for the 4 to 20 mA signal. The output level determined by the controller is multiplied by the disturbance in %. If, for example, the flow rate increases to the double 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.

With a large flow, the control process has a small transfer coefficient – the change to the dosing of the acid only has a small influence on the pH value.

In contrast, with a small flow, the transfer coefficient is larger – the change to the dosing of the acid has a greater influence on the pH value.

Without disturbance feedforward control, it is therefore quite possible that the plant will show a good control behavior for a high flow, but at a low flow rate it may show a tendency to oscillate due to the high transfer coefficient.

Due to the disturbance feedforward control, the controller gain is reduced for a lower flow, and the control variable tends to remain stable even in this area. This is a positive side effect.

6.6 Cascade control

The control loops presented in this book were so far single-loop:

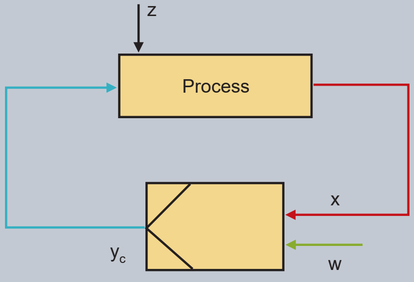


Fig. 91: The single-loop control circuit

The setpoint value is specified to the controller and it measures the actual value. Based on the control parameters, the controller output level is calculated and used to directly operate the actuator.

With **cascade control** at least 2 control loops are nested or cascaded (Figure 92). The structure divides the controlled system into at least 2 parts. The plant setpoint value is specified at the so-called master controller, which controls the actual value to this value:

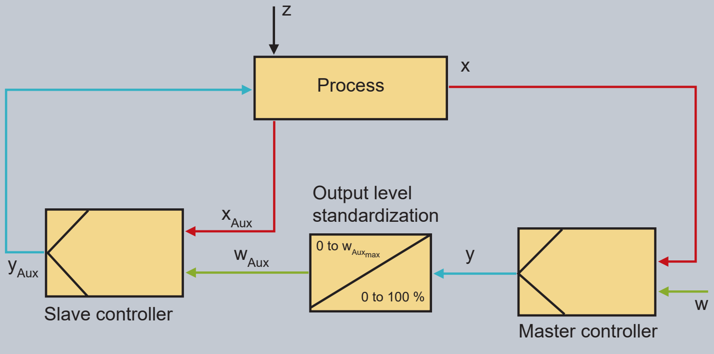


Fig. 92: Cascade control

In proportion to the output level of the master controller the slave controller controls an auxiliary actual value. The standardization of the output level determines how large the auxiliary actual value should be at an output level of 0 % resp. 100 % of the master controller. This structure can generally be used if an auxiliary actual value (x_{Aux}) can be measured in a control process and should be controlled in proportion to the master controller output level.

6.6.1 Reasons for using cascade control

The reasons for the introduction of cascade control vary and are shown as examples in this chapter.

Distribution of timing elements to several control loops

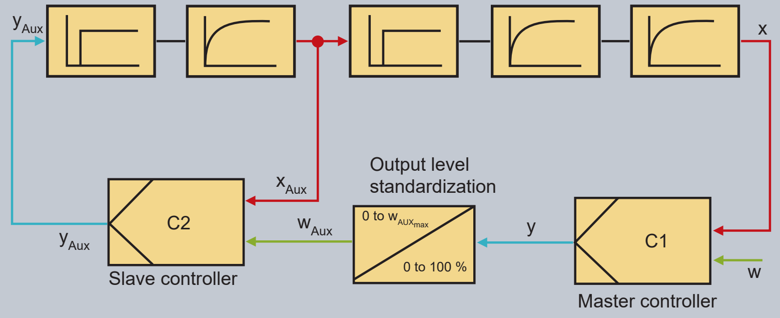


Fig. 93: Distribution of timing elements among several control loops

Due to the distribution of the timing elements, the entire delay time will no longer elapse before the controller can respond to a disturbance at the process input. After changing the disturbance variable in the inner control loop, the slave controller already reacts after the delay time of this partial control loop has elapsed. Disturbances can be compensated for more quickly.

The respective T_g/T_u ratio of the 2 individual process sections is greater than that of the entire control process. The sections and thus also the entire process are better controllable due to the cascade structure. The control quality becomes higher and sometimes control loops become controllable only by introducing cascade control.

Limiting the power in the control process resp. the auxiliary actual value

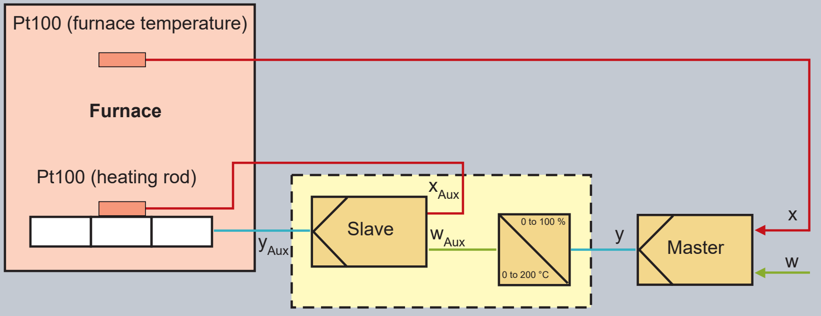


Fig. 94: Cascade control on a furnace

In the example shown (Figure 94), the heating rod temperature is limited to 200 °C. The set-point 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 of disturbances

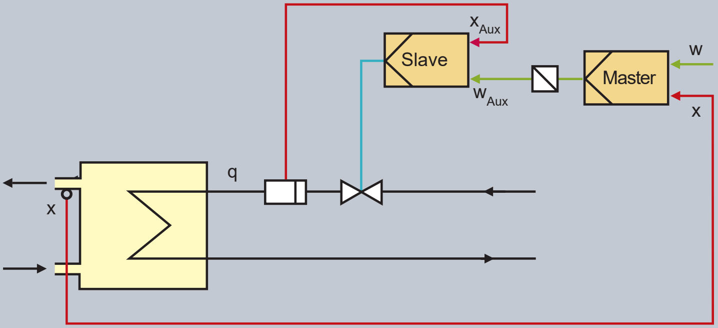


Fig. 95: Cascade control on a steam-powered flow heater

In the flow heater (Figure 95), a liquid temperature is adjusted to a defined inlet temperature (w) using steam. The temperature is controlled by the master controller. The slave controller controls the flow of steam for the flow 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 disturbance “steam pressure” therefore has no impact on the supply temperature of the liquid.

6.6.2 Controller structures and tuning of master and slave controller

When activating the I component for master and slave controller, 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, but the master controller ensures the controlling of the actual value to the setpoint.

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 master controller output level, this results in a typical setpoint value at the slave controller and autotuning can be started for the slave controller. After tuning the slave controller for 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 technology (mixture of reactants) and process engineering (manufacture of mixtures).

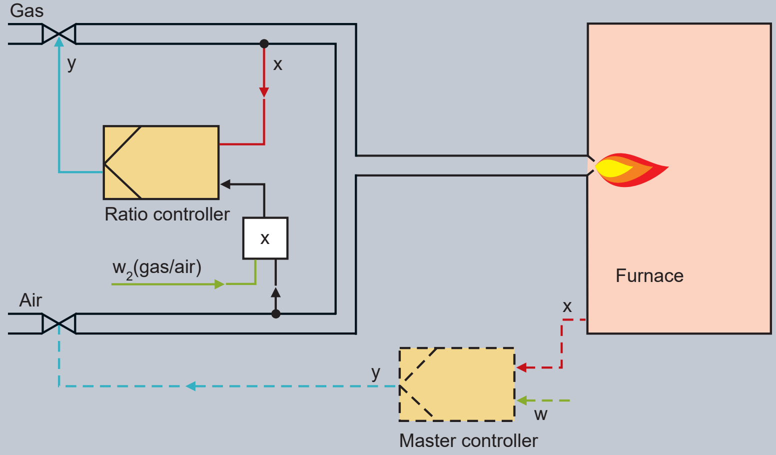


Fig. 96: Ratio control for providing an air/gas mixture

In the example shown, the air flow is measured and multiplied by a factor. The result is the required volume of gas, which represents the setpoint value for the ratio controller. For its part, the ratio controller adjusts the amount of gas to the required setpoint value. This internal system represents the ratio control.

The master controller, for its part, adjusts the value to the required furnace temperature. It operates the air flow. The volume of gas is adjusted to the set ratio by the ratio control.

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. Afterwards, the master controller is also switched to automatic mode and tuned.

7 The controller function and additional functions in JUMO controllers

JUMO controllers not only perform control tasks, they can also carry out a multitude of additional functions and thus offer the user many benefits. This chapter provides an overview of the controller function and a description of selected options.

7.1 Controller function setup

The control devices provide different configuration menus in the configuration program, or alternatively via the device front. The menus analog inputs, controller and outputs are used to set up the controller function.

The input is adapted to the sensor being used in the analog inputs menu (RTD temperature probe, thermocouple, 4 to 20 mA, etc.).

The controller type (two-state controller, continuous controller, etc.) and control direction are specified in the controller configuration menu (Figure 98). The source for the actual value can be defined in the controller inputs submenu of the same menu (Figure 97):

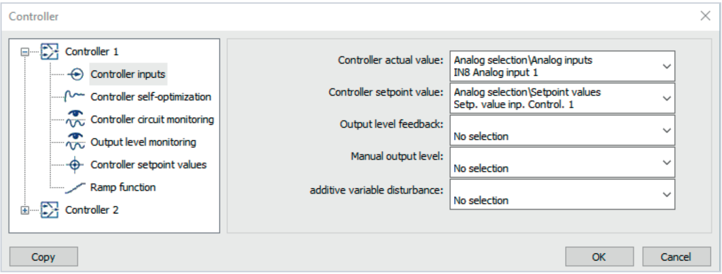


Fig. 97: Sources for controller actual value and external setpoint value

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 97).

In the configuration program under outputs the first and, if necessary, the second output is assigned to an analog or digital output.

Additional settings can be configured in the controller configuration menu:

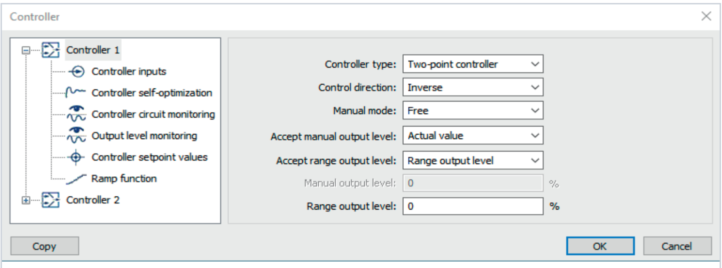


Fig. 98: Settings in the controller configuration menu

With the setting „manual mode - free“, the activation of the manual mode is possible.

With the setting “accept manual output level = actual value”, at the moment of changing to manual mode, the controller takes over the output level from automatic mode.

In general the “accept manual output level” parameter can also be used to define any output level that the controller should take over when it is switched to manual mode.

Manual mode cannot be activated if the setting “manual mode = locked” is selected.

The “accept 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).

7.2 Ramp function

JUMO controllers 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 processes require a ramped setpoint increase, however. In JUMO controllers the ramp function can be activated and a slope can be defined. After a new setpoint input (Figure 99), the current setpoint then changes with the defined slope up to the entered setpoint.

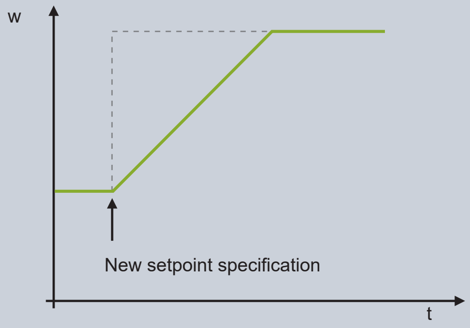


Fig. 99: Ramp-type setpoint specification

7.3 Program generator function

Program generators enable the specification of setpoint profiles. These profiles are given to the controller; the controller, for its part, controls the actual value to the currently specified value. A so-called program controller results from the program generator and controller.

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 100).

Fig. 100: Program of a program controller

In many cases, contacts are operated in the sections, for example, auxiliary heating or ventilation. So-called operating contacts are used for definition. These are assigned to the respective hardware (usually relays). The states 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 giving the product to the furnace, the relevant program is selected and started.

7.4 Limit value monitoring

The functionality allows 2 process variables to be compared and the limit value monitoring of 1 variable.

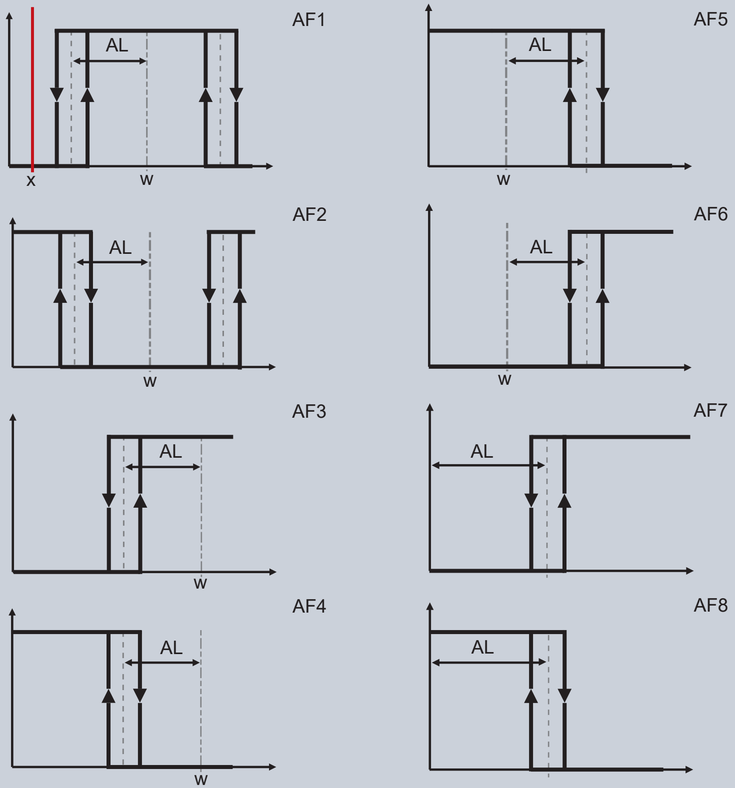


Fig. 101: Alarm functions for the limit value monitoring

The functionality can be used multiple times in a controller. For a limit value monitoring, 1 of 8 alarm functions can be selected. 4 different alarm functions exist (AF1, AF3, AF5, AF7), furthermore the respective following alarm function represents the inverted function (AF2, AF4, AF6, AF8).

Alarm functions 1 to 6 monitor 2 variables in relation to each other. The 2 variables are the setpoint value (w) and the actual value (x) of the limit value monitoring. The sources for both signals can be freely selected (for example, setpoint value and actual value of the controller, or analog input 1 and analog input 2).

Alarm function 1 (AF1) defines a window around the setpoint value of the limit value monitoring (w), for example. 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. 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.

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

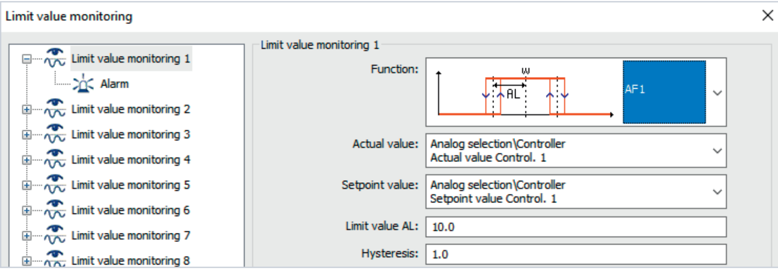


Fig. 102: Settings for monitoring the control deviation < 10 (configuration program)

In the simplest case, the result of the limit value monitoring is output via a binary output.

AF2 to AF8 perform the following basic functions:

AF2 is the inverse function of AF1 (Figure 101).

AF3 provides half the window of AF1 – if the rising actual value comes close to the setpoint value, the limit value monitoring will switch on. The function remains activated with a rising actual value.

AF4 is the inverse function of AF3.

AF5 provides the right half of the window of AF1 – if the actual value exceeds the setpoint by at least the value AL, the limit value monitoring will switch off. The function is activated with a smaller actual value.

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 binary inputs and the result of the limit value monitoring. Functions can be activated by changing the status of the respective binary signal. With the aid of the example configuration mask functions can be set up for binary input 1:

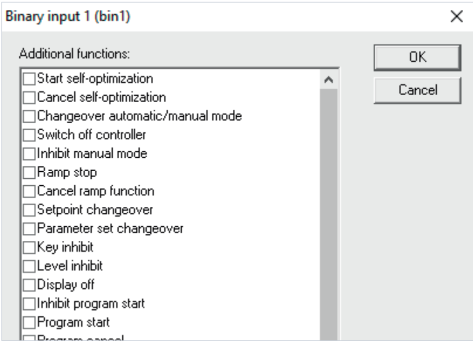


Fig. 103: Binary functions for binary input 1 (configuration program)

In the example shown, selecting **start self-optimization** (edge-triggered) allows autotuning to be started via binary input 1. With **cancel self-optimization** (edge-triggered) this can be terminated before the end.

The controller is usually in automatic mode and controls to the defined setpoint. Selecting **changeover automatic/manual mode** switches to manual mode with an active binary signal. For manual operation, an output level can be defined, which is adopted directly after the changeover.

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

Inhibit manual mode prevents a switchover to manual mode.

If the ramp function is active and the defined setpoint value has not yet been reached, the ramp setpoint value can be held with **ramp stop**. Selecting **cancel ramp function** 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 so-called setpoint value 1. Setpoint value 2 can be defined if required, and selecting **setpoint changeover** allows to change between setpoint value 1 and 2. Most JUMO controllers also have setpoint 3 and 4. To toggle between the 4 defined setpoint values, **setpoint changeover** needs to be selected for 2 binary inputs, for example (B1 and B2). The toggling is binary-coded.

The control parameters adapted to the process (P_b, r_t, and d_t etc.) are stored in a control parameter set. JUMO controllers have several parameter sets. Only the first is used per default. In some cases, the conditions in the process change to such an extent that the parameters in parameter set 1 no longer achieve a satisfactory control result. In this case, the control parameters must be modified. Parameter set 2 contains the same selection of control parameters as parameter set 1, and the required parameters for the other working point can be entered here. Selecting **parameter set changeover** allows to toggle between parameter set 1 and 2.

Selecting **key inhibit** blocks the keypad while a binary signal is activated.

Selecting **level inhibit** locks the levels for configuration and parameterization.

Selecting **display off** switches the display dark with otherwise full function of the controller.

Selecting **inhibit program start** prevents the program from starting when the program generator function is configured.

Program start and **program cancel** (both edge-triggered) allow to start and cancel a program.

Program stop pauses the program while the respective signal is active.

7.6 Start-up and diagnosis function

In many cases, controller tuning requires the recording of important process variables such as actual value, setpoint and output level.

The configuration program for JUMO controllers therefore includes the JUMO Startup software component. This can record freely selectable analog and binary signals. A connection to the JUMO controller is necessary during the recording.

Fig. 104: Data from a JUMO controller recorded online with JUMO Startup

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

The **diagnosis function** shows the status of inputs and outputs and provides important information on the controller status. The function supports troubleshooting and maintenance work:

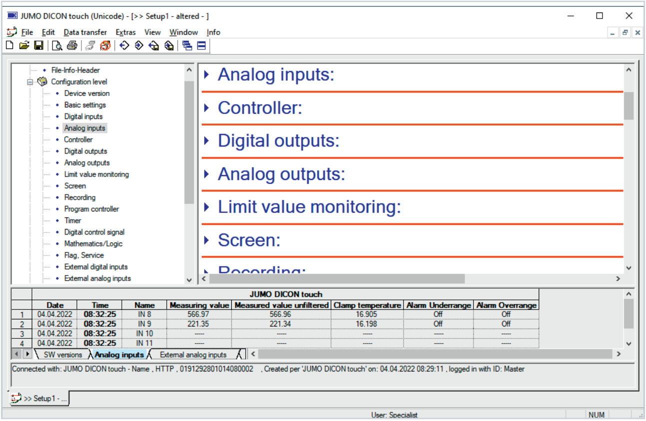


Fig. 105: Diagnosis for a JUMO DICON touch

7.7 Recording

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

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

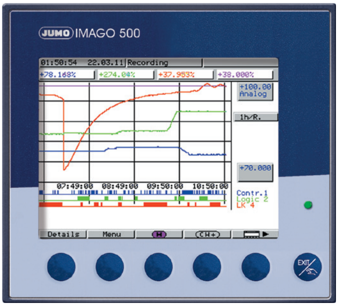


Fig. 106: Recording data in the JUMO IMAGO 500

7.8 Math and logic function

The math and logic function enables mathematical calculations and Boolean operations. Formulas can be entered in the formula editor.

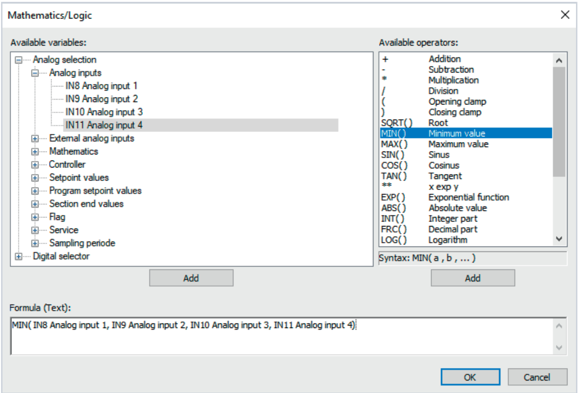


Fig. 107: Formula editor in the JUMO DICON touch

In the editor, the usable variables are located on the left and the admissible operators, including information on the syntax to be used, are located on the right.

On the basis of these 2 windows, a formula has been defined for calculating the minimum value of analog inputs 1 to 4. The 4 process variables could be 4 furnace temperatures, and the math function outputs the smallest of the 4 values. In the furnace, it should be ensured that the temperature at all measuring points corresponds at least to the setpoint. The result of the math function is defined in a further step in the controller as the source for the actual value.

8 List of abbreviations used

Controller parameters

PID behavior

P_{b1}	Proportional band of the P component; P_b
r_{t1}	Reset time of the I component; r_t
d_{t1}	Derivative time of the D component; d_t
P_{b2}	Proportional band for controller structure 2 (three-state controller)
r_{t2}	Reset time for controller structure 2 (three-state controller)
d_{t2}	Derivative time for controller structure 2 (three-state controller)

General parameters

Y_1	Upper output value limit of the controller output signal (not used with modulating controllers)
Y_2	Lower output value limit of the controller output signal (not used with modulating controllers)
Y_0	Working point correction of the P component

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

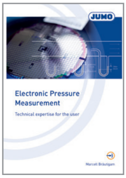
C_{y1}	Cycle time (effective for two-state and three-state controllers, $P_{b1} > 0$)
C_{y2}	Cycle time for controller structure 2 (effective for three-state controllers, $P_{b2} > 0$)
T_{k1}	Minimum ON period (effective for two-state and three-state controllers, $P_{b1} > 0$)
T_{k2}	Minimum ON period for controller structure 2 (effective for three-state controllers, $P_{b2} > 0$)
X_{Sd1}	Switching differential (effective for two-state and three-state controllers, $P_{b1} = 0$)
X_{Sd2}	Switching differential for controller structure 2 (effective for three-state controllers, $P_{b2} = 0$)
d_b	Contact spacing (or deadband) The contact spacing lies symmetrically around the setpoint value. In the case of three-state controllers, the 2 proportional bands are located separate from each other around this; in the case of modulating and position controllers, the motor actuator is not operated in the area of the contact spacing.

TT Runtime of the motor actuator; setting for modulating and position controllers

Other symbols

e	Control deviation (setpoint value - actual value)
K_{IS}	Transfer coefficient of a control process without compensation
K_P	Proportional coefficient of the controller
K_S	Transfer coefficient or gain of the control process with compensation
T_1, T_2	First and second time constant of a process of second order
T_{set}	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_r	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 process
T_I	Integral time of an I controller
T_c	Duration of oscillation for the actual value at P_{bc} (tuning method according to Ziegler/Nichols)
T_S	Time constant of a process of the first order
T_d	Dead time of a control process
T_u	Delay time of a control process
V_{max}	Maximum rate of rise (tuning method according to the rate of rise)
w	Setpoint value
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_c	Output level of a controller
z	Disturbance

Informative material from JUMO



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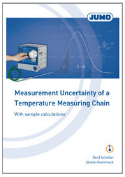

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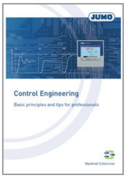

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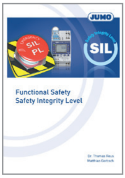

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