# Control Engineering – a Practical Guide

Manfred Schleicher

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## Preface and notes on the contents of this book

There are a great many books and publications available on control engineering, which are often very theoretical and difficult to follow. This book is a practical guide to introduce staff in planning, commissioning and service to the field of control engineering.
The reader should have received a technical education or undergone appropriate training.

The explanations are practically oriented and supported by examples. We have not introduced any advanced mathematics, but have rather used proven empirical formulae, wishing to promote a feeling for control engineering. Although a few sections (Chapters 1 and 7) refer specifically to JUMO equipment, the majority of the explanations have general validity.

## At this point we would like to give you a brief overview of the layout of this book:

In **Chapter 1** we want to impart the basic principles of control engineering. Following general notes on the closed control loop and its response, we present some items of equipment.

**Chapter 2** illustrates various types of process, and informs you how to characterize a process.

After reading **Chapter 3**, readers should basically be able to handle the parameters for a PID controller ($P_b$ , $r_t$ and $d_t$ ).

In **Chapter 4** we will show you various tuning methods and decide on which types of controller are suitable for various process variables.

Information on working methods and the configuration of 2-state, 3-state, modulating and actuating controllers can be found in **Chapter 5**.

**Chapter 6** explains special controller circuits – cascade control, for instance – and their functional or commercial advantages.

JUMO controllers have some additional functions, such as self-tuning or a program controller function, that are explained in **Chapter 7**.

## Seminars on control engineering

At the time of printing, we offer three different seminars on this subject. The present book is used as a working basis for the practice-oriented training. Participants receive not only theoretical instruction, but also take part in workshops on controlled processes.

You can find further information in the support section of our home page: www.jumo.net
- or just call us.

We hope you will enjoy reading this book and that it will provide you with the information you need. Any comments will be gratefully received.

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# Basic concepts

This chapter informs you about some basic concepts in control engineering and explains various components. We will start with the closed control loop and define the control-loop behavior. In addition, we will take a look at various sensors, actuators and controllers, using some JUMO components as examples.

## 1.1 The closed control loop

A closed control loop consists of the controlled process, a controller, and an actuator.

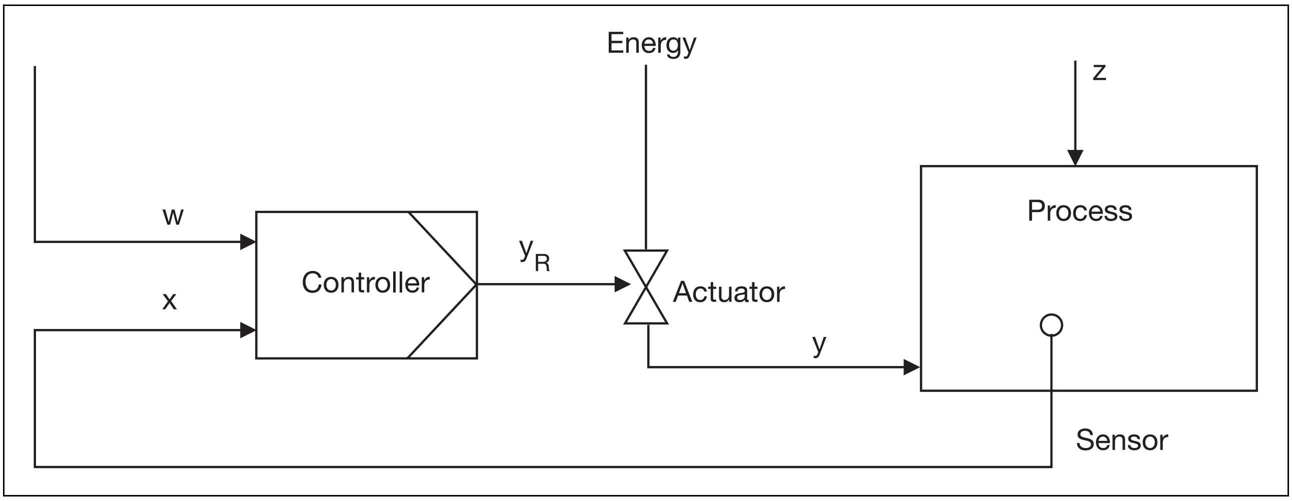


**Fig. 1: The closed control loop**

Fig. 1 shows an example of a closed control loop: a gas-fired oven.

**The controlled process**
The controlled process is the portion of the system in which the **process variable (x)** is to be held constant. In our example, the process variable (i.e. the process value) is a temperature. This is usually measured by a resistance thermometer or a thermocouple, and connected to an input on the controller.

In a closed control loop, the process value can be influenced by the **output level (y)**.
The output level represents energy – a flow of gas in our example.

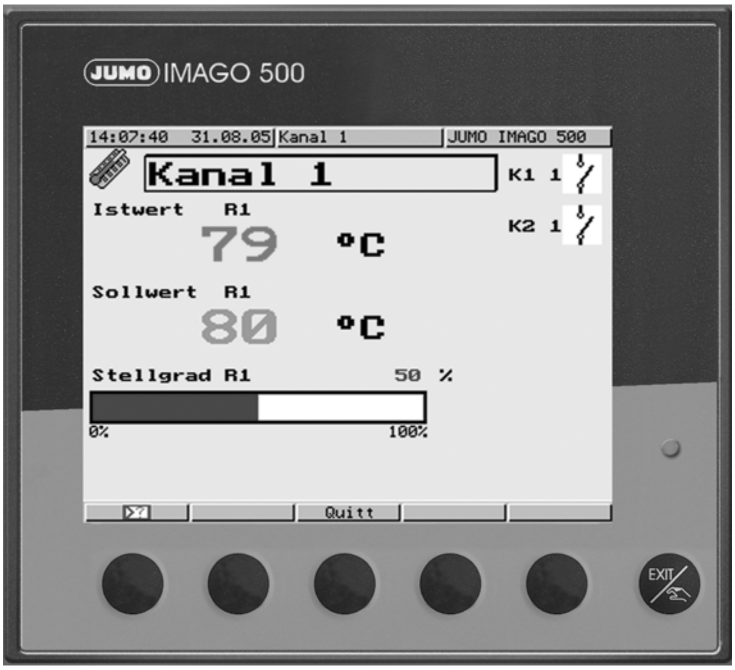
**Actuator**
In most instances, the controller cannot alter the output level directly, and so actuators (control devices) are used. Actuators are operated by the controller, through its **controller output level $y_R$**.
In our example, the actuating device is a gas valve.
If the controller generates an output level of 100 %, the maximum amount of gas will be fed into the process. Likewise, at a controller output level of 50 %, only half as much gas will be fed in.

**Controller**
The controller uses its output level (in this example, it lies between 0 and 100 %) to regulate the process value to meet the **setpoint (w)** that has been defined for the controller. The difference between the setpoint and the process value (w – x) is known as the **control deviation e**.

If a **disturbance z** alters its value, this will also have an undesirable effect on the process variable. You can read more about disturbances in Chapter 2 *“The controlled process”*.

From these explanations we can deduce, that in a control loop there is a distinction between the controller output level (the output signal from the controller) and the output level proper (the energy in the process). For a control engineer, the percentage of the maximum output that is fed into the process is important.
So for this reason, the controller output level $y_R$ is the decisive factor.

Fig. 2 shows a JUMO IMAGO 500 controller screen.
The most important variables are presented in the display.



Istwert R1 79 °C

Sollwert R1 80 °C

Stellgrad R1 50 %

0% 100%

**Fig. 2: Controller screen, JUMO IMAGO 500**

In this chapter we have met a number of control engineering parameters and their abbreviations. In addition, a large proportion of the abbreviations used in this book are printed in *„Appendix: Abbreviations“*, together with a brief explanation.

## 1.2 The control-loop response

Suitable parameters must be found to define the response of the controller. What result will be expected from the controller in a closed loop if, for instance, a new setpoint is applied?

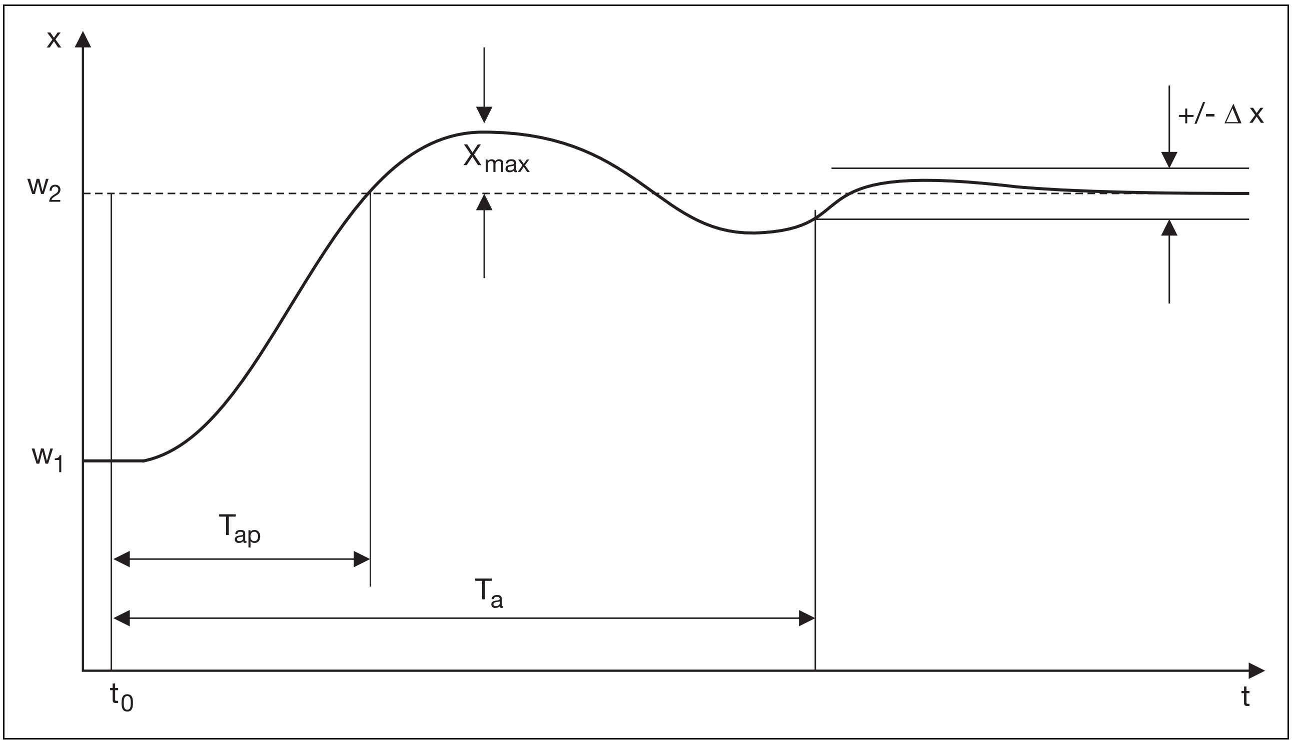


**Fig. 3: Criteria for the control-loop response**

It will take some time for the process value to stabilize to a steady value within a band around the the setpoint (+/- Δx). This time is called the settling time (**$T_a$**). The size of the band depends on the control requirements.

If the application of a new setpoint results in overshoot, then the maximum difference between the process value and the setpoint is known as the overshoot (**$X_{max}$**). The time taken for the process value to reach the setpoint for the first time is called the approach time (**$T_{ap}$**).

In this book we will only be concerned with the overshoot and the settling time.
At this point we can already note that the performance of a control loop is better if the values for $T_a$ and $X_{max}$ are smaller.

## 1.3 Process value acquisition / sensors and transmitters

In the field of electrical temperature measurement, resistance thermometers (e.g. Pt100) are frequently used. They have a temperature-dependent resistance, with very well known characteristics. The input that is used on the controller must be adapted to the resistance thermometer through the software, and the appropriate characteristic curve must be activated.
The characteristics of various types of resistance thermometers are stored in JUMO controllers.
If the appropriate characteristic has been activated, then the controller will convert the signal for the measured resistance into the corresponding temperature.

Thermocouples are also used, especially at high temperatures, and they generate higher voltages with increasing temperatures. Here, too, the linearization is carried out in the controller.

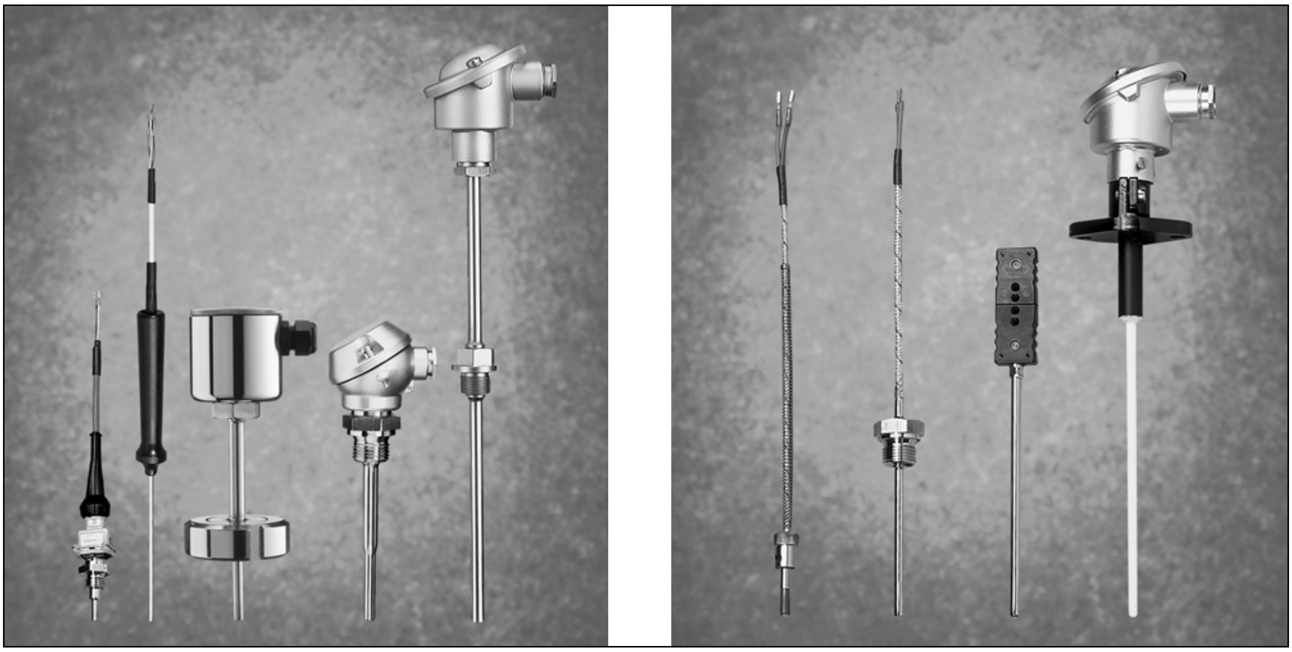


**Fig. 4:** **JUMO resistance thermometers and thermocouples**

For long distances between the sensor and the controller, temperature transmitters will be used. These already convert the signal from the resistance thermometer or thermocouple that is connected to the input into a linear output signal (e.g. 4 — 20 mA). On the controller, this signal just has to have the scaling set with a display start and end.

**Fig. 5:** **Head-mounted transmitter, type JUMO dTRANS T01 for connection to resistance thermometers or thermocouples**

**Fig. 6: 4-wire transmitter, type JUMO dTRANS T02 with display**

JUMO also supplies various types of pressure transmitter, which also provide linear output signals.

**Fig. 7: Pressure transmitters, JUMO MIDAS and dTRANS p02**

Finally, we would like to mention that JUMO produces a wide range of sensors and transmitters for analytical measurement variables (pH, redox potential, conductivity, dissolved oxygen etc.).

**Fig. 8:** **Inductive conductivity transmitter JUMO CTI-500 and combination electrode JUMO tecLine pH**

### 1.3.1 Sampling time

The transmitters mentioned above work on the basis of microprocessors that require a certain processing time. The measurement is acquired by the sensor, internally processed, and then output as a analog value. When the output has been updated, the input signal is acquired again. The time between successive samplings of the input is called the sampling time.

For controllers, the sampling time is especially important for the handling of the process value. In this case, the sampling time is the time taken from reading the input, calculating the output level and generating it at the output until the input signal is acquired again.

Typical sampling times for JUMO controllers are in the range from 50 — 250 milliseconds. For most control systems in process engineering, even 250 milliseconds is fast enough. For very fast events (e.g. in pressure measurement systems), the controller must operate with a very short sampling time.

## 1.4 Types of controller output

For temperature control systems, **relays** are very frequently used as the output devices. The switched contacts are usually implemented as changeover sets, sometimes as make (i.e. normally open) contacts. The controller activates, for instance, a power contactor that feeds energy into the process.

In order to achieve sufficiently accurate results for relatively fast temperature-controlled processes, the binary output will have to switch very frequently. In this case, a mechanical component would wear out fairly fast. For this reason, JUMO supplies controllers with **solid-state relays** and **logic outputs** to switch, for example, 230V AC or provide a 24V output.

For fast controlled processes (pressure, flow, speed etc.) it is usually not possible to control the output with a binary signal – this would lead to fluctuations of the process variable. For such applications, the controllers can be fitted with **continuous outputs**, which can be chosen for current or voltage output signals.

## 1.5 Actuators

Usually, the controller does not provide the output level for the process directly, but uses its output level to operate an actuator. The actuator then feeds energy to the process in proportion to this controlling signal. At this point we will look at a some important types of actuator.

### 1.5.1 Actuators for binary control

The simplest actuator, which can be operated by a binary signal from the controller (24V DC, 230V AC etc.) is a **power contactor**. If the controller closes its contact, then the contactor is activated and electrical energy is fed into the process. Power contactors are suitable for slow processes that do not require frequent switching.

If faster control loops require higher switching rates, then it will be necessary to use electronic switches. An example of such a device is the **thyristor power switch**.
This device (for example, the TYA that is illustrated) can be operated by the controller with voltages in the range from 4 — 32V DC and switch voltages up to $660\,V_{rms}$.
This switching takes place without any mechanism. So a very high switching rate can be chosen. But it must be taken into account that such a switch has a power loss in the ON state, and the load will not be completely isolated from the voltage in the OFF state, since there is a leakage current.

**Fig. 9: JUMO thyristor power switch, TYA series**

# 1 Basic concepts

For analytical measurement, **dosing pumps** are frequently used.
This type of actuator expects pulses at the input. Each pulse causes the dosing pump to produce a specific amount of liquid. The controller achieves a higher output level by increasing the pulse frequency at the output. JUMO supplies controllers for operating dosing pumps.

**Fig. 10: Dosing pump**

**Solenoid valves** are either activated by a controller, and fully open, or inactive (and closed).

**Motorized actuators** are operated by two relays in the controller.
While relay 1 is activated, connecting a voltage to the corresponding lead, the actuator (a valve, in Fig. 11) moves towards the open position. Likewise, the actuator moves towards the closed position when relay 2 is activated.
The advantage of this type of actuator is, that if an actuator motor is available, it is fairly simple to fit it out with the control element proper (valve, flap, slide valve etc.). Such assembly can be simple. Even if the motor actuator is operated by a binary signal, it will still provide a continuous output level.

You can read more about such actuators, and the possible controllers to operate them, in Chapter 5.5.1 *"The modulating controller"* and Chapter 5.5.2 *"The actuating controller"*.

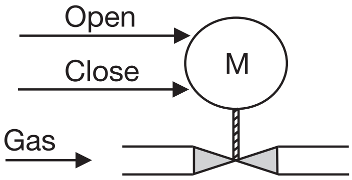


**Fig. 11: Schematic motorized actuator, consisting of an actuator motor and a valve as the actuator**

### 1.5.2 Actuators for continuous (analog) control

Many applications require a continuous output level. For instance, one reason is that very fast processes will not achieve a stable process value with binary controls.

JUMO has two types of (quasi-) continuous actuators available for the continuous control of electrical energy.

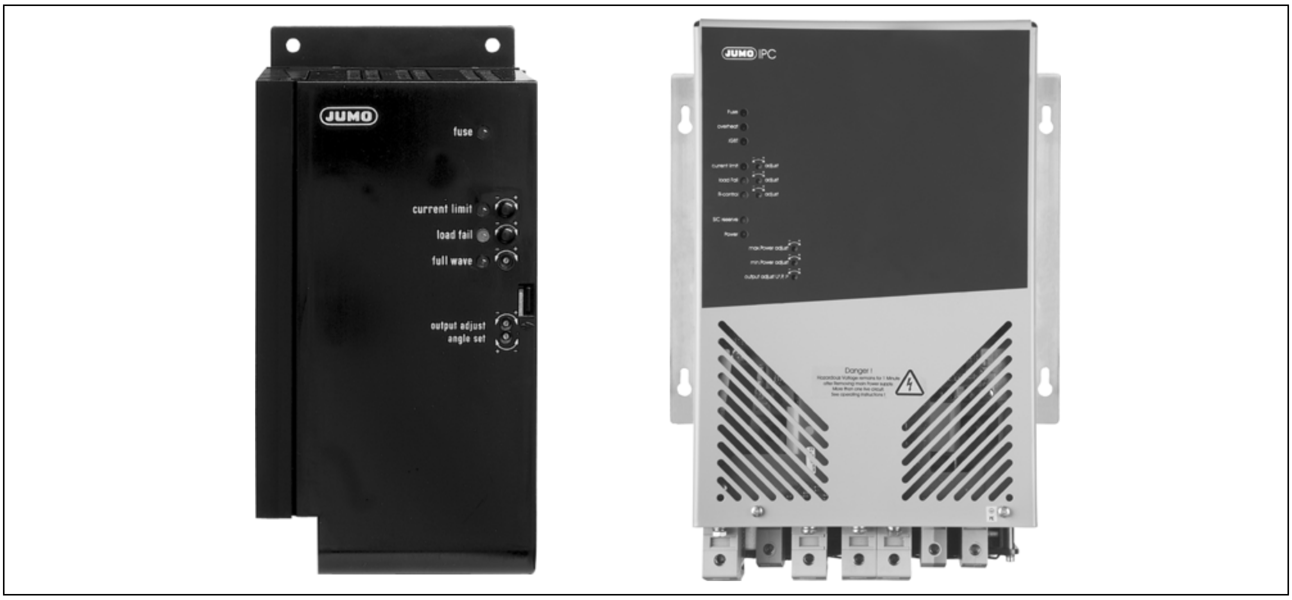


**Fig. 12:** **Thyristor power unit, and IGBT power converter with amplitude control**

The thyristor power unit is connected to the electrical supply voltage and the output signal from the controller. Putting it simply, it works like a very fast switch, increasing its relative ON time in proportion to the output level of the controller.

Thyristor power units can operate in two different modes.
In burst-firing mode, they always switch a defined number of complete supply voltage cycles through to the load, and are shut off between bursts (Fig. 13).

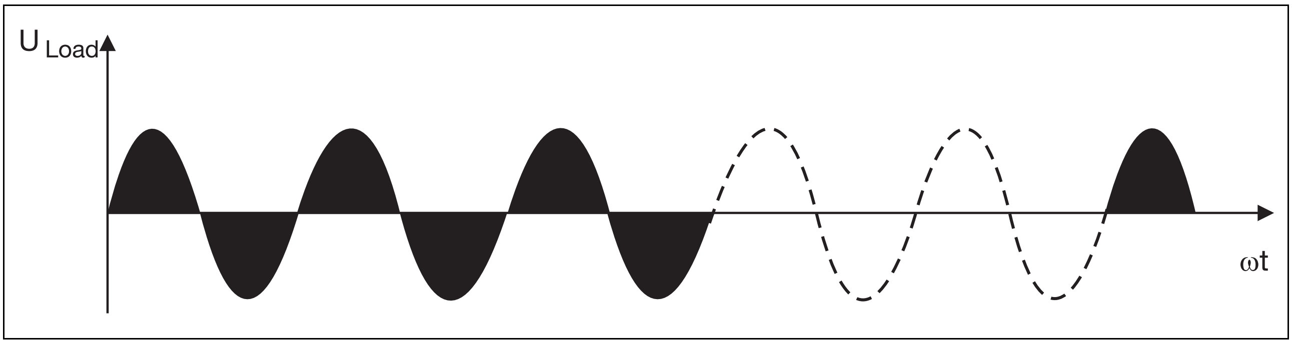


**Fig. 13:** **Output signal of a thyristor power unit in burst-firing operation at 60 % output level**

The time for switching on and off is so short that, for many processes, this type of control can be considered to be continuous.

For faster processes (e.g. regulating light intensity), the thyristor power unit can be changed over to phase-angle operation. In this case, it switches a portion of every half-wave through to the load, and generates a larger output level by reducing the phase-angle $\alpha$ (Fig. 14) at which the thyristor is triggered.

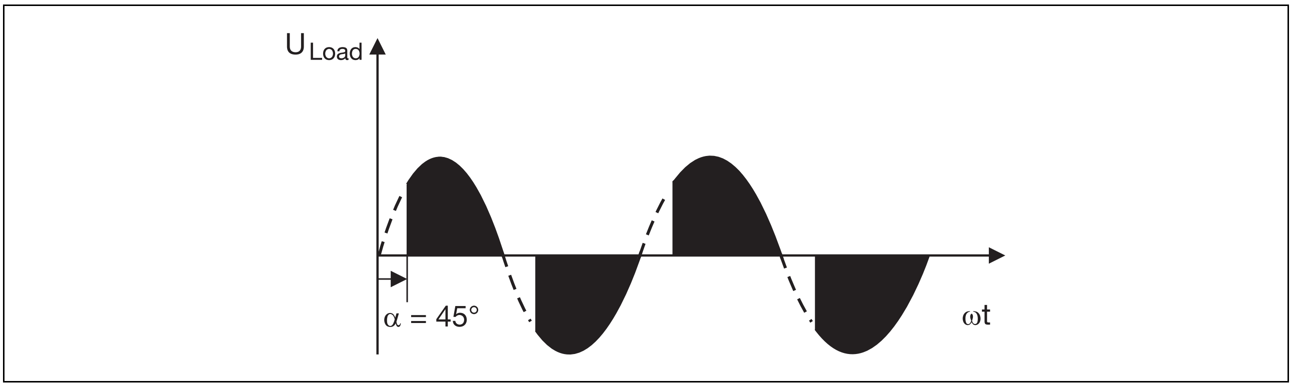


**Fig. 14: Output signal from a thyristor power unit in phase-angle operation**

The **IGBT power converter with amplitude control** is, unlike the thyristor power unit, a truly continuous actuator. It varies the amplitude of its output voltage in proportion to the output level required by the controller.

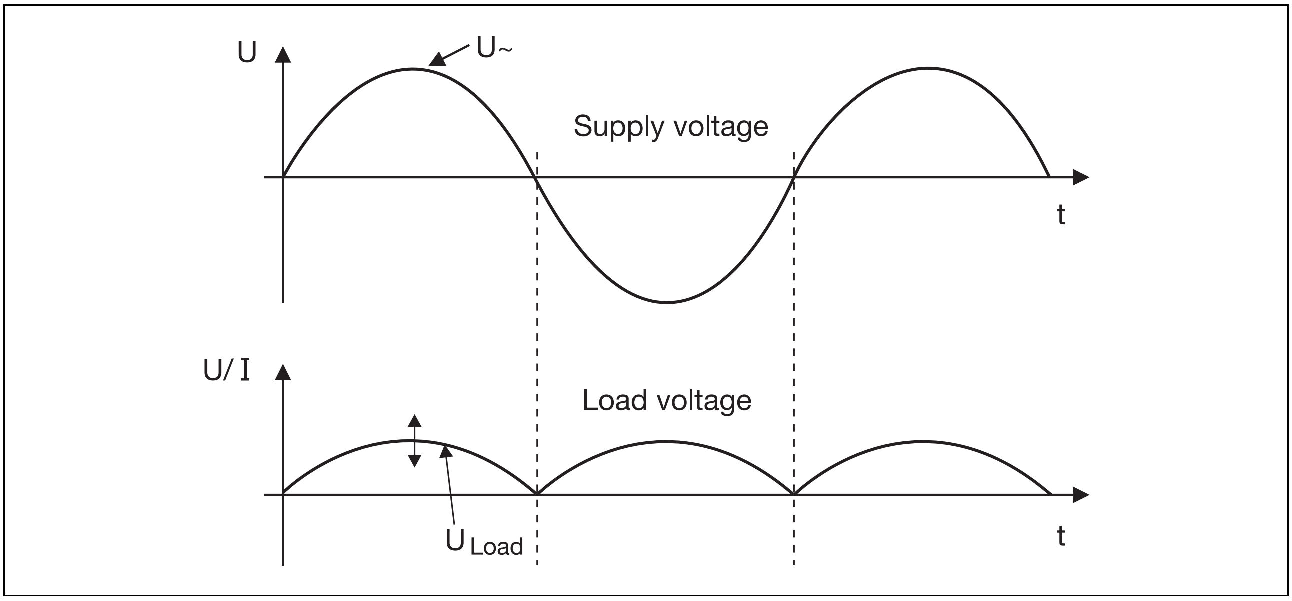


**Fig. 15: Amplitude control with an IGBT power converter**

For the continuous control of gases or liquids, **proportion valves** are available. These open to an extent that is proportional to the control signal (e.g. 4 — 20mA).

## 1.6 Controller types

The types of actuator described here require certain controller types, which we will now look at.

**Continuous controllers** provide a continuous output signal (typically 0/4 — 20 mA or 0/2 — 10 V). The output level can vary over a range from 0 to 100 %, whereby the output signal is proportional to the output level.

**2-state controllers** have a switching or binary output. Although this can only provide full power or no power to the process, an output level of 0 — 100 % can still be produced: such controllers vary the relative ON time of their outputs in proportion to the required output level.

**3-state controllers** can be thought of as two individual controllers. For instance, one controller uses one output to operate the actuator for heating, while the second controller uses a second output to activate the cooling.

**Modulating** and **actuating controllers** are suitable for operating motorized actuators. Two outputs on the controller operate the actuator motor to move the actuator in the open or shut direction as required.

## 1.7 JUMO compact controllers

JUMO supplies four main series of compact controllers, as well as sector-specific devices.

As a representative sample we will mention here some features of the most economical type (the iTRON series) and the controllers with the widest range of functions (IMAGO 500).

**Fig. 16: JUMO iTRON**

Controllers in the JUMO iTRON series can be configured as 2-state or 3-state controllers. The process value can be acquired by attaching a sensor (resistance thermometer or thermocouple) or a standard signal. The controller has binary outputs that produce the controller output level or the result of process value monitoring. In automatic mode, the controller shows the process value in its display. Binary inputs can be used to trigger binary functions, such as setpoint switching. The instrument can be configured through the keys or a corresponding setup program.

# 1 Basic concepts

We would now like to provide a brief overview of the JUMO IMAGO 500 controller.

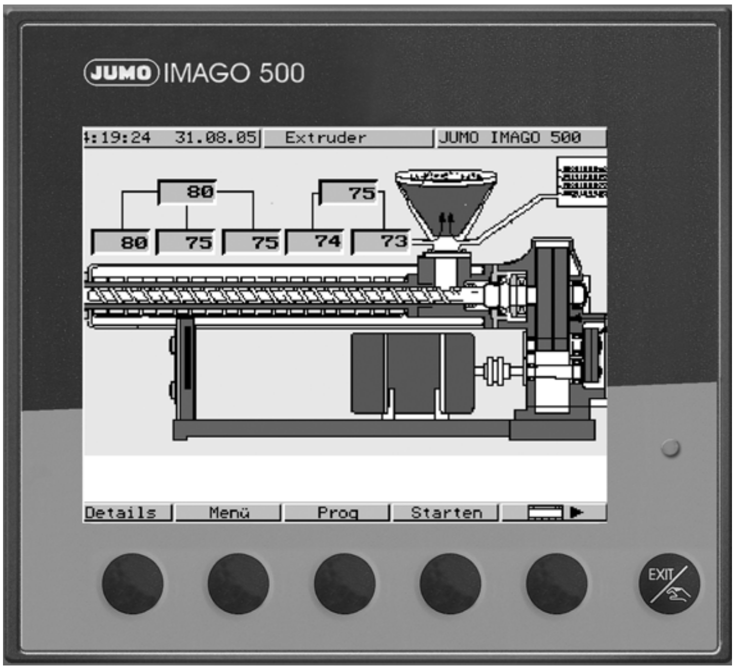


**Fig. 17: Customer diagram on a JUMO IMAGO 500**

The JUMO IMAGO 500 is an 8-channel controller, and up to 8 sensors can be connected. All the types of controller that are presented in Chapter 1.6 *“Controller types”* can be configured. It has a modular design: modules can be retrofitted or replaced. This instrument can also be provided with a MODbus or PROFIBUS-DP interface. Relay modules can be connected, to provide a maximum of 28 outputs. The controller can make a data recording, and the measurements can be downloaded to a PC via an interface. Freely definable customer-specific diagrams (Fig. 17) and texts provide a powerful insight into the installation. Various functions enable the controller to take on control tasks.

# The controlled process

This chapter deals with the characteristics of controlled processes, both self-regulating and not self-regulating. You will learn about P-action processes with a dead time and delays. At the end of the chapter you will be shown how to characterize a process.

## 2.1 General aspects of controlled processes

The controlled process is the portion of the system in which the process variable must be regulated to meet the setpoint. From the control engineering aspect, the controlled process begins at the point where the controller applies its output level (assigning the actuating element to the process is a bit of a simplification, but satisfactory in practice!). The controlled process ends at the point where the process value is acquired: the sensing device.

The controlled process is subject to disturbances that affect the process value if they change.

Fig. 18 shows a controlled process in the form of a gas-fired oven.

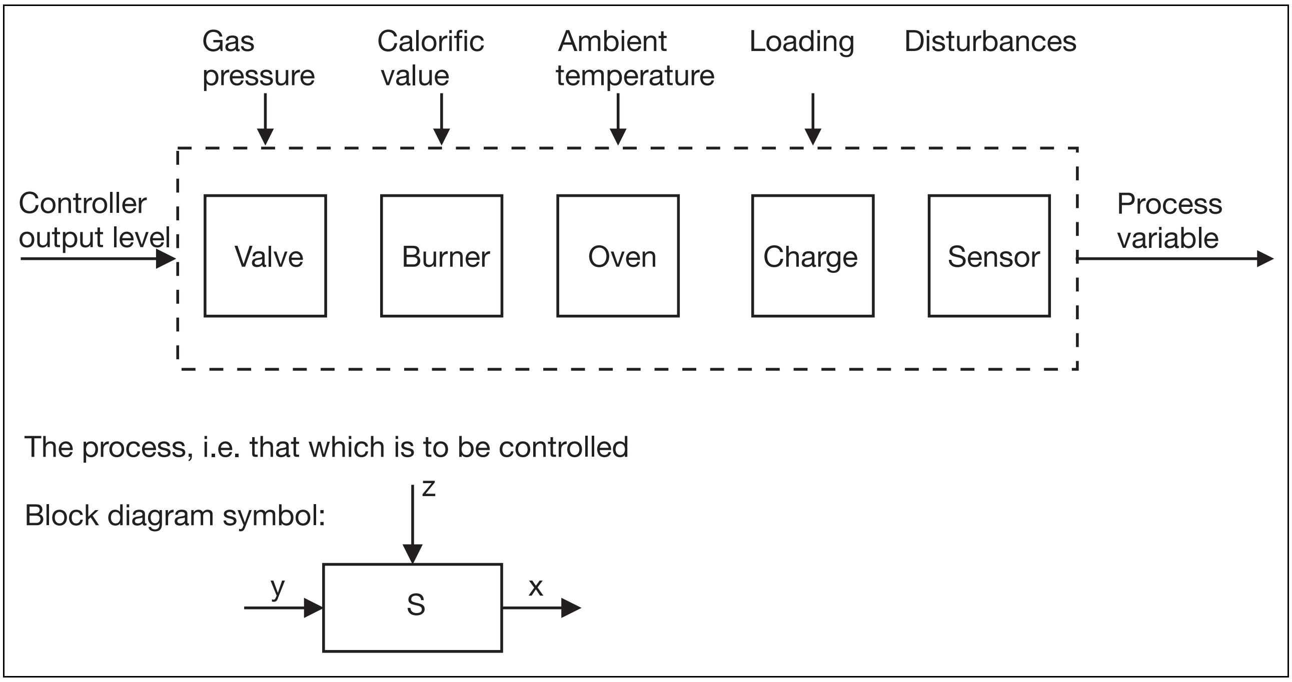


**Fig. 18: Input / output variables in a controlled process**

In our example, the controller output level is applied to a valve. The controlled process starts here. A charge of material being treated is in the oven, and a temperature sensor is inserted into the charge. This is the end of the controlled process.

Now let us look at the flow of energy.
If the controller generates an altered output level, then the valve will move fairly quickly to the new position. The gas flow in the burner changes rapidly. But the inside of the oven heats up slowly, and the temperature of the charge will increase after some time. In our process there are delay and energy storage elements present, which slow down the distribution of the energy.

The disturbances in our example are those variables that will cause a change in temperature, even though the output level remains constant.

**Example**
If the output level is just large enough to produce the required temperature in the charge, and the ambient temperature - a disturbance variable - falls, then the temperature of the charge will also fall if the output level remains the same. In a closed loop, the controller can only counteract the disturbance by producing a higher output level.

## 2.2 Processes with and without self-regulation

### 2.2.1 Processes with self-regulation

The controlled process shown in Fig. 18 is what is known as a process with self-regulation. This means: if you set an arbitrary output level for the controller, in manual mode, and wait until the process value has stabilized, the controlled variable - the process variable - will always be proportional to the output level.

If you record the static characteristic of a process (the process value as a function of the output level), it will be non-linear in most cases.

**Example**
For the recording of the static characteristic for the process shown in Fig. 18, the output level is increased in 10 % steps, and held until the oven temperature has stabilized. You will find that the temperature increments for each step are larger for lower temperatures than for higher temperatures. The characteristic is non-linear!

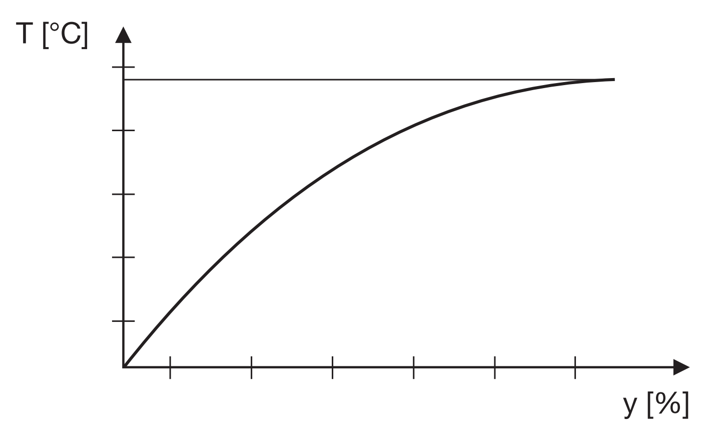


**Fig. 19: Non-linear characteristic**

The non-linearity is one of the reasons why the controller parameters may have to be altered for different setpoints, in order to keep on getting a good control-loop response.

### 2.2.2 Processes without self-regulation

A process that does not have self-regulation typically responds to an output level with a continual change of the process value. The process value deviation depends on the process characteristics and is proportional to the output level and the time.

Fig. 20 shows the response of a process without self-regulation, which does not have delay or dead time elements:

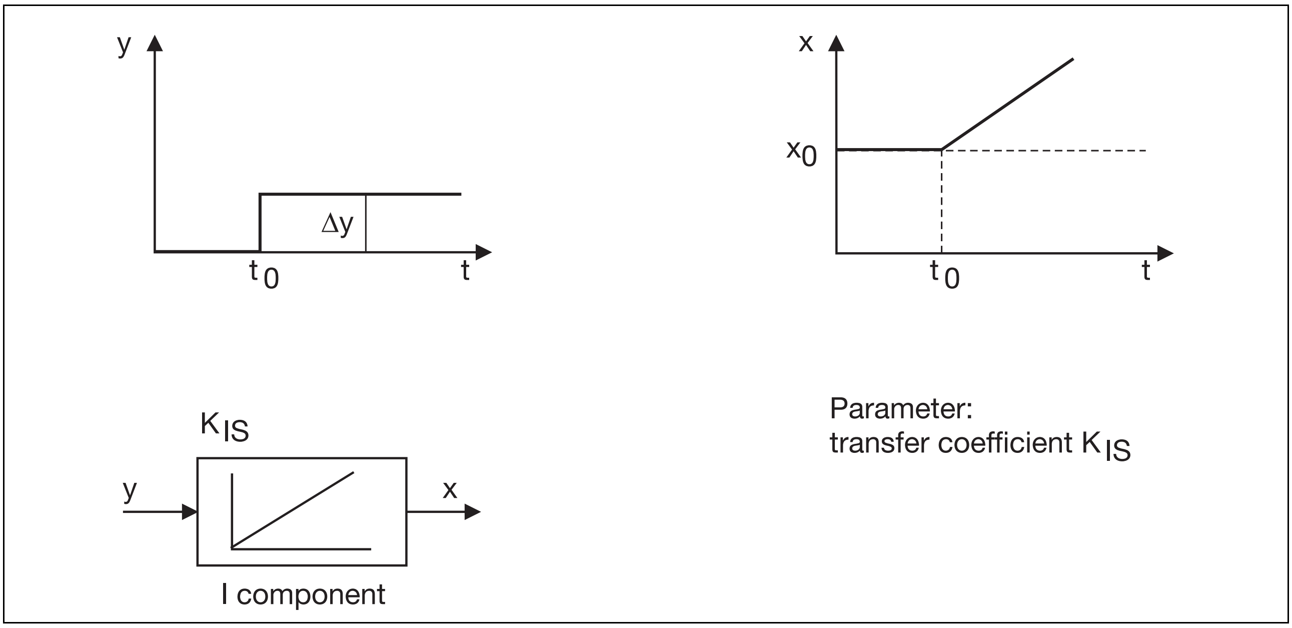


**Fig. 20: Step response and block-diagram symbol for a process without self-regulation**

If the output level for the process is 0% (Fig. 20), then the process value remains unchanged. If, for instance, the output level makes a step change, then the process value also starts to change. This change is faster if the output level is higher. Because of the integrating effect of such a response, such processes are known as integral processes or I processes.

If an output level is applied to a process that does not have self-regulation, the process value will typically keep on changing until it reaches some kind of limit.

For a constant output level:

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

$K_{IS}$ is called the transfer coefficient for the process without self-regulation.

For changing output levels:

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

Examples of processes without self-regulation

- positioning
- filling level (Fig. 21)

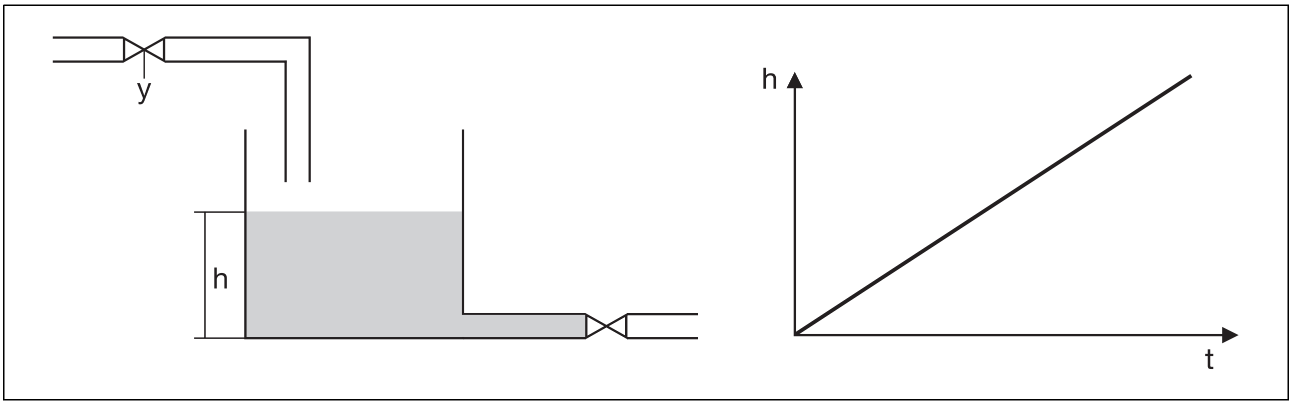


**Fig. 21: Filling level**

Probably the best-known example of a process without self-regulation is the filling of a tank with an inlet and an outlet. The outlet valve, which represents the disturbance, is closed. If the inlet valve is now opened and left at the same setting, then the level (the process variable) in the tank will gradually rise, steadily and continuously.

The level in the tank will rise faster if the flow rate is higher. The level will rise until the tank overflows. There is no self-regulation in this case. Even after a disturbance, e.g. if the outlet is used, there will be no stable state, as there would be for a process with self-regulation (exception: if input flow = output flow).

## 2.3 Processes (elements) with P action, dead time and delays

In this section we will look at processes or process elements that exhibit one of the effects mentioned above. All remarks apply to processes that are self-regulating.
To begin, we look at the elements in their “pure” form, although we will see later that most processes involve all types to some extent.

### 2.3.1 P processes

Proportional processes amplify the applied output level by the transfer coefficient $K_S$ without any delay.

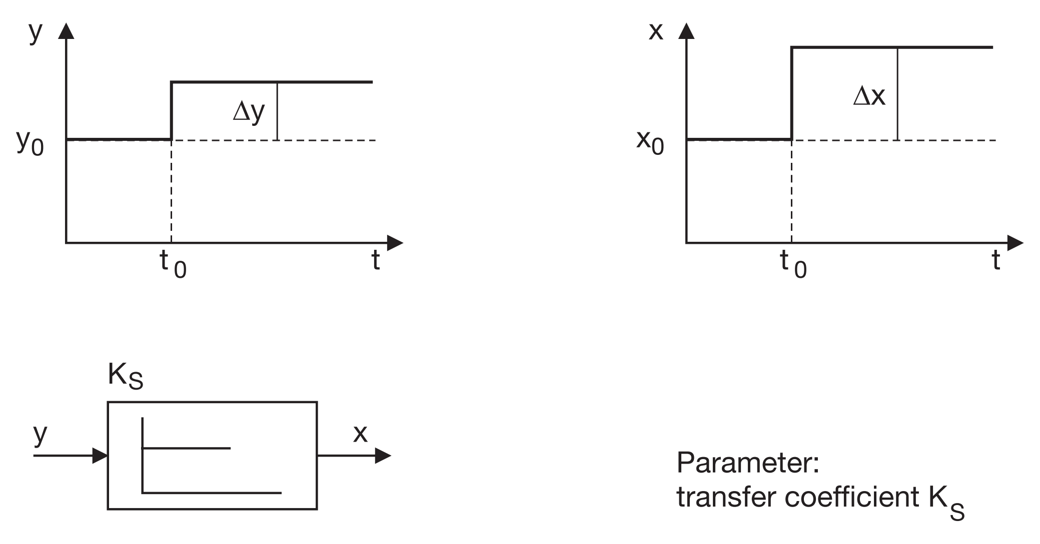


**Fig. 22: Step response and block-diagram symbol for a P process**

If an output level is applied to such a process, then a stable process value is instantly established (the output level is multiplied by the transfer coefficient $K_S$). If the output level makes a step change, then the process value will also increase in proportion to the output level, without delay.

The relationship between a process variable increment Δx and an output level increment Δy is as follows:

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

In practice, however, P processes that respond with absolutely no delay do not exist.
In reality, the P action is combined with time-dependent elements which we will study in the next section.

### 2.3.2 Processes with dead time: $PT_t$ processes

A P process or a P element can occur, for instance, in combination with a dead time element. The result is a $PT_t$ process.

This process is also defined by the transfer coefficient, but by a dead time as well.

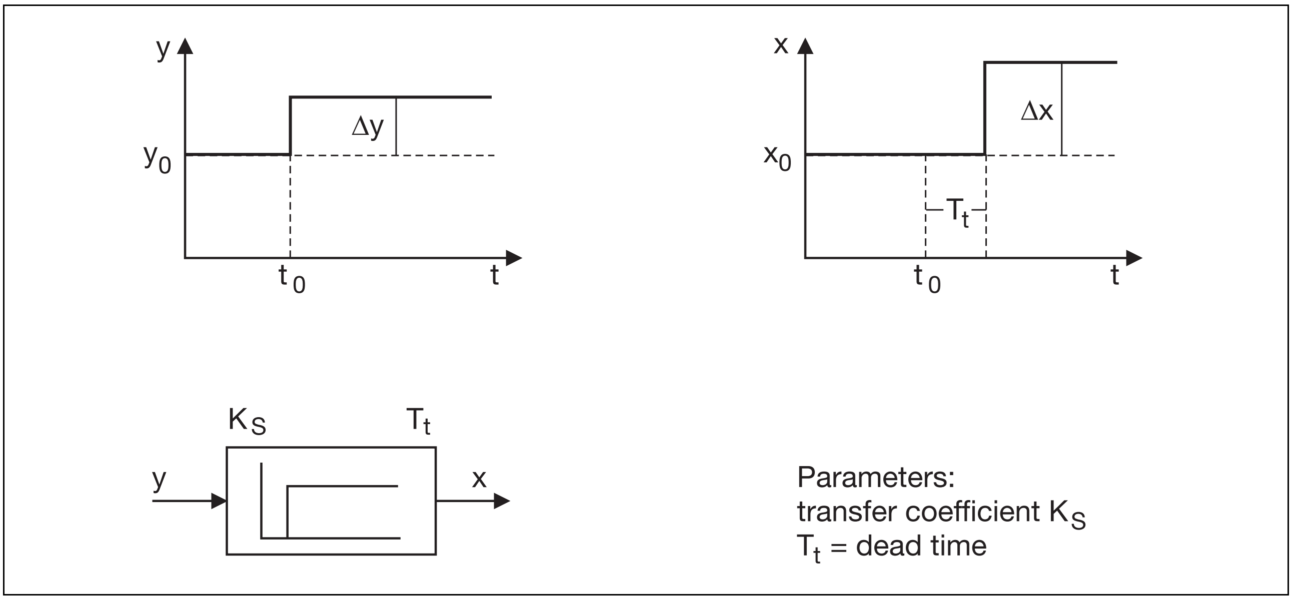


**Fig. 23: Step response and block-diagram symbol for a $PT_t$ process**

The process acts like a P process, but the change of process value caused by an output level step change only appears after the dead time. The relationship between the changes of the output level and the process value is:

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

One example of a $PT_t$ process is a conveyor belt, where a constant flow of bulk material is to be regulated.

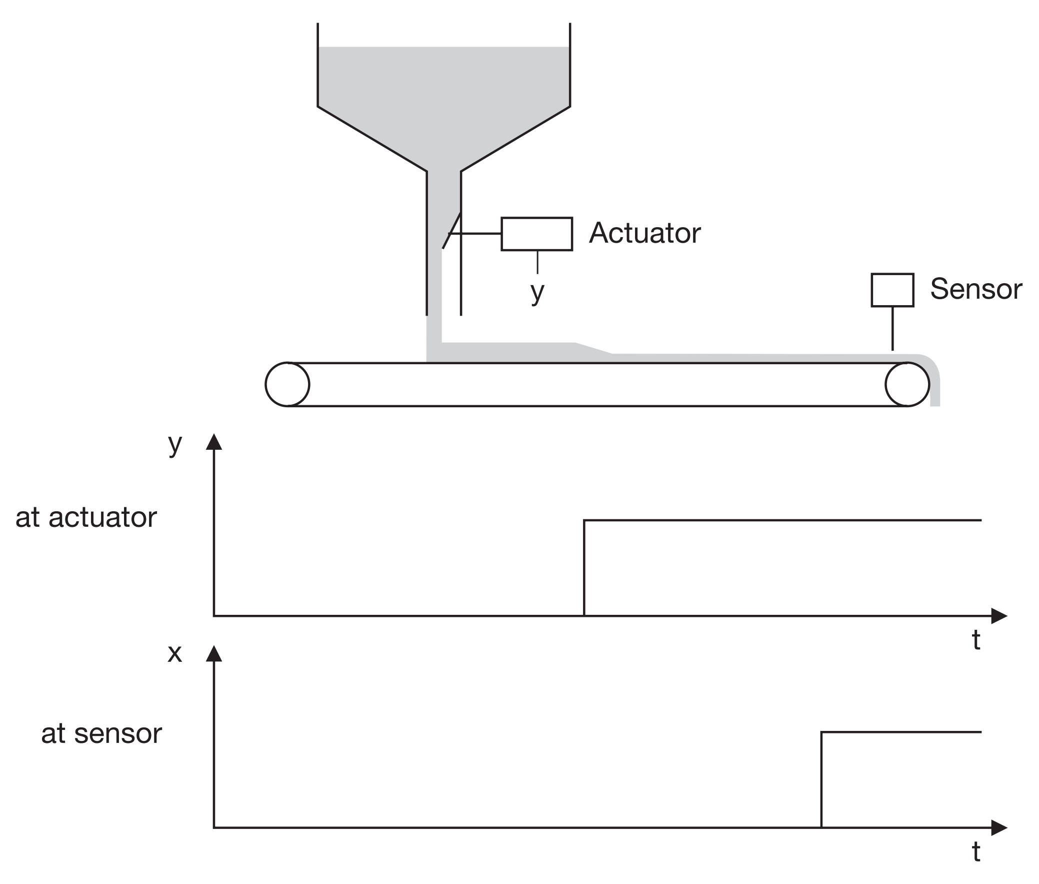


**Fig. 24: Regulating bulk material flow on a conveyor belt**

The controller applies its output level to a slide valve. If the output level of the controller is increased in a step change, and we assume that the slide valve also acts without any delay, then a certain amount of material per time unit will fall onto the conveyor belt. But the conveyor belt requires some time before this material reaches the sensor. This time – the delay before the sensor detects the change of output – is the dead time for this process.

**Numerical example**
If we assume that the output level is increased in a step from 0 to 50%, and the sensor requires 10 seconds to detect the material flow of 100 tons/hour then the dead time is 10 seconds.

This process is also defined by the transfer coefficient. To determine this factor, we could, for example, make an output step change from 50% to 75%. In our example, this should produce a process value of 150 tons/hour.

The transfer coefficient is given by the change in the process value divided by the change in the output level.

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

What is the significance of the transfer coefficient, in our example $2 \frac{t}{h \bullet \%}$?

If the output level is raised by 1 %, then the quantity conveyed will increase by $2 \frac{t}{h}$.

In our example, this process can be defined by a $K_S$ of $2 \frac{t}{h}$ and a dead time of 10 seconds.

Dead times make it more difficult to optimize a control loop, and should be minimized as far as possible in the design of the system.

### 2.3.3 Processes with a delay: $PT_n$ processes

In processes with delays, the new process value will only be reached some time after the output level has been set. This delay is the result of various energy storage elements being charged up before the process as a whole can reach the new energy level.

These processes can be mathematically represented by an equation that has a exponential term for each element with an energy storage capacity. Such terms lead to a process being described as 1st order, 2nd order, 3rd order... and so on.

In this section we will look at the responses that are caused by such delays.

**Process with one delay (1st order)**
In controlled processes with one delay, i.e. one energy storage element, if the output level makes a step change, the process variable will instantly start to change at a certain rate, and then approach the final value ever more slowly (Fig. 25).

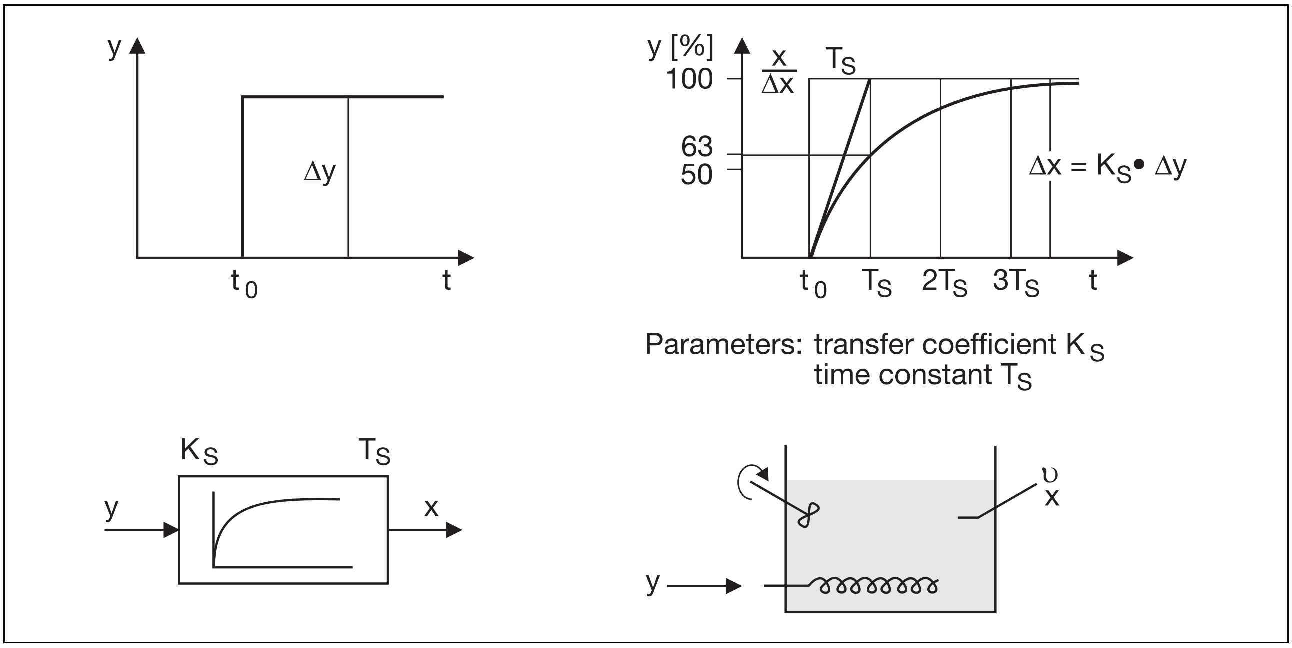


Fig. 25: 1st order process; $PT_1$ process

Fig. 25 shows at bottom right an example that approximates to a 1st order process.

The water bath shown in the example has one energy storage element: the water itself! The energy that is supplied by the input actuator device (e.g. a thyristor power unit) is instantly converted by the heater coil in the diagram into thermal energy (the heater coil itself does not store energy, it heats up instantly). So the thermal energy is instantly conducted into the water. This starts to warm up, without any delay. We are assuming that the sensor used here has negligible mass and that the heat conduction between the water and the sensor is very good.

If the power (the output level) to the heater coil is increased in a step change, the water temperature will change according to the following equation:

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

How can we determine the parameters $K_S$ and $T_S$ for this 1st order process?

We can, for instance, increase the power in a step change to 5 kW, and record the curve of the process value (i.e. the water temperature). So:

$$\Delta y = 5\ \text{kW} \qquad (7)$$

The process value was 20 °C before the step, and after the step it increased to, say, 80 °C. So:

$$\Delta x = 60\ °\text{C} \qquad (8)$$

From the recorded trace of the step response we can calculate the transfer coefficient of the process, this is:

$$K_S = \frac{(\text{change in process variable})}{(\text{change in output level})} = \frac{60\ °\text{C}}{5\ \text{kW}} = 12\frac{°\text{C}}{\text{kW}} \qquad (9)$$

The transfer coefficient can be simply interpreted as follows:
if we increase the power by 1 kW, the temperature will be increased by 12 °C.

Now we can determine the time constant for this process.
From the process value recording, we can read off the time taken for the process value to achieve 63 % of the final change. In our example, a process value change of 63 % is reached at

$$20\ °\text{C} + 60\ °\text{C} \bullet 63\% \approx 58\ °\text{C} \qquad (10)$$

The time taken for the water temperature to rise by 58 °C corresponds to the time constant $T_S$, and we will assume that this takes 100 seconds in our example.

So the water temperature increases according to the following equation:

$$\Delta x = 12 \frac{°C}{kW} \bullet 5\ kW \bullet \left(1 - e^{\frac{-t}{100\ s}}\right) \qquad (11)$$

Fig. 26 shows the step response of our process.

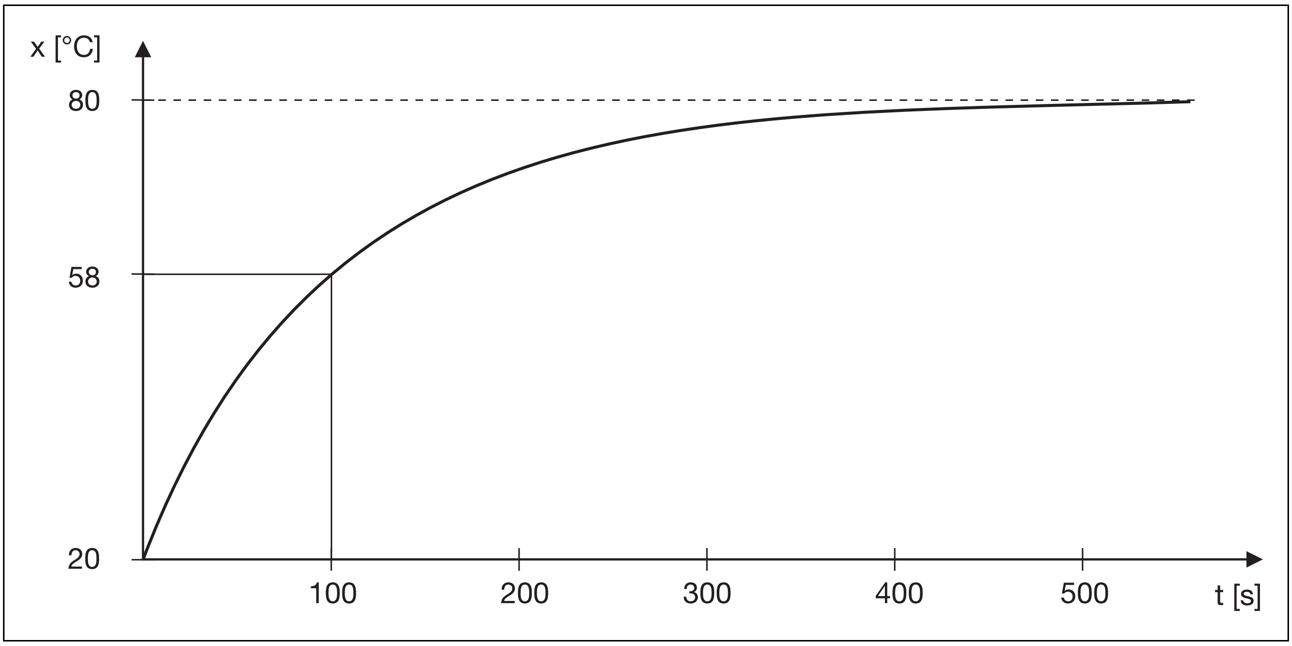


**Fig. 26:** **Example of the step response curve for a 1st order process**

**Process with 2 delays (2nd order)**
In a process with 2 delays there are two energy storage elements.

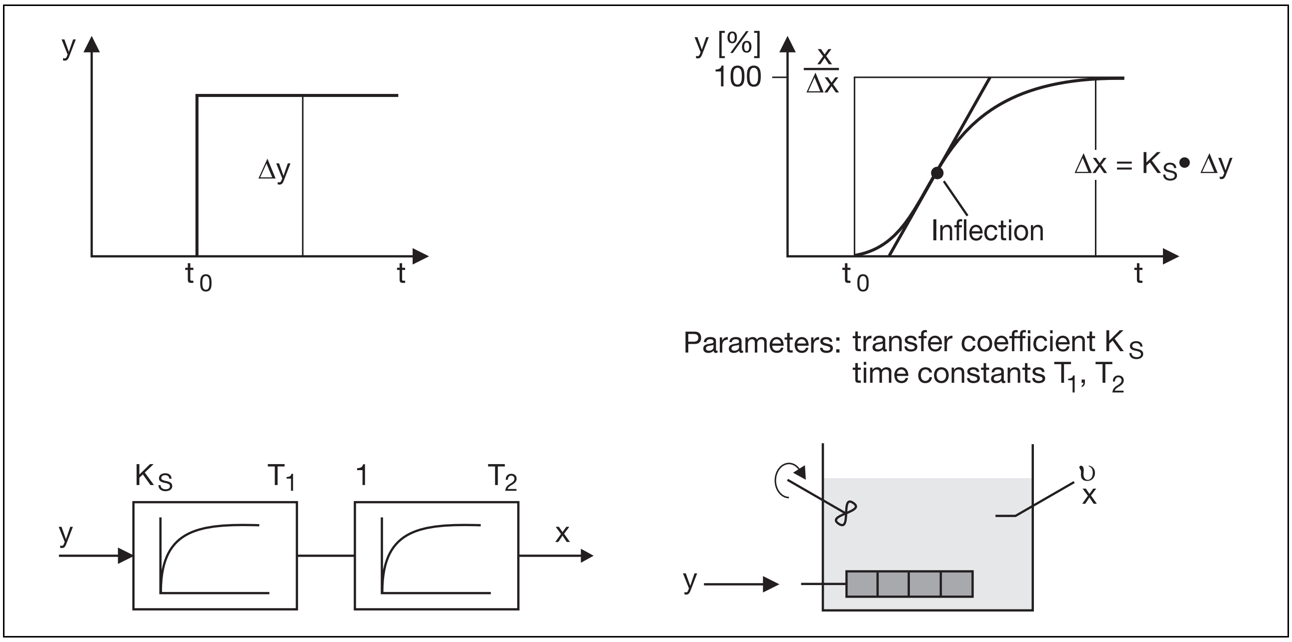


**Fig. 27:** **2nd order process; PT$_2$ process**

A process with two delays is called a $PT_2$ process, and is defined by the transfer coefficient and the time constants for the two energy storage elements.

As the block-diagram symbol (Fig. 27) indicates, for practical purposes the $K_S$ value is taken to be 1.

Fig. 27 also shows a 2nd order process, where the energy passes through two energy storage elements. Whereas our water bath example was a $PT_1$ process with a heater coil, we will now replace this by a heater element. This heater element has a relatively large mass, and is thus a second energy storage element.

So if the heating power makes a step change from 0 to 5 kW, the energy is initially used to heat up the heater element. The water will only be heated up when the heater element itself has warmed up considerably.

For this reason, the process value in processes of this type will start to change in a delayed fashion after the application of the step (Fig. 27), increasing its slope, which then becomes flatter and flatter until it reaches the final value. The step response has a point with the maximum rate of change (see Fig. 27) where the tangent must be drawn.

*In mathematical terms, this maximum slope occurs only at one point, the inflection point.*
*In practice, the slope is fairly constant in the area of the inflection point, so it is difficult to determine this point precisely. So in what follows, we refer to the "region of maximum slope" and not the inflection point.*

If a step is applied to a 2nd order process, the process value will alter according to the following equation:

$$\Delta x = K_S \bullet \Delta y \bullet \left(1 - \frac{T_1}{T_1 - T_2} e^{\frac{-t}{T_1}} + \frac{T_2}{T_1 - T_2} e^{\frac{-t}{T_2}}\right) \qquad \text{Equation is valid for } T1 \neq T2 \qquad (12)$$

This formula includes both time constants and the transfer coefficient $K_S$. It requires some rather involved mathematics to derive both time constants from the step response. In practice, processes of 2nd and higher orders are characterized by equivalent parameters (see Chapter 2.4 *"Recording the step response for processes with at least 2 delays and a dead time"*).

**Higher-order processes**
In practice, processes usually have more than two energy storage elements. But the step responses have the same basic appearance as for the 2nd order process already described.
They also exhibit a delay time and a region of maximum slope.

## 2.4 Recording the step response for processes with at least 2 delays and a dead time

Processes usually involve several energy storage elements with a delay and a dead time

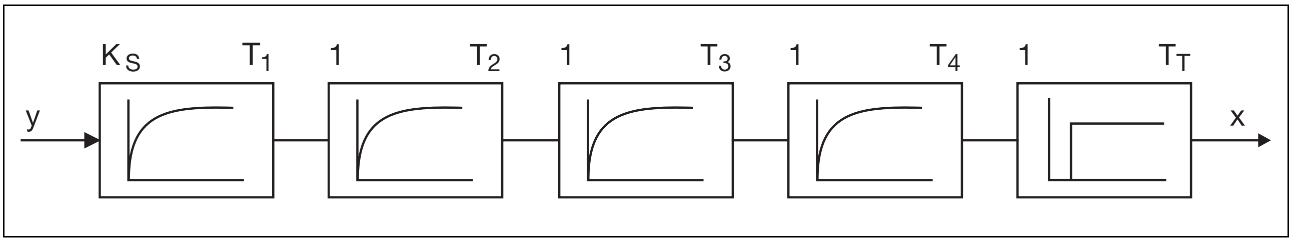


**Fig. 28: Block diagram of a process with several delays and a dead time**

The block diagram shows a process with 4 delays and a dead time element. In a real process, it is in practice not known what order the process has, and how many dead time elements are included. And the corresponding time constants are totally unknown.

So processes of the 2nd order or higher are characterized by replacement parameters. With the aid of the replacement parameters and empirical formulae it is then possible to determine favorable control parameters.

These replacement parameters are: the transfer coefficient ($K_S$) which we have already met, and the delay time ($T_u$) and response time ($T_g$).

To determine the replacement parameters, the step response must be recorded.
To do this, a step change is applied to the output level, and the curve of the process value is recorded (see Fig. 29). By fitting a tangent to the process value curve you can determine the region with the maximum slope. This tangent is drawn in the diagram. The time from the output step change to the intersection point of the inflectional tangent with the time axis is the delay time ($T_u$); the time from the interception point on the time axis to the interception point of the inflectional tangent with the maximum process value is the response time ($T_g$). The transfer coefficient for the process is given by the change in the process value divided by the change in the output level.

**Example**
It is necessary to determine $K_S$, $T_u$ and $T_g$ for an industrial oven. The oven has cooled down, the internal temperature is 20°C. The controller is operated in manual mode, and an output step change is made from 0 to 50%. The process value is recorded. Fig. 29 shows the curve of the process value.

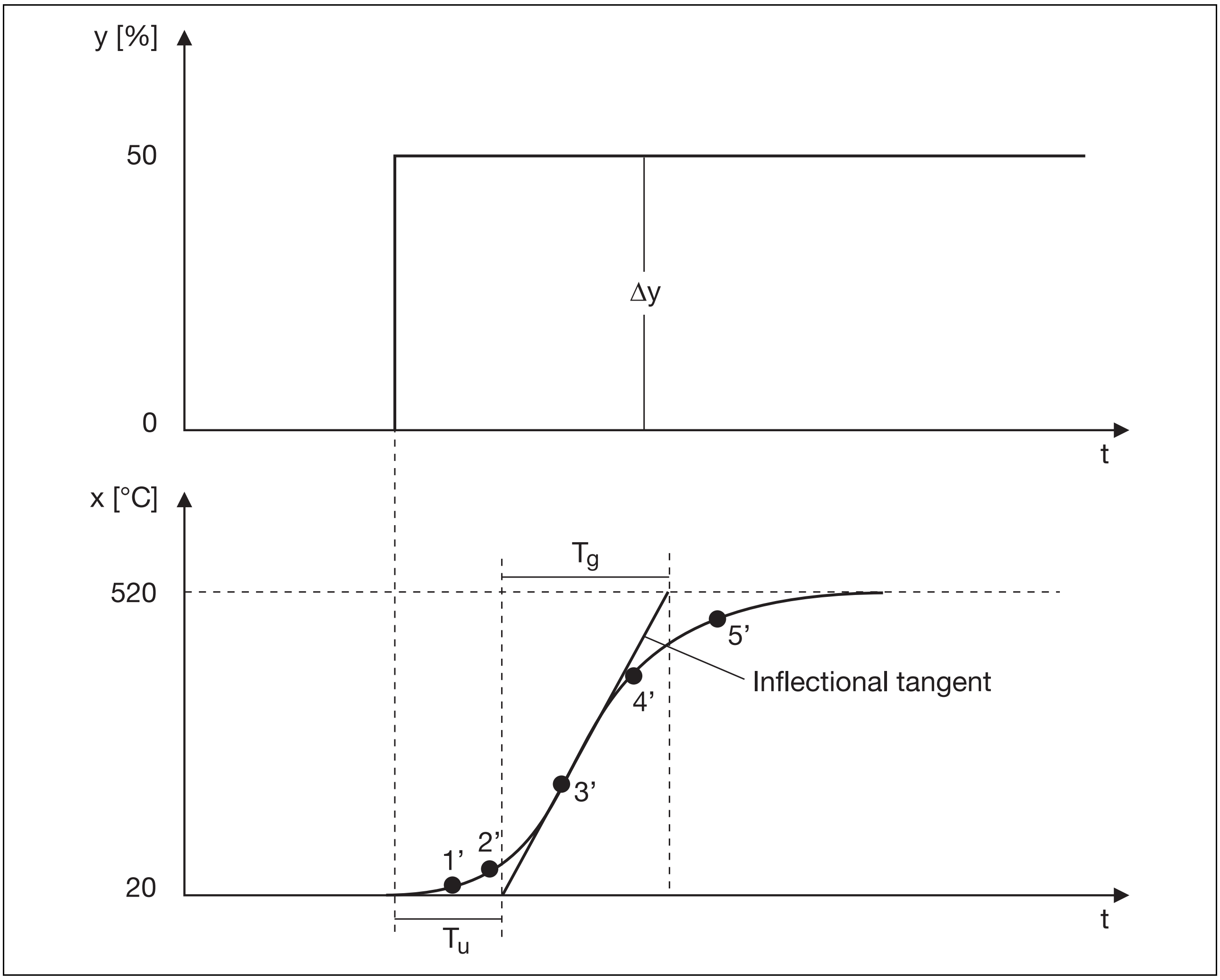


**Fig. 29: Determining the delay time and response time**

We now draw a line parallel to the time axis, at the level of the maximum process value (520 °C). Now we can already determine the transfer coefficient (gain).

$$K_S = \frac{(\text{change in process variable})}{(\text{change in output level})} = \frac{500\ °C}{50\ \%} = 10\frac{°C}{\%} \qquad (13)$$

The inflectional tangent must be drawn in the diagram. Let us follow the step change from left to right and look at the curve of the process value (points 1', 2' etc.). Starting at 1', we look at the slope. The slope is fairly flat at 1'. Now, looking at the points further to the right (2', 3'), we can see that the slope becomes progressively steeper.
Moving further to right (4', 5'), we can see that the slope becomes flatter again. So we can determine the region with the maximum slope. The tangent drawn at point 3' in Fig. 29 indicates the maximum slope.

The times can now be determined in the way that has already been described.

Later on, we will see that the three replacement parameters for a process can be used to set up the most favorable control parameters.

The ratio $T_g/T_u$ can be taken as a measure of the controllability of a process.

| | |
|---|---|
| $T_g/T_u > 10$ | good control characteristics |
| $T_g/T_u = 10...3$ | can be controlled |
| $T_g/T_u < 3$ | difficult to control |

As we could see in Chapter 2.2.1 *“Processes with self-regulation”*, the characteristics of controlled processes are non-linear. This means that $K_S$ is larger at low temperatures than at high temperatures. For our industrial oven, we would have determined a medium $K_S$, because we defined a very large step change. This is the reason why, in practice, steps are used that lie in the region of the subsequent working point.

More on this topic can be found in Chapter 4.3.2 *“Step-response method according to Chien, Hrones and Reswick”*.

# Continuous controllers

This chapter explains how a PID controller operates.

The P, I, and D components are studied one after another, using as an example a continuous controller (0/2 — 10V, 0/4 — 20mA). The method of operation can analogously be applied to controllers with binary outputs. The additional know-how that is required for this is presented in Chapter 5 *"Switching controllers"*.

## 3.1 P controller

A P controller (proportional controller) derives the control deviation from the setpoint and the process value, and multiplies it by a certain factor. This amplified signal is then presented as the output level signal (see Fig. 30).

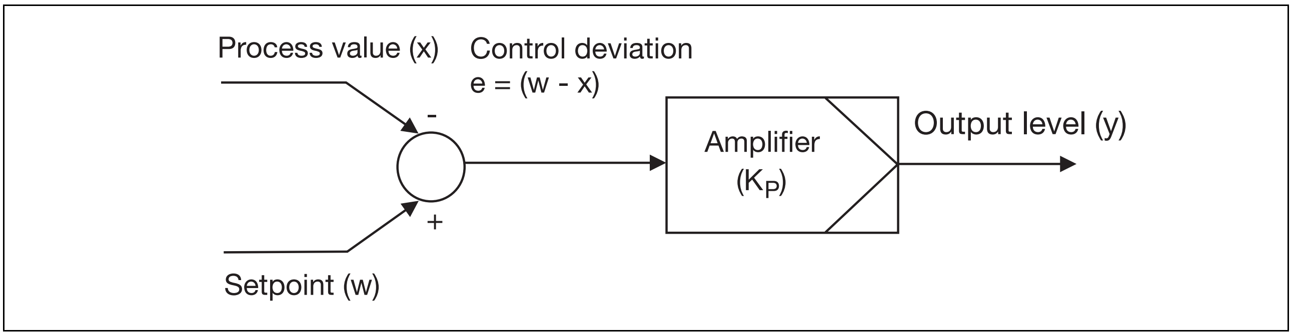


**Fig. 30: Operating principle of a P controller**

The amplification is known as the proportional coefficient $K_P$, and can be freely defined on the controller. The equation for the controller is thus:

$$y = K_P \bullet (w - x) \qquad (14)$$

The dimensional unit for $K_P$ is always % divided by the variable that is being controlled (°C, bar, rpm, etc.).

**Examples**
A P controller for a temperature control process has $K_P$ set to 10%/°C and, with a control deviation of 5°C, it produces an output level signal of 50%.

Another example is a P controller for pressure regulation, with $K_P$ set to 4%/bar. For a control deviation of 20bar this would produce an output level of 80%.

Fig. 31 shows the step response of a P controller. A step is created in the control deviation (by increasing the setpoint), and the way in which the output level builds up at the output is evaluated.

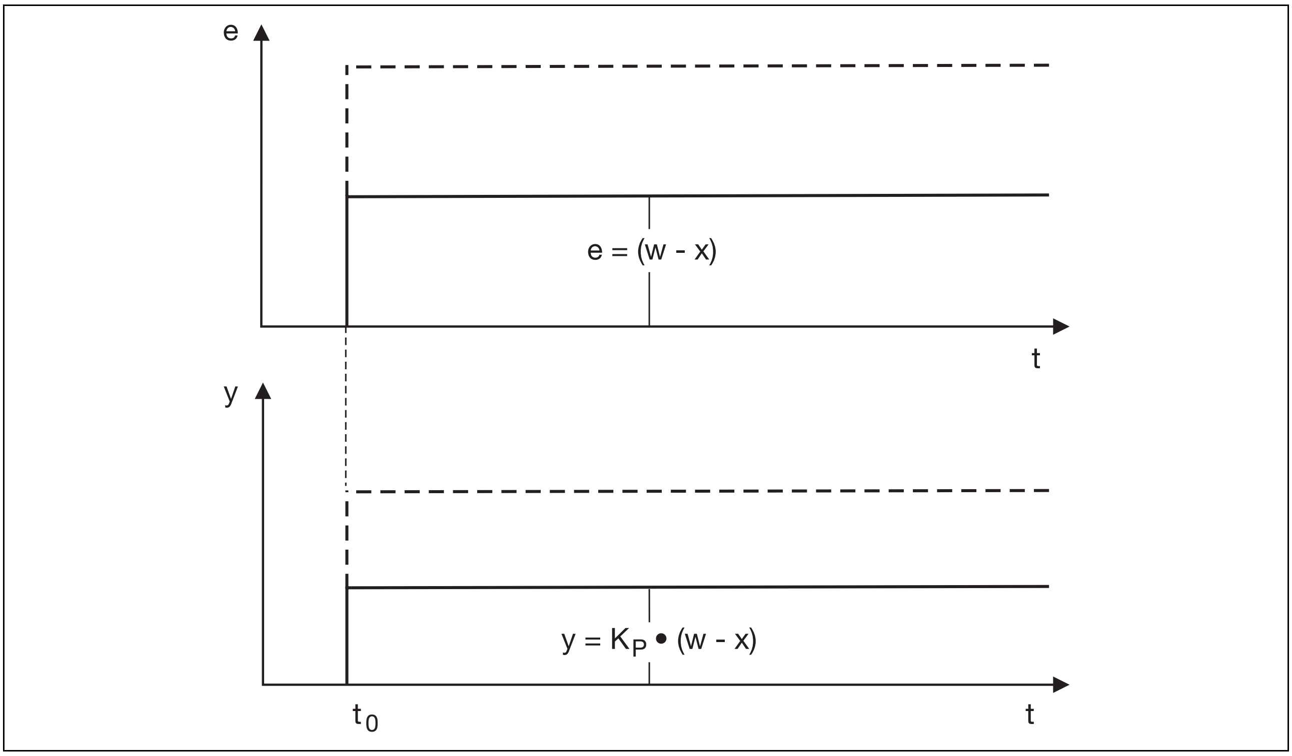


**Fig. 31: Step response of a P controller**

Fig. 31 shows that the P controller alters its output signal in proportion to the control deviation, without any delay.

### 3.1.1 Proportional band

In JUMO controllers, the P component is not defined by the proportional coefficient, but by the proportional band ($P_b$) of the controller. The proportional band defines a band (above or below the setpoint, depending on requirements) in which the output level varies proportionally with the control deviation.

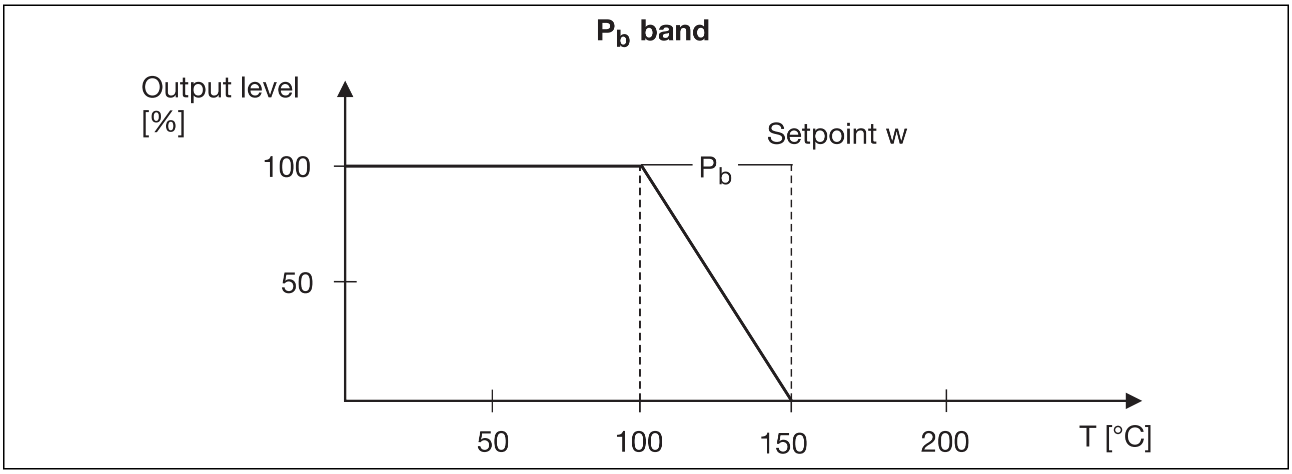


**Fig. 32: Characteristic curve for a proportional controller**

Fig. 32 shows the characteristic curve for a proportional controller used, for example, for heating. The output level is drawn along the y axis. The setpoint is drawn along the X axis (in this case, the characteristic curve touches the X axis). The process value has also been marked in Fig. 33.

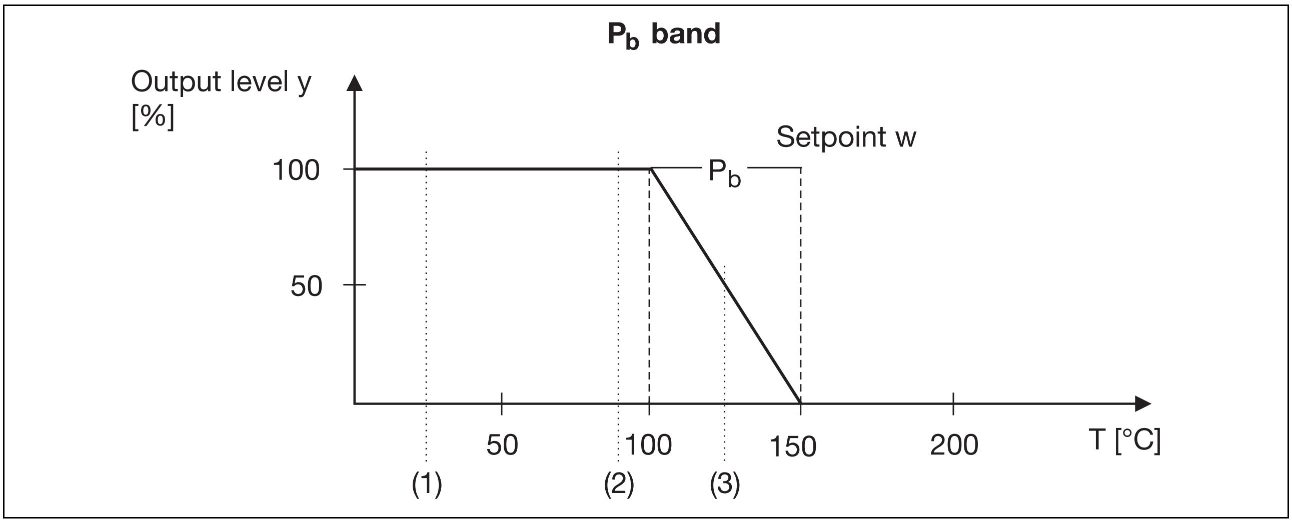


**Fig. 33: Characteristic curve for a proportional controller, with process value marked**

In our example, the proportional band is 50°C, which means that for a control deviation that is larger than 50°C, the output level will be 100%. If the control deviation is smaller than the proportional band, then the output level will be reduced in proportion to the control deviation.

If we imagine that the process value is about 25°C (1), then the interception point on the curve shows that, in this case, the controller will produce an output level of 100%.

Because of this high output level, the process value will rise rapidly, and reach about 90°C some time later (2). The output level will still be 100%, and will only be reduced from a value of 100°C or higher. We will then be in the proportional band ($P_b$).

If, for instance, we are in the middle of the proportional band (125°C), then the output level will be 50% (3). When the process value reaches 150°C, there is no longer a control deviation, and the output level will be 0%.

So, during the approach to the setpoint, the proportional band $P_b$ makes it instantly clear when the controller will reduce the output level.

**Remaining control deviation**

In our example, if we are considering an oven that has reached a process value of 150°C, then no more heat energy will be fed into the oven. The temperature will fall below 150°C and the output level will be increased. So the process will reach a settled state (if a process value of 125°C requires an output level of 50%, as is here the case).

The disadvantage of the P controller is the remaining control deviation that arises. For this reason, it is very rarely used. The P component is mostly combined with an I component, and frequently with a D component as well.

In our example, the remaining control deviation can be reduced by reducing $P_b$ and thus increasing the gain. Assume that the process reaches a settled state at a process value of 125°C with an output level of 50%. If the proportional band is now reduced to 25°C, the output level will be raised to 100% and the process value will be moved closer to the setpoint.

But the smaller you make the $P_b$ setting, the more the process value will tend to oscillate.

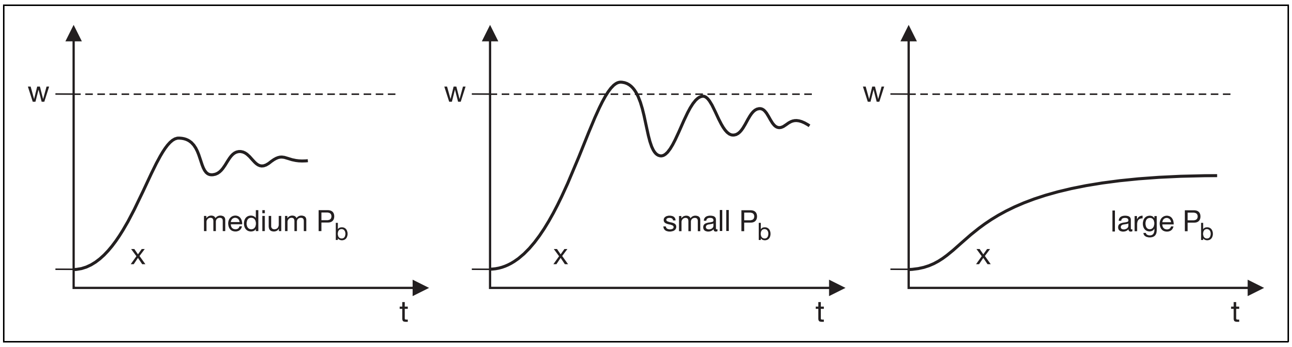


**Fig. 34: Control loop response for various $P_b$ values**

The large oscillations with a small $P_b$ are a result of the supply of energy being reduced very suddenly when the process value enters the proportional band, so that there is not enough time to reach a steady state.

**Relationship between proportional coefficient and proportional band**
The proportional coefficient and proportional band are related as follows:

$$K_P = \frac{1}{P_b} \bullet 100\% \quad \text{or} \quad P_b = \frac{1}{K_P} \bullet 100\% \qquad (15)$$

The control system in Fig. 32, with a $P_b$ of 50 °C would thus constitute a control loop with a $K_P$ of 2 %/°C.

### Direction of control action: inverse and direct, working point correction

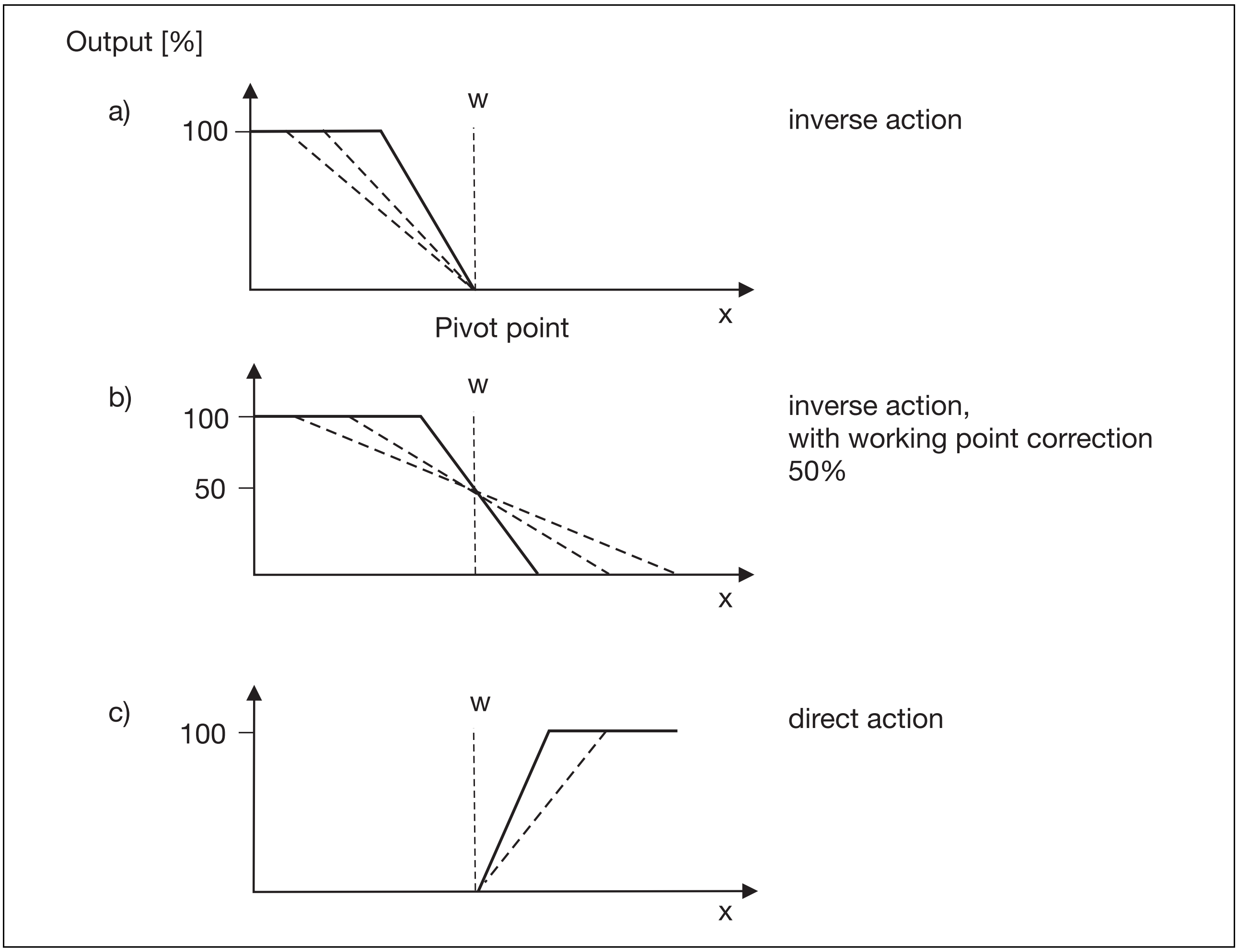


**Fig. 35: Various characteristics for P controllers**

a) The diagram shows the characteristic of a P controller, as we have already studied.
If the process value is below the proportional band, then the output level is 100%. If the process value moves into the proportional band, the output level is reduced, and will eventually be 0% when the setpoint has been reached. If an output level is required when the process value is below the setpoint, then inverse action is needed. This is the case, for instance, for heating or humidifying.

b) In this case, an offset is applied to the output level as a correction - the working point correction. For JUMO controllers, this parameter is designated Y0, and is 50% in the example. So, for a control deviation of 0°C, the output level will be 50%.
By varying the Y0 value, the control deviation can be trimmed to 0 for a P controller. But this only applies to one working point, and then only when the conditions in the control loop remain unchanged. In practice, the I component is the element that removes the control deviation, and this will be explained later in this chapter. For this reason, working point correction is very rarely used.

c) If an output level is required when the process value is above the setpoint, then the controller operates with direct action. This is, for instance, required for cooling or dehumidifying. For large process values, the output level remains at 100% until the proportional band is reached. The output level is now steadily reduced until the control deviation is 0.

## 3.2 I controller

Mathematically, the I controller generates the area that is created by the integration of the control deviation over time.

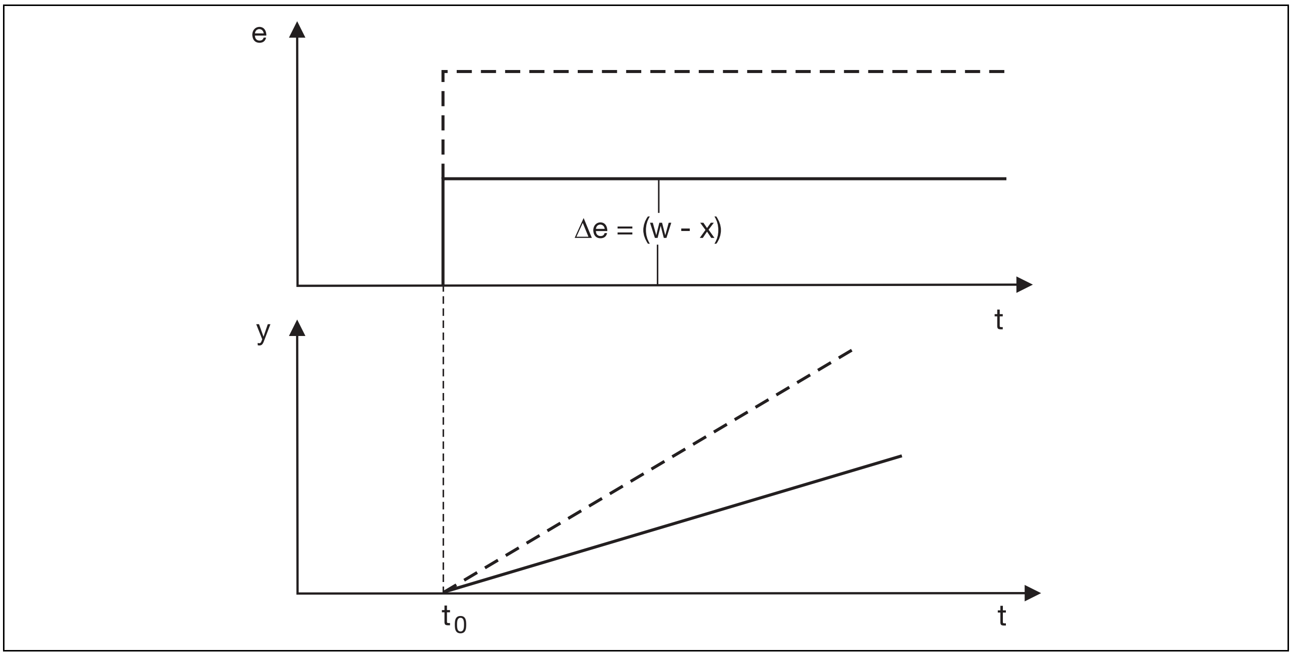


**Fig. 36: Step response for an I controller**

Fig. 36 shows the step response of an I controller. Before the step, the control deviation is 0, and the I controller holds the present output level. So if the output level was previously 0%, it will remain at this value. If the control deviation jumps to a positive value, then the controller integrates the control deviation, as mentioned above, and builds the output level accordingly.
In other words, the controller increases its output level as soon as a positive control deviation appears. If the control deviation remains constant, the output level will be ramped up until it reaches 100%, and then held at this value. If the control deviation that is applied is twice as large, then the controller will build up the output level twice as fast (see the dotted line in Fig. 36). If the process value is above the setpoint (negative control deviation) then the output level will be reduced accordingly.

Now let us look at an I controller in a closed loop.

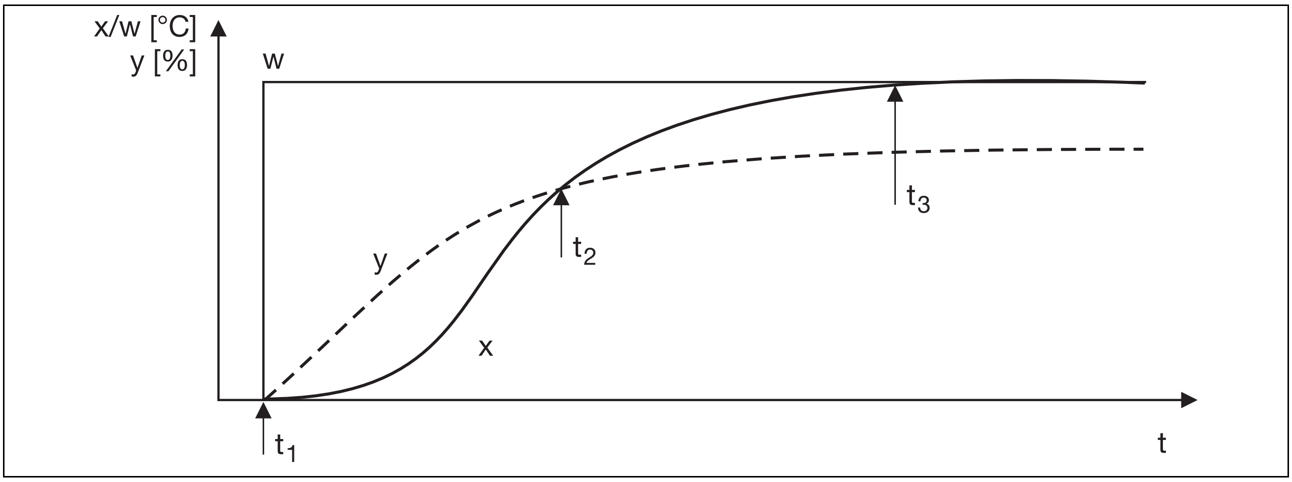


**Fig. 37: An I controller in a closed loop**

Fig. 37 shows the setpoint, process value and output level for an I controller in a closed loop.

$t_1$: A setpoint is newly defined, the output level is immediately increased by the I controller, but the process value only changes after some time.

$t_2$: The process value becomes steadily larger, and so the control deviation becomes smaller. The curve of the output level therefore becomes flatter and flatter.

$t_3$: The controller has settled, the control deviation is 0.
The I controller maintains the output level that it has built up.

The I controller has the general advantage that it regulates the control deviation to zero.
The disadvantage is its sluggish response.

**The integration time ($T_I$)**
The speed of an I controller can be varied through the integration time.
For a constant control deviation, the controller equation is:

$$\Delta y = \frac{1}{T_I} \bullet \Delta e \bullet t + y_{t_0} \qquad (16)$$

$y_{t_0}$ : output level at the start of the event

This means that the smaller $T_I$ is, the faster the I controller will build up the output level.

From this formula you can see that $T_I$ is the time that the controller needs to raise its output level by the amount of the applied control deviation (ignoring the dimensions).

**Example**
Imagine an I controller for an oven. The value set for $T_I$ is 60 seconds, and the control deviation is 2 °C. For an increase of 2 % in the output level, the controller requires 60 seconds.

If the control deviation changes, the output level is generated according to the following equation:

$$y = \frac{1}{T_I} \bullet \int_{t_0}^{t} e \bullet dt + y_{t_0} \qquad (17)$$

$t_0$: time at the start of the event

For varying settings of the integration time, an I controller responds as follows:

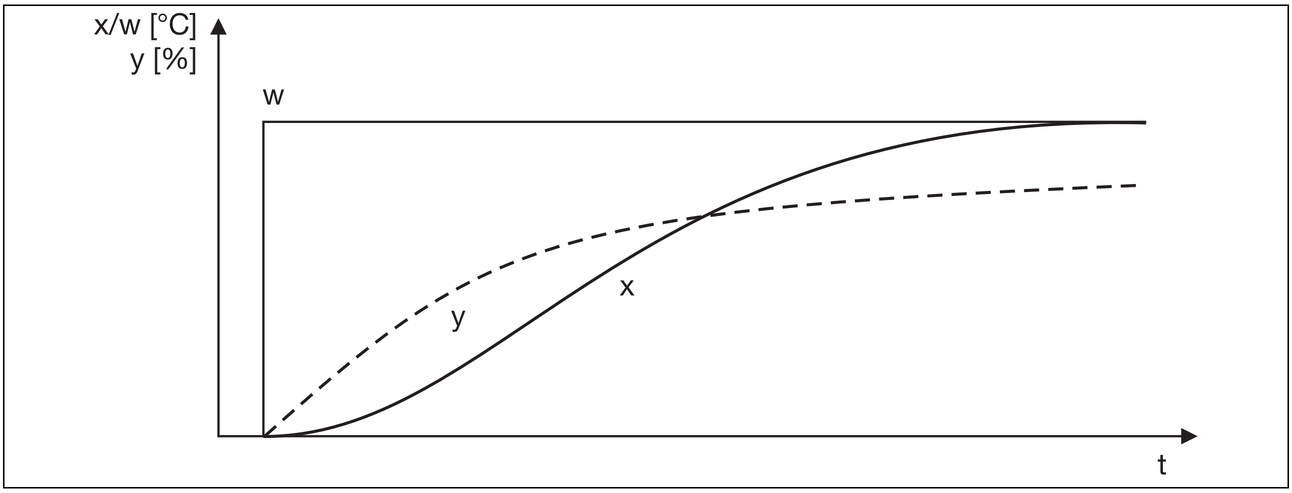


**Fig. 38: I controller with a large $T_I$ setting**

As can be seen in Fig. 38, a controller with a long integration time will build up the output level slowly. The process value approaches the setpoint very steadily, but very slowly.

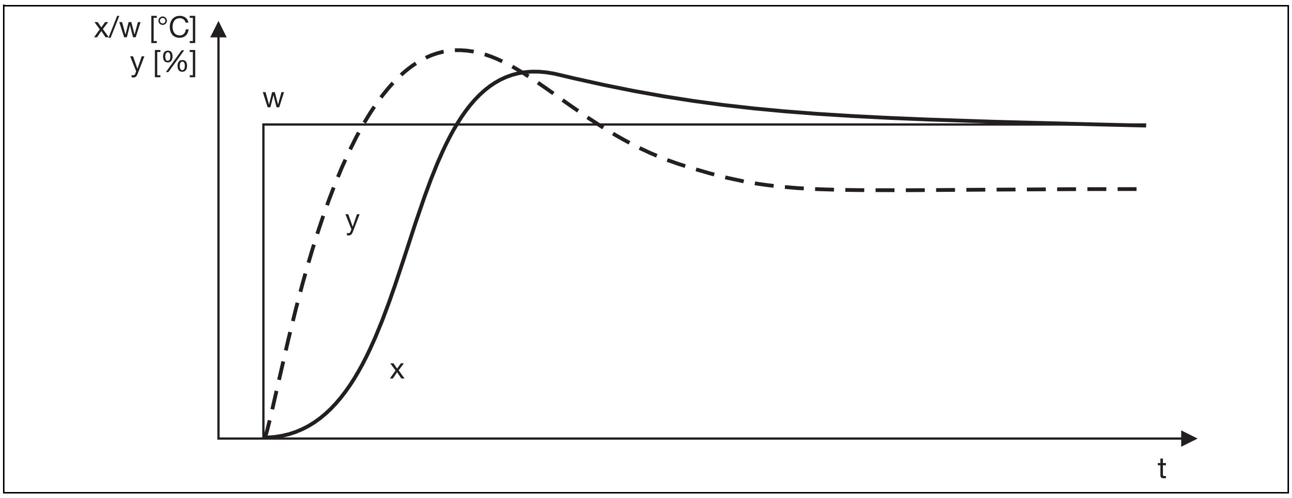


**Fig. 39: I controller with a small $T_I$ setting**

Fig. 39 shows that a controller with a short integration time will build up the output level too quickly. When the process value reaches the setpoint, the controller has produced an excessive output level, and the process value overshoots the setpoint.

**$T_I$ and $r_t$**
If, as will be described in the next section, an I component is combined with a P component, then the parameter for the integrating action is known as the reset time ($r_t$).
For all types – I, PI, or PID controllers – only one parameter should be used for the integrating action of the I component. For this reason, in JUMO controllers, the integration time is also defined by the reset time, even for controllers with an I structure. The parameter $T_I$ is not used.

**Application of I controllers**
I controllers are used with pulsating variables (e.g. pressure control) and processes that have a comparatively short response time compared with the delay time ($T_g/T_u$ <3). In order for the controller to be able to react quickly, the reset time is set to a low value for controllers with a fast response.

## 3.3 PI controller

A PI controller can be thought of as a combination of a P component and an I component. It combines the advantages of both components: speed (P) and zero remaining control deviation (I). If a control deviation occurs with a PI controller, the P component amplifies it and produces a relatively large output level. The I component produces an increasing output level as long as the positive control deviation is still present, and thus ensures that the final control deviation goes to zero.
Fig. 40 shows the step response of a PI controller.

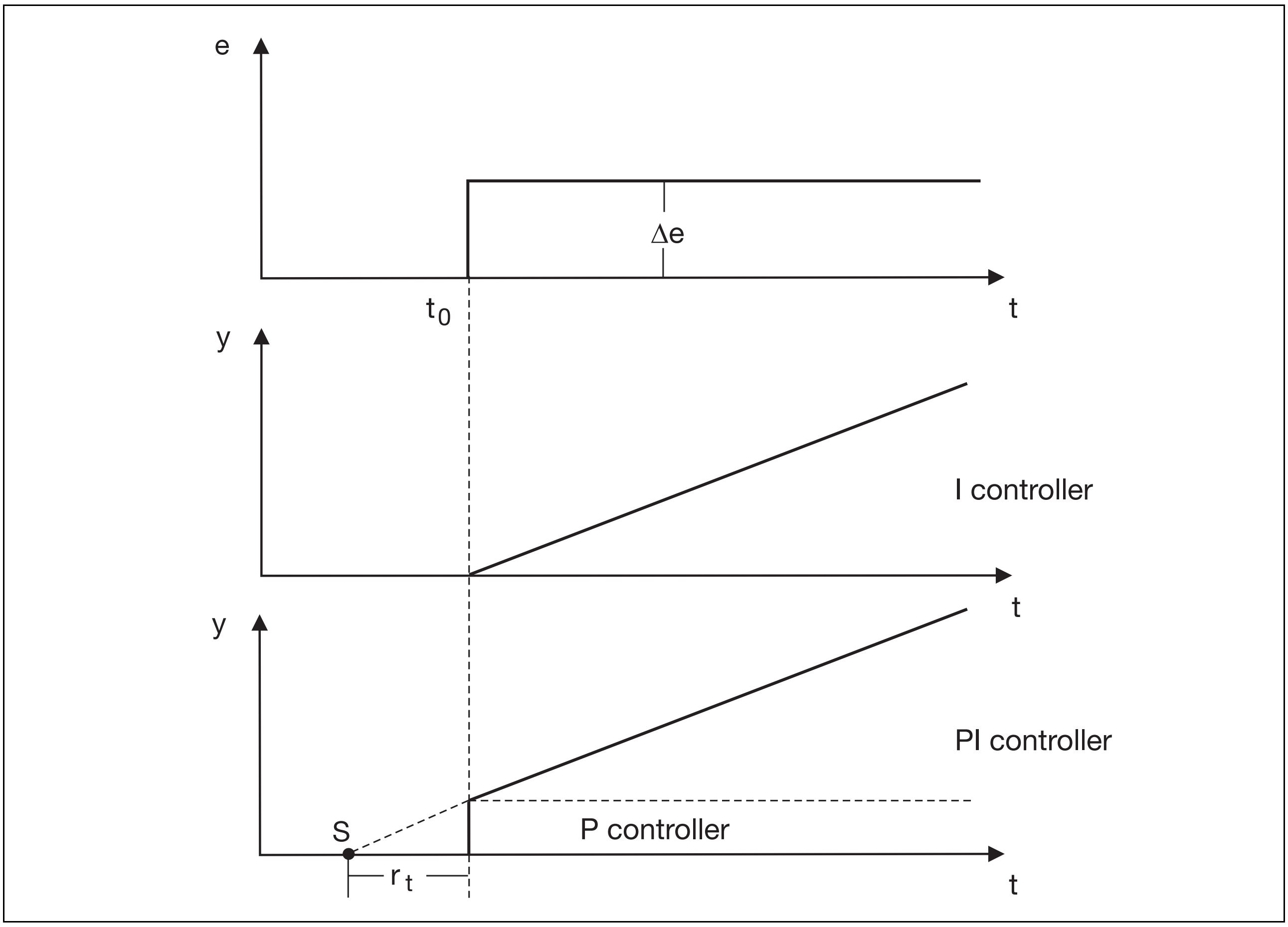


**Fig. 40: Step response for a PI controller**

There are two parameters to be set for a PI controller. The smaller you make the $P_b$ setting, the stronger will be the P component. The I component also responds faster if $r_t$ has a smaller setting.

If the step response of a PI controller is recorded (Fig. 40), then the $r_t$ set on the controller can be derived from the output level curve in the diagram. Extend the line of the output level curve backwards. The time between the intercept with the time axis and the step is the reset time.

For a constant control deviation, the output level is derived from the following equation:

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

or, after re-arranging:

$$\Delta y = \underbrace{\frac{100\%}{P_b} \bullet \Delta e}_{\text{P component}} + \underbrace{\frac{100\%}{P_b} \bullet \frac{1}{r_t} \bullet \Delta e \bullet t}_{\text{I component}} \qquad (19)$$

As can be seen from the equation, the $P_b$ setting also affects the integration action: if $P_b$ is reduced, the I component will also act faster.
This topic will be covered in detail in Chapter 3.5.1 *“Block diagram of a PID controller”*.

At this point, what is of practical importance is that: As the settings for $P_b$ and $r_t$ are made smaller, the amplification becomes larger (reduction of $P_b$) and the I component acts faster (reduction of $r_t$ ).

If the control deviation is not constant, then the controller operates to the following equation:

$$\Delta y = \frac{100\%}{P_b} \bullet \left( e + \frac{1}{r_t} \bullet \int_{t_0}^{t} e \bullet dt \right) \qquad (20)$$

**PI controller in a closed loop**
Fig. 41 shows the response of a PI controller in a closed loop.

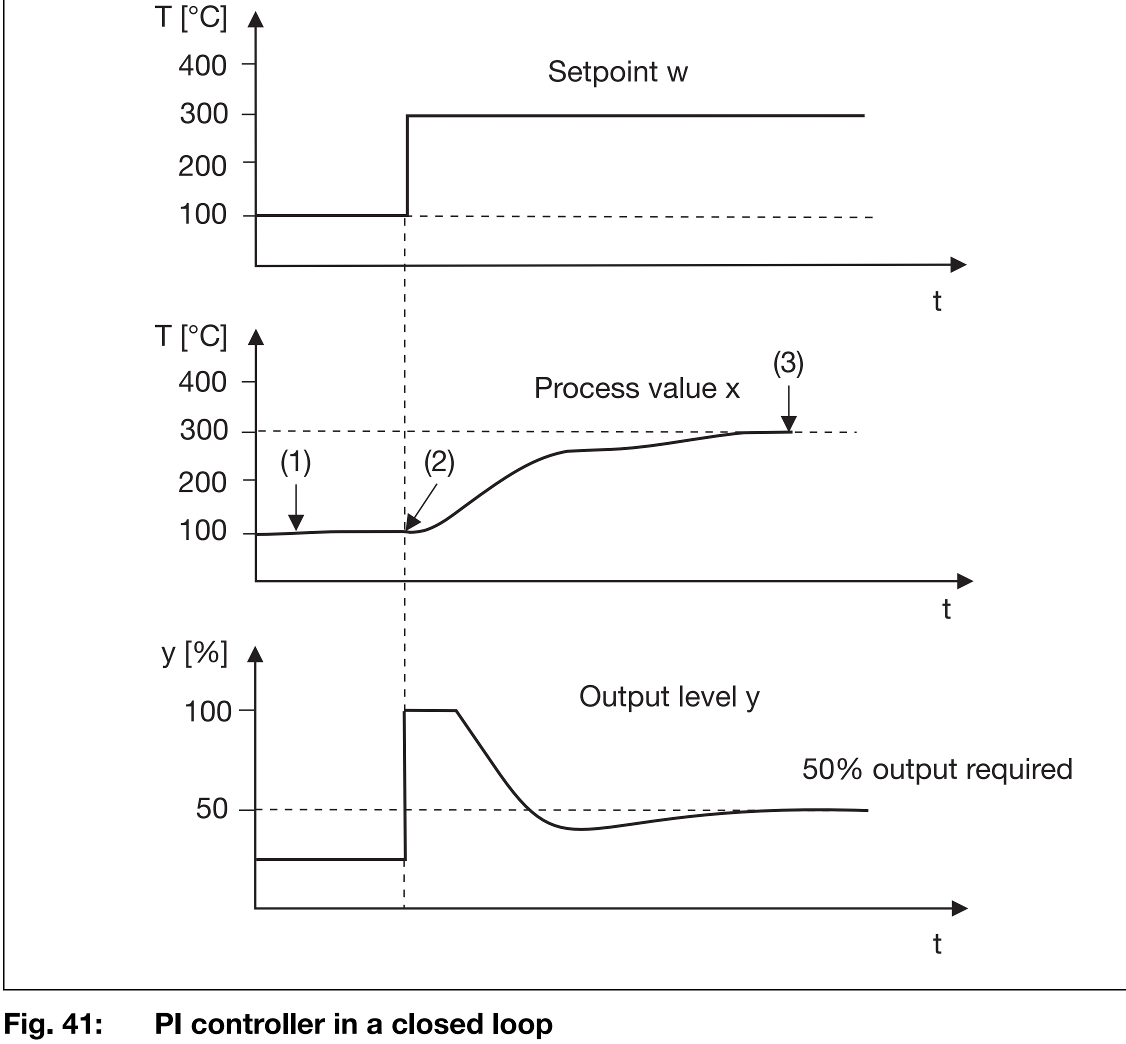


**Fig. 41:** **PI controller in a closed loop**

Fig. 41 shows the variables: setpoint, process value and output level, for a PI controller used for temperature control.

(1) The setpoint is 100 °C, the controller has settled (no remaining control deviation), and the output level is 25 %. The output level signal can only come from the I component, since the P component is inactive (control deviation is 0).

(1) The setpoint is altered to 300 °C, and the output level jumps to 100 %. At this moment, the change of output level comes entirely from the P component, which amplifies the considerable control deviation. The output level from the P component is reduced as the control deviation becomes smaller and smaller. At the same time, the I component integrates the control deviation continuously, and increases its output level until the system has settled.

(1) In the settled state (control deviation = 0) the I component is once more providing the entire output level (50 % in this example).

## 3.4 PD controller

The D component reacts to changes in the process variable, and acts to compensate them. For this reason, a D component is never used on its own, but always in combination with P or PI components. This section explains how it works in a controller with a P component.

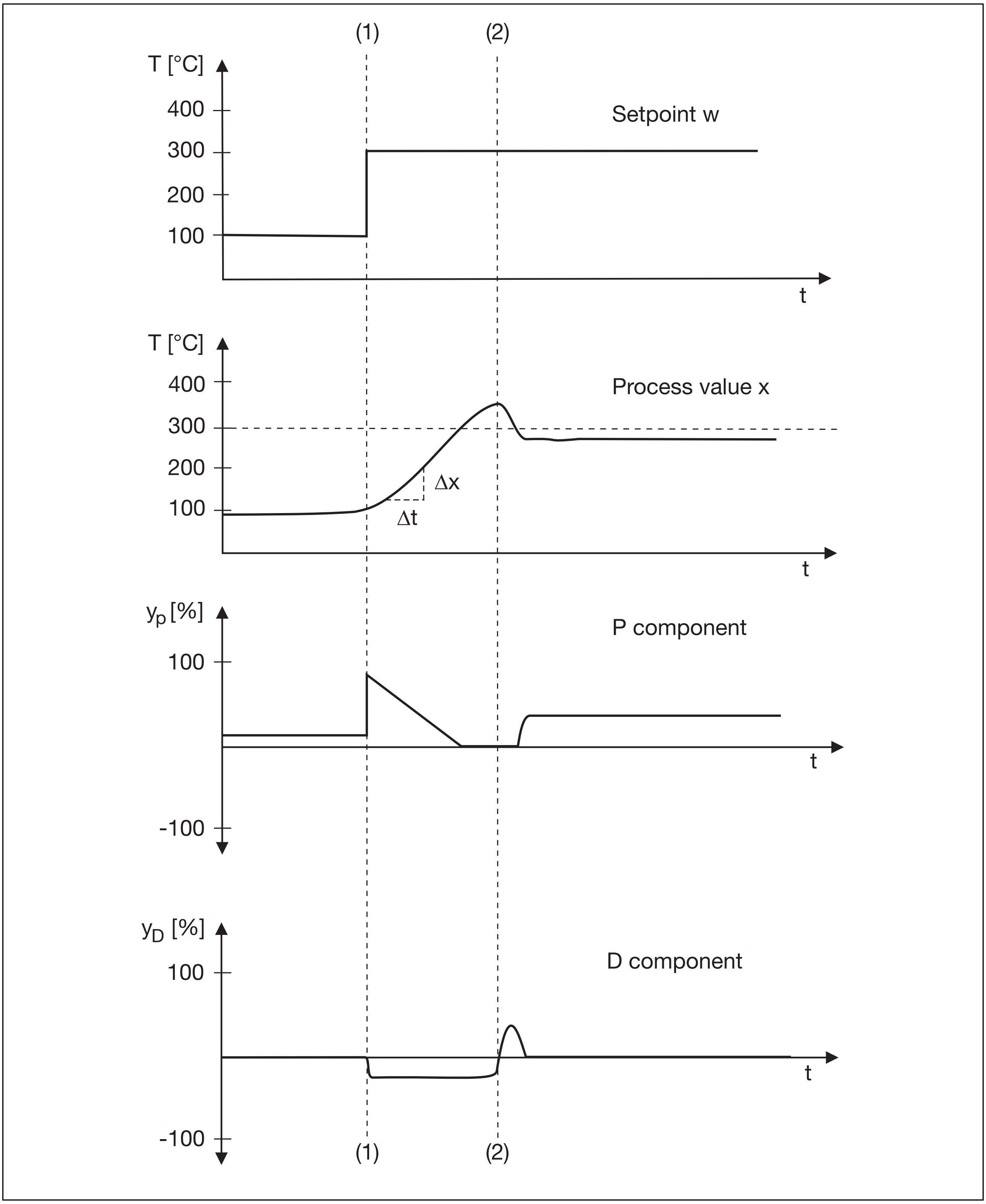


**Fig. 42:** **A PD controller in a closed loop**

Two situations must be studied with regard to the effect of the D component.

- The process value for the control loop has stabilized to a constant value. A disturbance acts to reduce the process value. The D component now provides an additional positive output level that helps to move the process value towards a higher level again.
- If the setpoint is raised, the process value for the control loop will also become larger.
  The D component detects the rising process value, and produces a negative output level that slows the approach of the process value to the new final value.
  This situation is shown in Fig. 42.

Fig. 42 shows the curves for the process value and setpoint of a PD controller in a closed loop. It also shows the portions of the output level that are provided by the P and D components.

**P component**
A setpoint of 100°C is applied at the start of the diagram, but the process value is somewhat below 100°C. This results in a control deviation and an output level from the P component.
If a setpoint of 300°C is now applied at (1), there is initially a large control deviation, which causes a high P output level. After a short time, the control deviation becomes smaller and so the P output level is also reduced. If the process value goes beyond the setpoint, the P component output level becomes 0%. If, after some time, the process value goes below the setpoint, a P component output level >0% will again be produced.

**Now let us look at the D component:**
At the start of the diagram, the process value is unchanged. So no output level is provided by the D component. The process value rises from (1) on. The D component detects the rising process value, and produces a negative output level. This is deducted from the P component output level, the total output level becomes smaller, and so the process value rises more slowly. The D component continuously responds to the process value and detects the slope (rate of change). The faster the process value changes, the larger will be the D component. In (2), the slope of the process value is 0, which means that the D component is also 0%. The process value falls from (2) on. Here too, the D component counteracts the change, by producing a positive output level that is added to the P component of the output level.

The strength of the D component can be altered by the user. A higher setting for the derivative time $d_t$ produces a stronger effect.

We will once more examine the effect of the D component in a closed loop. To start, let us look at the response of a PD controller with an inactive D component ($d_t$ = 0sec), see Fig. 43:

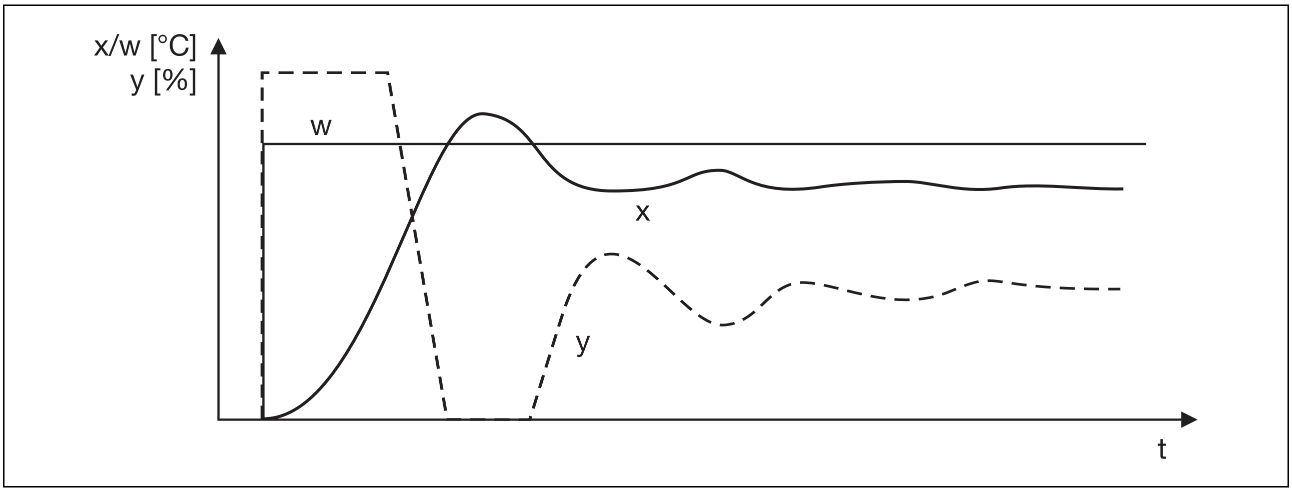


**Fig. 43:** **PD controller with $d_t$ = 0s (D component ineffective), P controller**

# 3 Continuous controllers

Fig. 43 shows that the control loop exhibits a fairly oscillatory response (reason: $P_b$ is set relatively small, and $d_t$ is 0 seconds).

In Fig. 44 a) we can see that a more favorably adjusted $d_t$ with the resulting damping produces a much smoother response:

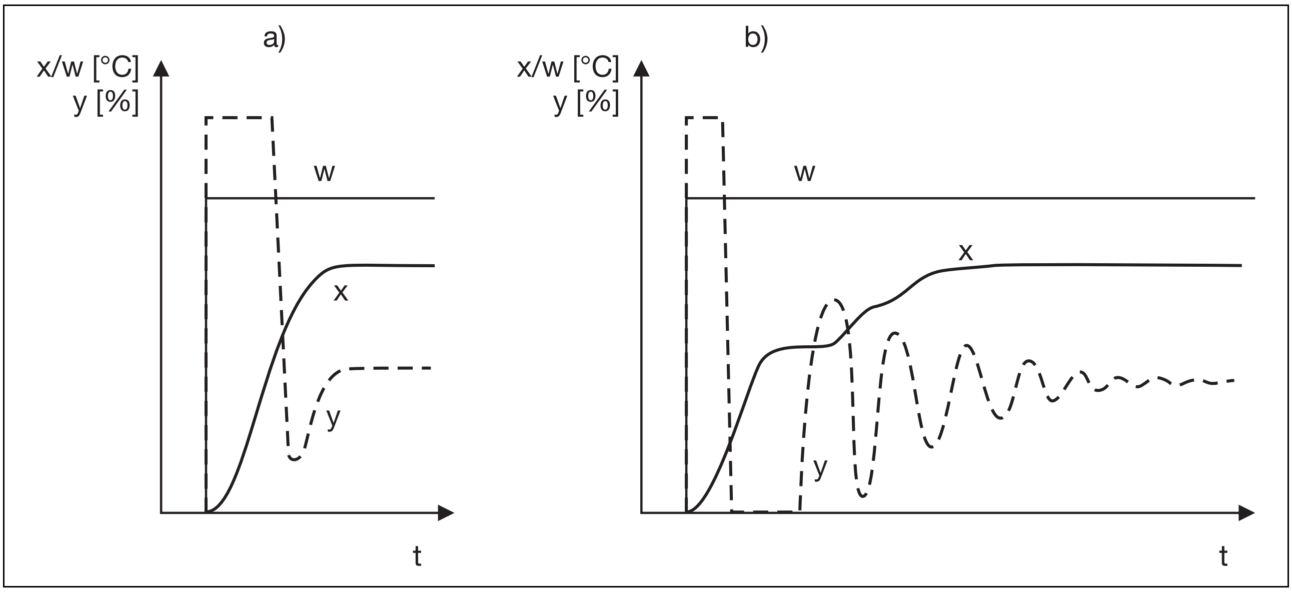


**Fig. 44: PD controller with a) optimum setting for $d_t$ and b) $d_t$ set too high**

The D component continuously responds to the process value Fig. 44 a) and reduces the overall output level more strongly if the slope of the process value increases (damping effect).

In Fig. 44 b), $d_t$ has been set too high. When the setpoint changes, the P component causes an output level of 100%. The D component detects the slope (rate of change) of the process value and reduces the overall output level (to 0% in this case), which reduces the rate of change of the process value. The reduced slope of the process value causes the D component to reduce its negative portion of the output level, and thus allows the process value to rise more steeply. The faster change of process value causes the D component to reduce the overall output level again...

Fig. 45 shows the response curve for a PD controller, from which one can derive the $d_t$ setting that was made for the controller.

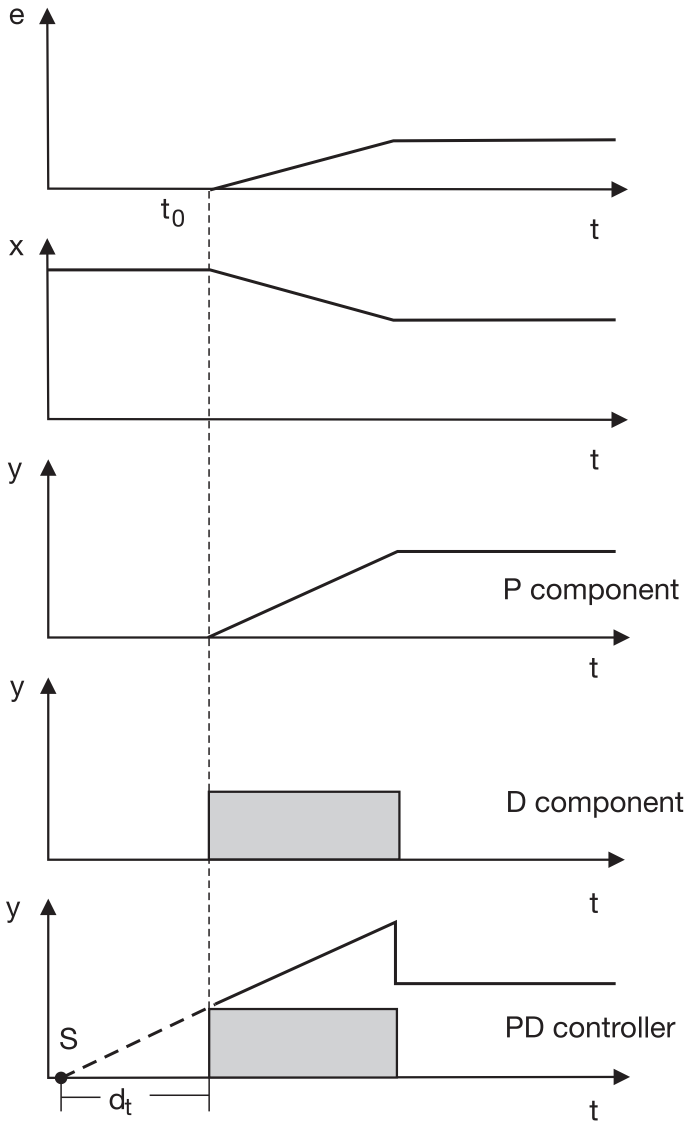


**Fig. 45: Response curve for a PD controller**

Fig. 45 shows, from top to bottom, the control deviation (rising continuously) and the P and D components.
If there is to be a D effect, the change in control deviation must be the result of a change in the process value. That is why the process value curve has been included. The following curves show the P component, the D component, and the resulting overall output level,

The P component amplifies the momentary control deviation all the time. As soon as the process value falls, the D component will also provide an additional positive output level that helps to speed up the stabilization and settling of the process value. The D component of the output level is proportional to the slope of the process value ($\Delta x / \Delta t$) and also to the $d_t$ setting.

If one now looks at the overall output level, and extends the ramp backwards (to the left), then the period from the intercept on the time axis to the start of the ramp is the derivative time $d_t$ of the controller.

On a PD controller (for heating, for instance), the controller equation is a ramp with a constant slope.

$$y = \frac{1}{P_b} \bullet 100\% \bullet \left(e - d_t \bullet \frac{\Delta x}{\Delta t}\right) \qquad (21)$$

If the process value is changing, the output level is derived from the following equation:

$$y = \frac{1}{P_b} \bullet 100\% \bullet \left(e - d_t \bullet \frac{dx}{dt}\right) \qquad (22)$$

$\frac{dx}{dt}$ describes the slope of the process value (for instance, in °C/sec for temperature control).

### 3.4.1 The practical D component - the $DT_1$ element

Basically, you can also evaluate the step response of a PD controller, just as was done previously for a P or PI controller. But the rate of change for a step is (theoretically) infinitely large. So the D signal component caused by a step would theoretically be an infinitely high and infinitely narrow spike (Fig. 46).

This means that, theoretically, the output level would have to be infinitely large for an infinitely short time, and then return immediately to the output level that corresponds to the P component. This is, however, impossible for mechanical and electrical reasons, and such a short impulse would anyway hardly have an effect on the process. In practice, the immediate disappearance of the D component is prevented by generating the D output component from a $DT_1$ circuit element. This element consists of a D component, as already discussed in this chapter, in series with a $T_1$ section.

Fig. 46 shows the step response of the practical D component. $T_1$ is the time constant for the $T_1$ section. In practice, this time constant is set to $d_t/4$, and altered in the same ratio if $d_t$ is changed. The relationship between $T_1 = d_t/4$ means that if $T_1$ is known, the derivative time $d_t$ can be determined.

$T_1$ is fixed by the manufacturer, and cannot be altered by the user.

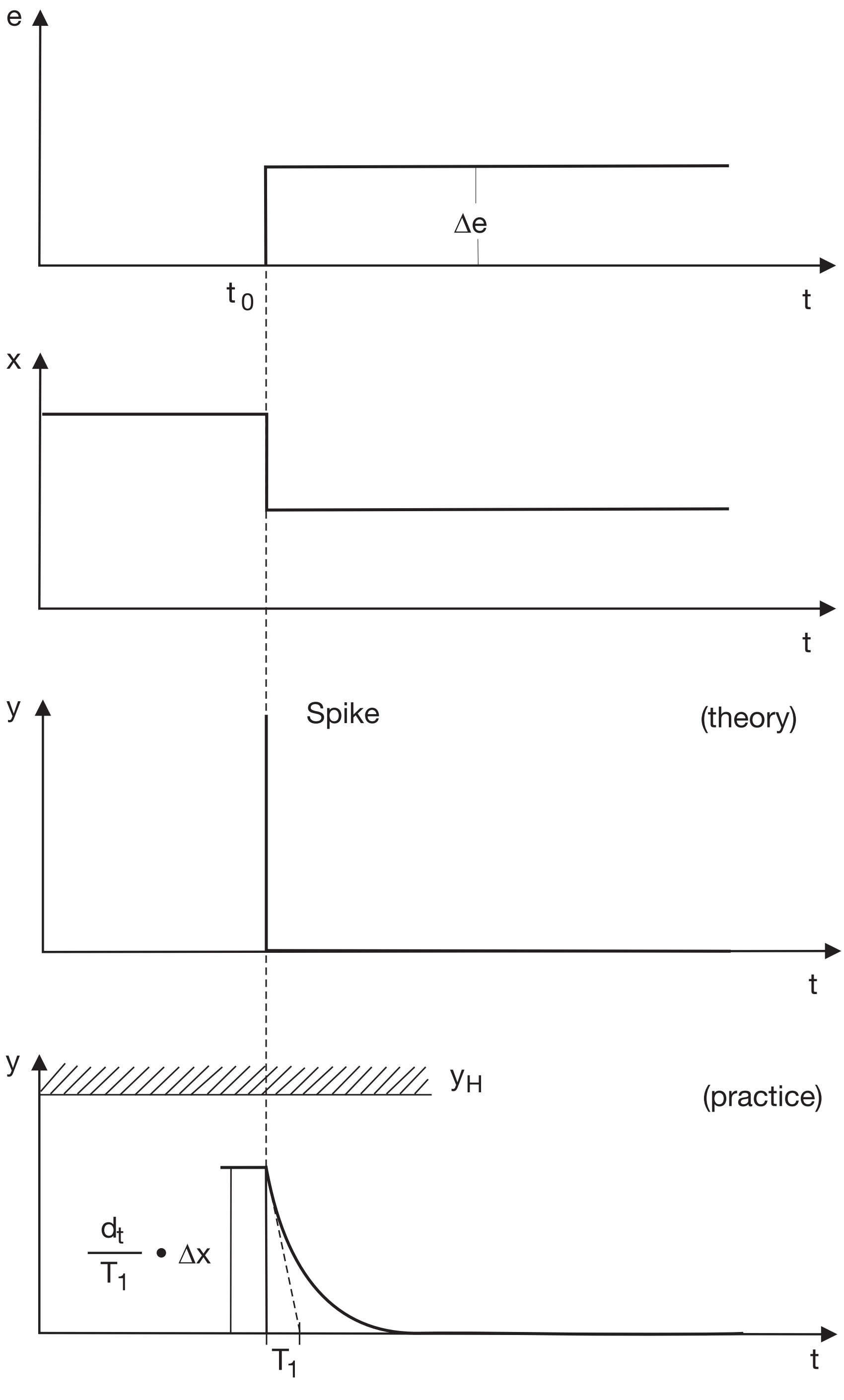


**Fig. 46:** **Step response for an $DT_1$ element**

## 3.5 PID controller

The most frequently used controller is a PID controller. In this type of controller, it is necessary to set the parameters $P_b$ , $r_t$ and $d_t$, which can be derived from the step response.

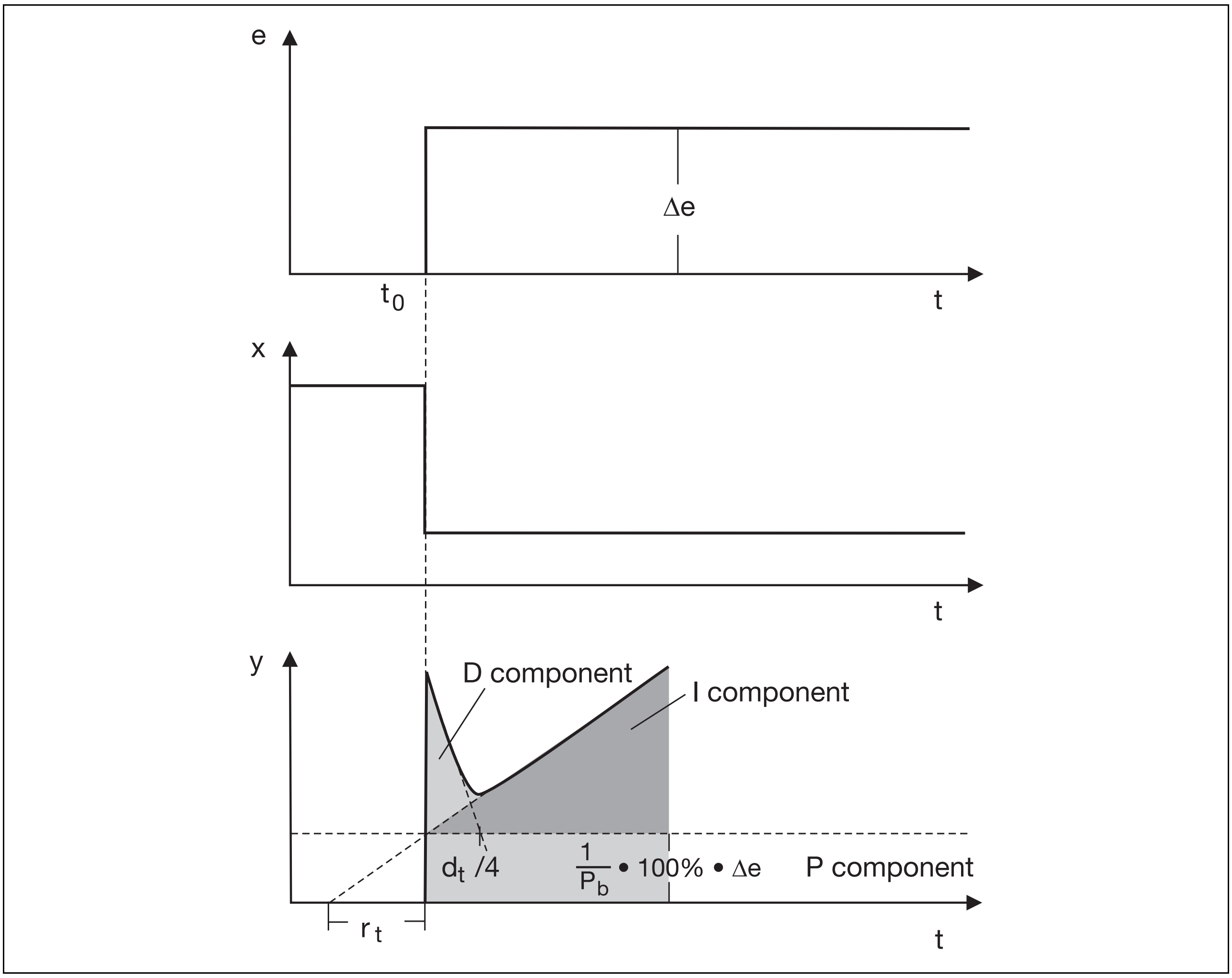


**Fig. 47: Step response for a PID controller**

The P and I components basically respond to the control deviation, while the D component responds to the process value change. For this reason, the change of the control deviation (Fig. 47) should result from a change of the process value. The process value curve is also drawn in the diagram.

If the process value suddenly falls, the D component will instantly generate an additional positive output level that helps to counteract the process value movement. The P component also generates a positive output level at the start, since it amplifies the control deviation. In addition, the I component increases its portion of the output level, in response to the control deviation, but the I component ramp only becomes visible when it reaches the same size as the D component.

The equation for the controller is thus:

$$\Delta y = \frac{1}{P_b} \bullet 100\% \bullet \left(e + \frac{1}{r_t} \bullet \int e \bullet dt - d_t \bullet \frac{dx}{dt}\right) \qquad (23)$$

The control parameters have different effects on the individual components:

**A larger $P_b$ means a reduced P component**

➔ reduced gain: more stable response, but also more sluggish

**A larger $r_t$ means a reduced I component**

➔ integration is slower: more stable response, but also more sluggish

**A larger $d_t$ means a larger D component**

➔ acts more strongly against the process value change, thus producing more stable response.Do not make $d_t$ too large.

### 3.5.1 Block diagram of a PID controller

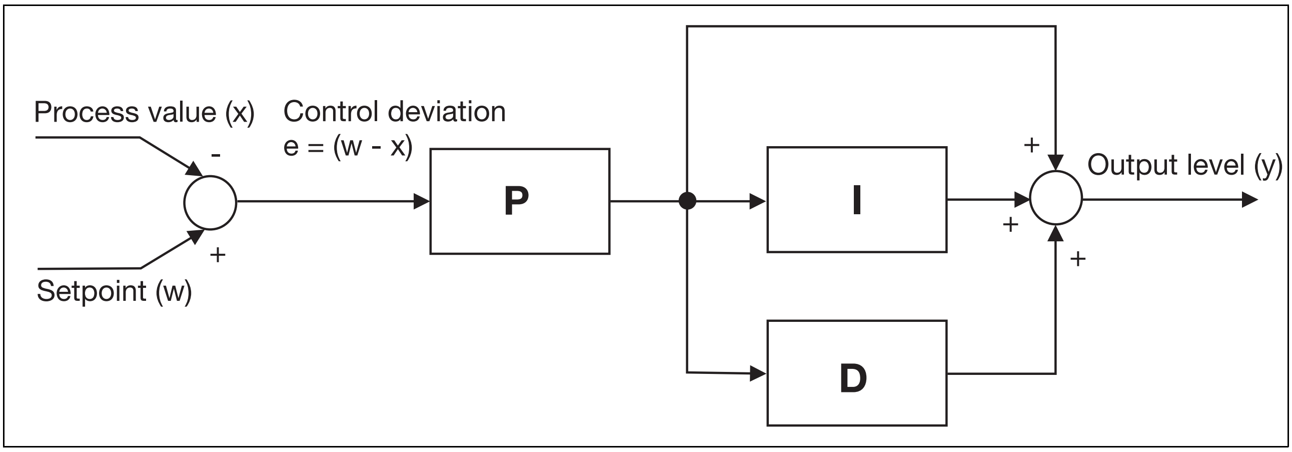


**Fig. 48: Block diagram of a PID controller**

As can be seen in this chapter, from the controller equations for the PI, PD and PID controllers, the I and D responses of a PID controller are affected not only by the settings for the parameters $r_t$ and $d_t$, but also by the proportional gain (through $P_b$).
So if you increase the proportional gain for a PID controller to twice the value (by halving $P_b$ ), then the controller will not only have a doubled proportional response, but the effects of the I and D components will also be doubled.

**Example**
The PID controller shown in Fig. 48 has the settings: $r_t$ = 10 seconds and $P_b$ = 100 (the D component is ignored for this example). The control deviation is 2.

Disregarding dimensions, the P component has a gain of $1\left(K_P = \frac{1}{P_b} \bullet 100\%\right)$.

The control deviation thus has a direct effect on the I component. From Chapter 3.2 *"I controller"*, we know that an I controller requires the time $r_t$ to produce the response to the input at its output. So it will take 10 seconds before the I component has added 2 % to the output level. The $P_b$ is now reduced to 50, and the amplification for the P component is 2.
But the control deviation is multiplied by the factor 2 before it is fed to the I component. So in 10 seconds the I component will add 4 % to the output level. The effect of the I component has also been increased by the factor 2. The advantage of this block structure is that one can, for example, increase the effect of all components by reducing the $P_b$ parameter.

**An alteration of the proportional gain**
**in a PID controller affects the I and D responses to the same extent**

# The closed control loop / Optimization methods

In this chapter you will learn how the setpoint and disturbance responses are defined, and how to set the control parameters for a stable control response.
The optimization methods that will also be presented are an aid to determining the suitable parameters for the controller. And then we will illustrate the controller structures that can be applied for various process values, according to the situation.

## 4.1 Setpoint response / disturbance response

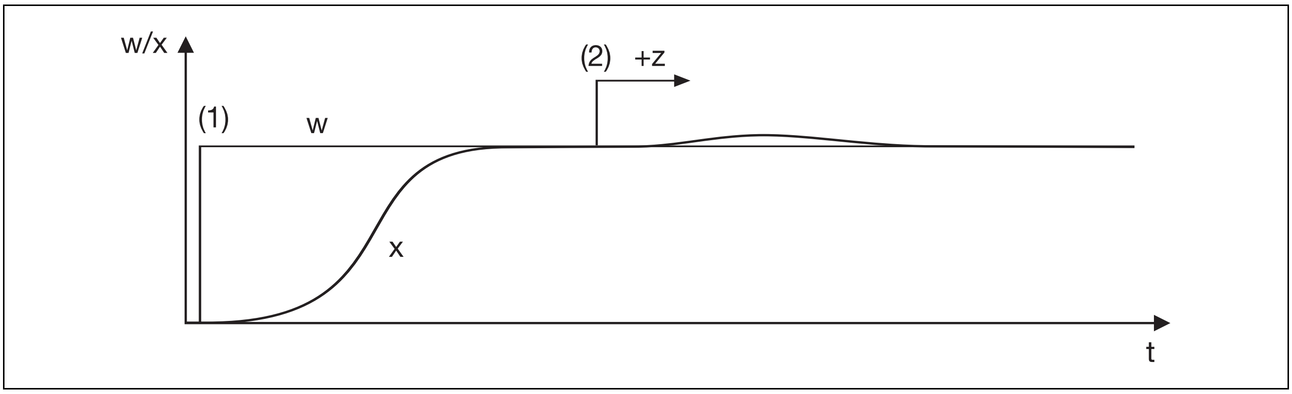


**Fig. 49: Setpoint and disturbance responses of a control loop**

In Fig. 49, a new setpoint is applied at (1). The setpoint response shown here is pretty good. The process value moves towards the setpoint fairly fast, and reaches it without any overshoot.

At (2), a disturbance variable changes, and this causes a control deviation. The controller alters its output level to compensate for this (in our example, it reduces the output signal) until the process value has been brought back to the setpoint.

When looking at the behavior of the control loop, we must distinguish between the response to a setpoint and the response to a disturbance.
For the setpoint response we evaluate how the control loop regulates the process to meet a new setpoint. The disturbance response is the reaction of the controller to the presence of a disturbance.

A controller can be optimized for setpoint response, and in this case it will reach the setpoint as quickly as is possible without overshoot. But if disturbances occur with such a controller (the “+z” in Fig, 49), they will not be compensated for as fast as would otherwise be possible, since a controller that is optimized for setpoint response is somewhat slower ($P_b$ , $r_t$ and $d_t$ tend to be larger).

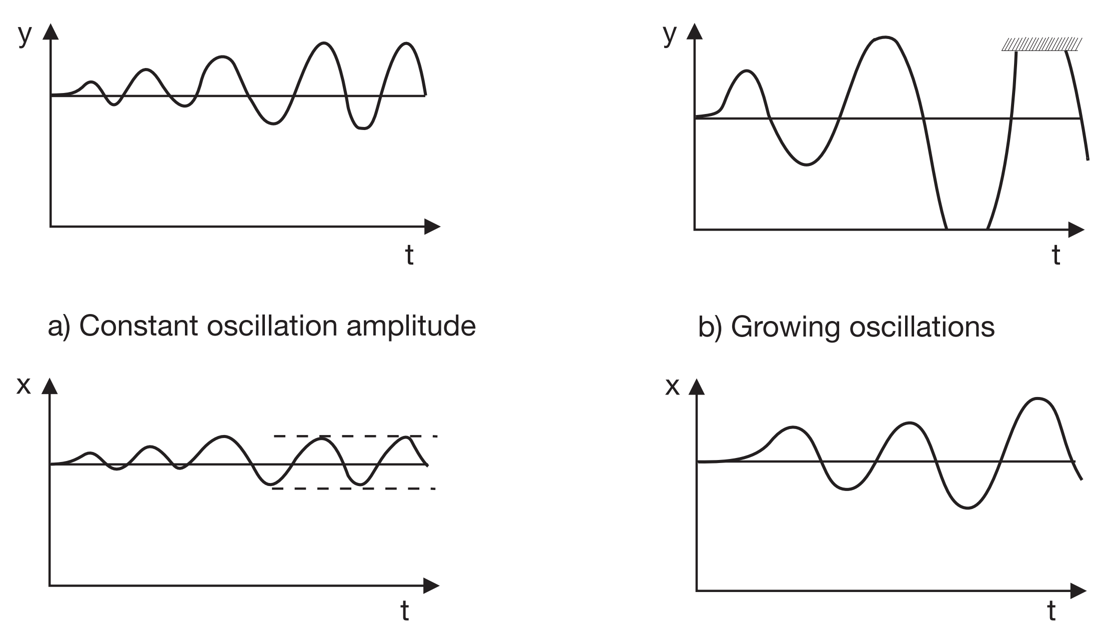
In order to achieve a good disturbance response, the controller must react faster ($P_b$ , $r_t$ and $d_t$ must be set to lower values). However, a change of setpoint will cause an overshoot of the process value.

At this point it must be made clear that a controller can either be optimized for setpoint response or for disturbance response. In practice, you often have to make a compromise.
The adjustment is made in such a way that disturbances are corrected as fast as possible without causing an overshoot when a new setpoint is applied, or no more than an acceptable overshoot.

If a JUMO controller needs to be optimized for both setpoint and disturbance response, then it is possible to determine the corresponding parameters and save them in two parameter sets. The appropriate parameter set is then selected according to the operating conditions. If the process value is outside a defined band about the setpoint, then the parameter set for good setpoint response will be activated. If the process value is within this band, then the controller switches over to the parameter set for good disturbance response.

## 4.2 Stable and unstable control-loop response

Almost any control loop can become unstable if the controller is set up incorrectly.



a) Constant oscillation amplitude

b) Growing oscillations

**Fig. 50: The unstable control loop**

An incorrect setting on the controller can lead to oscillation of the output level (Fig. 50, a). The output level builds up until it is oscillating between a maximum and minimum value. The oscillating output level causes an unstable process value.

The periodic cycling of the output level can become so extreme, that it oscillates between 0 and 100 % (Fig. 50, b). The process value will have correspondingly large variations.

A control loop will become unstable if $P_b$ , $r_t$ and $d_t$ become too small (proportional gain is too high, the I component is integrating too fast, the damping is too weak).
To achieve a stable operation, you can, for instance, start by increasing the value of $P_b$. If the output level and process value do not stabilize, then the parameter pair $r_t$ and $d_t$ can be increased (it is recommended that you first check that $d_t$ is about $r_t$ /4, since such a ratio is favorable for most applications). The $d_t$ must be adjusted accordingly. Now increase the parameter pair $d_t$ and $r_t$, keeping the ratio the same.

## 4.3 Optimization methods

In this section we will look at four different optimization methods that can only be applied to processes that are self-regulating.

These methods have a common factor: that the optimization must be carried out under realistic operating conditions (e.g. the optimization must not be made for an empty oven, if you want to determine good parameters for a full oven).

**The methods are:**

the oscillation method (Ziegler-Nichols) - for fast processes

process step response (Chien, Hrones, Reswick) - for slow processes

the slew rate - for slow processes

the empirical method - for fast processes

Before starting to use one of these methods, you should check whether the optimization (self-tuning) that is provided in JUMO controllers can be used or leads to success (Chapter 7.1 *"Self-tuning"*). In most cases, this method will produce very good to satisfactory results.

### 4.3.1 Oscillation method according to Ziegler and Nichols

The oscillation method according to Ziegler and Nichols can be applied to comparatively fast processes (such as speed control).

The procedure produces good parameters for P, PI and PID controllers.
The control loop is deliberately destabilized during this procedure.
The controller is switched over to a P structure, and a relatively large $P_b$ is set, but one that does not yet cause instability. A setpoint is now defined, one that lies within the intended range of operation (Fig. 51 (1)).

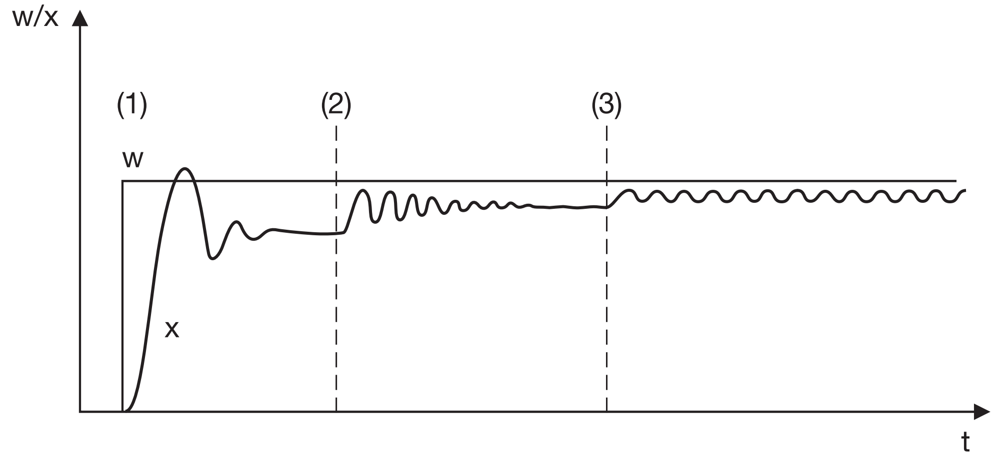


**Fig. 51: Setpoint and process value during the oscillation method**

Fig. 51 (1) illustrates how the process value settles down to a final value after a brief oscillation. The process value is below the setpoint (as is to be expected, since a P controller is being used).

The $P_b$ is now reduced (Fig. 51 (2)): The process value rises, and requires a longer time to settle down. The proportional band may have to be reduced several times, until the process value starts to oscillate. The resulting curve is shown in Fig. 51 (3).

The critical value of $P_b$ ($Pb_k$, the proportional band beyond which continuous oscillations appear) must be determined as precisely as possible.

Let us take a close look at the oscillation of the process value (Fig. 52).

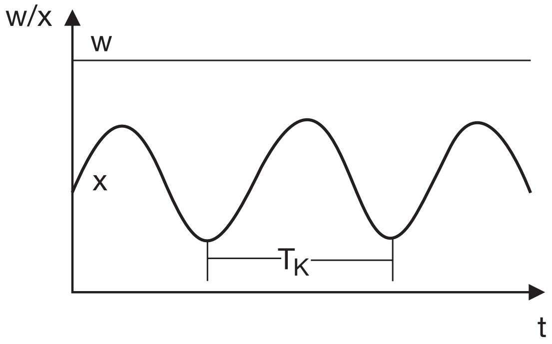


**Fig. 52: Oscillation period (critical cycle time)**

The second parameter that is required for this procedure is the critical cycle time - the oscillation period ($T_K$):
The oscillation of the process value is used, for instance, to determine the period between two minimum values. This value (in seconds) is then applied in the following table, together with the $Pb_k$ (the last setting for the controller).

| Controller structure | Control parameters |
|---|---|
| P | $P_b = Pb_k / 0.5$ |
| PI | $P_b = Pb_k / 0.45$<br>$r_t = 0.83 \cdot T_K$ |
| PID | $P_b = Pb_k / 0.6$<br>$r_t = 0.5 \cdot T_K$<br>$d_t = 0.125 \cdot T_K$ |

**Table 1: Formulae for settings according to the oscillation method**

### 4.3.2 Step-response method according to Chien, Hrones and Reswick

The use of the method according to Chien, Hrones and Reswick makes it possible to determine the controller parameters fairly quickly, even for slow processes.
This method can be applied to processes that are 2nd order or higher.

The special feature of this method is, that it makes a distinction between formulae for setpoint response and for disturbance response.

In order to use the table that is provided, the process gain, the delay time, and the response time must all be determined from the step response. In Chapter 2.4 *“Recording the step response for processes with at least 2 delays and a dead time”* there is a detailed description of how to go about this. For this reason, we will use an example for a direct demonstration of the method.

A controller with a PID structure is to be used to run an industrial oven.
The aim is to achieve a good disturbance response, and the setpoint is typically around 200°C.

To start, the controller is switched over to the manual mode. The output level is gradually increased to a process value that is below the setpoint that will later be the target value (wait for the process to settle to a steady value). Take as an example, an output level of 60%, that produces a temperature of 180°C. Starting at 60%, an output level step change is made to, say, 80%, and the curve of the process value is recorded (the relationships are shown in Fig. 53).

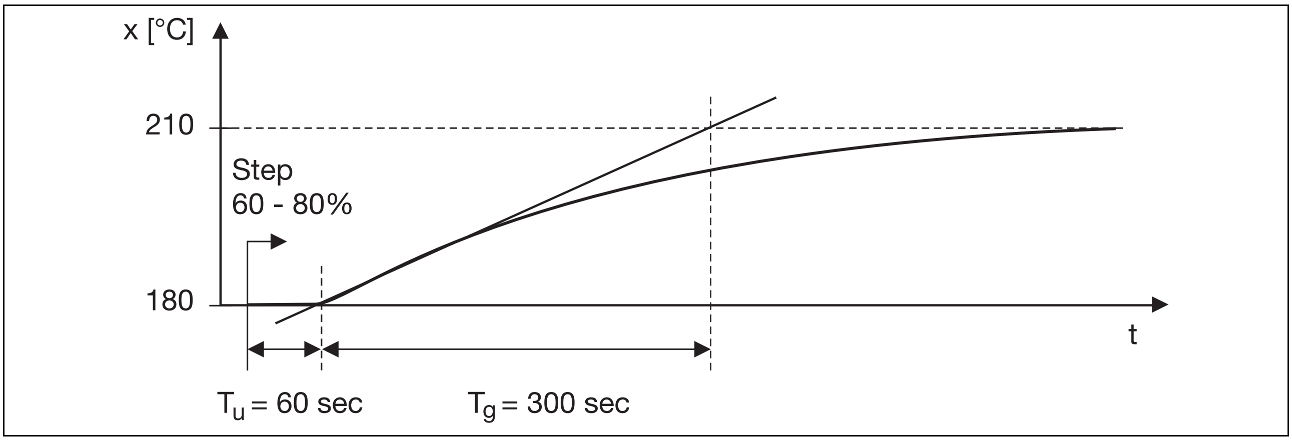


**Fig. 53: Step response of the industrial oven**

The tangent of the curve is measured, and from this is derived, for example:
Delay time $T_u$ = 60 sec, response time $T_g$ = 300 sec

With the aid of Table 2 it is then possible to determine favorable control parameters.

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

**Table 2: Formulae for settings according to the process step response**

The process gain is given by the change in the process value divided by the step size (expressed at % of output level).

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

With the values determined for $T_u$ and $T_g$, the following parameters can be derived:

$$P_b = 1.05 \bullet K_S \bullet \frac{T_u}{T_g} \bullet 100\% = 1.05 \bullet 1.5\frac{°C}{\%} \bullet \frac{60\,\text{sec}}{300\,\text{sec}} \bullet 100\ \% = 31.5°C$$

$$r_t = 2.4 \bullet T_u = 2.4 \bullet 60\ \text{sec} = 144\,\text{sec}$$

$$d_t = 0.42 \bullet T_u = 0.42 \bullet 60\,\text{sec} \approx 25\,\text{sec}$$

On the one hand, the output level step should be selected to be large enough to produce a step response (the process value curve) that can be evaluated. On the other hand, it is vital that the step remains within the setpoint range that will be used in later operation.

**Example**
The typical working point of the industrial oven in this example is around 200 °C. If a step is generated in the output level that alters the process value by 70 °C, for example, then the evaluation of the step response will probably not produce suitable control parameters for operation at 200 °C. At lower temperatures, the conditions are not the same as in later operation (for one thing, the process gain will be different than for the later operating range, and this in its turn affects the calculation of $P_b$).

### 4.3.3 Method according to the slew rate

The method according to the slew rate can also be applied to slow processes. With this method, a freely selected step is applied to the process for just as long as it takes for the curve of the process value to reach its maximum slope (the slew rate). Since the evaluation of the process value is made from this moment on (it is not necessary to wait until the process value has settled to its final value), this method saves a lot of time. But, just as for the step response method, the process must be 2nd order or higher.

The work involved in optimizing a controller for the industrial oven mentioned in Chapter 4.3.2 *“Step-response method according to Chien, Hrones and Reswick”* would be about the same.

1. Application of an output level that produces a process value that is smaller than for the later working point (e.g. 180 °C at 60 % output level, it is necessary to wait for the system to settle!).
2. Application of an output level step change to 80 %, and recording of the process value curve.

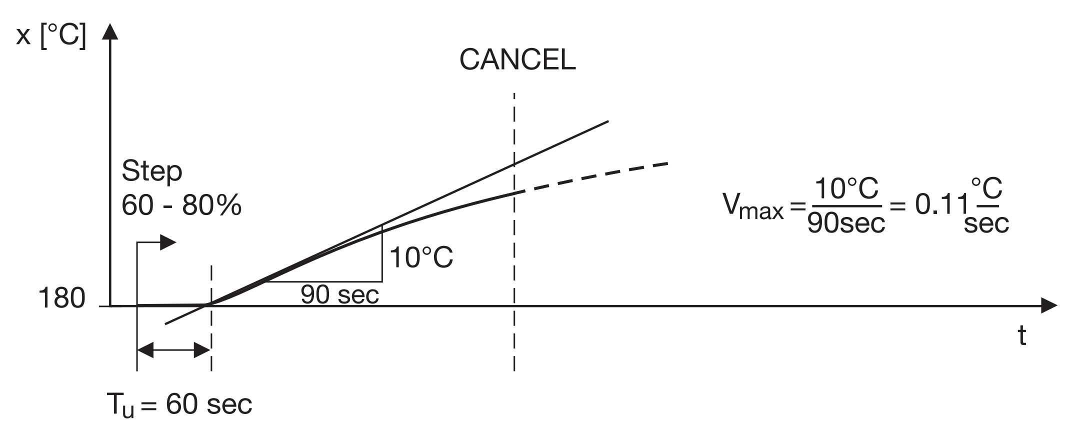


**Fig. 54: Process value curve with the slew rate method**

After application of the step, the process value starts to rise after some time. The recording of the curve can be stopped when the process value curve has reached its maximum slope (the slew rate).

In this procedure too, the tangent to the curve is drawn and the delay time is measured. The second parameter is determined by drawing the tangent to the curve to mark the slope as a triangle. This is used to determine the maximum slew rate.

$$V_{max} = \frac{\Delta x}{\Delta t} \qquad (24)$$

The $V_{max}$ that is determined (about 0.11 °C/sec in our example) is used, together with the $T_u$ that was measured (60 sec), in the following formulae.

| Controller structure | Control parameters | |
|---|---|---|
| P | $P_b = V_{max} \cdot T_u \cdot y_H / \Delta y$ | $y_H$ = maximum output range (usually 100 %)<br>$\Delta y$ = applied output step (20 % in our example) |
| PI | $P_b = 1.2 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$<br>$r_t = 3.3 \cdot T_u$ | |
| PD | $P_b = 0.83 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$<br>$d_t = 0.25 \cdot T_u$ | |
| PID | $P_b = 0.83 \cdot V_{max} \cdot T_u \cdot y_H / \Delta y$<br>$r_t = 2 \cdot T_u$<br>$d_t = 0.5 \cdot T_u$ | |

**Table 3: Formulae for setting according to the slew rate for self-regulating processes**

For a PID controller, our example produces the following values:

$$P_b = 0.83 \bullet V_{max} \bullet T_u \bullet \frac{y_H}{\Delta y} = 0.83 \bullet 0.11 \frac{°C}{sec} \bullet 60sec \bullet \frac{100\%}{20\%} \approx 27.4°C \quad (25)$$

$$r_t = 2 \bullet T_u = 2 \bullet 60sec = 120sec \quad (26)$$

$$d_t = 0.5 \bullet T_u = 0.5 \bullet 60sec = 30sec \quad (27)$$

### 4.3.4 The empirical method for determining control-loop parameters

This procedure is used to determine favorable settings for the P, D, and I components, one after another. Starting from the initial state, the typical setpoint is repeatedly applied, so this method is only suitable for fairly fast processes (e.g. speed or flow rate as process variables).

Even if the final aim is to find good values for a PID structure, the P response is defined first. We set up a relatively large proportional band (the size depends on the process) and define a setpoint that lies within the later operating range.
We will see that the control loop responds very sluggishly, and the process value remains way below the setpoint. Now we reduce $P_b$, repeatedly approaching the setpoint while this is done. We keep on reducing the proportional band until the process value reaches a steady final value after two or three oscillations. We now have a stable control loop, but with a remaining control deviation. The result could look something like Fig. 55 a).

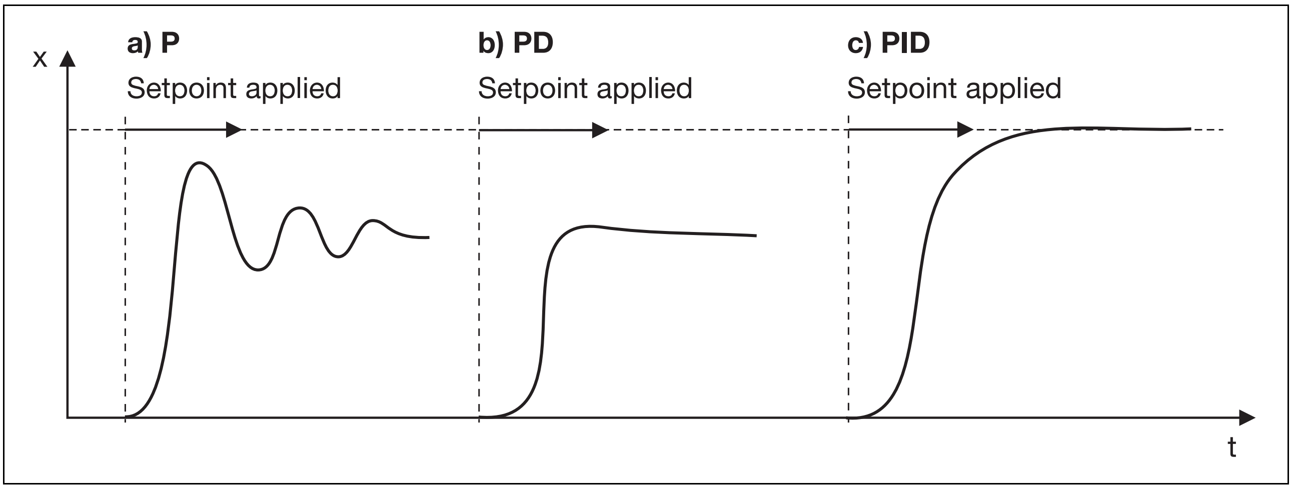


**Fig. 55: Setting a PID controller according to the empirical method**

We now activate the D component (now operating the controller with a PD structure) to dampen the process value response. Starting from a very small $d_t$ , we again repeatedly approach the setpoint with increasing values of $d_t$. The $d_t$ has a favorable setting when the process value approaches the final value with the smallest possible oscillation.

**If the controller drives the output level to 0% one or more times while the process value is approaching the final value, then the $d_t$ setting is too high.**

The result for our control loop could look something like Fig. 55 b).

Now the I component is activated, by switching over to a PID structure. The $r_t$ is set to $r_t = d_t \times 4$. Our control loop response could look like the example in Fig. 55 c).

**Note**
For some processes, it is not possible to activate all components (see Chapter 4.4 *“Which controller structure should be used for various process variables ?”*). When using the empirical method, if you discover at the start that it is not possible to achieve stable control with the P structure, then it will only be possible to make the optimization as an I controller.

If in another process it is seen that the control loop becomes unstable when the D component is activated (switch from a P to a PD structure), then the optimization must be made as a PI controller.

### 4.3.5 Checking the controller settings for a PID structure

If a PID controller is optimized with one of the procedures outlined in this chapter, then the control response is not necessarily the best possible. In such a case, Fig. 56 can help when making a subsequent fine optimization.

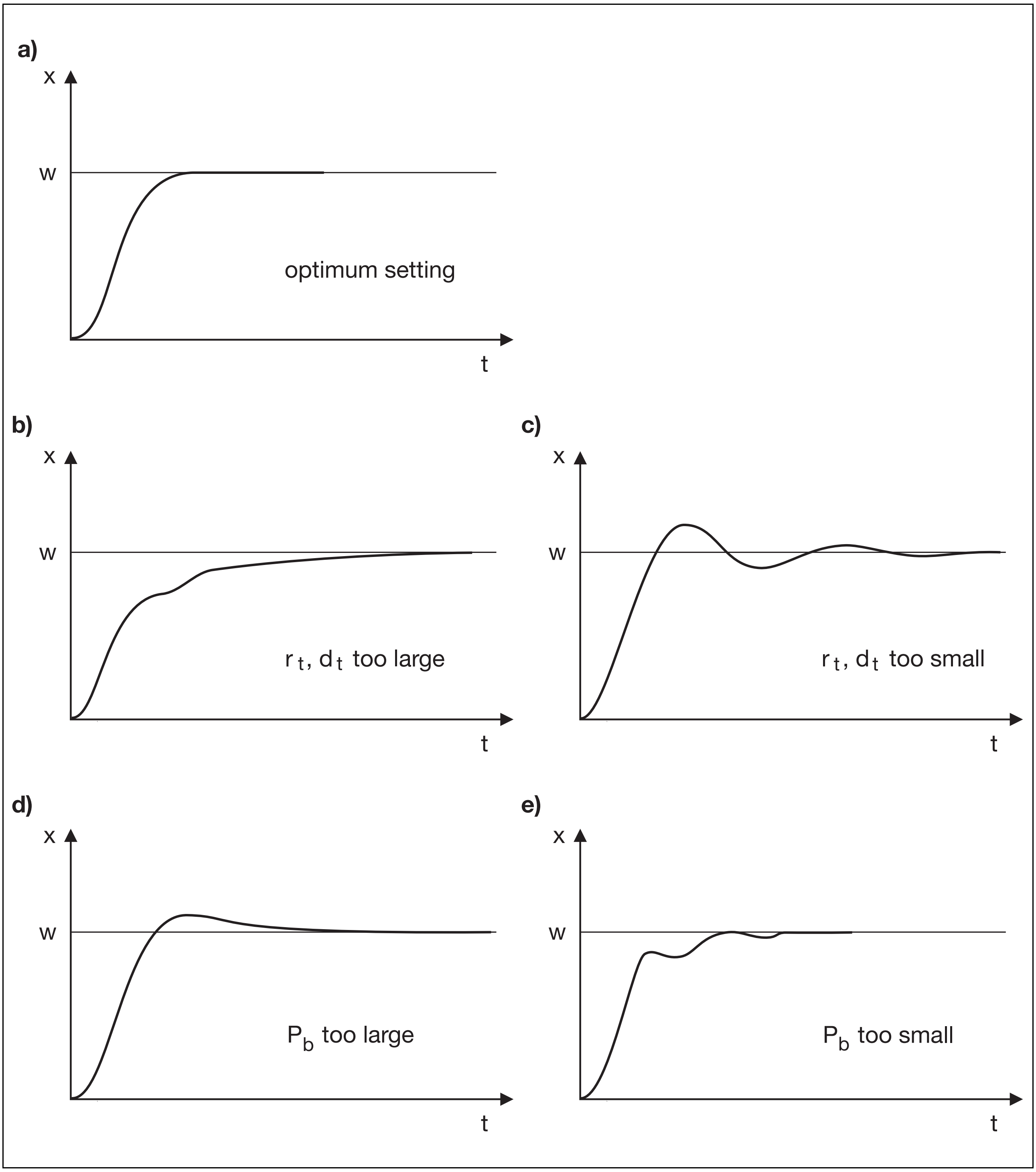


**Fig. 56: Examples of possible incorrect adjustment**

Let us take a closer look at the diagrams.

a) This control-loop response is achieved with an optimum setting.

b) The process value increases fairly sharply when the setpoint is applied, so the proportional band appears to have a good setting. But when the control deviation becomes smaller, the rate of change of the process value slows down. As the control deviation becomes smaller, the output level that is produced by the P component also becomes smaller. This is where the I component is important. In the example here, the I component is integrating too slowly (the $r_t$ setting is too large, it must be reduced). Considering the relationship $d_t = r_t / 4$, the derivative time must also be reduced.

c) In the example here, the I component is set too high (the $r_t$ setting is too small). The I component integrates the control deviation until this has gone to 0. The I component is changing the output level too quickly. By the time the process value reaches the setpoint, the output signal is too large. The result is that the process value oscillates about the setpoint. Considering the relationship $d_t = r_t / 4$, the derivative time must also be increased.

d) This control response indicates that the $P_b$ setting is too high. When the setpoint is applied, the output signal reaches 100% from the P component alone. The I component cannot build up an output level in this phase. If $P_b$ has been set too large, then the process value enters the proportional band at a very early stage, the P output level becomes less than 100%, and the I component cannot build up an output level signal. In this case, the I component takes a long time to build up its output level. By the time the process value reaches the setpoint, the output level is too high and the process value overshoots the setpoint. The correction is to use a smaller $P_b$ : When the setpoint is applied, the process value remains below the proportional band for a longer time. The P component produces 100% for a longer time, and the I component builds its output signal somewhat later - this reduces the probability of an overshoot.

e) If the proportional band setting is too small, then the process value approaches the setpoint very rapidly. The process value moves into the proportional band comparatively late (just before reaching the setpoint) and the output level is reduced almost in a jump. Now the process value also falls, after some delay, and because of the relatively large proportional gain, this causes a large increase in the P output level... The whole time, not only the D component but also the I component is acting to reduce the control deviation. A larger $P_b$ would stabilize the process value.

## 4.4 Which controller structure should be used for various process variables?

In general:
For most applications, the PID structure exhibits the best control response. However, there are some process variables that force the deactivation of specific components. For instance, a D component can lead to instability in processes with fluctuating process variables.
The P component increases the fluctuation, and may have to be switched off.

If the ratio of response time to delay time is fairly small (the process is difficult to control), then it may also be necessary to switch off the P and D components, as the control loop may otherwise become unstable.

It is not easy to prescribe the most favorable controller structure for various process variables, since it also depends on the way in which the process control has been implemented. For the author, it is important to mention those structures that produce the best results in most cases, or where one is keeping on the safe side (a stably operating control loop).

**Temperature**
This type of process is always self-regulating. The response time is often much longer than the delay time. A PID structure will nearly always be the most suitable for this type of process control.

**Pressure**
In this type of process control, the ratio of response time / delay time is fairly low ($T_g$ / $T_u$ <3). From the control engineering point of view, these processes must be treated as processes with a dead time. Furthermore, the process value often fluctuates a lot. For these reasons, an I structure is advisable in most cases.

**pH value**
The following applications may be distinguished: For a flow-through control (e.g. in a piping installation), PID structures will mostly be used. For regulation in a static container, a P or PD structure is used (the I component would cause overshoot).

**Speed**
In rotating systems there will frequently be resonances and thus harmonics. The D component in particular will be strongly affected by harmonics. For this reason, a PI structure is usually chosen.

**Flow**
In this situation, the ratio of response time / delay time is often low ($T_g$ / $T_u$ <3). I structures usually produce the best results.

**Level**
These processes are not self-regulating (an example of such a process can be found in Chapter 2.2.2 *“Processes without self-regulation”*). In principle, a PID structure produces the best control response. But the I component must not be made too large ($r_t$ not too small), otherwise the process value will tend to oscillate. Such a process must not be controlled by an I structure, since this alone would cause instability.

**Conveying (loose material)**
This type of process is usually dominated by a dead time (see also Chapter 2.3 *“Processes (elements) with P action, dead time and delays”*). With such processes, a P structure alone will always cause oscillations of the process variable (and for $P_b$ <100 even continuous oscillation). A D component also frequently causes instability. In most cases, I structures produce the best results.

The table provides a summary:

| **Process variable** | **The following controller structure will usually (!) produce the best results** |
|---|---|
| Temperature | PID |
| Pressure | I |
| pH value | Flow control: PID; containers: P, or PD |
| Speed | PI |
| Flow | I |
| Level | PID |
| Conveying (loose material) | I |

**Table 4: Selection of the controller structure for the most important process variables**

# Switching controllers

This chapter explains the method of operation of 2-state, 3-state, modulating, and actuating controllers.

## 5.1 Discontinuous and quasi-continuous controllers

The previously discussed controllers with a P, PD, I, PI, or PID action can produce any value between 0 and 100 % for the output level y. This means that the controller can always hold the process value w at the same value as the setpoint x.

Unlike continuous controllers, discontinuous and quasi-continuous controllers cannot produce a continuous output signal, but use outputs that can only have the status ON or OFF.
The outputs of these controllers are often implemented as relays, but solid-state relays are also common. These controllers are also occasionally provided with logic outputs.

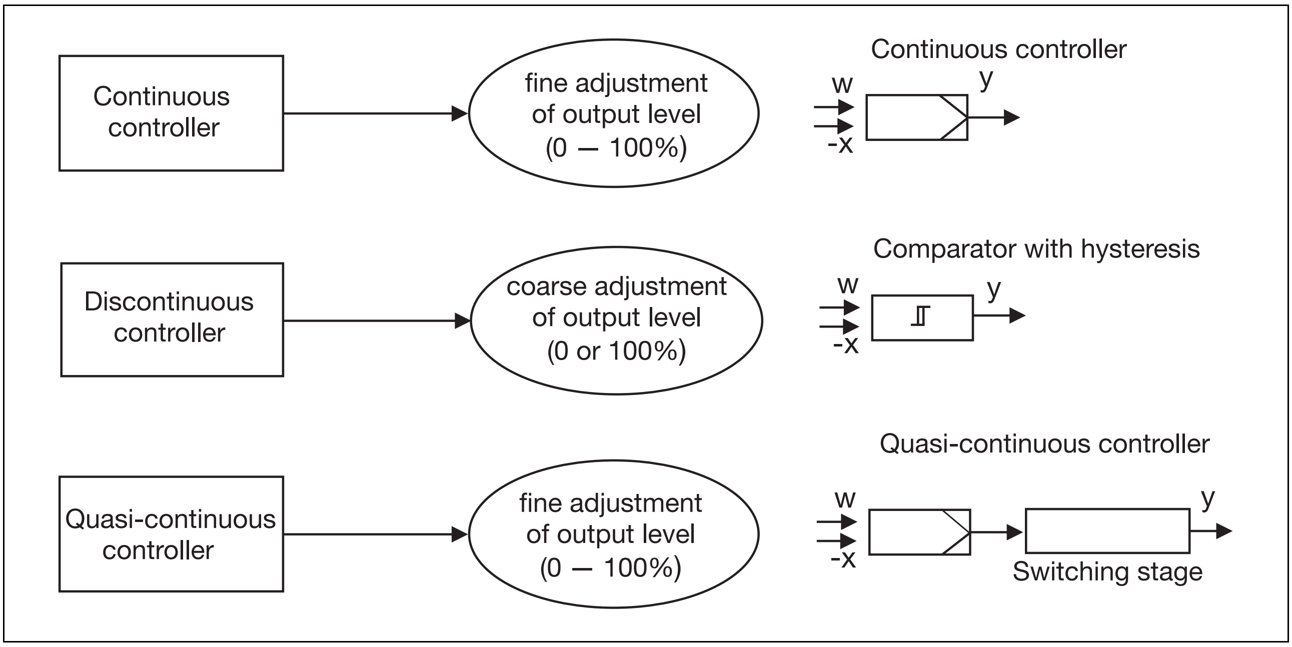


**Fig. 57: Continuous, discontinuous and quasi-continuous controllers**

**Discontinuous controllers**
operate like a comparator with hysteresis (see Fig. 57): They close a contact until a prescribed setpoint has been reached. The contact is then opened, and the process value starts to drop. When the process value has fallen to a preset hysteresis value below the setpoint, power is applied to the process again. A thermostat is an example of a discontinuous controller.

**Quasi-continuous controllers**
can be thought of as a combination of a continuous controller and a switching stage (see Fig. 57). The continuous controller determines the output level, as we already saw in Chapter 3 *“Continuous controllers”*. The switching stage varies the ON time of the output according to the output level that was determined. If such a controller switches frequently enough, then the response of the control loop is effectively the same as for a continuous controller.

In the following chapter we will look at discontinuous and quasi-continuous controllers that have **one** binary output. Since this output can have two different states, this type is known as a 2-state controller.

## 5.2 The discontinuous 2-state controller

A discontinuous 2-state controller functions like a thermostat. If the process value is below the setpoint, it closes the output contact, and the heating runs at full power. If the setpoint is reached, the power is set to 0%, i.e. switched off. If the process value now falls, when it goes below the level (setpoint minus switching differential ($H_{yst}$), the output will be switched on again.

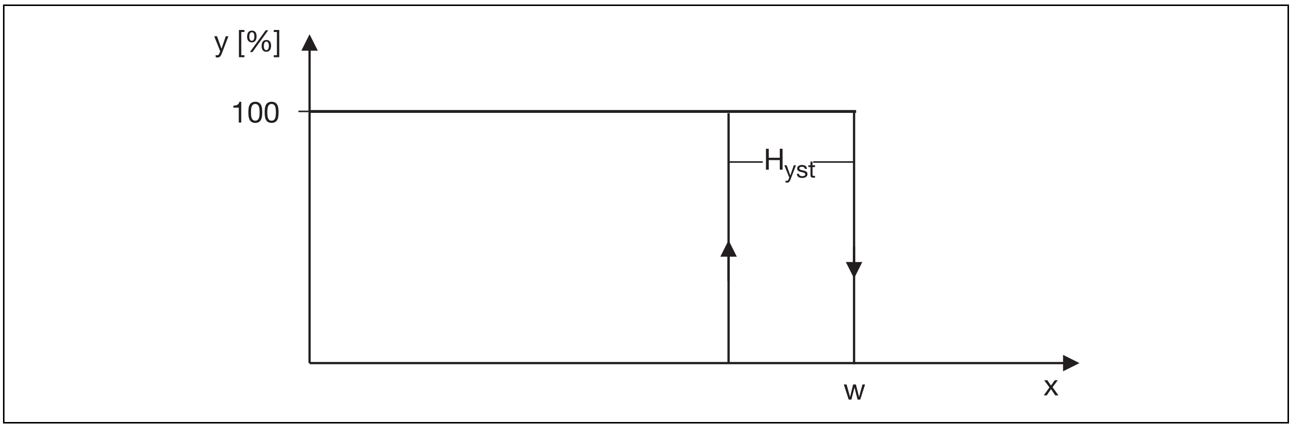


**Fig. 58: Characteristic of a discontinuous 2-state controller**

For JUMO instruments, a 2-state controller becomes a discontinuous controller if $P_b$ is set to 0 (the usual factory setting). In this case, the preset $H_{yst}$ will be taken into consideration.

Discontinuous 2-state controllers are frequently used as thermostats.

**Fig. 59: JUMO room thermostat, type AMFRc-1333**

In the next two sections we will look at the response of a discontinuous 2-state controller in first-order and higher-order processes.

### 5.2.1 Discontinuous 2-state controller in a first-order process

If a discontinuous 2-state controller is operated in a first-order process, then the heating is switched on if the system has cooled down. Since there is only one energy storage component, the temperature will instantly start to rise (Fig. 60). If the setpoint is reached, the power is set to 0%, i.e. switched off, and the process value will not go above the setpoint. Theoretically, the process value instantly starts to fall and after a certain time it will have fallen to the lower switching point (setpoint minus switching differential).
The heating is switched on again, and the process value starts to rise again…

So in a first-order process, the process value moves within the band defined by the switching differential – that is the best you can achieve with a discontinuous controller.

The switching frequency is higher and the controlled process becomes faster as the switching differential is made smaller.

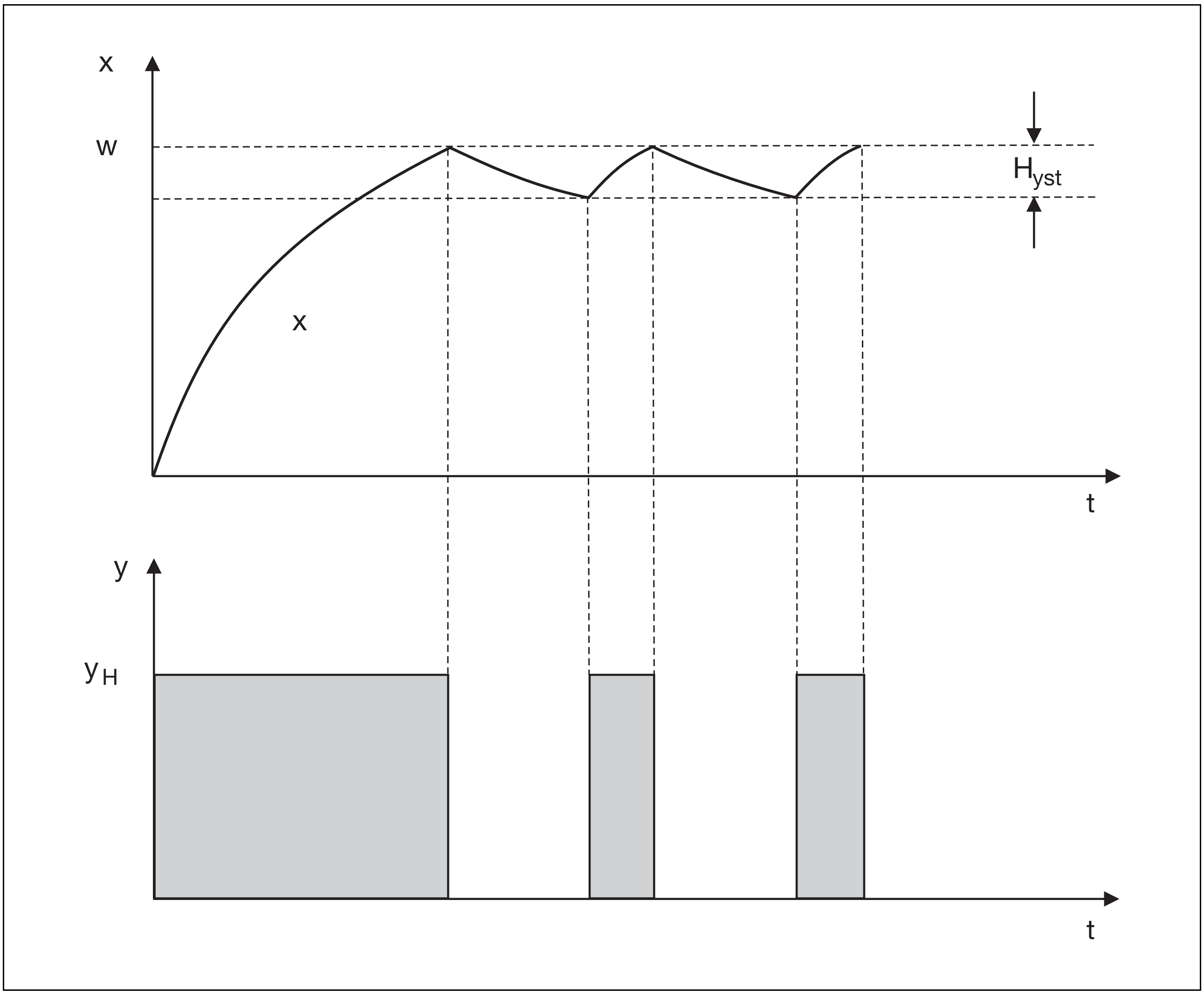


**Fig. 60: Discontinuous 2-state controller in a first-order process**

### 5.2.2 Discontinuous 2-state controller in a higher-order process

If a discontinuous controller is operated in a higher-order process, then the heating is switched on if the system has cooled down. Since there is more than one energy storage component, the temperature will only start to rise after some time (the energy storage components must first be charged up). When the setpoint is reached, the power is set to 0%, i.e. switched off. Because of the system delay time $T_u$, the process value will go above the setpoint. After a while, the process value will fall and reach the lower switching point. The heating will be switched on, but the process value will only increase after a delay (the energy storage components must be charged up again).

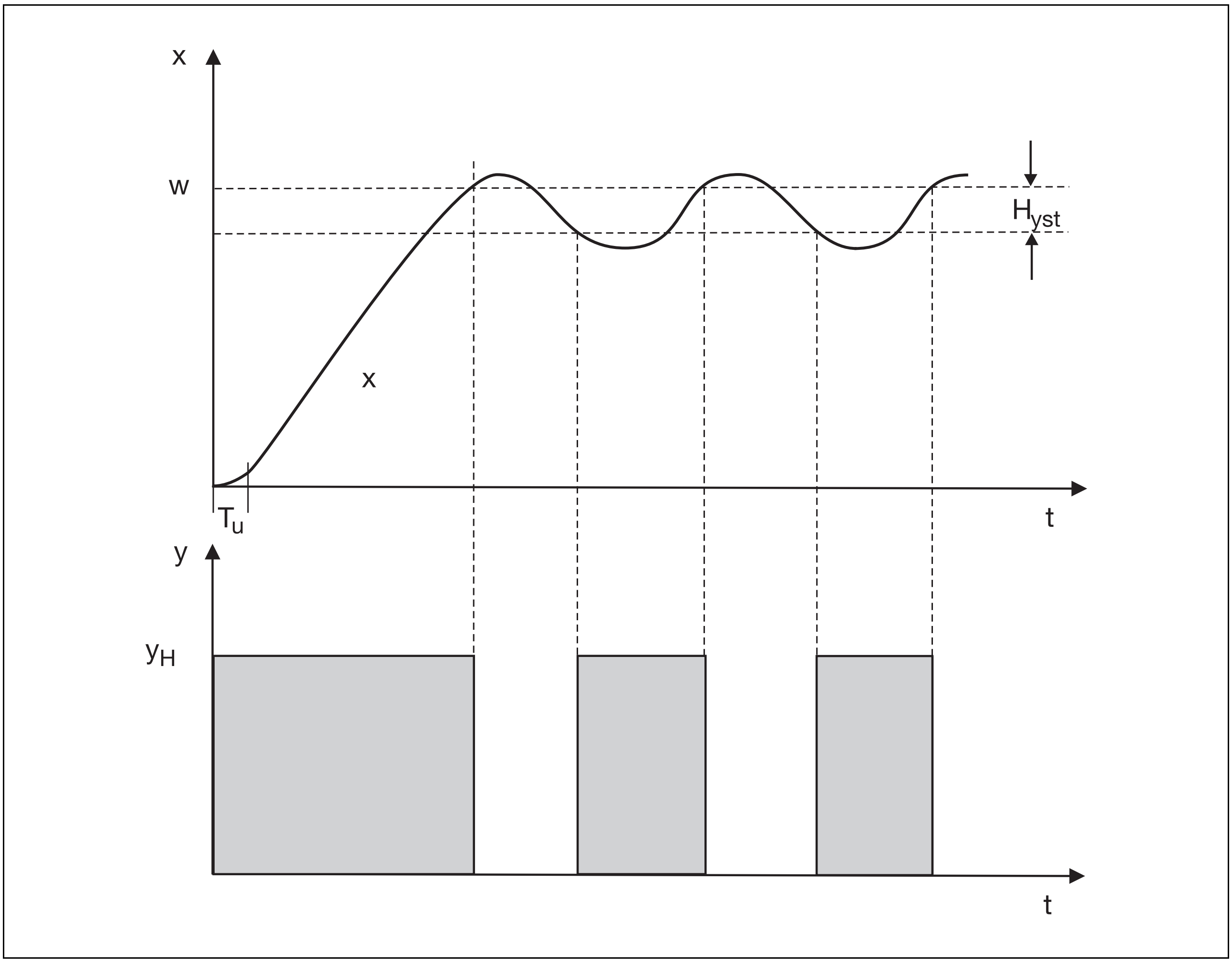


**Fig. 61: Discontinuous controller in a higher-order process**

In a higher-order process, the oscillation of the process value will be larger than the switching differential. In a thermostat, for instance, the switching differential may be 5°C, but the process value will oscillate with an amplitude of 10°C.

**Summary**
Control systems using discontinuous controllers can be very favorably priced, e.g. in the form of a thermostat. It makes sense to use this type of control if the resulting variations of the process value do not cause a problem.

In compact controllers, 2-state controllers are usually implemented as quasi-continuous controllers (a discontinuous controller configuration is the exception, or the result of ignorance).

If the process is fairly slow, then the response is effectively the same as for a continuous controller.

## 5.3 Quasi-continuous 2-state controllers: the proportional controller

A quasi-continuous controller consists of a continuous controller and a switching stage. If such a controller is operated as a purely proportional controller, then the operating characteristic will be as we have seen in Chapter 3.1.1 *“Proportional band”*.

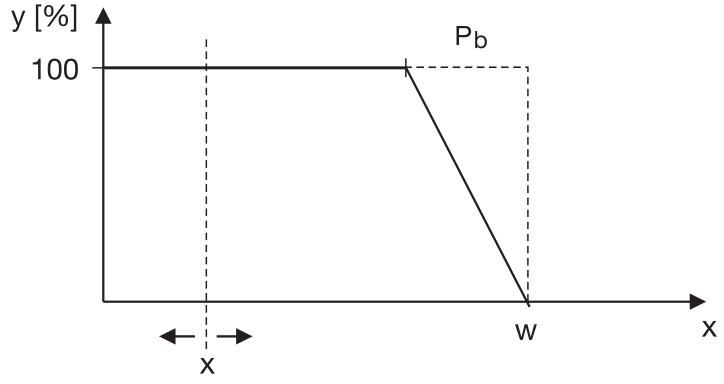


**Fig. 62: Proportional band of a quasi-continuous proportional controller**

The quasi-continuous controller has a characteristic that is shown in Fig. 62, and also produces a 100 % output level (the relay is closed the whole time) until the process value has moved into the proportional band. When the process value is within the proportional band, and continues to move towards the setpoint, the output level will be continually reduced.

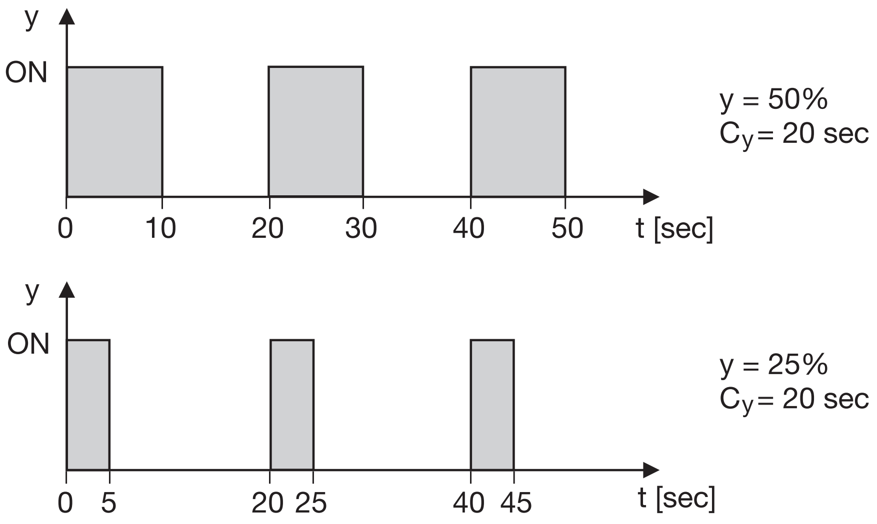
So how can the energy feed be effectively continuously dosed by a switching output, i.e. without steps?

In the end, it makes little difference over a longer period whether an oven is heated up by 50 % of the heating current all the time, or full current for half the time.
Instead of altering the magnitude of the output signal, the quasi-continuous controller effectively changes the output level by varying the relative ON time.

**Example**
A quasi-continuous 2-state controller with an output level of 43 % will switch the output ON for 43 % of the time, and OFF for 57 %.

The controller is continually calculating the output level. So it must be told, in what period it has to switch on (once) and off (once). The sum of the ON and OFF times is known as the cycle time $C_y$.

**a) Different output levels**



**b) Same output level (y = 25%) for different cycle times**

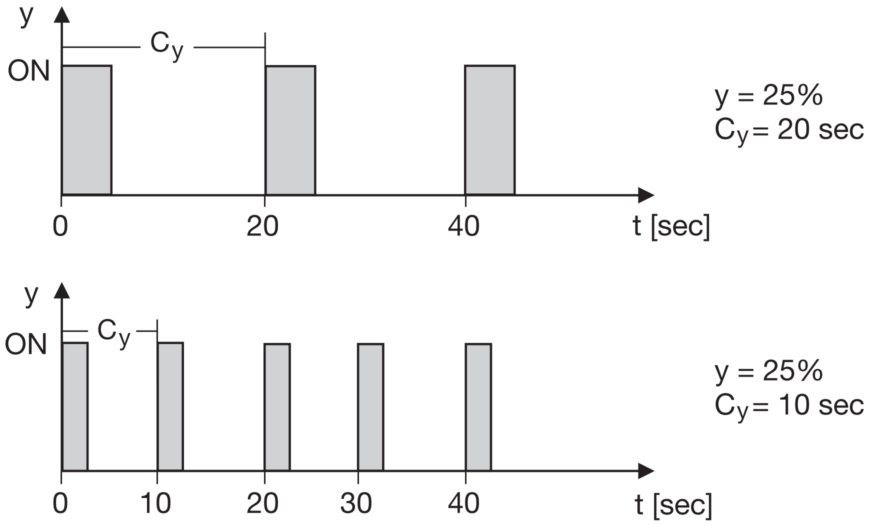


**Fig. 63: Various output levels and cycle times**

Fig. 63 shows, in the top half, the output signal from the controller at an output level of 50% and 25%, i.e. the controller closes the output contact for 50% or 25% of the time respectively.

In the lower half of Fig. 63, the same output level (25%) is shown, but for different switching cycle times. In the second case, the cycle time is set to be shorter (10 sec), so the energy flow is more finely dosed and the switch between 0 and 100% will cause fewer fluctuations in the process value.

The relationship with the switching cycle time is: the longer the cycle time is, the more likely it is that the process value will oscillate. So $C_y$ must be chosen to be small enough that there are no fluctuations in the process value, or that they are acceptable for the process.

With mechanical switches, the cycle time $C_y$ should only be set to be as small as necessary, since a smaller $C_y$ reduces the operating life of relays and contactors.
With electronic outputs (e.g. triacs, solid-state relays, open-collector outputs), $C_y$ can be set to be as small as is feasible.

**Example of estimation of relay operating life**
The cycle time for a controller used for temperature control is $C_y$ = 20 seconds.
The relay that is used has a contact life of 1 million switching operations.

With the given $C_y$ there will be 3 switching operations per minute, i.e. 180/hour. So for a specified life of 1 million operations, the operating life would be 5,555 hours = 231 days. If one assumes an operating period of 8 hours/day, then the result is about 690 days. So with around 230 operational days per year, the expected lifetime would be about 3 years.

The calculation of the switching cycle time for a 2-state controller should be made before the real optimization is carried out. The controller should be switched over to manual mode, and a typical output level should be generated. The $C_y$ for JUMO controllers is usually factory-set to 20 seconds. If a fluctuation of the process value is observed with this cycle time, then $C_y$ must be reduced until a stable process value is achieved.

**Note**
It may also be possible to set $C_y$ to >20 sec, and still achieve a stable process value.

### 5.3.1 I and D action of a quasi-continuous 2-state controller

As far as I and D action is concerned, the same explanations apply as already presented for a continuous controller. The I component, for example, will cause an increase in the output level as long as a control deviation is detected. But instead of increasing an output signal voltage, the I component increases the relative ON time for the output.

Now let us take another look at the quasi-continuous 2-state controller, as a combination of a continuous controller and a switching stage.

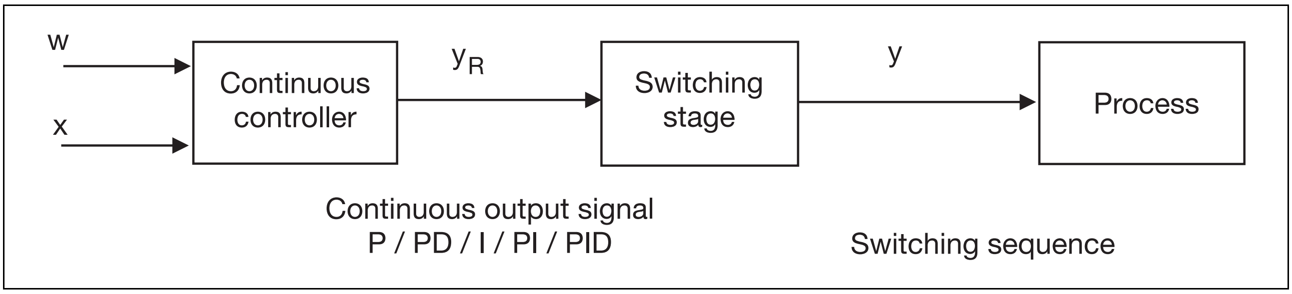


**Fig. 64: Quasi-continuous controller as a continuous controller followed by a switching stage**

The structure of the controller can be freely chosen (P ... PID). The appropriate $C_y$ and the controller parameters are then defined. The controller then uses these settings, the defined setpoint, and the development of the process value, to calculate its output level $y_R$ (the output level is usually visible in a display on the controller). The following switching stage then converts this output level (taking account of the preset $C_y$ value) into switching pulses.

**Example**

On the quasi-continuous controller shown above, the continuous controller section produces an output level of 50%. For the switching stage, the 50% output level is also interpreted as a relative ON time of 50%. Let us assume that $C_y$ is 10 seconds, so the switching stage will switch its output on or off every 5 seconds.

When a favorable setting for $C_y$ has been found for a 2-state controller, then the remarks in Chapter 3 *“Continuous controllers”* about the P, I, and D components will also apply. The optimization procedures presented in Chapter 4 *“The closed control loop / Optimization methods”* can also be applied to these controllers.

**Minimum ON time ($T_k$)**

Some actuators need to be activated for a certain minimum run-time: a gas oven, for instance, where the gas must be ignited and then completely burnt. Another example would be a refrigerator that has to be switched on for a minimum time.

For such applications, some JUMO controllers have the option of setting a parameter “Minimum ON time ($T_k$). This is usually factory-set to 0 sec, and so it will have no effect.

If $T_k$ has been set >0sec, then the binary output will be switched on for at least this time. The controller will still attempt to keep to the defined switching cycle time $C_y$, but the minimum $T_k$ will have priority (Fig. 65):

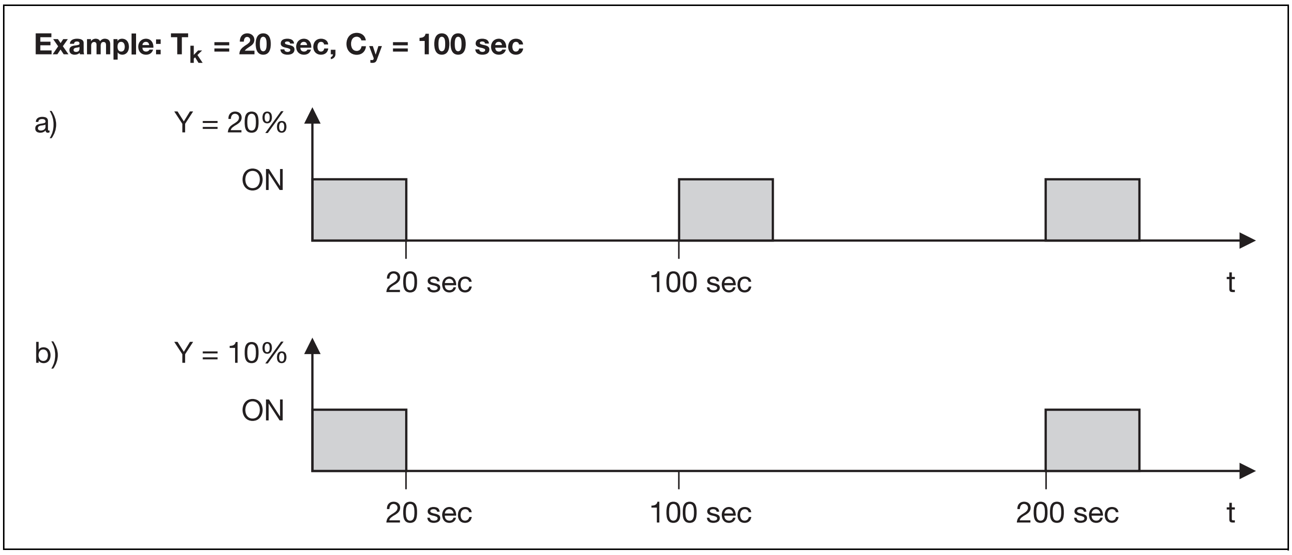


**Fig. 65:** **Output signal from a 2-state controller with $T_k$ = 20 sec**

Fig. 65 shows the output of a 2-state controller when $T_k$ is set to 20 seconds and $C_y$ is set to 100 seconds. Even at the lowest output levels, the controller will activate the output for at least 20 seconds.

In Fig. 65 a) the controller produces an output level of 20 %. It closes the output for 20 sec and opens it again for 80 sec (in this case, a switching cycle time of 100 sec can be maintained).

In Fig. 65 b) the controller produces an output level of 10 %. Here too, it will close the output for 20 seconds. In order to achieve an effective output of 10 %, it must open the output for a period that is 9 times as long. So in this case, the controller will increase the switching cycle time to 200 seconds.

## 5.4 The 3-state controller

A 3-state controller can simply be thought of as a parallel circuit of two individual controllers.

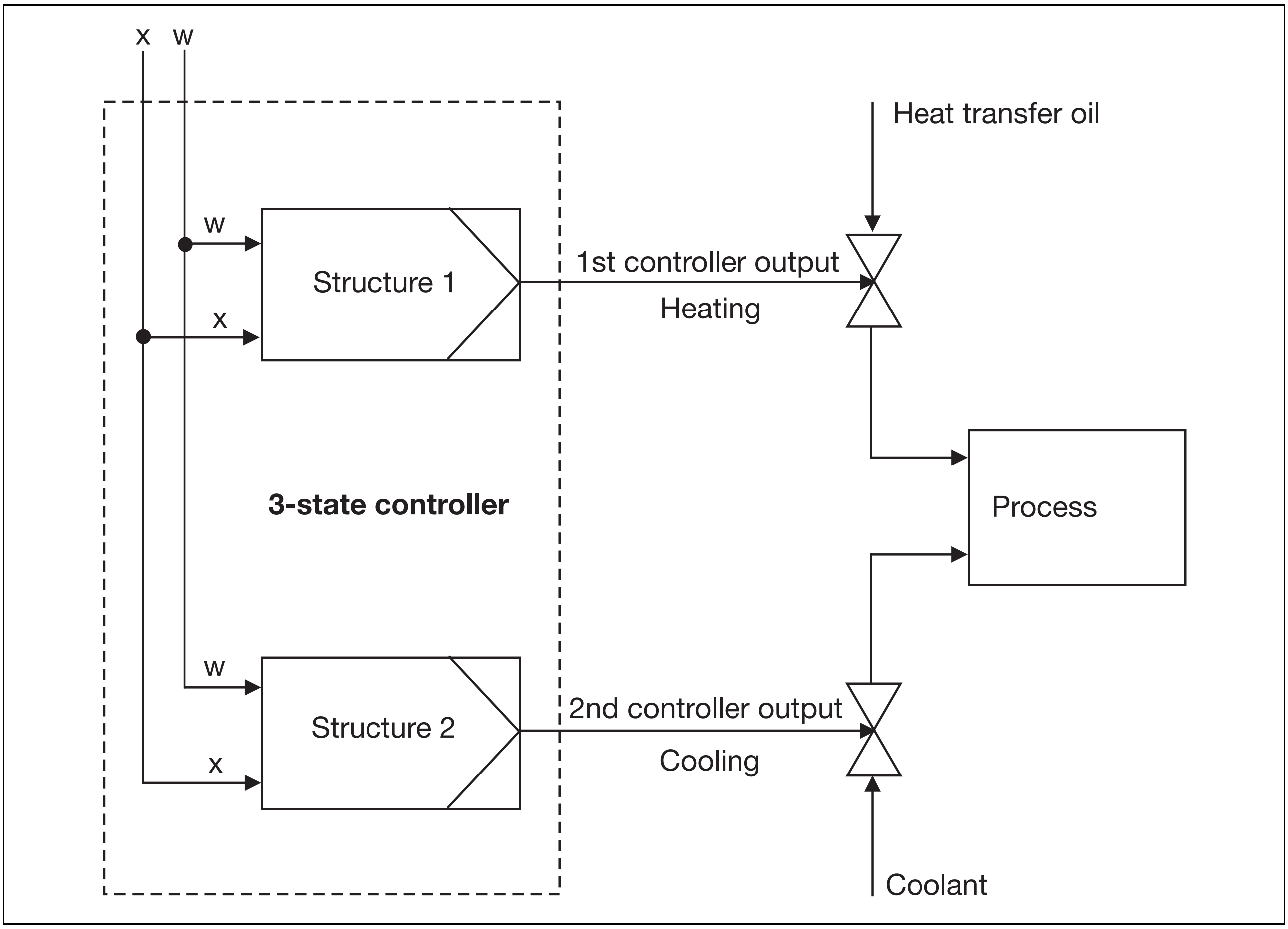


**Fig. 66: Arrangement of a 3-state controller**

With this layout one can, for instance, apply heating if the process value is below the setpoint, and cooling if it is above the setpoint. Another application would be, for instance, the humidification and drying of a climatic chamber. In the combined controller, a different output level is assigned to each output. For instance, the first controller output is often used for heating, and the second controller output for cooling. All the parameters that are relevant for the “heating” controller are identified by the $index_1$, and all the parameters for the “cooling” controller are identified by the $index_2$.

Now let us first look at the response of a 3-state controller when both structures operate discontinuously.

### 5.4.1 The discontinuous 3-state controller

Both structures operate discontinuously if $Pb_1$ and $Pb_2$ are set to 0.
In such a case, the preset switching differentials ($Hyst_1$ and $Hyst_2$) will be taken into consideration (Fig. 67).

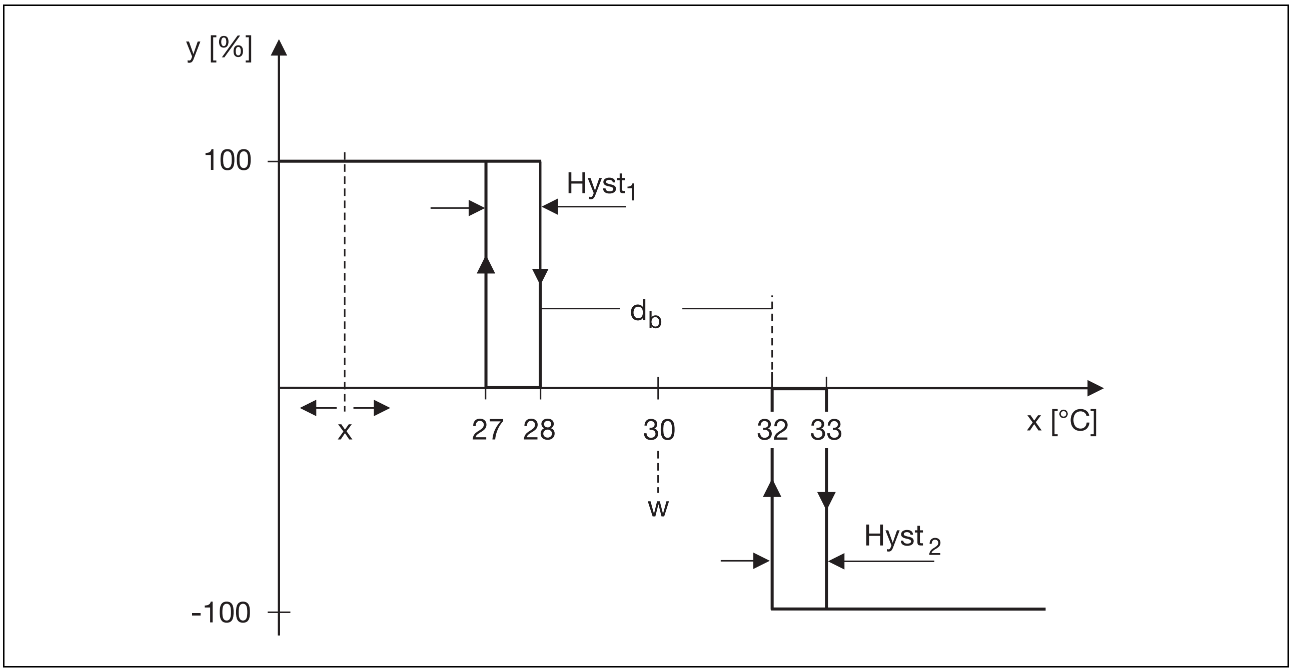


**Fig. 67: Characteristic of a discontinuous controller with 2 outputs**

Fig. 67 shows a concrete example of the method of operation of a discontinuous 3-state controller. The two switching differentials ($Hyst_1$ and $Hyst_2$) are set to 1 °C, and a setpoint of 30 °C is applied. For a 3-state controller, it is also necessary to set a value for the contact spacing ($d_b$ = dead band), 4 °C in this example. This prevents non-stop switching between heating and cooling (which would be a useless waste of energy).

Let us assume a low process value (Fig. 67). The output level is 100 % and the heater contact is closed. The process value rises, until the contact opens at 28 °C. After some time, the process starts to cool down. When it goes below 27 °C, the heating is switched on again. When just heating is required, the process value will (in the most favorable conditions) be maintained within the band $Hyst_1$ (for an explanation, see Chapter 5.2.1 *"Discontinuous 2-state controller in a first-order process"*).

Now let us imagine that the process value rises because of a higher ambient temperature. When the enhanced temperature goes above 33 °C the output level becomes -100 % (i.e. the cooling contact is closed). The cooling plant causes the temperature to fall, and is switched off at 32 °C. So when just cooling is required, the process value will (in the most favorable conditions) be maintained within the band $Hyst_2$.

When a 3-state controller is configured, both controller structures should function in a quasi-continuous mode. This mode of operation is explained in the next section.

### 5.4.2 The quasi-continuous 3-state controller

A quasi-continuous 3-state controller (where each output is activated by a proportional controller) can also be simply thought of as a combination arising from the coupling of two quasi-continuous controllers. The two controller structures of the 3-state controller become quasi-continuous when each $P_b$ is set >0. The switching differential is no longer taken into consideration. The switching cycle time for each controller can be freely configured. The contact spacing setting remains effective.

Fig. 68 shows the characteristic of a quasi-continuous 3-state controller that is being used to regulate a climatic cabinet (both controller sections are set up with a P structure).

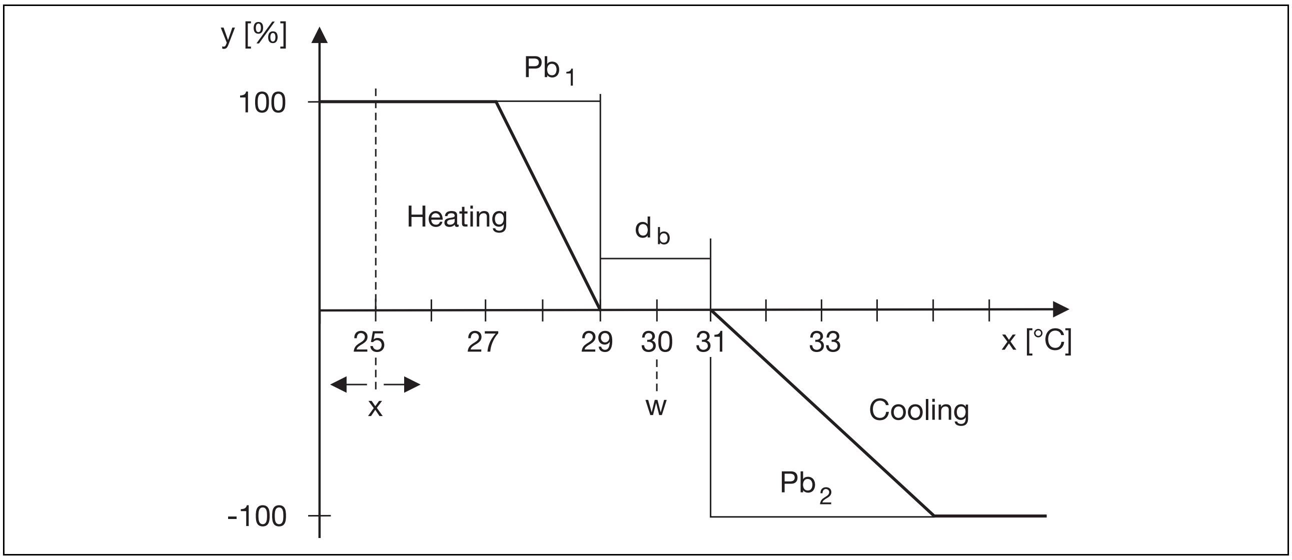


**Fig. 68: Characteristic of a quasi-continuous 3-state controller**

As shown in Fig. 68, the parameters $Pb_1$ and $Pb_2$ can be separately adjusted. This is necessary, because the process gain for the two output levels is usually different. For instance, a heater array has a considerably different process response compared with a cooling system (e.g. a fan).

The method of operation of such a controller is described below. The process value in the climatic chamber is 25 °C, the control system is switched on.

**Heating**
The heating relay pulls in and the heating is active with an output level of 100 %, so the process value will increase. As the process value rises above 27 °C (start of the proportional band), the output level for heating is gradually reduced, so the relay starts to switch on and off in accordance with the preset cycle time ($C_{y1}$) and the ON times become shorter and shorter. The control deviation (and thus the output level) becomes smaller, until an output level is reached that is sufficient to maintain the process value. We will then have a positive output level (e.g. 25 % at 28.5 °C).

**Cooling**
Now the ambient temperature rises (fault), and the inside of the climatic chamber is heated up. The process value increases, and when it has risen into the dead band (29 °C), the output level is 0 %, so there is neither heating nor cooling. From a temperature of 31 °C and above, the cooling relay starts to switch on and off (the output level is now negative). The control deviation also becomes larger, until an output level is reached that is sufficient to maintain the resulting process value.

A P structure is activated for both controller sections, and for this reason the system cannot control to the setpoint, neither for heating nor for cooling.

### 5.4.3 I and D action of a quasi-continuous 3-state controller

If both controllers are set up as PID structures, then an I and D action is also defined ($r_{t1}$ , $r_{t2}$ , $d_{t1}$ and $d_{t2}$ ). The I component ensures that the system can always control to the setpoint, and the D component counteracts the change of the process value.

The P components are only active outside the dead band which separates the two proportional bands, and prevents non-stop switching between heating and cooling.

The setting for the contact spacing (dead band) must be carried out after optimization, and must be made so that there is no unwanted switching from heating to cooling.

Table 5 shows which parameters have to be set for a 3-state controller if both controller structures are to function in a discontinuous or quasi-continuous mode.

| | **Structure selected** | **Parameters to be set** | | | | | |
|---|---|---|---|---|---|---|---|
| **Discontinuous** | | $Pb_1 = 0$<br>$Pb_2 = 0$ | – | – | – | $d_b$ | $Hyst_1$;<br>$Hyst_2$ |
| **Quasi-continuous** | P | $Pb_1$; $Pb_2$ | – | – | $C_{y1}$; $C_{y2}$ | $d_b$ | – |
| | PI | $Pb_1$; $Pb_2$ | $r_{t1}$; $r_{t2}$ | – | $C_{y1}$; $C_{y2}$ | $d_b$ | – |
| | PID | $Pb_1$; $Pb_2$ | $r_{t1}$; $r_{t2}$ | $d_{t1}$; $d_{t2}$ | $C_{y1}$; $C_{y2}$ | $d_b$ | – |
| | PD | $Pb_1$; $Pb_2$ | – | $d_{t1}$; $d_{t2}$ | $C_{y1}$; $C_{y2}$ | $d_b$ | – |
| | I | – | $r_{t1}$; $r_{t2}$ | – | $C_{y1}$; $C_{y2}$ | $d_b$ | – |

**Table 5: Parameters to be set for a 3-state controller**

On some controllers, it is also possible to define the minimum ON time ($T_{k1}$, $T_{k2}$ ).

Of course, the structures for a 3-state controller can be combined as required. For instance, structure 1 could have a PID action, and structure 2 could have a PI action. Furthermore, the 1st controller output could be a continuous signal while the 2nd controller output is a discontinuous signal. This would be the case, for instance, if a thyristor power converter was being operated (for heating) and a refrigeration unit was activated by a contact (for cooling).

## 5.5 Controller for regulating motorized actuators

Motorized actuators consist of a positioning motor and an actuator element, and are linked together by a common shaft. The actuator elements are often valves or flaps. If a positioning motor is available, it is fairly simple to assemble a motor actuator. The two connecting leads of the motor can be used to open the actuator (anti-clockwise rotation) or close it (clockwise).

Actuating and modulating controllers are available for regulating motorized actuators, and they will be presented in this section.

### 5.5.1 The modulating controller

A modulating controller is fitted with two binary outputs for operating the motorized actuator.
Fig. 69 shows such a controller with a motorized actuator in a closed control loop.

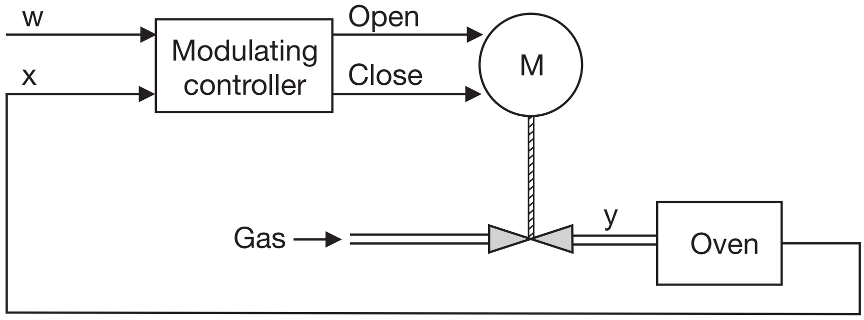


**Fig. 69: A modulating controller with a motorized actuator in a closed control loop**

If one of the controller relays is activated, the valve is moved accordingly. The outputs are mutually inhibiting. Unlike a 3-state controller, if there is no control signal this does not mean that an output level of 0% is produced. In this case, the valve holds its position and could, for example, be 60% open. Sometimes someone tries to use a 3-state controller to control a motorized actuator. This method is wrong.

For a modulating controller, the valve setting corresponds to the output level and can vary from 0 to 100%. The modulating controller continuously monitors the process and setpoint values. It is continuously calculating how many percent the valve has to be opened or closed, in accordance with the preset controller parameters.

**Example**

In a modulating controller, a PI structure ($P_b$ = 25°C, $r_t$ = 120 sec) has been set up, the stroke time for the actuator (TT) is 60 seconds. The process value and setpoint are 0°C. The setpoint is changed to 10°C. This creates a control deviation of 10°C.

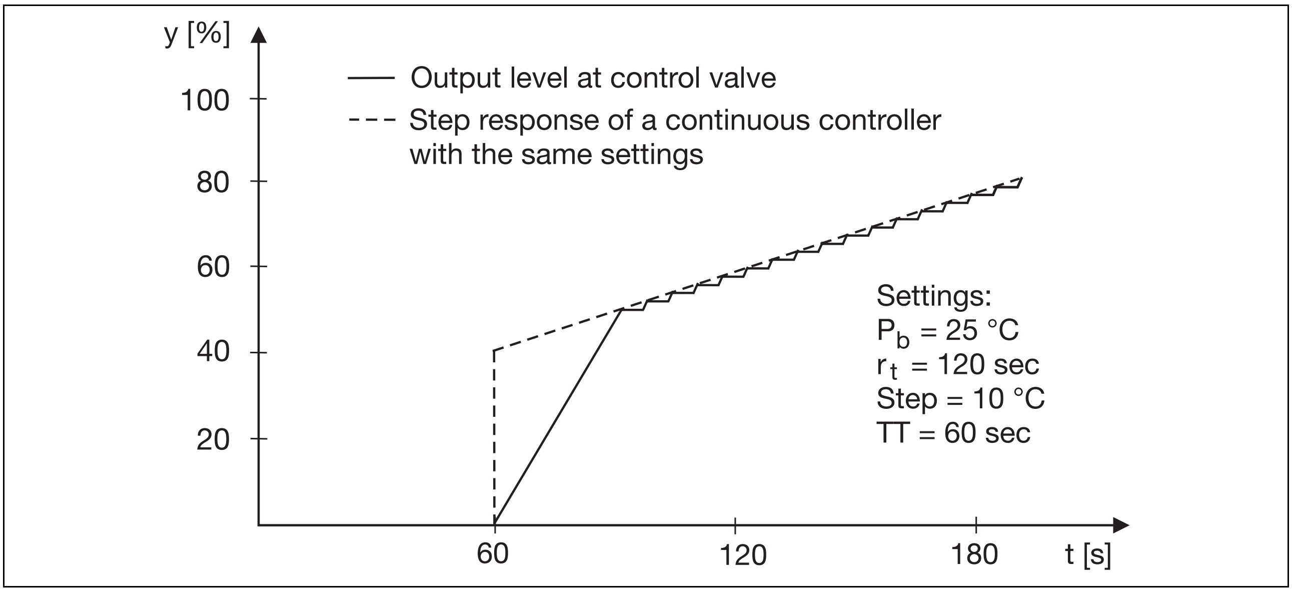


**Fig. 70: Step response of a system of modulating controller and control valve**

Because of the controller parameters, a continuous controller would make a jump in its output level to 40% (P component, Fig. 70) and increase the output level in accordance with the reset time $r_t$ = 120sec (I component). The modulating controller would also attempt to open the valve to 40 %, and respond to the I component. But the valve opens with a delay, since it is relatively sluggish. In order to achieve the intended regulation, the modulating controller requires information about the speed at which the valve can operate. This is provided by the actuator stroke time TT (the time the actuator needs to move from fully closed to fully open, or the other way round). In Fig. 70 the actuator stroke time is 60 seconds.

The modulating controller does not have any information about the position of the actuator. So it is only possible to set the parameters for those controller structures that have an I component (PI and PID).

Now let us look at the control-loop response of the modulating controller.

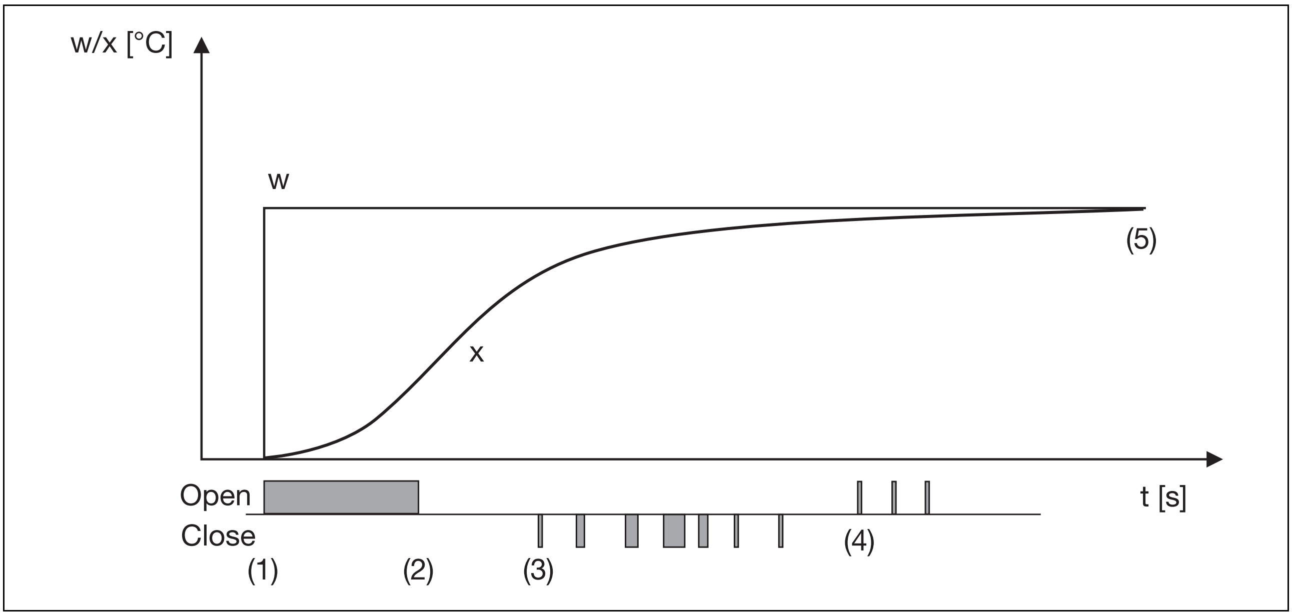


**Fig. 71: Control-loop response of a modulating controller with PI structure**

Fig. 71 shows the setpoint, process value, and the two outputs from the modulating controller. A new setpoint is applied at (1). The controller detects that the process value is outside the proportional band, and activates the OPEN output until at least the proportional band has been reached (valve is 100% open). At time (2), the process value enters the proportional band. The P component is reduced, the I component is increased. Initially, the reduction in the P component approximately matches the increase in the I component, and the valve setting remains at 100%: there is no control. At (3) the controller calculates that the output level must be reduced, so it slowly closes the valve. At (4) the controller calculates that it is necessary to increase the output level for the valve. At (5), the process value reaches the setpoint, and there is no further control movement.

As far as the control-loop response (P, I and D) is concerned, a modulating controller can be viewed as a continuous controller.

**Contact spacing (dead band)**
Even though a modulating controller may have settled, from time to time the actuator will be operated (open, close, open etc.)

Let us assume that the process value is a bit above the setpoint, and the controller briefly closes up the valve. The controller activates the actuator for at least the duration of its sampling period (typical values for JUMO controllers are from 50 to 250 msec). In our example, the short closing movement will lower the process value, which then finishes up below the setpoint. The controller will now go to OPEN for a sampling period, and the process value will move above the setpoint, and so on.

This continual opening and closing shortens the operating life of the actuators, and can be eliminated by increasing the contact spacing ($d_b$ = dead band). The contact spacing is symmetrical about the setpoint. If the process value enters this band, there is no further actuator movement. The $d_b$ is set after the controller has been optimized, and is only made large enough to prevent a continual opening and closing. If the contact spacing is larger than necessary, then the resulting control deviation will also be too large.

### Manual mode

Since the modulating controller does not know the actual position (degree of opening) of the actuator, it is not possible to move the actuator to a defined position in manual operation. If the system is switched over to manual mode, then there is initially no control of the actuator. In manual mode, you can only open or close the actuator.

### Final limit switch

The following situation is imaginable for a modulating controller:
A setpoint is requested, but it is not possible for the system to achieve such a value. Because of the I component, the controller will try to open the actuator more and more, even though it is already 100 % open.
This would place an unnecessary load on the motor windings. For this reason, motorized actuators often include final limit switches. If the modulating controller keeps on activating the actuator, and it has already reached 100 %, then the limit switch will interrupt the current. Switches are provided for both final limits. If you assemble a motorized actuator yourself, it is a good idea to include these components.

Table 6 shows the parameters to be set for a modulating controller.

| **Controller structure** | **PI** | **PID** |
|---|---|---|
| **Parameters to be set** | $P_b$ | $P_b$ |
| | $r_t$ | $r_t$ |
| | - | $d_t$ |
| | $T_T$ | $T_T$ |
| | $d_b$ | $d_b$ |

**Table 6: Parameters to be set for a modulating controller**

### 5.5.2 The actuating controller

An actuating controller is even better for regulating motorized actuators. The full description is “continuous controller with integrated actuating controller for motorized actuators”. If, for instance, a JUMO controller is configured as an actuating controller, then it has the following structure.

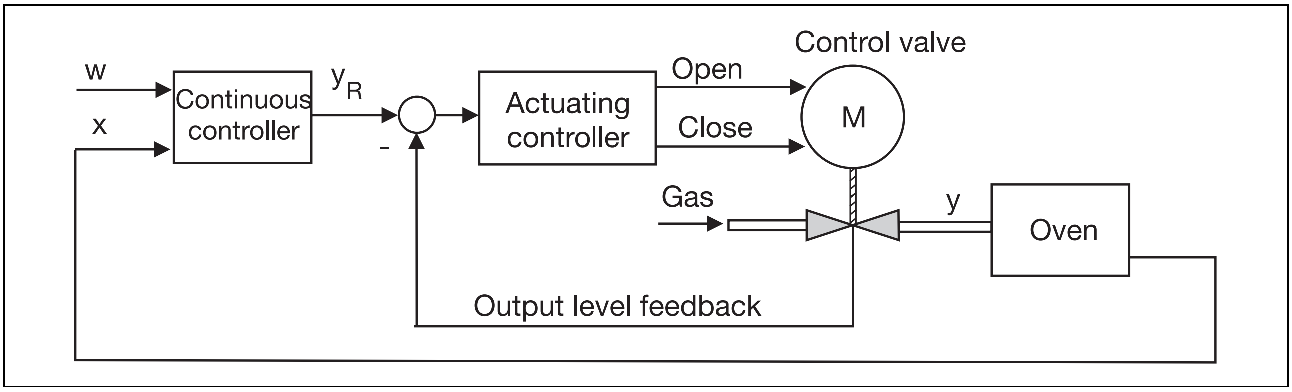


**Fig. 72: Actuating controller with a control valve in the control loop**

The actuating controller consists of a continuous controller, that can be set up for all the familiar structures (P ... PID). The continuous controller calculates its output level according to the preset parameters, the setpoint, and the process value. The actual actuating controller regulates the motorized actuator to meet the output level required by the continuous controller (e.g. 80% valve opening for an output level of 80%). In order for this to work, the actuator must be able to provide an output level feedback. This is usually implemented in the form of a potentiometer that has 3 connecting leads connected to, say, input 2 of the controller. The position of the potentiometer slider now tells the controller the degree of opening of the valve. Furthermore, the controller must be configured so that, for example, input 2 can be used for the output level feedback. Since output level feedback is now available, the subordinate actuating controller can always regulate to the required output level. The subordinate controller does not have to be optimized; the controller parameters are adapted through the entry of the actuator stroke time.

In actuating controllers too, the contact spacing is symmetrical about the setpoint, and the user must set it to be large enough to prevent continual opening and closing.

An actuating controller will achieve a better control-loop response than a modulating controller. In addition, any level of output can be set in manual mode, and the motorized actuator will be moved to the corresponding position.

Output level feedback is mandatory for an actuating controller, otherwise a modulating controller will have to be used.

The parameters to be set for an actuating controller are shown in Table 7:

| Controller structure | P | PD | I | PI | PID |
|---|---|---|---|---|---|
| **Parameters to be set** | $P_b$ | $P_b$ | - | $P_b$ | $P_b$ |
| | - | - | $r_t$ | $r_t$ | $r_t$ |
| | - | $d_t$ | - | - | $d_t$ |
| | $T_T$ | $T_T$ | $T_T$ | $T_T$ | $T_T$ |
| | $d_b$ | $d_b$ | $d_b$ | $d_b$ | $d_b$ |

**Table 7: Parameters to be set for an actuating controller**

## Special circuits for better control-loop performance

Until now, we have looked at single-loop control circuits. In these cases, the process under control is affected solely by the output level of the controller. The options presented in this chapter can be used to improve the performance of the control loop or to reduce costs.

### 6.1 Base load

When a base load is applied, then only a portion of the entire output level is affected by the controller, while the remainder is permanently applied to the process.

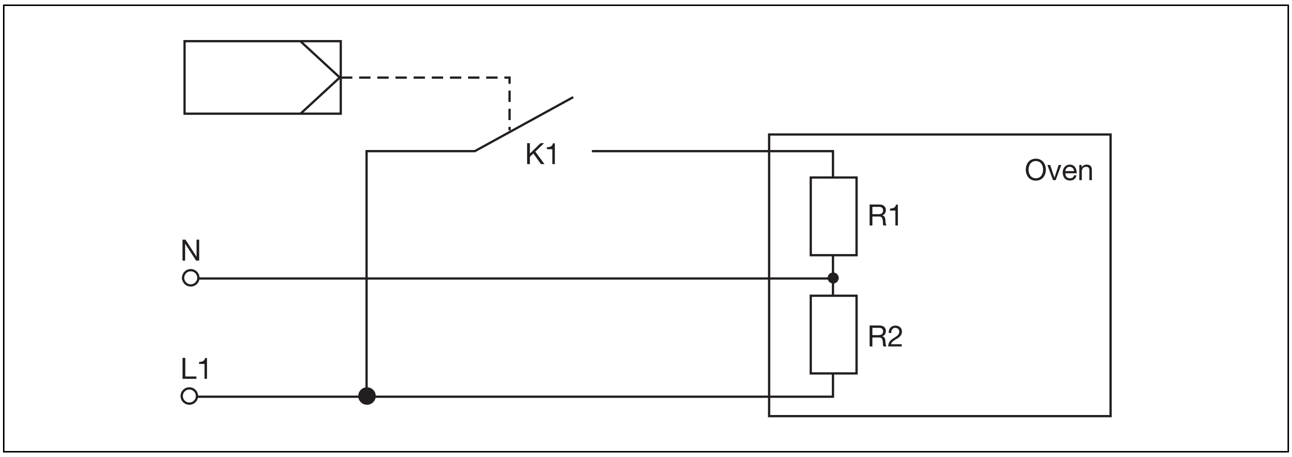


**Fig. 73: Base load setting**

In the example of Fig. 73, Heating 2 is permanently switched on, while Heating 1 is regulated by the controller.

If a base load is applied, then the actuating element only regulates a portion of the power (so a smaller actuator can be selected ➔ cost reduction). Furthermore, the load changes on the supply will be less extreme when a 2-state controller is used.

A base load setting can also be used if the setpoint for a controlled process has to be defined over a large range. Consider, for instance, an industrial furnace that requires setpoints to be entered over a range from 200 to 1000°C. For low setpoint values, the problem is that the heating is over-dimensioned. The likely result is that the process value will overshoot the setpoint when heating up.
Solution: for low setpoint values, the base load is switched off, and only switched on above a predefined value. In some cases, for even larger setpoints, the base load can even be added in stages. This method has the advantage that the controller can always operate at relatively large output levels, over the entire range of working points. This improves the performance of the control loop.

In some applications, a relatively large power level is required for heating up. But then, because of good insulation, relatively small output level variations are required for stabilizing the working point. The high excess power that is provided causes an overshoot. For large control deviations, JUMO controllers can activate a 2nd output to provide additional power. This is then switched off when the control deviation has fallen below a certain value. Regulation about the setpoint is then made by the first output of the controller, using only a fraction of the power.

## 6.2 Split-range control

With split-range control, the output level from the controller is applied to more than one actuator. The reason may be, for instance, that one actuator has inadequate performance, or that energy (and thus costs) need to be saved in an installation.

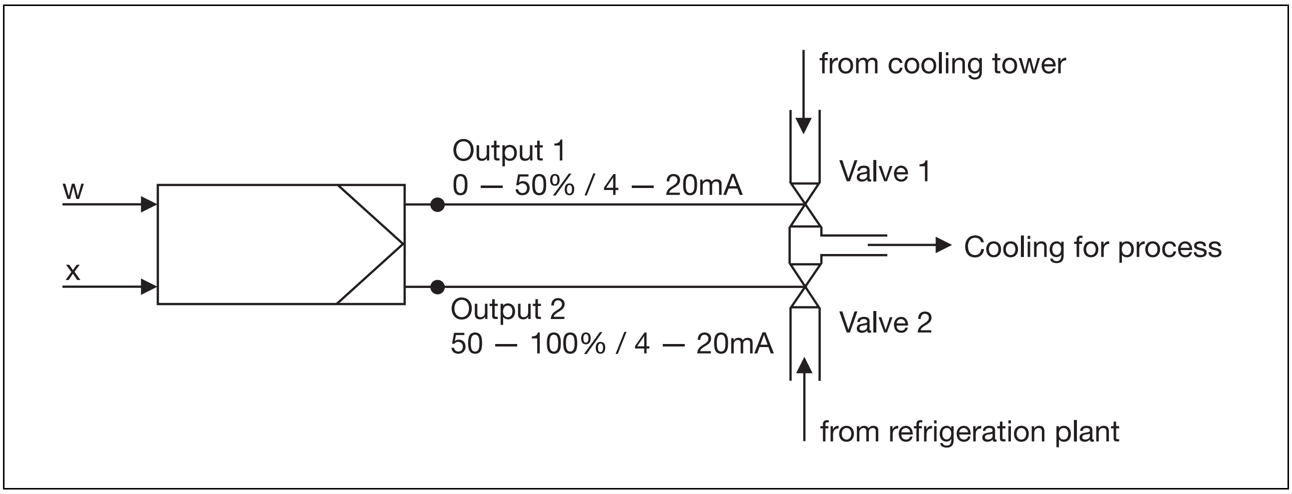


**Fig. 74: Split-range control**

In the illustrated section, cooling power is applied to a process. In this installation it is more favorable to use the cooling tower than the refrigeration plant for cooling.

**The controller output level (0 ... 100%) is split between two analog outputs.**
If the output level is from 0 — 50%, then Output 1 is active, with a 4 — 20mA signal (for Valve 1 0 — 100%). If the controller calculates an output level from 50 — 100%, then Output 2 is active, with at 4 — 20mA signal (Output 1 remains at 20mA).

## 6.3 Maintaining disturbances constant

As became clear in Chapter 2 *"The controlled process"*, disturbances will only affect the process value if they vary. In some applications it is possible to maintain the disturbances at a constant level.

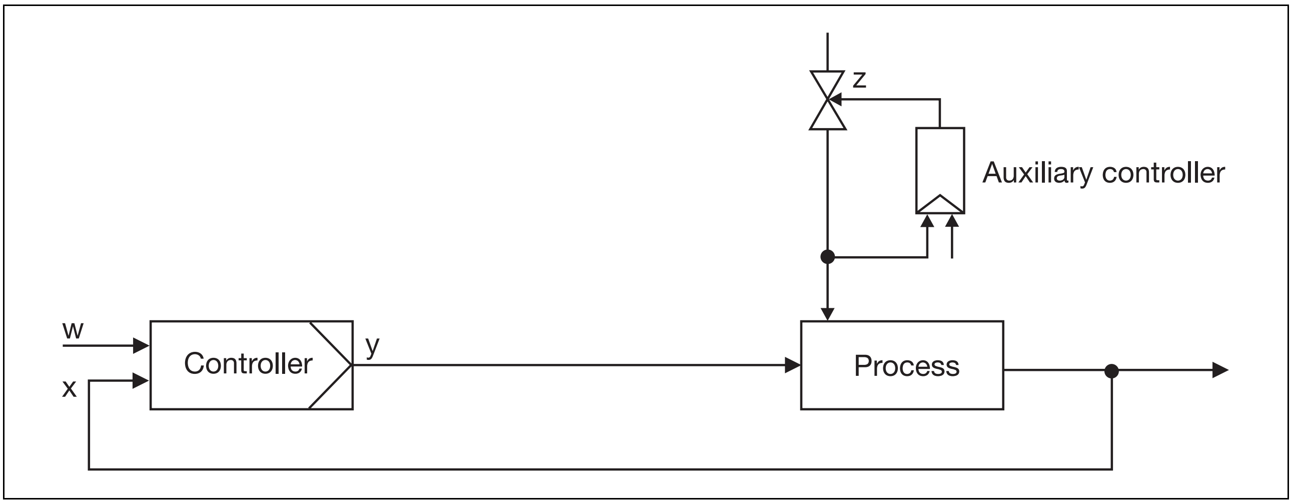


**Fig. 75: Maintaining disturbances constant**

Fig. 75 shows a schematic for a gas-fired oven. In this case, one of the disturbances is the supply pressure to the gas valve. If the controller has stabilized the setpoint, then a drop in gas supply pressure at the same valve setting would lead to a reduction in the process value. The controller would then increase its output level, in order to bring the process value back to the setpoint.

With an auxiliary controller, the supply pressure can be kept constant.
A setpoint is defined for the auxiliary controller that is lower than the minimum pressure that is to be expected in the supply network, and the auxiliary controller eliminates the pressure variations. In the example shown here, this constant value could simply be achieved with a pressure reducer.

## 6.4 Additive and multiplicative feed-forward control

If the influence of a disturbance on the process value is known, then the output level of the controller can be compensated for the disturbance. In principle, you can provide a supplement to the output level that is proportional to the disturbance (additive feed-forward control), or alter the entire output level by a factor that is proportional to the disturbance (multiplicative feed-forward control). So within the process, you don't wait for the disturbance to have an effect, but immediately alter the output level to compensate for the alteration that would otherwise be caused by the disturbance.

### 6.4.1 Additive feed-forward control

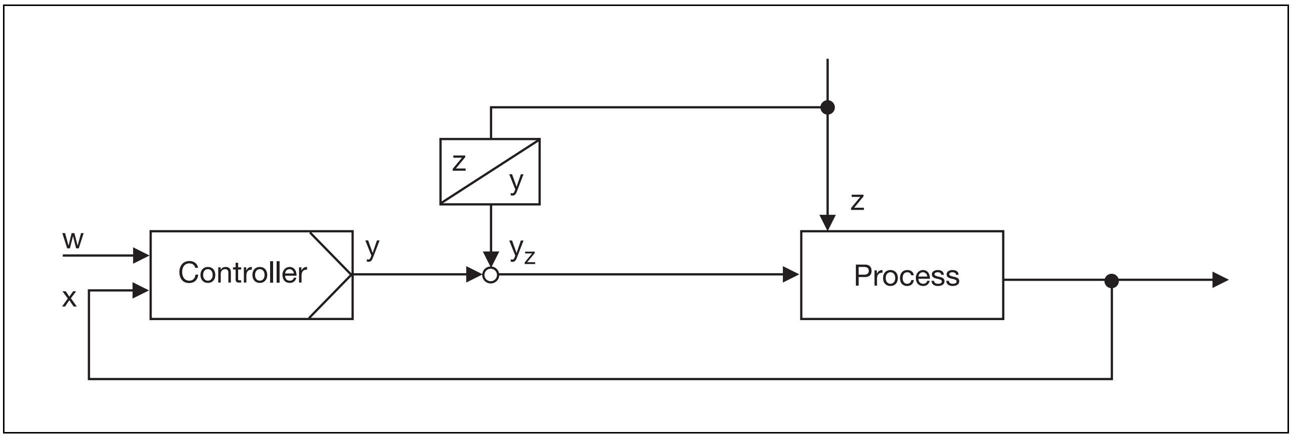


**Fig. 76: Principle of additive feed-forward control**

This type of feed-forward control can be used if an alteration of the disturbance makes it necessary to supplement or reduce the output level.

The principle of additive feed-forward control can be illustrated by the following example.

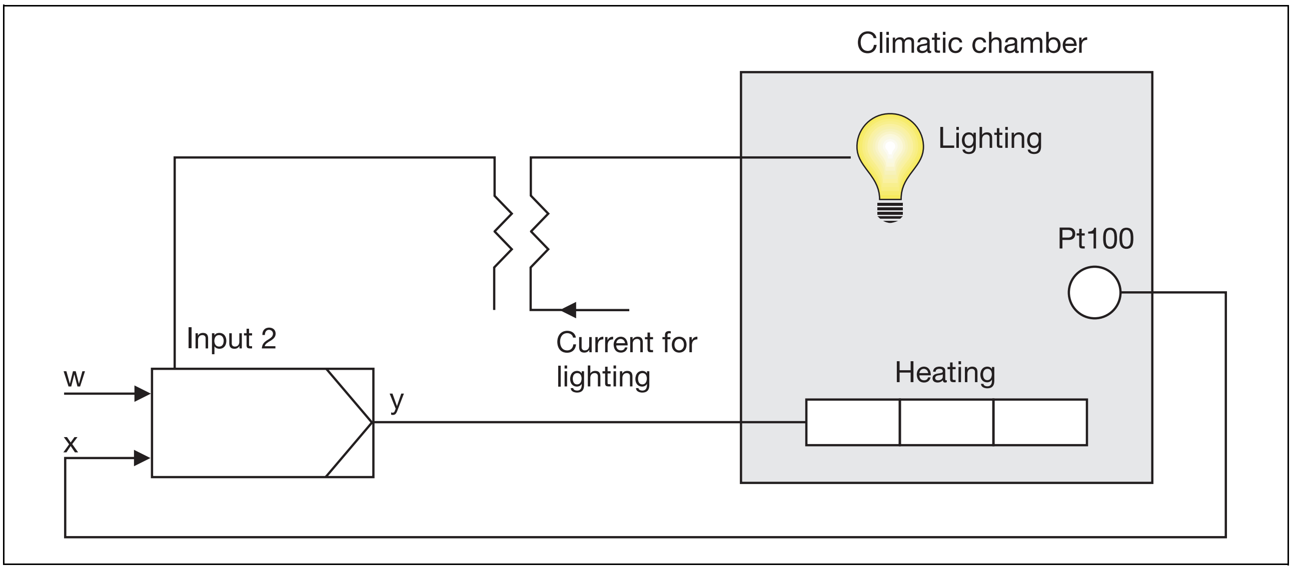


**Fig. 77: Example of additive feed-forward control**

The example shows a climatic cabinet that contains highly sensitive samples. The temperature must be controlled quite precisely, and the light in the cabinet is also regulated (this task is not performed by the controller).

To begin, let us look at the application without additive feed-forward control. In the climatic chamber, the system regulates precisely to a setpoint of 37 °C. The heat that is generated by the lighting in the cabinet is the disturbance. If the lamp is suddenly switched on, it produces heat in addition to the proper heating. The temperature rises, e.g. to 40 °C, and the controller reduces its output level until the climatic chamber has the correct value of 37 °C once again.

This disruption of the process value can be reduced by additive feed-forward control.
The current that flows in the lighting circuit is measured, converted in a current transformer (1000 : 1, for example) and applied to Input 2 of the controller. The input signal is appropriately scaled and then used by the controller as an additive feed-forward control value. If the lighting current increases, then the controller output level is reduced. The reduction in the heating power matches the heat generated by the lighting. In this way, the total heating power in the system remains constant when the light is switched on. The various delay elements in the system will still cause a shift of the process value, but the deviation will be much less than before.

It must be noted, that the additive feed-forward control is not a limitation of the output level.

The scaling of Input 2 must be made so that a corresponding reduction output level is made when the lighting is switched on.

Example: The controller produces an output level of 0 — 100 % for 0 — 1000 W output power. The lighting has an overall power of 100 W. The current transformer produces 5 mA at the maximum lighting power. So Input 2 is scaled so that 0 — 5 mA corresponds to 0 to -10 (at 5 mA the output level is reduced by 10 %, at 0 mA there is no reduction).

**Summary:**
**If a change in a disturbance requires a proportional addition /subtraction to the output level, then additive feed-forward control is used.**

### 6.4.2 Multiplicative feed-forward control

Multiplicative feed-forward control influences the overall proportional coefficient (gain) $K_P$ and thus the overall output level. If the disturbance variable that is measured alters its value, then the value set in the controller for $K_P$ ($\frac{1}{P_b} \bullet 100\%$) is altered in the same ratio over a range from 0 — 100%.

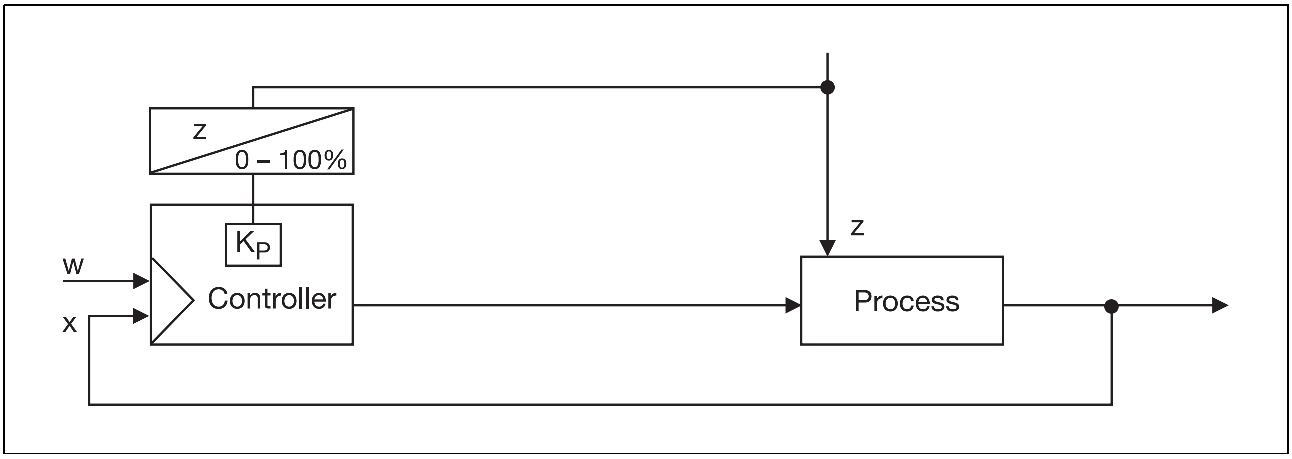


**Fig. 78: Principle of multiplicative feed-forward control**

This method is applied in processes where the output value from the controller has to be changed to the same extent as the disturbance.

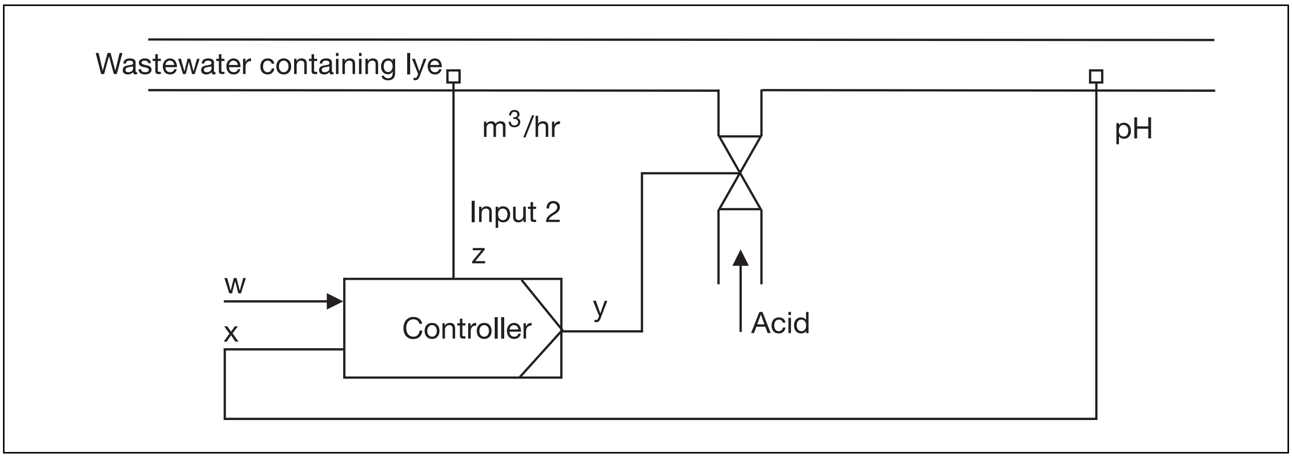


**Fig. 79: Neutralization plant**

The example to be used is a neutralization plant (Fig. 79), in which alkaline wastewater has to be neutralized by adding an acid. The process variable is the pH value, which should be in the neutral range. The controller influences the pH by regulating the flow of acid (y). First, let us look at operation without multiplicative feed-forward control.

The controller has settled to an output level of, say, 30% for a certain flow rate. Now let the disturbance (the flow rate) change, so that the wastewater flows twice as fast. The pH will increase, and the controller will increase its output level, until the process variable has been brought back to the setpoint. This will happen at an output level of 60% (i.e. twice as much acid). So we can see, that for a constant process variable, the output level has to be altered in proportion to the disturbance (all other conditions being constant).

**Let us look at our example with multiplicative feed-forward control.**
In this case, too, the controller has settled at an output level of, for example, 30 %. Now the disturbance variable (flow rate) changes to be twice the value. The multiplicative feed-forward control alters the proportional gain (which corresponds to the overall gain, Fig. 48) so that it is also doubled. The new output level from the controller immediately becomes 60 %, and there will be no significant control deviation.

In our example, the scaling of Input 2 must be made so that a flow rate of 0 — 100 % generates a factor of 0 — 100 %. If the flow-rate sensor produces a current signal of 4 — 20 mA (0 — 60 $m^3$/hr), then the scaling can be set to 0 — 100 %.
The controller will calculate an output level for 60 $m^3$/hr of 100 %, and at, for instance 30 $m^3$/hr, will multiply this by 50 %.

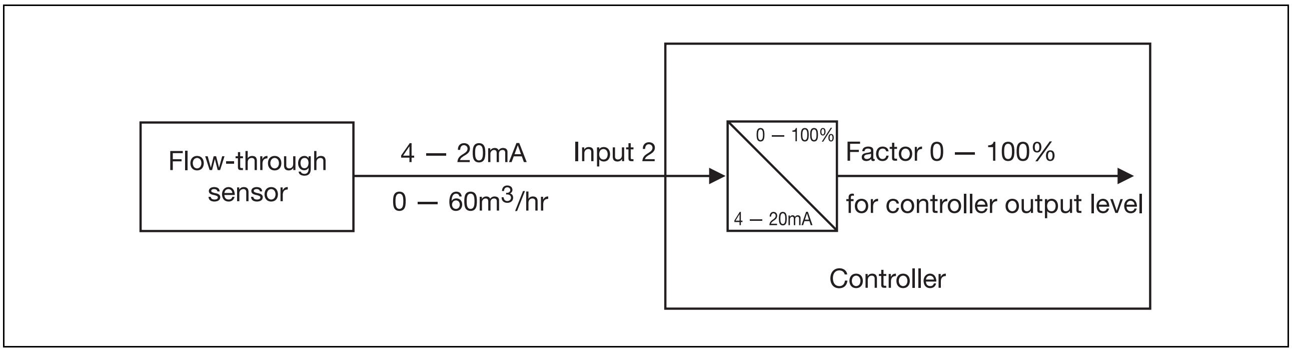


**Fig. 80: Example of scaling of Input 2 (feed-forward control)**

**Summary:**
**If the overall output level of the controller has to be multiplied by a factor 0 — 100 % (proportional to a disturbance variable), then multiplicative feed-forward control is used.**

## 6.5 Coarse / fine control

If a setpoint has to be regulated in a bulk (mass) or energy flow, then it may make sense to use a “coarse” controller to regulate the process value approximately to the setpoint value. The fine controller then has the task of removing the remaining control deviation.

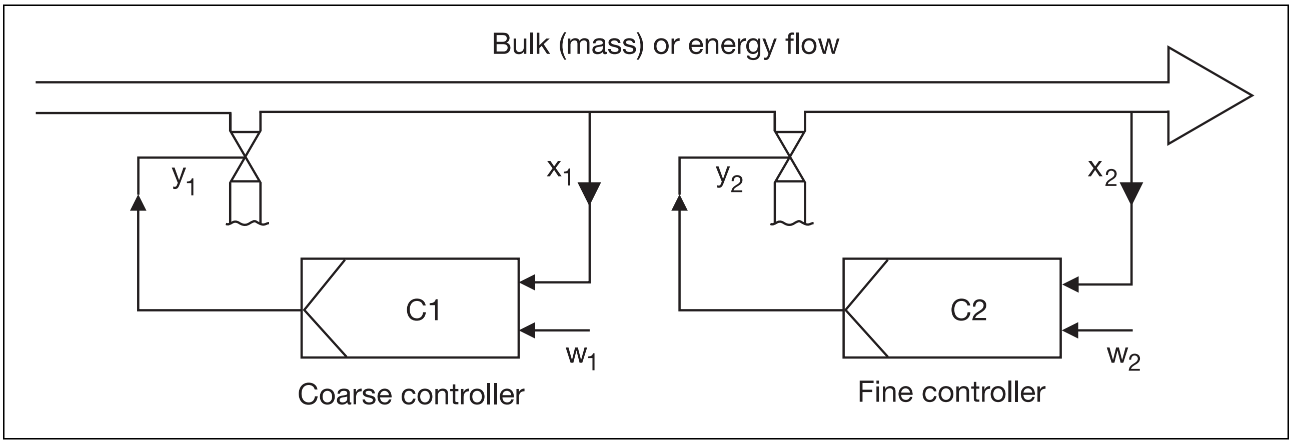


**Fig. 81: Coarse / fine control**

Once more we will take a neutralization plant as an example, in which wastewater has to be regulated to a pH of 7.

The coarse controller must act very quickly, but does not have to remove the entire control deviation. So it is frequently implemented as a P or PD structure.

The fine controller has the same setpoint applied, and has to eliminate the remaining control deviation. A PID structure is frequently used here.

## 6.6 Cascade control

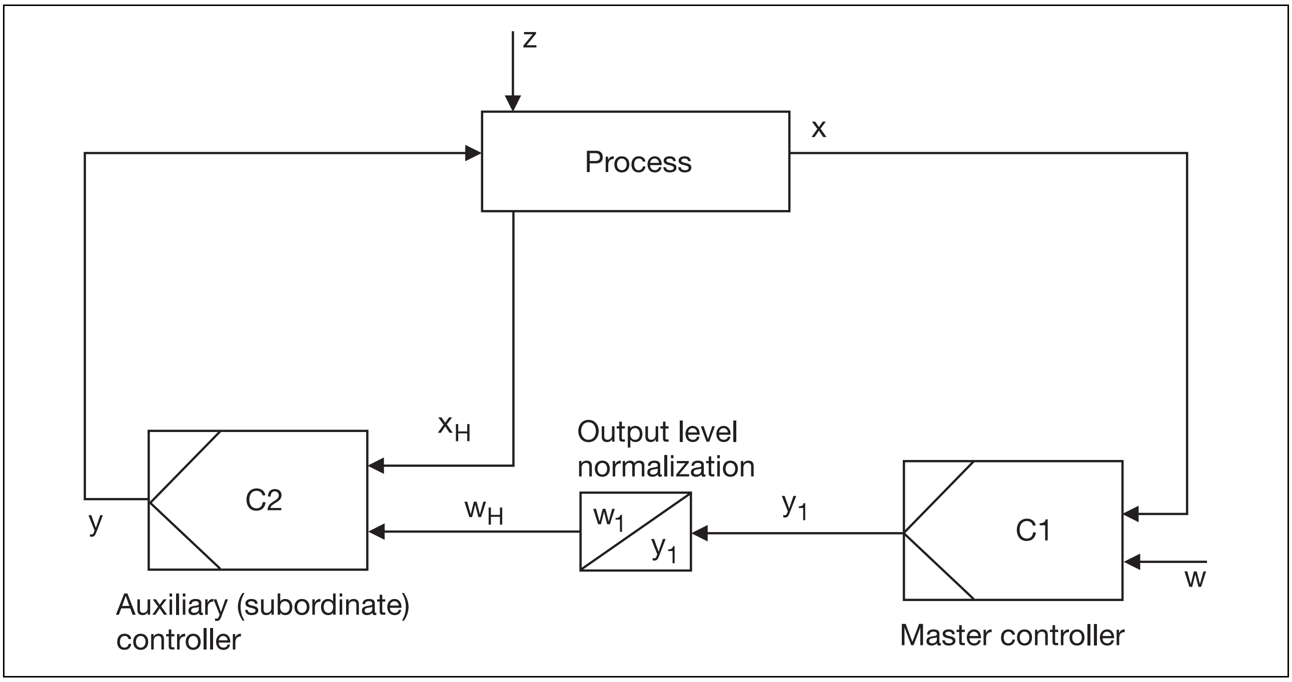


**Fig. 82: Cascade control**

In cascade control, several control loops are nested, one inside another. At least 2 controllers are present. The master controller is an analog controller, and its output level ($y_1$) is applied to the subordinate auxiliary controller. The auxiliary controller takes the output level of the master controller, normalizes this level, and uses the result as its setpoint ($w_H$). So the master controller uses its output level to give the auxiliary controller the value for the setpoint to which it has to regulate the auxiliary process value ($x_H$).

Fig. 83 shows an oven in which various setpoints have to be regulated. The heater element must not go above 200°C. The reason could be, for instance, that higher temperatures could ignite a gas that is present in the oven, and so cause an explosion.

We will use this example to show how a cascade control works, and what advantages it brings.

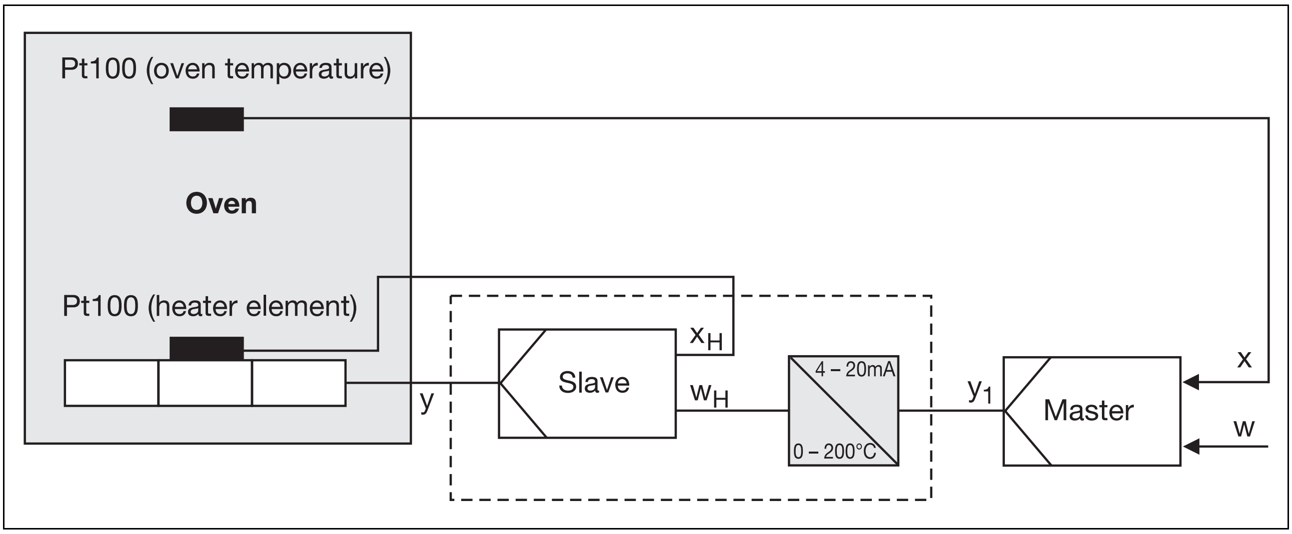


**Fig. 83: Cascade control for an oven**

In this example, the master controller is responsible for regulating the inside of the oven to the required setpoint. The setpoint for the oven temperature is applied to this controller, and the necessary output level is produced. The output signal (here: 4 — 20mA for 0 —100%) is fed to the subordinate controller (usually to Input 2).
The output level normalization is made in the subordinate controller: 4 — 20mA or 0 — 100% output level corresponds to 0 to 200°C setpoint for the subordinate controller. If the master controller produces a setpoint of, for example, 100%, then this means a setpoint of 200°C for the subordinate controller (which accordingly regulates the heater element to 200°C). So the master controller uses its output level (0 — 100%) just to produce a setpoint of 0 to 200°C for the heater element. In our application example, the heater element will never go above 200°C.

In the example shown here, the cascade control has the advantage that the temperature of the heater element is under control (no temperatures above 200°C). There are similar applications where it is necessary to prevent energy building up to excessive levels during the control procedure and thus causing the process value to overshoot the setpoint.

Furthermore, it can be observed that, in general, the implementation of a cascade control makes it easier to solve the control task, since the delay time in the control loop is split between at least two controllers.

**Optimization**
When optimizing a cascade control, it must be noted that the internal (subordinate) control loop must be optimized first, and then the outer control loop. In our example, this means that we first switch the master controller over to manual mode, and apply a middling output level (e.g. 60%).
For the subordinate controller (which is in automatic mode), the 60% output level is interpreted as 120°C setpoint for the heater element. We can now carry out self-tuning for the subordinate controller, as described in Chapter 7.1.1 *“Oscillation method”*. After self-tuning, the subordinate controller has been tuned to its optimum. Now we can switch the master controller over to automatic mode, and carry out self-tuning for this controller as well (the subordinate controller remains in automatic mode).

**Structure of the controllers**
The subordinate controller must have a fast response. For this reason, a P or PD structure is usually chosen. In our example it is of secondary importance whether a required output level of 50% is actually regulated to 100°C or, say, 95°C. The precise targeting of the setpoint is the responsibility of the master controller.

If self-tuning is carried out for the subordinate controller, it must be noted that it will usually activate the PID structure. So it should be manually switched over to a P or PD structure after self-tuning.

In most cases, a PID structure will be chosen for the master controller.

Please note that the subordinate controller must have a second analog input (in the example, this is scaled to 4 — 20mA / 0 to 200°C). The input must be configurable for external setpoint provision.

## 6.7 Ratio control

Ratio controllers are used for burner controls (regulation of the gas / air mixing ratio), in analytical measurement (mixing of reagents) and in process engineering (manufacture of mixture products).

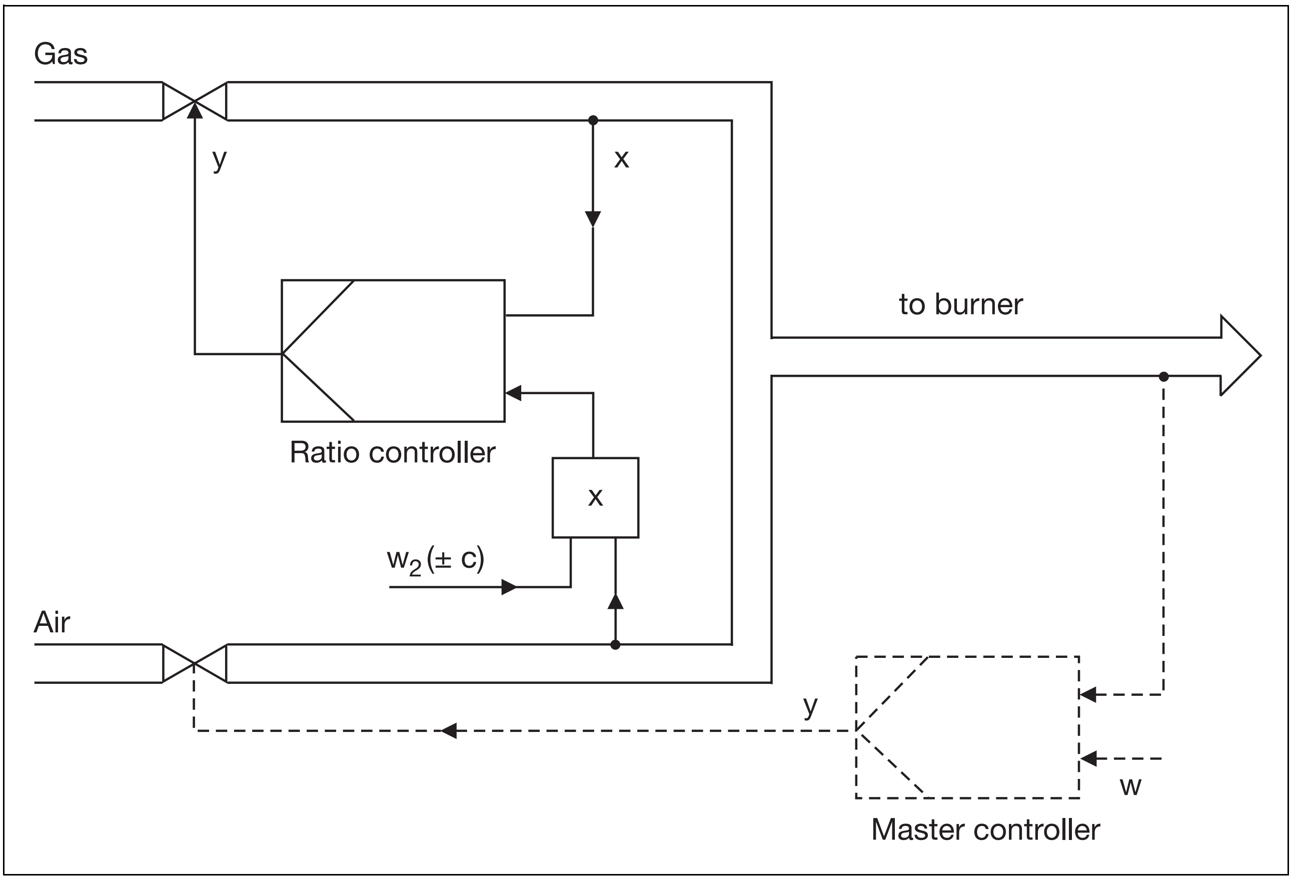


**Fig. 84: Ratio control**

In Fig. 84, the ratio controller measures the air flow in the feed line. The measured air quantity is multiplied by an adjustable ratio setpoint ($w_2$). The result is the setpoint for the quantity of gas to be regulated by the ratio controller.

In order to be able to regulate the total quantity for the burner, it is necessary to use a second controller (shown as dotted lines). The master controller is used to define the total quantity. For instance, when the setpoint is increased, the master controller opens the air valve, and the ratio controller regulates the gas to meet the preset ratio. The process has settled when both the total quantity and the ratio have settled to the correct values.

Instead of regulating the total quantity, the master controller will often control the furnace temperature directly. In this example too, if a higher setpoint is provided for the furnace temperature, the master controller will open the air valve, and the ratio controller will regulate so as to meet the required ratio.

**Optimization of the ratio controller and the master controller**
The ratio controller is optimized first. The master controller is switched over to manual mode, and a typical output level (e.g. 50%) is applied. The air valve is opened halfway, and then the ratio controller can be optimized. In this particular example, difficulties may arise because an unfavorable gas / air mixture may be incombustible.

When the ratio controller has been optimized, then the master controller can be switched back to automatic mode and optimized in its turn.

**Note**
Some JUMO controllers can be directly configured as ratio controllers.
On such controllers, the required ratio can be entered as a setpoint. The present ratio will also be displayed as a process value.

# Special controller functions

Up to now we have familiarized ourselves with the basic controller function of a JUMO compact controller, but such controllers have a multitude of additional functions. These features enable, for instance, simpler servicing and cost reductions through the saving of peripheral components.

This chapter presents some important functions that, to some extent, only apply to JUMO controllers.

## 7.1 Self-tuning

Self-tuning (sometime referred to as autotuning) is used by JUMO compact controllers to determine not only the most favorable control parameters (for the controller) but also additional parameters, e.g. the cycle time for 2-state and 3-state controllers.

Self-tuning by the oscillation method has been incorporated in almost all JUMO compact controllers. As we will see, this method cannot be applied in some special processes. So the step-response method is also available in some instruments. Both methods are illustrated in this chapter.

In both cases, the controller identifies the type of process and uses it as a basis for calculating the control parameters. **Tuning must therefore be carried out under realistic operating conditions.** For instance, tuning should not be carried out for an empty hardening oven, if it is later going to contain 2,000 kg of steel.

### 7.1.1 Oscillation method

For the oscillation method, the controller alternately produces 0 and 100 % at its output.
It then uses the resulting process value response to calculate the most favorable control parameters.

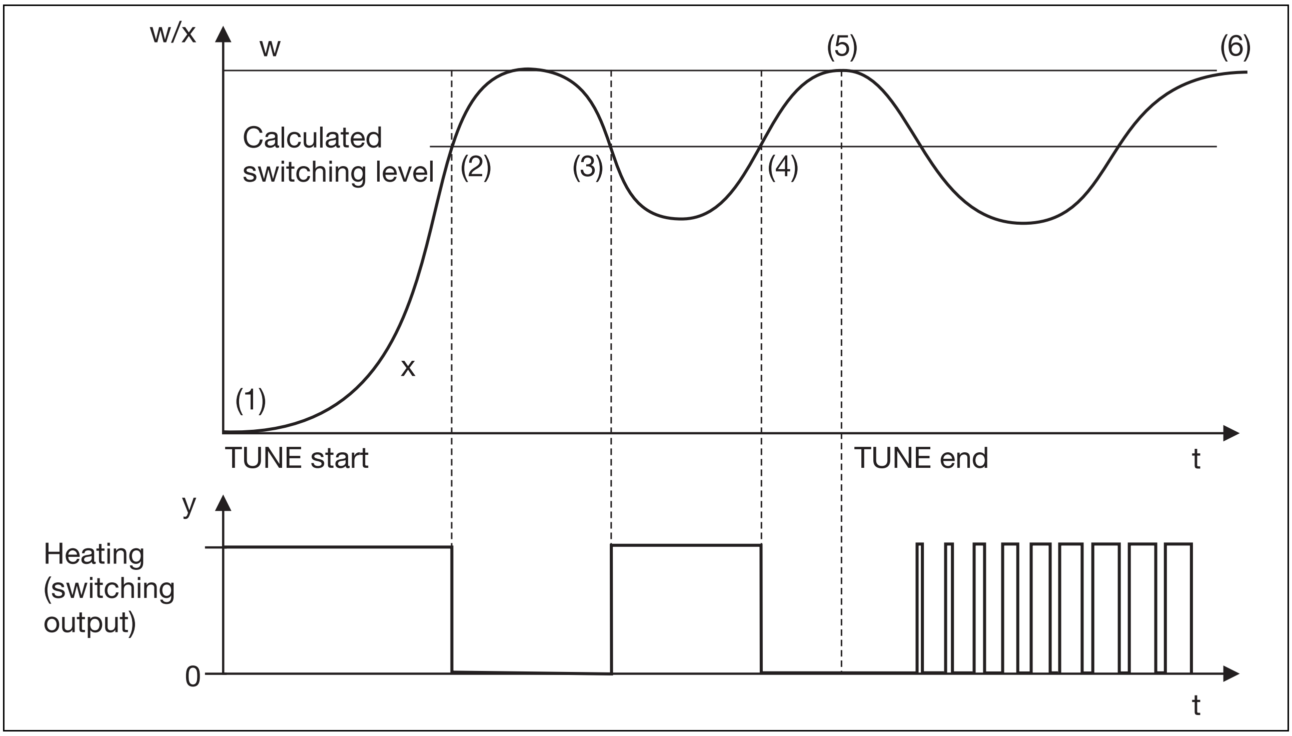


**Fig. 85: Self-tuning according to the oscillation method**

For a temperature control process, tuning can be started in the cold state. However, it is important that a setpoint is provided which is typical for the plant or system.
If, for instance, the operating setpoint is 800 °C, then it does not make sense to perform self-tuning at 200 °C (the process would show a different response at this operating temperature).
In this example, a setpoint of about 800 °C must be defined before starting self-tuning.

Let us take a closer look at the way self-tuning works (Fig. 85):

(1) The system is in the cold state, a typical setpoint is selected, and then tuning is started. The controller sets its output signal to 100 % and the process value starts to rise.

(2) The controller makes an internal calculation of its switching level. When this is reached, the output signal is set to 0 %. The system still continues to heat up. In the ideal case, the process value would reach the setpoint precisely, before starting to fall.

(3) The oven cools down, and the output power is once more set to 100 %.

(4) The output is switched off again.

(5) If the process value reaches the maximum again, tuning is finished. The controller accepts the parameters that have been determined for its active parameter set, and controls to the given setpoint (6).

**Note**
**To be safe, take into account that the process value can overshoot the setpoint during self-tuning. If such a condition could cause damage to the system or the material being treated, then this method must be used with caution (for instance, by providing a somewhat lower setpoint during self-tuning).**

Self-tuning can also be started when the process value is close to the setpoint. In this case, the switching level is set to about the same as the setpoint, and the process value will certainly overshoot the setpoint.

The tuning method just described is the standard procedure for JUMO controllers, and provides very good to satisfactory results in most cases. However, in the following applications this method is either difficult to use or not usable at all:

- where output level jumps of 0 ↔ 100 % are forbidden for the process
- where it is difficult to provoke the oscillation in the process
  (e.g. for an oven with very good thermal insulation)
- where the process value must not exceed the setpoint in any circumstances.

In such cases, the step-response method can be applied.

### 7.1.2 Step-response method

For the step-response method, a quiescent output level and a step size must be defined for the controller. The controller then uses the response of the process value to the step to calculate the most favorable control parameters.

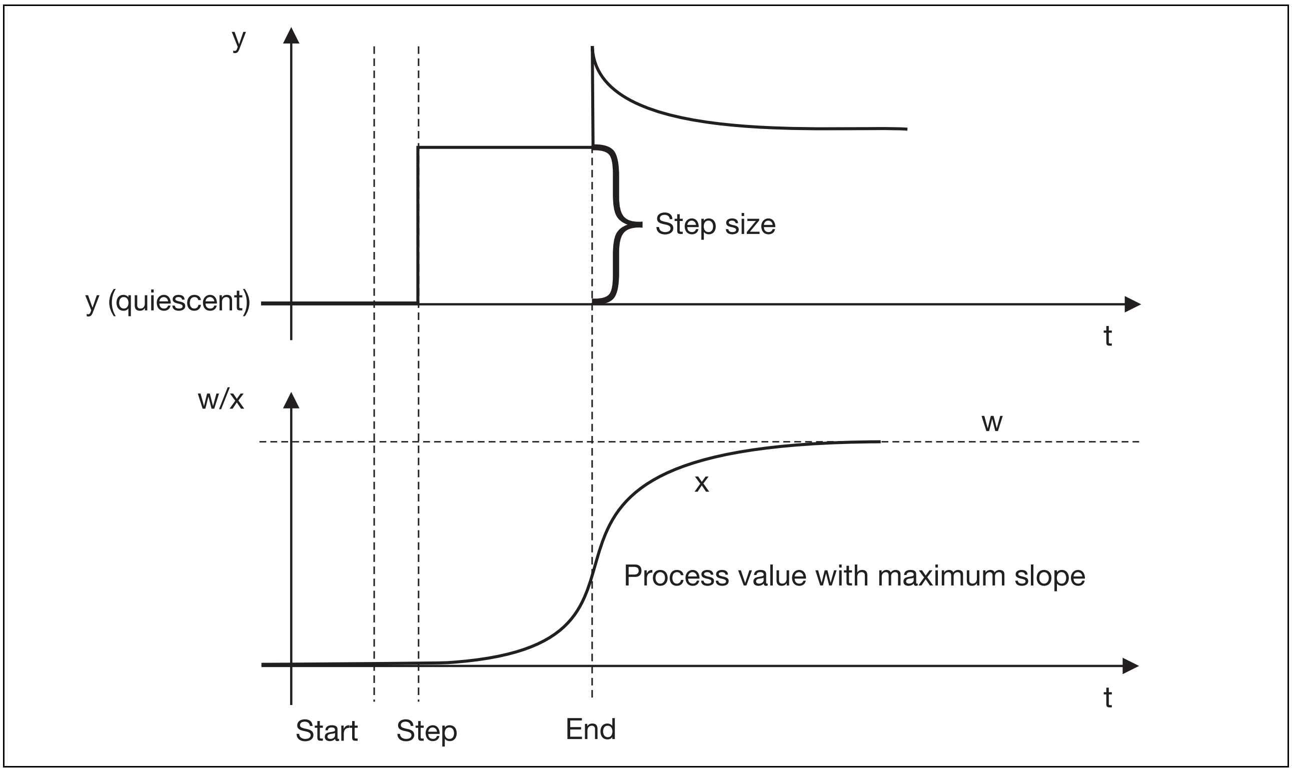


**Fig. 86: Self-tuning according to the step-response method**

Fig. 86 shows how this method works, starting from the cold state. The setpoint for the system is defined and self-tuning is started. The controller produces the quiescent output level (in the example: 0 %). If the process value fluctuates, the controller waits until it has stabilized. The output level is now increased by the predefined step, and the process value rises. The controller waits until the process value is rising at the maximum rate. The control-loop parameters are calculated at this point, and then used to control to the predefined setpoint.

As already mentioned in Chapter 7.1.1 *“Oscillation method”*, this method can still be applied in situations where a given process value must not be exceeded during self-tuning.

In this case, the controller is switched over to manual mode, and an output level is applied that manipulates the process value below the critical region (time must be allowed for the value to settle after each change). Let us say, we determine an output level of 65 % for a process value of 200 °C. The minimum step size is 10 %. Tuning works more precisely if a larger step is selected. In our example, we will configure a quiescent output level of 45 % and a step size of 20 %.

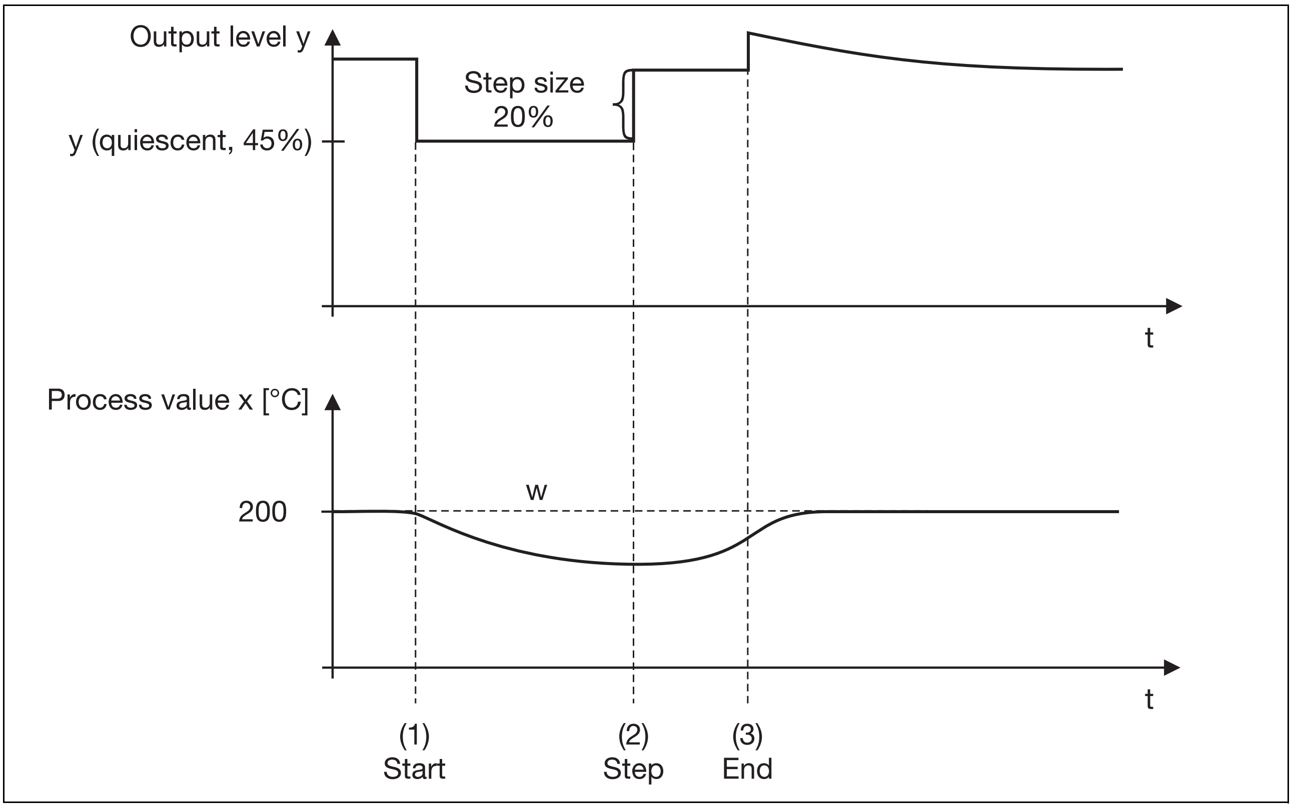


**Fig. 87: Start of self-tuning during operation**

Fig. 87 shows the relationships during the subsequent self-tuning. In (1), the controller is switched into automatic mode and tuning is started. The controller sets its output level to 45% and the process value starts to fall. When the value has stabilized, the output level is increased by the step size (20%) (2). When the controller detects the maximum rate of change for the process value curve, it calculates the most favorable parameters for itself and uses them to control to the predefined setpoint (200°C in this case).

### 7.1.3 Additional information on tuning methods

The oscillation method can be used for all configurable controllers (continuous, 2-state, 3-state, modulating and actuating controllers).

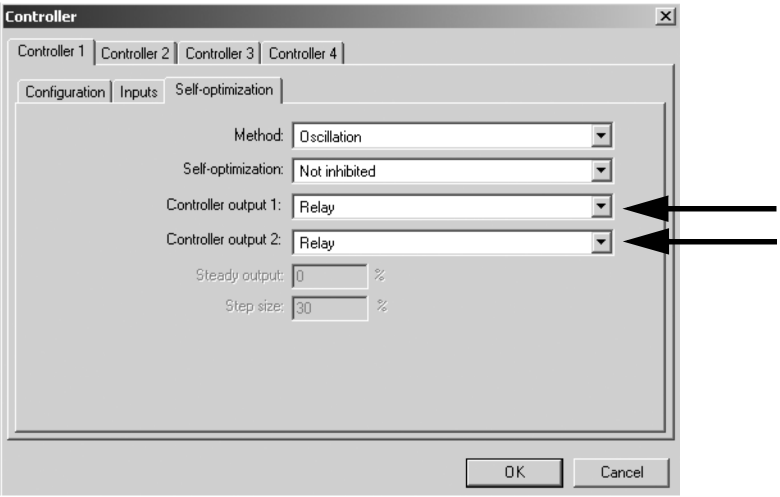
The same generally applies for the step-response method, but this can only be used in a limited fashion for modulating controllers. The quiescent (standby) output level can only be set to 0%, and the step size to 100%. This is due to the fact that a modulating controller does not have any information about the momentary valve/actuator position, see Chapter 5.5.1 *"The modulating controller"*.

For both methods:
Regardless of which controller structure has been set up in the parameters, the controller always switches over to a PID response, and calculates the corresponding $P_b$ , $r_t$ and $d_t$.

There are two exceptions:
If the setup has been made for a PI structure before tuning, this will be retained and the controller will be optimized as a PI controller. This is because a D component could cause some processes to become unstable. If this is known to be the case (e.g. frequently for pressure and flow-rate processes), then a PI structure can be set before self-tuning. If a first-order control process is detected, the controller will also switch over to a PI structure.

In addition to the control-loop parameters for a PID response, the controller will calculate the switching cycle times for 2-state and 3-state controllers. It will also dimension a filter for the process value input. In the case of a 3-state, modulating or actuating controller, it is also necessary for the user to implement a **manual** setting for the contact spacing, see Chapter 5.4 *“The 3-state controller”*.

In order to determine a suitable switching cycle time during self-tuning – for a heating and cooling unit, for instance – the types of the outputs must be configured in the controller before tuning.



Method: Oscillation
Self-optimization: Not inhibited
Controller output 1: Relay
Controller output 2: Relay
Steady output: 0 %
Step size: 30 %

**Fig. 88: Setting the controller output types for self-tuning**

The following settings are possible for the controller outputs:

- relay: the switching cycle time is defined to be as short as is necessary. The relays are operated as gently as possible.
- solid-state + logic: the dimensioning of the cycle time is arranged to be as small as possible (the output will switch very frequently).
- analog output

## 7.2 Startup and teleservice / diagnostics

Sometimes it is necessary to record process variables during commissioning, servicing operations and so on (e.g. the process value curve when a new setpoint is applied).
In such situations, additional equipment is normally required: a recorder to record the values, and a second sensor must be inserted in the process, at some cost and effort.

In most cases, JUMO controllers can be configured via the interface with the help of a corresponding configuration program (Setup). Startup (an option within the configuration program) can be used to record many of the process variables that are available within the controller, and they are then available on the PC.

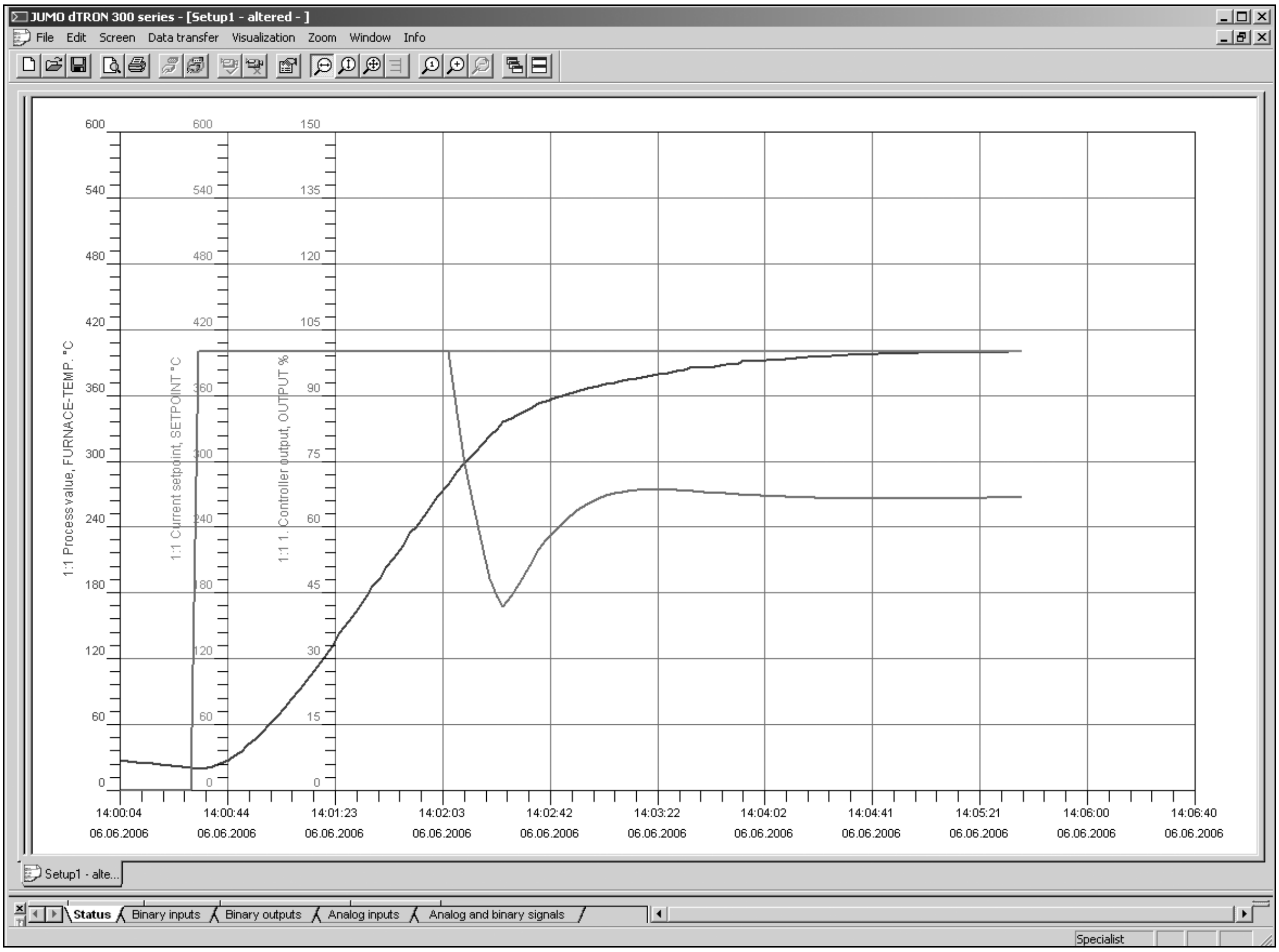


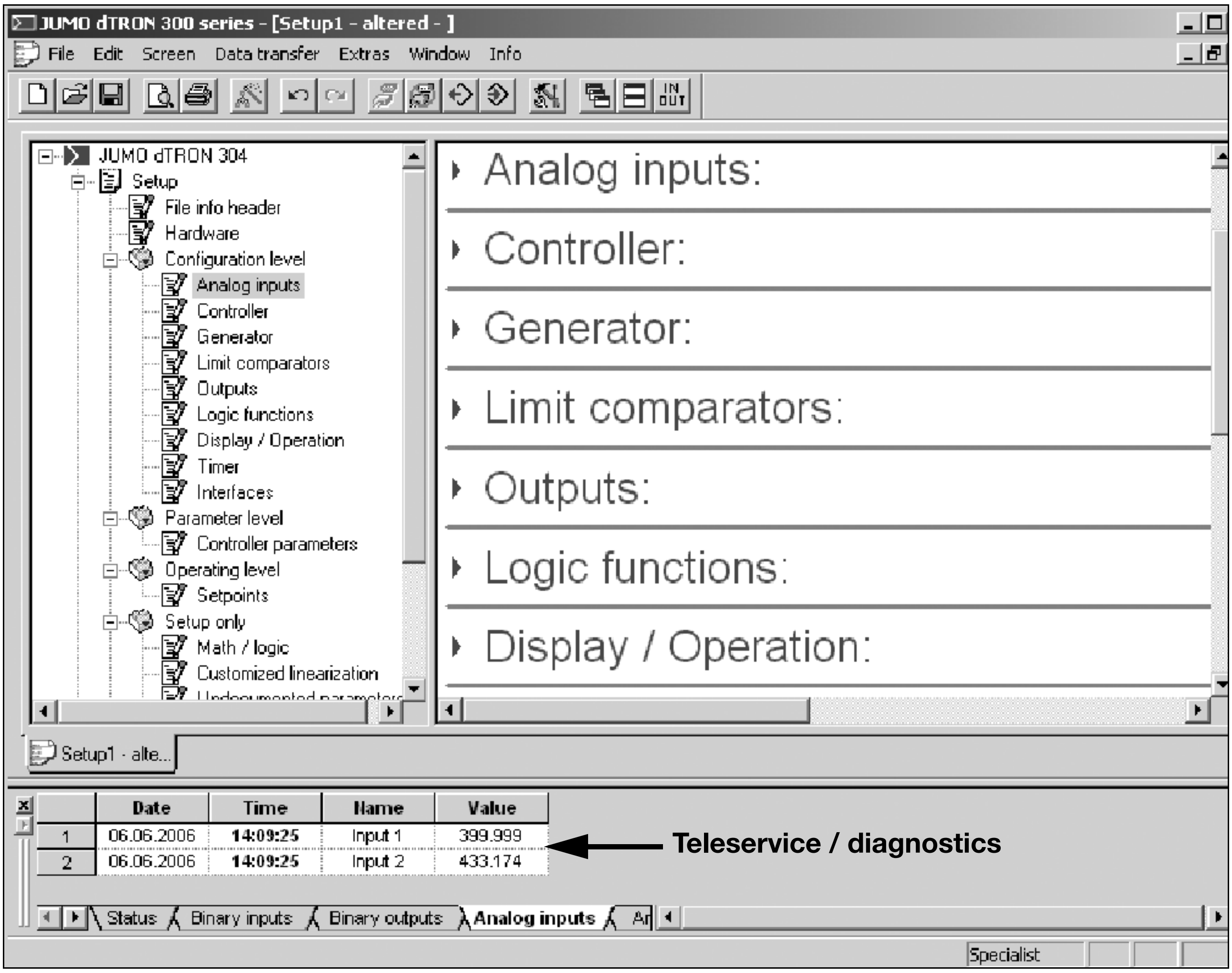
**Fig. 89:** **Data recorded online from a JUMO controller, using Startup**

In the example of Fig. 89, the setpoint, process value and output level have been recorded during a setpoint change.

The recorded diagrams can be printed out or saved as a file, and are then available for system documentation.

**Teleservice / diagnostics**

Thanks to the function known as teleservice or diagnostics, important variables are available online in Setup as long as the controller and PC are linked together.



| | Date | Time | Name | Value |
|---|---|---|---|---|
| 1 | 06.06.2006 | 14:09:25 | Input 1 | 399.999 |
| 2 | 06.06.2006 | 14:09:25 | Input 2 | 433.174 |

**Fig. 90: Teleservice / diagnostics for a JUMO dTRON 300**

A service engineer can make use of this function to get a quick overview of the controller (status of inputs, controller output level etc.).

## 7.3 Recording function

With JUMO instruments, not only a number of paperless recorders but also several controllers are equipped with a recording function. This option can be used to record any chosen signals from the recorder and view them on the screen.

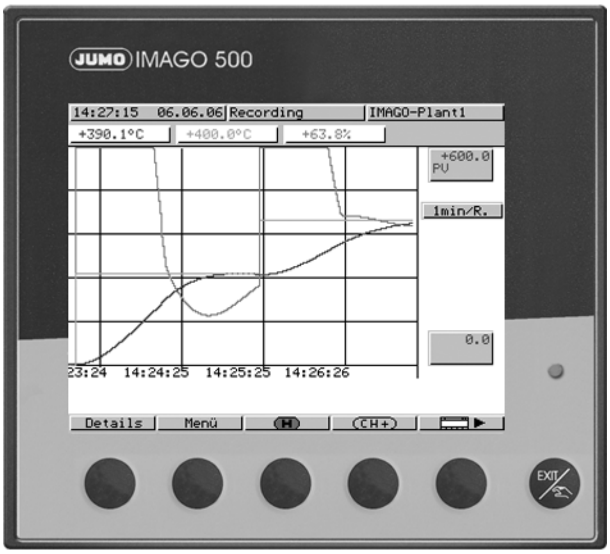
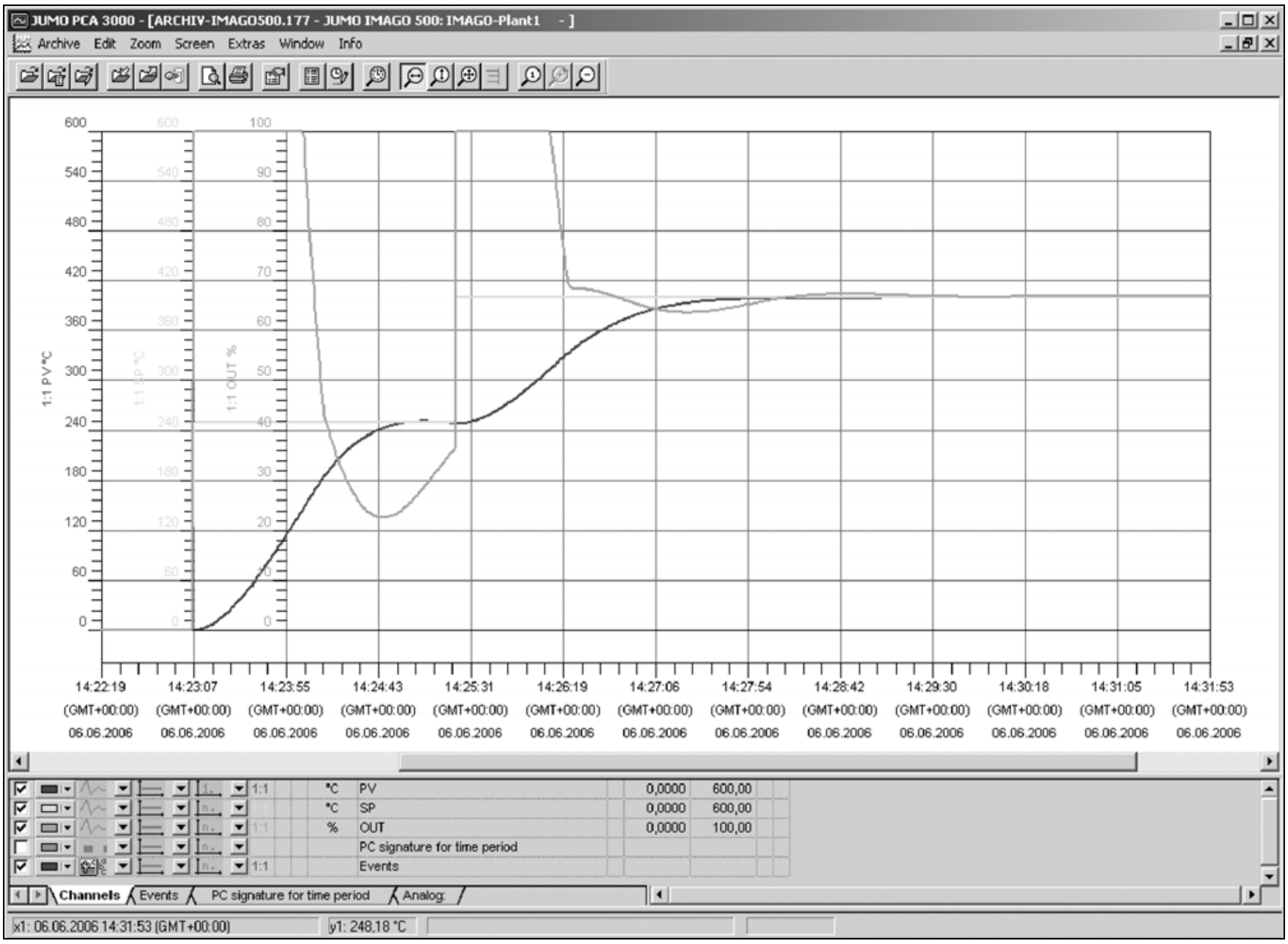


**Fig. 91: Recording function of the JUMO IMAGO 500**

The control-loop response of a system is illustrated in Fig. 91. The data are stored in the instrument in a ring memory. If the ring memory is completely full of data, the data that are overwritten will always be the oldest data.

The recording can, for instance, be downloaded and evaluated every day by a PC, and archived on the hard disk.

The PCA3000 evaluation software makes it possible to evaluate the data.



| | | | | | |
|---|---|---|---|---|---|
| ☑ | 1:1 | °C | PV | 0,0000 | 600,00 |
| ☑ | | °C | SP | 0,0000 | 600,00 |
| ☑ | 1:1 | % | OUT | 0,0000 | 100,00 |
| ☐ | | | PC signature for time period | | |
| ☑ | 1:1 | | Events | | |

x1: 06.06.2006 14:31:53 (GMT+00:00)

y1: 248,18 °C

**Fig. 92: Evaluating measurement data with JUMO PCA3000**

Fig. 92 shows measurement data that have been recorded by a JUMO IMAGO 500 and, after downloading, are now available on a PC.

## 7.4 Ramp function

If the user makes a change to a setpoint on a controller, then acceptance of the new setpoint means a step change in the value.

The jump in the value on acceptance - of a new temperature setpoint, for instance - is not permissible for some processes.

- Certain materials have to be heated up or cooled down slowly.
- If a higher setpoint is applied, then the heating power will jump from some lower value to, for instance, 100 %. This causes intensive heating in the direct vicinity of the heater, which may lead to damage or destruction of the material being processed. Furthermore, large temperature differences (temperature gradients) are created within the process, which may also have a negative effect on some materials.

If the ramp function is active, the newly defined setpoints will not be approached by a step change, but along a steady slope (ramp). The slope of the ramp can be configured in the controller, e.g. in °C / minute.

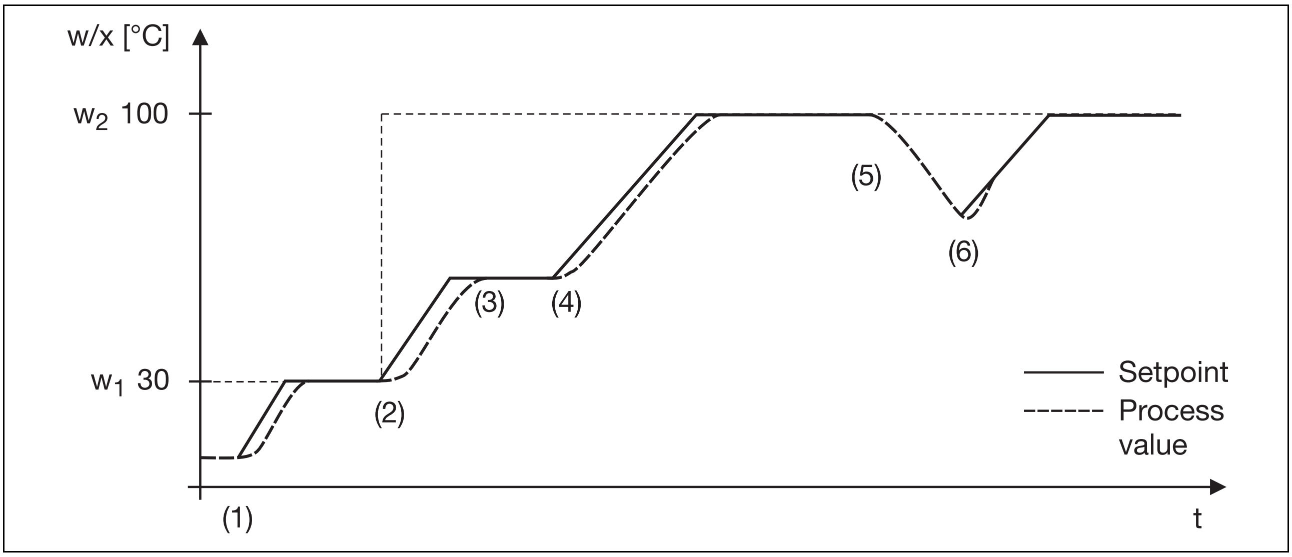


**Fig. 93: Ramp function**

Fig. 93 shows in detail how the ramp function works, for most JUMO controllers:

(1) The controller is switched on. The system has a low process value at the moment. A setpoint of 30 °C is entered for the controller. Thanks to the ramp function, the setpoint is set to the present process value, and then approaches 30 °C along the ramp with the specified slope.

(2) The setpoint is altered to 100 °C, and the setpoint for the ramp rises with the slope that has been configured.

(3) The ramp is stopped (this is possible, e.g. with a binary input).

(4) The ramp continues (for instance, because the binary input with the Ramp Stop function has been opened) and reaches the new setpoint of 100 °C.

(5) There is an interruption in the electrical supply, the process value starts to drop.

(6) The electrical supply is re-established. The present process value is taken as the setpoint for the ramp again. The setpoint rises to 100 °C, with the slope that was defined by the user.

## 7.5 Program controller

A program controller is used when it is necessary to define the setpoint as a profile.
Fig. 94 shows a setpoint profile, with five different control contacts.

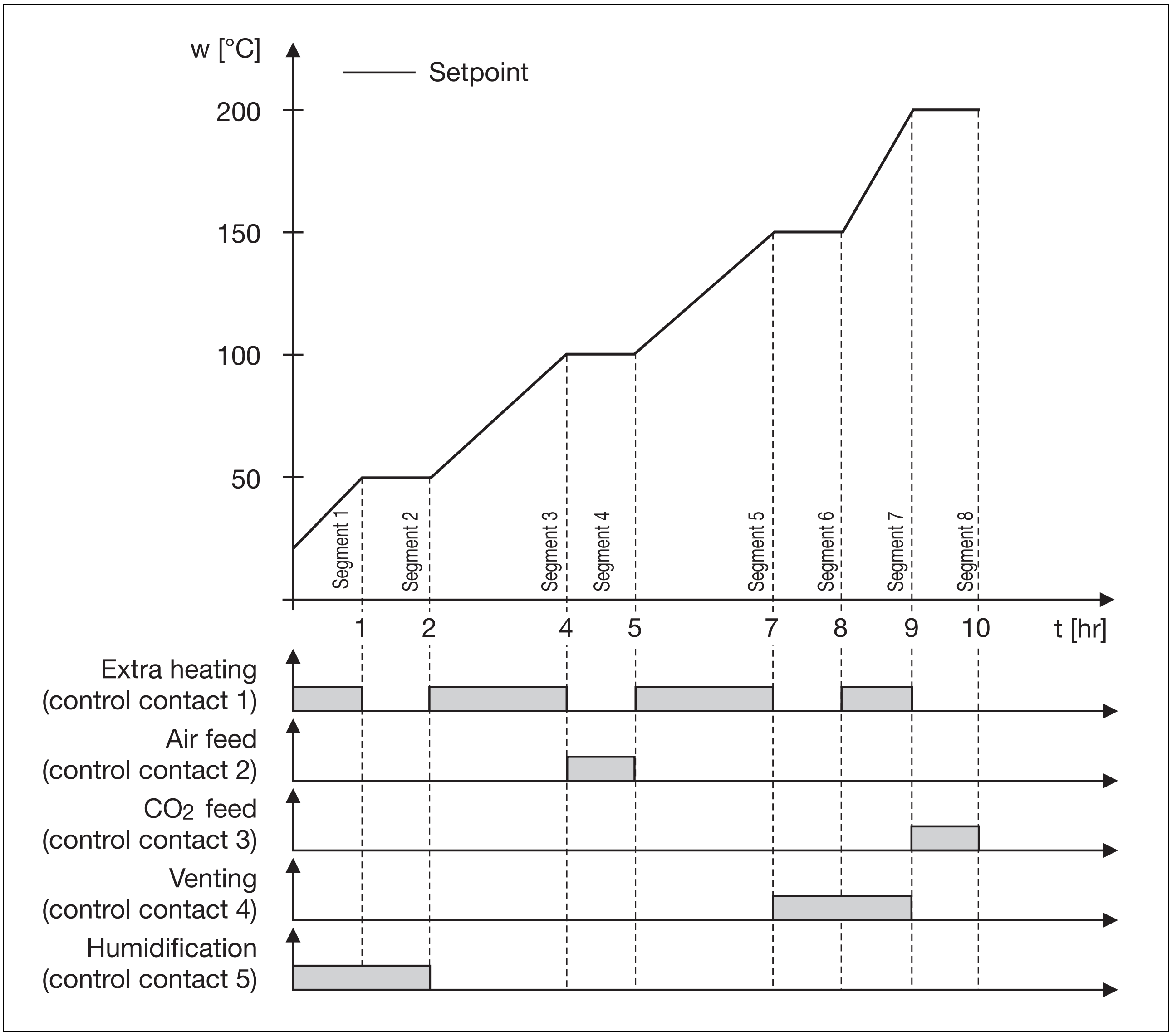


**Fig. 94: Program for a program controller**

A program is made up from different segments, which are defined (for the profile) by the setpoint at the start of the segment, and the duration of the segment (example: Segment 1 is defined by the setpoint 25 °C and the segment time 1 hr). The setpoint at the end of Segment 1 is defined by the setpoint at the start of Segment 2 (50 °C).

JUMO produces and supplies program controllers that are capable of implementing up to 50 programs with 1000 segments.

As well as the setpoint profile, it is often necessary to control flaps, ventilators, valves etc. The status of the corresponding outputs can be defined for each segment through elements known as control contacts.

On some controllers, it is possible to define which parameter set is to be used by the controller for each segment. In addition, it is frequently possible to define a tolerance band for the setpoint. If the process value moves outside the tolerance band, then the program will be stopped (if it has been so configured). If the process value returns to a value within the tolerance band, then the program will continue.

## 7.6 Limit comparators

When working with JUMO controllers, it is often very helpful to make use of limit comparators. Depending on the instrument version, 1 to 16 limit comparators may be available.

A limit comparator can function according to various characteristic responses. These characteristics are known as limit comparator functions. The user can select between 8 different functions, whereby it is possible to monitor a signal by comparison with a fixed value, or to make a comparison between two signals.

As an example, we will explain the “Limit comparator function 7” characteristic:

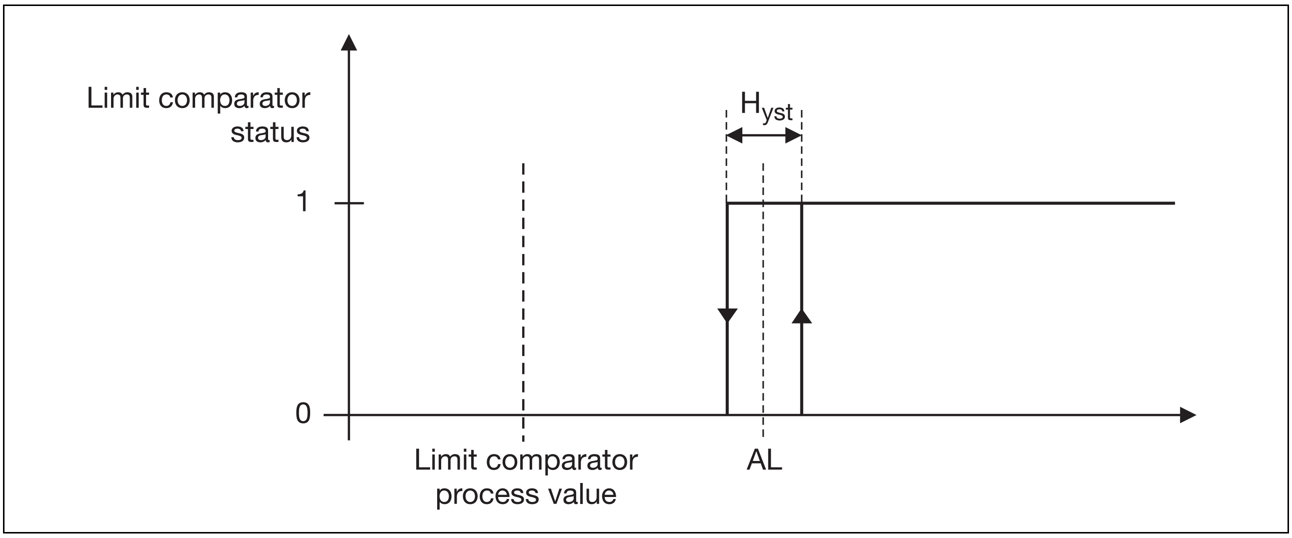


**Fig. 95: Limit comparator function 7**

Limit comparator function 7 monitors the “Limit comparator process value” (e.g. the signal at an analog input) to detect whether it exceeds a threshold AL. It is also possible to define a hysteresis $H_{yst}$ for this value. The output of the limit comparator can be used, for instance, to switch a relay or initiate a binary function.

## 7.7 Binary functions

Binary signals can be used in JUMO controllers to initiate various functions. Binary signals can be, for example, the switch status at binary inputs or the status of limit comparators etc.

Typical binary functions are:

**Start / cancel self-tuning**
Self-tuning can be started or stopped by a binary event.

**Setpoint switching**
Several setpoints are available in the controller, but only one can be active at a given time. The changeover can, for instance, be made by a binary input.

**Process value changeover**
If a controller system is using analog input 1 as the process value, then a binary signal can be used to change over to using analog input 2.

**Parameter set switching**
In JUMO controllers it is usually possible to define 2 sets of parameter (structure, dimensioning $P_b$, $r_t$ and $d_t$ etc.). A limit comparator can be used to evaluate, for instance, whether a certain setpoint has been exceeded. If this is the case, then the system changes over to parameter set 2.
So smaller setpoints are handled by the control parameters in set 1, and larger setpoints are handled by the parameters in the second set.

**Key lock**
A binary signal can be used to lock the keys.

**Program start and stop**
The program controller can start or stop a program, depending on a binary event.

## 7.8 Manual mode

In the automatic operating mode, the proper control functions are active (the system controls to the predefined setpoint). But the controller can also be switched over to the manual mode. When the switch is made to the manual mode, the present output level is accepted as the manual output. The keys can be used to set the output level continuously, between 0 and 100 %.

On JUMO controllers you can also configure a fixed value for the manual output level, and this will be the value used when the system switches to manual mode. If, for instance, an output level of 0 % has been set, and the controller switches over to manual mode, then the output will be set to 0 %.

## 7.9 Output level limiting

JUMO controllers have an upper (Y1) output level limit and a lower (Y2) output level limit.

The **upper output level limit (Y1)** is set at the factory to 100 %. That means: if the controller calculates an output level of 100 %, then the controller output really will produce this level. But, if Y1 is, for instance, set to 60 %, and the controller has calculated a working point of 100 %, then the output will be limited to 60 %.

The upper output level limit can be applied in situations where the actuator is too generously dimensioned for the required working point.

The **lower output level limit (Y2)** can, for instance, be used in a 3-state controller to limit the cooling action to a defined maximum (e.g. if Y2 = -75 % then the cooling is limited to 75 % of the theoretical maximum).

If no minimum output level has to be set for the heating, then the lower output level limit (Y2) can also be set to >0 %. If, for instance, a Y2 of 5 % has been defined, then the output level will always be at least 5 % (even if the controller has calculated an output level <5 %).

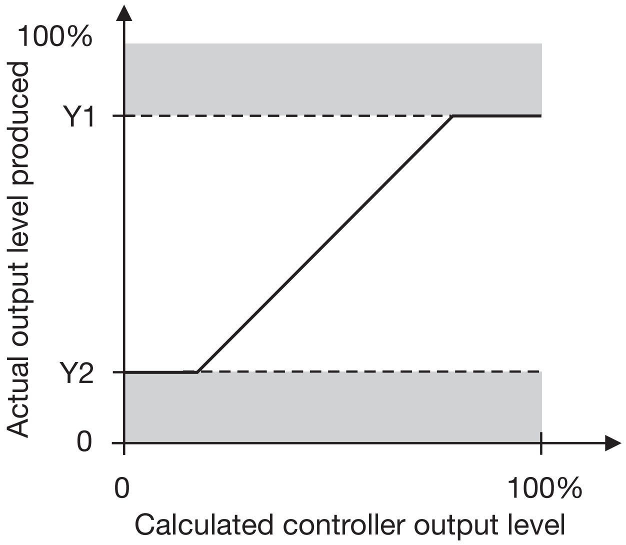


**Fig. 96: Output level limiting**

## 7.10 Customized linearization

If, for instance, a Pt100 is connected to a controller, then this uses a measuring current to determine the resistance. But the user is only interested in the temperature that corresponds to the measured resistance. The characteristic curve for a Pt100 (the resistance values for the corresponding temperatures) is stored in the instrument. Thanks to this, the user only has to select the linearization for Pt100, and then the instrument will automatically indicate the temperature of the Pt100. Controllers usually include a large number of stored linearizations (other temperature-dependent resistance values, thermocouples etc.).

If a sensor is used for which the instrument does not have a linearization, then the user can set up a customized linearization. The characteristic curve of the sensor must be known, and the user then enters interpolation points for the linearization (value pairs within the operating range – in the case of a temperature-dependent resistance these would be paired values for the resistance and the corresponding temperature). The controller uses the interpolation points to carry out the linearization.

Another example of customized linearization is the measurement of the volume in a container that has been constructed with a conical lower section and a cylindrical upper section (Fig. 97).

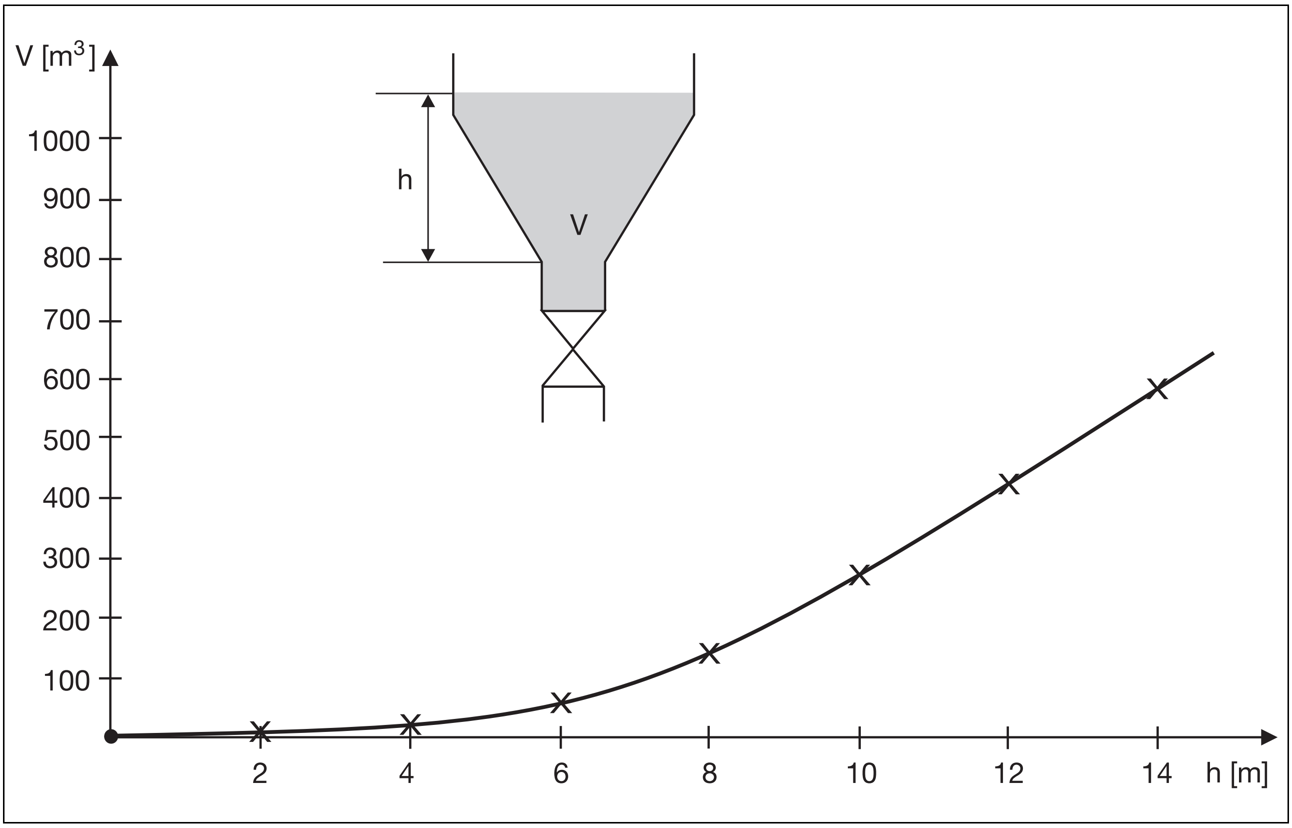


**Fig. 97: Determination of the volume according to the level with the help of customized linearization**

The volume of a certain container of this type can be determined from the level, in accordance with the diagram shown in Fig. 97. The marked points are defined as interpolation points in the controller (the actual signal from the sensor must be entered, e.g. in mA, instead of the level). The controller links the interpolation points together and calculates the volume at any time from the level that is measured.

## 7.11 Humidity measurement

JUMO has been supplying sensor systems for humidity measurement for many years. The range covers hygrometers that operate according to the capacitive and hygrometric measurement methods. The corresponding probe usually provide Pt100 or standard signal outputs.

Many JUMO controllers are, for instance, supplied to the meat processing industry. In this sector, the psychrometric method of measurement is used as before.

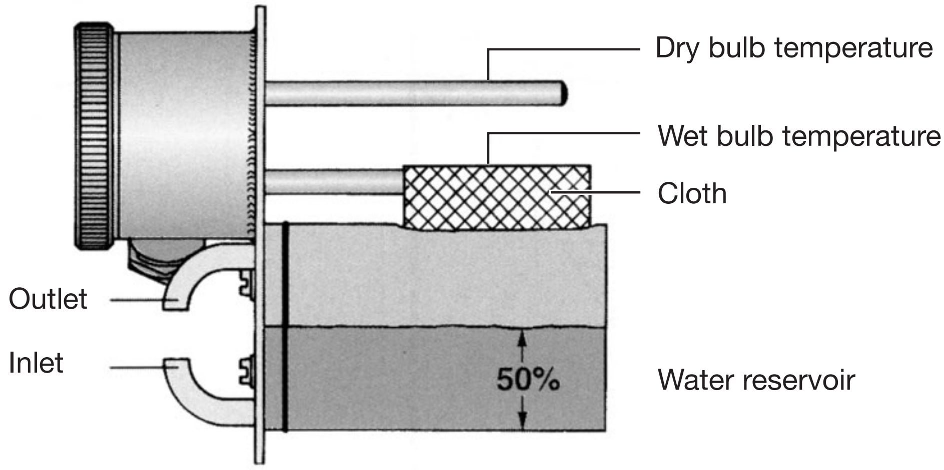


**Fig. 98: Electrical psychrometer**

The electrical psychrometer (Fig. 98) has an installation that is relatively insensitive compared with other humidity measurement methods, thus permitting measurement to a large extent in gases that are contaminated, corrosive, or contain solvents.

The determination of the relative humidity is made through the measurement of two temperatures.

- The **dry bulb temperature** is measured by a resistance thermometer – this corresponds to the ambient temperature.
- In a psychrometer, a second resistance thermometer is wrapped in a wet cloth. This so-called **wet bulb temperature** will be lower, depending on how much water evaporates. If the surroundings have a lower humidity, then the evaporation will be more rapid.

So there is a clear relationship between the relative humidity and the dry bulb / wet bulb temperatures.

If both temperature signals are connected to a JUMO controller, then some instruments are able to determine the relative humidity directly from these signals.

## 7.12 Interfaces

JUMO delivers three different types of interface for its controllers.

**Setup interface**
In most cases, the configuration of the instruments can be carried out in an associated configuration program. In this case, the user makes use of the “setup” interface.
The connection between the PC and the instrument is made by the setup cable.

**Fig. 99: DICON 500 process controller with a setup cable**

**RS422 / RS485 interface with MODbus protocol**
The MODbus protocol is very widely used in the field of process visualization systems. The connection is made via the above-mentioned serial interfaces. JUMO also supplies a visualization software (SVS-2000N), with which JUMO instruments can be represented on the PC and the corresponding process variables can be recorded, without any programming knowledge being required.

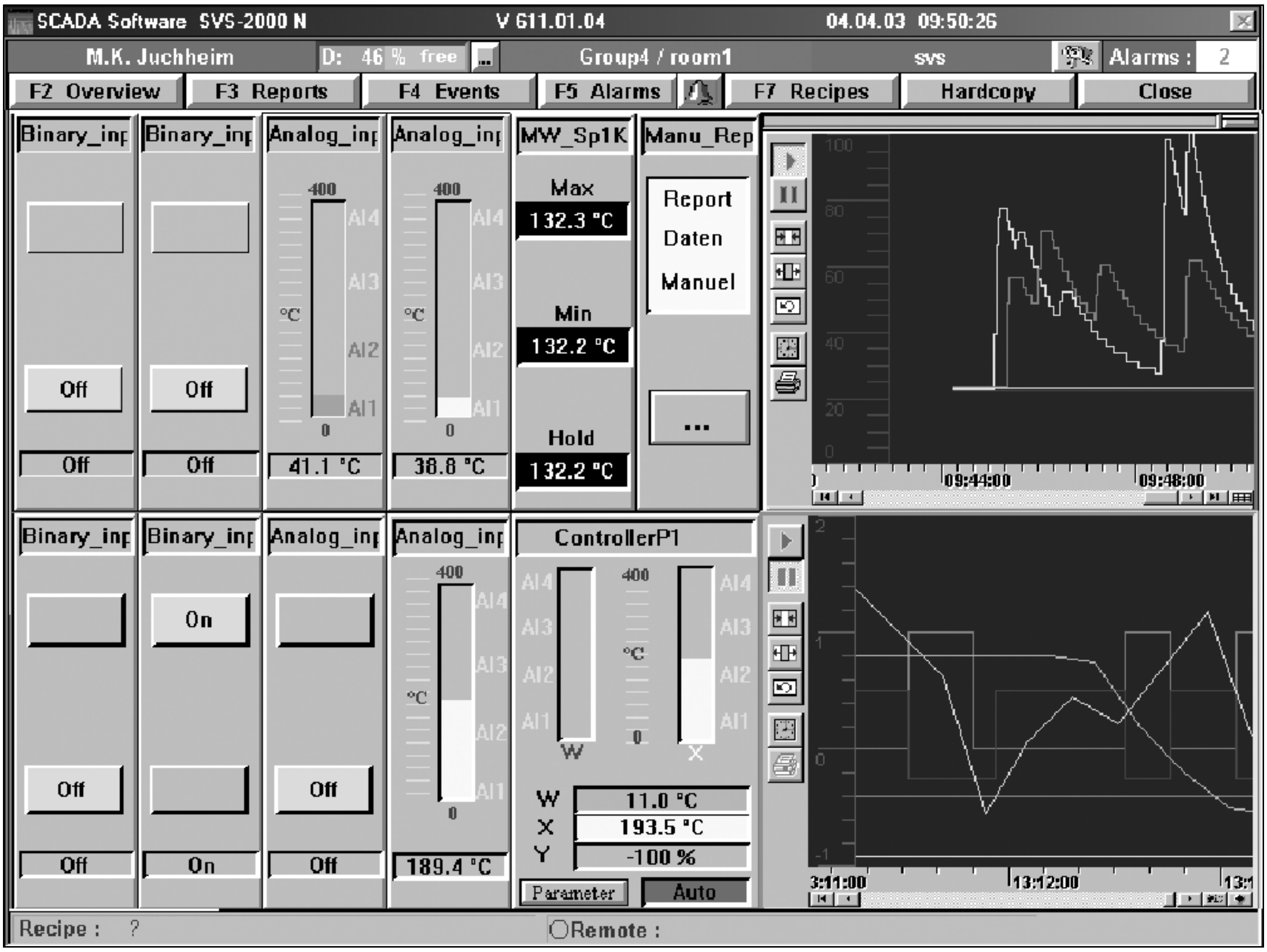


Fig. 100: **JUMO SVS-2000N**

**PROFIBUS-DP**
Controllers frequently have to be linked to a PLC. In the majority of applications this is done through PROFIBUS-DP. A large number of JUMO controllers are equipped with this interface.

**Note**
The fundamentals of bus systems and advice on linking to JUMO instruments are provided in the publication “Digital Interfaces and Bus Systems - fundamentals and practical advice for the connection of field devices” – see also the “Support” section at www.jumo.net

## Controller parameters

This section lists all the parameters for a JUMO controller (grouped according to function) that affect the control-loop functionality itself. In JUMO controllers you will find them at the parameter level or in the setup program, in the “Controller parameters” menu.

### PID action

| | |
|---|---|
| $P_b$ | Proportional band of the P component |
| $r_t$ | Reset time of the I component |
| $d_t$ | Derivative time of the D component |

### General parameters

| | |
|---|---|
| Y1 | Upper output level limit for the controller output signal<br>(not used with a modulating controller) |
| Y2 | Lower output level limit for the controller output signal<br>(not used with a modulating controller) |
| Y0 | Working point correction for a P controller (only meaningful with a P controller) |

### Parameters for 2- or 3-state controllers, modulating and actuating controllers

| | |
|---|---|
| $C_{y1}$ | Cycle time for the first binary output<br>(effective for 2- and 3-state controllers, $Pb_1$ >0) |
| $C_{y2}$ | Cycle time for the second binary output<br>(effective for 3-state controllers, $Pb_2$ >0) |
| $Tk_1$ | Minimum “on” time for the first binary output of the controller<br>(effective for 2- and 3-state controllers, $Pb_1$ >0) |
| $Tk_2$ | Minimum “on” time for the second binary output of the controller<br>(effective for 3-state controllers, $Pb_2$ >0) |
| $Hyst_1$ | Switching differential for the first binary output<br>(effective for 2- and 3-state controllers, $Pb_1 = 0$) |
| $Hyst_2$ | Switching differential for the second binary output<br>(effective for 3-state controllers, $Pb_2 = 0$) |
| $d_b$ | Contact spacing (dead band) db<br>The contact spacing is symmetrical about the setpoint. For 3-state controllers: the P components are moved apart by this amount. For modulating and actuating controllers: the motorized actuator is not activated within this band. |
| TT | The actuator stroke time (setting for modulating and actuating controllers) |

# Appendix: Abbreviations

## Further abbreviations

| | |
|---|---|
| $e$ | Control deviation (between setpoint and process value) |
| $K_{IS}$ | Transfer coefficient for the controlled process without self-regulation |
| $K_P$ | Proportional coefficient for the controller |
| $K_S$ | Transfer coefficient (gain) for the controlled process with self-regulation |
| $T_1$, $T_2$ | 1st and 2nd time constants in a 2nd order process |
| $T_a$ | Settling time: the process value for the control loop has stabilized to a constant value within a defined band about the setpoint |
| $T_{ap}$ | Approach time for the process value in a control loop to reach the setpoint for the first time |
| $T_g$ | Response time of a controlled process |
| $T_I$ | Integration time for an I controller |
| $T_K$ | Oscillation period of the process value at $Pb_k$ (optimization method according to Ziegler / Nichols) |
| $T_S$ | Time constant of the 1st order process |
| $T_t$ | Dead time of a process |
| $T_u$ | Delay time of a process |
| $V_{max}$ | Maximum slew rate (optimization method according to slew rate / rate of change) |
| $w$ | Setpoint |
| $x$ | Process value, process variable |
| $X_{max}$ | Overshoot |
| $Pb_k$ | The critical $P_b$, at which the process variable starts continuous oscillation (optimization method according to Ziegler / Nichols) |
| $y$ | Output level, manipulated variable (ANSI) |
| $y_H$ | Output level range of a controller, mostly 100 % |
| $y_R$ | Output level of a controller |
| $z$ | Disturbance |

# Index

# Index

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

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

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

In addition to JUMO Technical Literature and our new Software-Downloads we offer as well the possibility to order our brochures and CD-ROM catalogues online.

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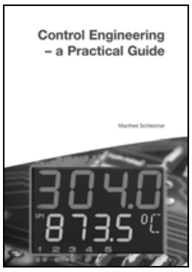

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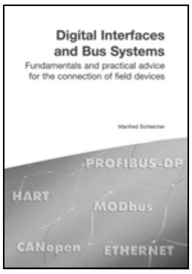

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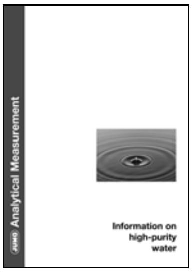

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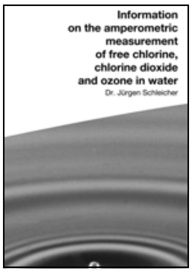

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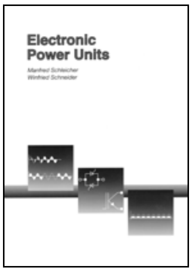

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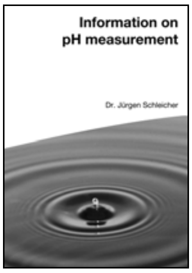

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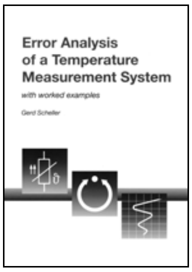

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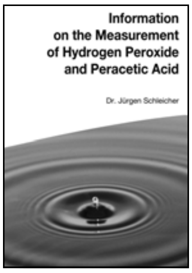

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