Technical Information

Controllers and Controlled Systems

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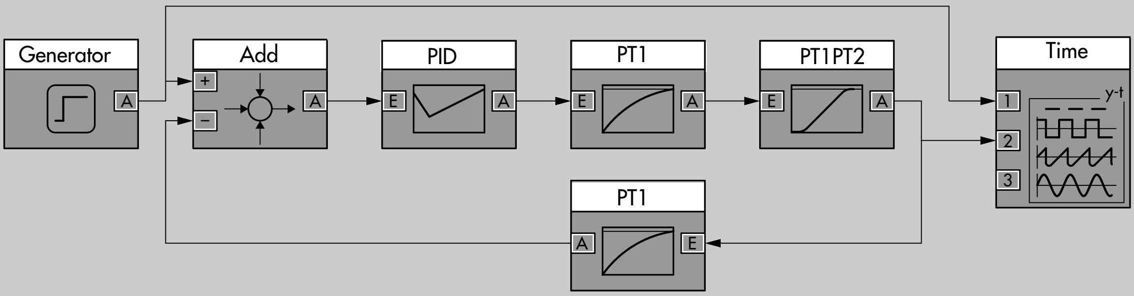

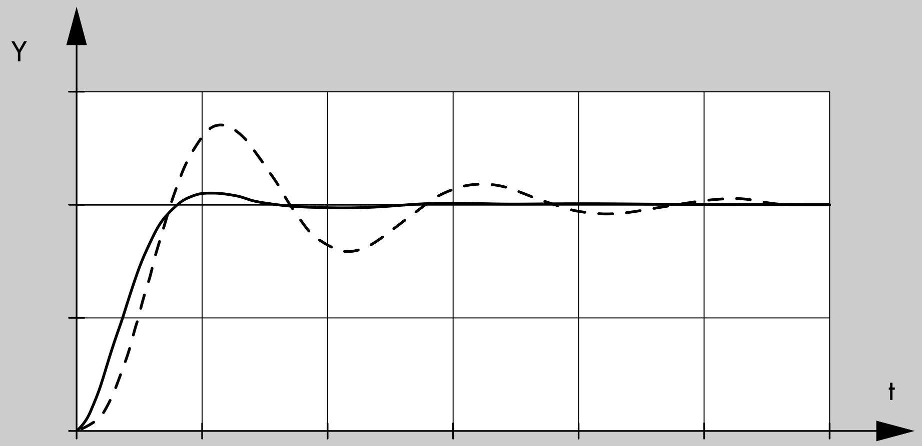

Part 1 Fundamentals

Technical Information

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Controller and Controlled Systems

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Introduction

control in language use

In everyday speech, the term 'control' and its many variations is frequently used. We can control a situation, such as a policeman controlling the traffic, or a fireman bringing the fire under control. Or an argument may get out of control, or something might happen to us because of circumstances beyond our control. The term 'control' obviously implies the restoration of a desirable state which has been disturbed by external or internal influences.

Control processes exist in the most diverse areas. In nature, for instance, control processes serve to protect plants and animals against varying environmental conditions. In economics, supply and demand control the price and delivery time of a product. In any of these cases, disturbances may occur that would change the originally established state. It is the function of the control system to recognize the disturbed state and correct it by the appropriate means.

In a similar way as in nature and economics, many variables must be controlled in technology so that equipment and systems serve their intended purpose. With heating systems, for example, the room temperature must be kept constant while external influences have a disturbing effect, such as fluctuating outside temperatures or the habits of the residents as to ventilation, etc.

control in technology

In technology, the term 'control' is not only applied to the control process, but also to the controlled system. People, too, can participate in a closed loop control process. According to DIN 19226, closed loop control is defined as follows:

Closed loop control is a process whereby one variable, namely the variable to be controlled (controlled variable) is continuously moni-tored, compared with another variable, namely the reference variable and influenced in such a manner as to bring about adaptation to the reference variable. The sequence of action resulting in this way takes place in a closed loop in which the controlled variable continuously influences itself.

continuous or sampling control

Note: 'Continuous' here also means a sufficiently frequent repetition of identical individual processes of which the cyclic program sequence in digital sampling controls is an example.

Being a little in the abstract, this definition is illustrated below with practical examples from control engineering applications. On the one hand, controlled systems and controllers will therefore be discussed as independent transfer elements and, on the other hand, their behavior in a closed control loop will be shown and compared.

Controlled Systems

In control engineering, a controlled system is primarily characterized by its dynamic behavior which also determines the scope and quality required to solve a control task. Frequently, the so-called step response of the controlled system is used to reflect this dynamic behavior.

step response indicates the dynamic behavior

The step response reveals how the controlled variable reacts to a change in the manipulated variable. This is determined by measuring the controlled variable after a step change in the manipulated variable. Depending on the resulting dynamic behavior, the controlled systems can be classified as follows:

classification of controlled systems

- P controlled systems (proportional control action)
- I controlled systems (integral control action)
- Controlled systems with dead time
- Controlled systems with energy storing components (first-, second- or higher-order)

with or without self-regulation

This classification as well as the controllability of systems will be discussed in the following chapters in more detail. It must be differentiated between controlled systems in which a new equilibrium is established after a disturbance or change in the manipulated variable and systems with a continuously changing controlled variable:

- Systems with self-regulation only change until a new stable output value is reached.
- Systems without self-regulation do not reach a new state of equilibrium.

Systems without self-regulation require closed loop control, because the manipulated variable must become zero as soon as the controlled variable reaches the required equilibrium. Only by means of closed loop feedback control can this be reached at the right point of time and to the proper extent. Practical experience shows that systems with self-regulation are often much easier to control than systems without self-regulation, because the latter have a tendency to oscillate, i.e. they tend to be more unstable. Therefore, a properly adapted controller is more important in the case of systems without self-regulation.

P controlled system

In controlled systems with proportional action, the controlled variable x changes proportional to the manipulated variable y. The controlled variable follows the manipulated variable without any lag.

P control action without any lag is possible in theory only

Since any energy transfer requires a finite amount of time, P control action without any lag does not occur in practice. When the time lag between manipulated and controlled variable is so small, however, that it does not have any effect on the system, this behavior is called proportional control action of a system or a P controlled system.

▸ Example: Flow control

If the valve travel changes in the pressure control system illustrated in Fig. 1, a new flow rate q is reached (almost) instantaneously. Depending on the valve flow coefficient, the controlled variable changes proportional to the manipulated variable; the system has proportional control action.

new equilibrium without lag

Fig. 2 shows the block diagram symbol for proportional action and the dynamic behavior of a P controlled system after a step change in the input varia-

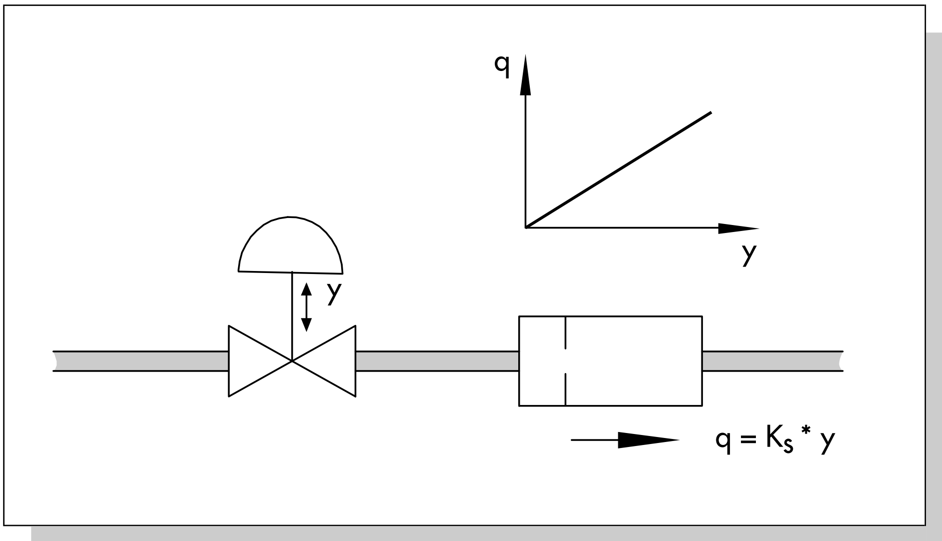

Fig. 1: Proportional controlled system; reference variable: flow rate

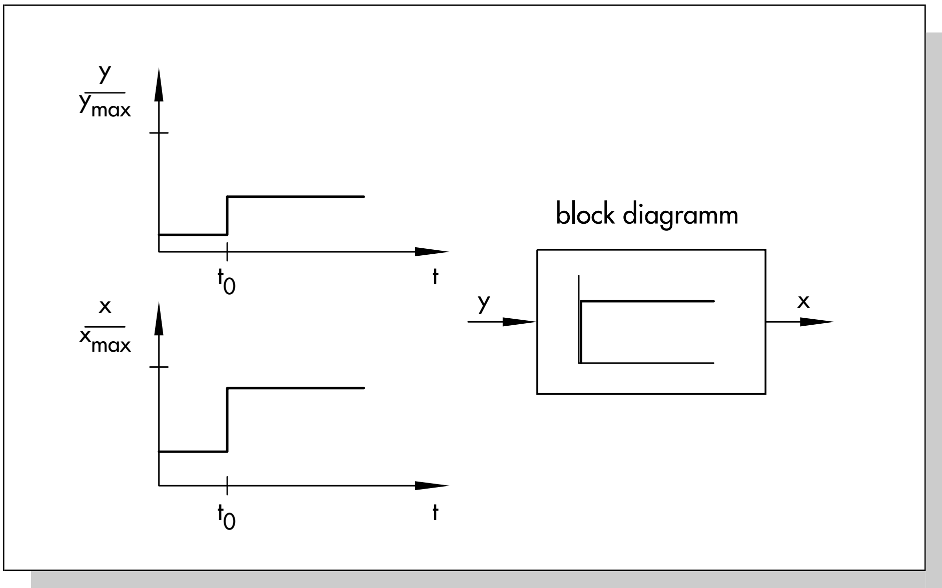

Fig. 2: Dynamic behavior of a P controlled system (y: control valve travel; x: flow rate in a pipeline)

ble. The characteristic curves clearly show that a proportional controlled system is a system with self-regulation, since a new equilibrium is reached immediately after the step change.

I controlled system

systems without self-regulation

Integral controlled systems are systems without self-regulation: if the manipulated variable does not equal zero, the integral controlled system responds with a continuous change – continuous increase or decrease – of the controlled variable. A new equilibrium is not reached.

- Example: Liquid level in a tank (Fig. 3)

In a tank with an outlet and equally high supply and discharge flow rates, a constant liquid level is reached. If the supply or discharge flow rate changes, the liquid level will rise or fall. The level changes the quicker, the larger the difference between supply and discharge flow.

marginal conditions limit the I control action

This example shows that the use of integral control action is mostly limited in practice. The controlled variable increases or decreases only until it reaches a system-related limit value: the tank will overflow or be discharged, maximum or minimum system pressure is reached, etc.

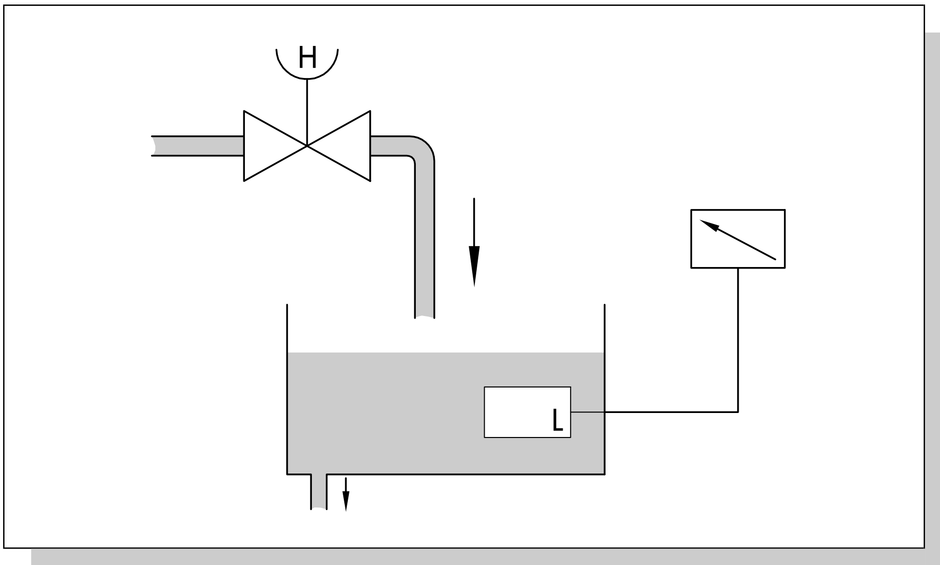

Fig. 3: Integral controlled system; controlled variable: liquid level in a tank

short integral-action time causes high rise time

Fig. 4 shows the dynamic behavior of an I controlled system after a step change in the input variable as well as the derived block diagram symbol for integral control action. The integral-action time T_n serves as a measure for the integral control action and represents the rise time of the controlled variable. For the associated mathematical context, refer to the chapter 'Controllers and Control Elements '.

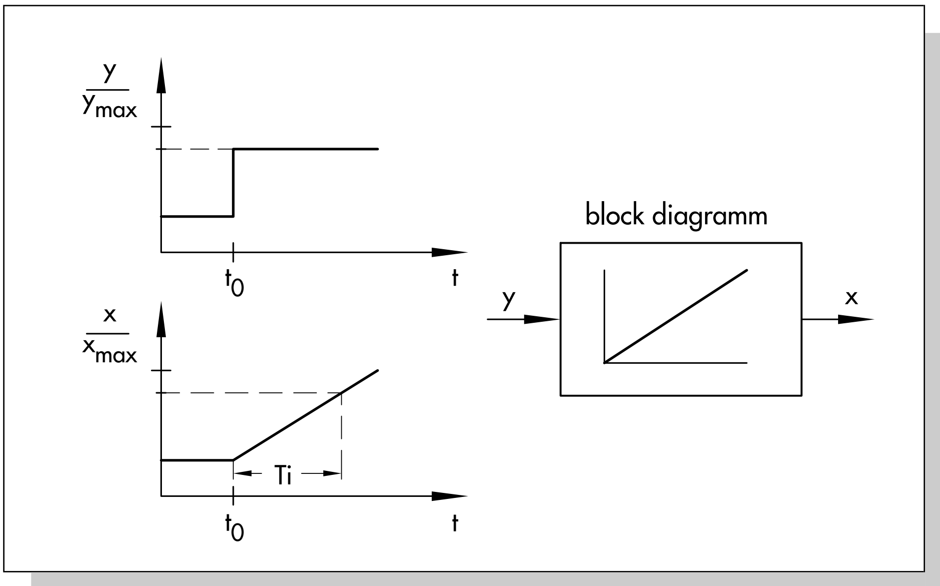

Fig. 4: Dynamic behavior of an I controlled system (y: valve travel; x: liquid level in a tank)

Controlled system with dead time

In systems with dead time there is no dynamic response until a certain amount of time has elapsed. The time constant T_L serves as a measure for the dead time or lag.

- Example: Adjustment of conveying quantity for conveyor belt (Fig. 5)

delayed response through lag

If the bulk material quantity fed to the conveyor belt is increased via slide gate, a change in the material quantity arriving at the discharge end of the belt (sensor location) is only noticed after a certain time.

Pressure control in long gas pipes exhibits similar behavior. Since the medium is compressible, it takes some time until a change in pressure is noticeable at the end of the pipeline.

Often, several final control elements are the cause of dead times in a control loop. These are created, e.g. through the switching times of contactors or the internal clearance in gears.

systems with dead times tend to oscillate

Dead times are some of the most difficult factors to control in process control situations, since changes in the manipulated variable have a delaying effect on the controlled variable. Due to this delay, controlled systems with dead times often tend to oscillate. Oscillations always occur if controlled variable and manipulated variable periodically change toward each other, delayed by the dead time.

In many cases, dead times can be avoided or minimized by skillful planning (arrangement of the sensor and the control valve; if possible, by selecting short pipelines; low heat capacities of the insulation media, etc.).

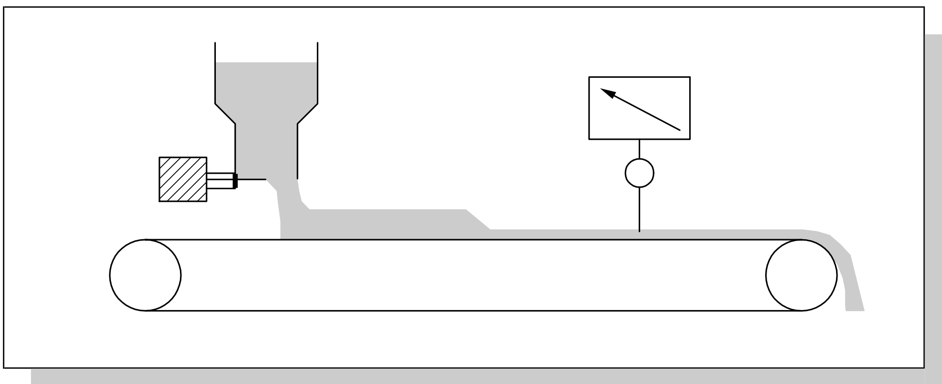

Fig. 5: Controlled system with dead time

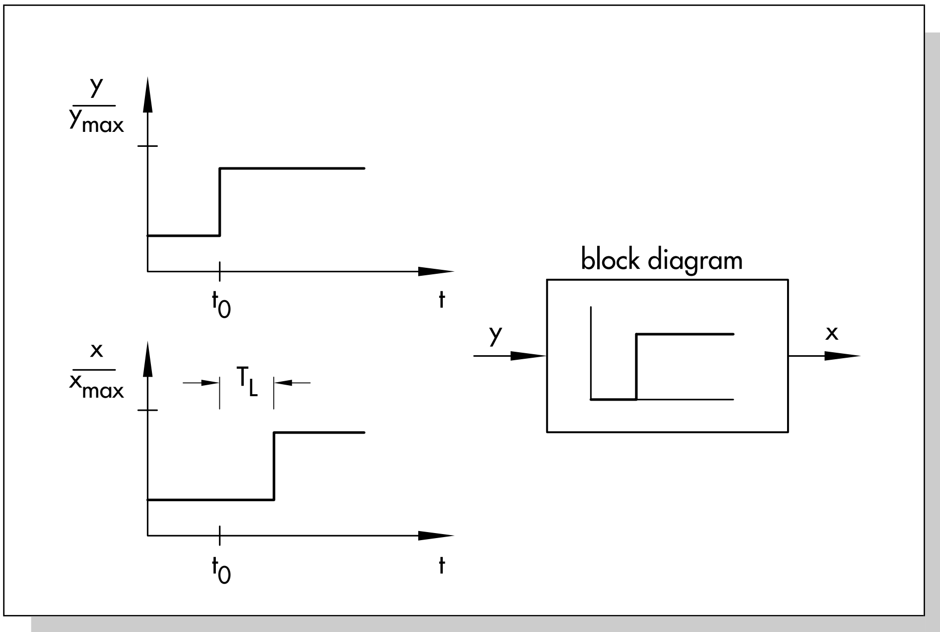

Fig. 6: Dynamic behavior of a controlled system with dead time (y: slide gate position; x: conveying quantity)

Controlled system with energy storing components

delays caused by storing components

Delays between changes in the manipulated and controlled variable are not only created due to dead times. Any controlled system usually consists of several components that are characterized by the capacity to store energy (e.g. heating system with heat storing pipes, jackets, insulation, etc.). Due to these components and their energetic state which changes only gradually, energy consumption or discharge occurs time delayed. This also applies to all condition changes of the controlled system, because these are originated in the transfer or conversion of energy.

▸ Example: Room temperature control

A heating system is a controlled system with several energy storing components: boiler, water, radiator, room air, walls, etc.

When the energy supply to the boiler is changed or the radiator shut-off valve is operated in the heated room, the room temperature changes only gradually until the desired final value is reached.

It is characteristic of controlled systems with energy storing components that the final steady-state value is reached only after a finite time and that the speed of response of process variable x changes during the transitional peri-

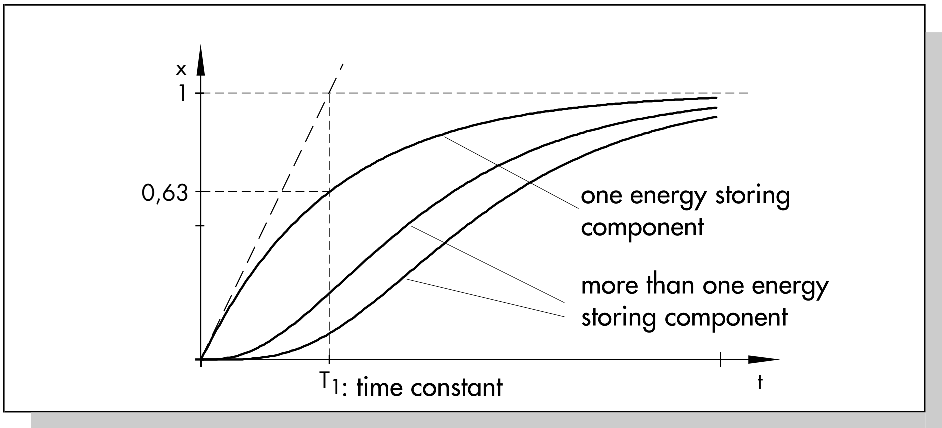

Fig. 7: Exponential curves describe controlled systems with energy storing components

od (Fig. 7). In principle, the speed of response slows down as it approaches its final value, until it asymptotically reaches its final value. While the output variable may suddenly change in systems with dead times, systems with energy storing components can only change steadily.

exponential curves characterize dynamic behavior

The dynamic behavior of the system depends on those lags that produce the decisive effect, thus, on the size of the existing storing components. Essentially, large components determine this factor so that smaller components frequently have no effect.

▸ Example: Room temperature control

The dynamic behavior of a room temperature control system is significantly influenced by the burner capacity and the size of boiler, room and radiator. The dynamic behavior depends on the heating capacity of the heating pipes only to a very small extent.

classification of systems with lags

Controlled systems with energy storing components are classified according to the number of lags that produce an effect. For instance, a first-order system has one dynamic energy storing component, a second-order system has two energy storing components, etc. A system without any lags is also referred to as a 'zero-order system' (see also P controlled system). A behavior resembling that of a zero-order system may occur in a liquid-filled pressure system without equalizing tanks.

- First-order system

temperature control via mixing valve

A first-order system with only one dynamic energy storing component is illustrated in Fig. 8: the temperature of a liquid in a tank equipped with inlet, outlet and agitator is adjusted via mixing valve. Due to the large tank volume, the temperature changes only gradually after the valve has been adjusted (step change).

The dynamic behavior of a first-order system is shown in Fig. 9. A measure for the speed of response is the time constant T_1. It represents the future time

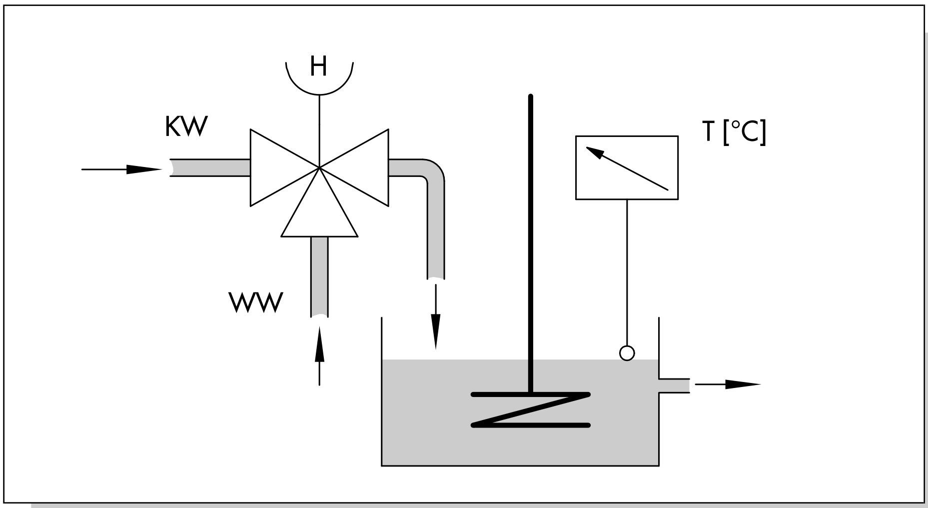

Fig. 8: First-order controlled system; controlled variable: temperature

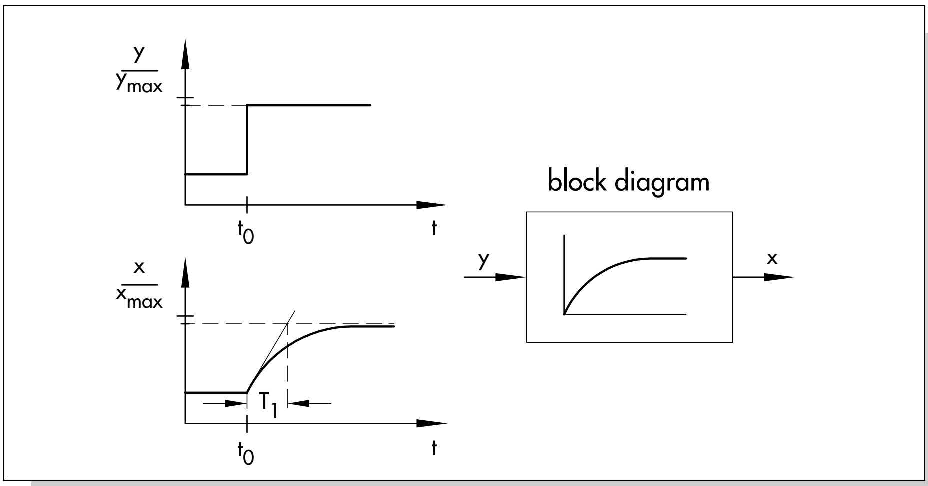

Fig. 9: Dynamic behavior of a first-order controlled system – PT_1 element (y: valve position; x: temperature of liquid in tank)

necessary for the controlled variable x (response curve) to reach 63% of its final value after a step input has been introduced. The course of the function is derived as follows:

$$x(t) = 1 - e^{-\frac{t}{T_1}}$$

Such delayed proportional behavior with a first-order lag is also referred to as PT_1 behavior. The higher the time constant T_1, the slower the change in the controlled variable and the larger the energy storing component causing this lag.

time constant defines the dynamic behavior

If the dynamic behavior of a system is only known as a response curve, T_1 can be graphically determined with the help of the tangent shown in Fig. 9.

- Second-order and higher-order systems

If there are two or more energy storing components between the manipulated variable and the controlled variable, the controlled system is referred to as second- or higher-order system (also called PT_2, PT_3 system, etc.). When two first-order systems are connected in series, the result is one second-order system, as shown in Fig. 10.

n^{th} order systems exhibit PT_n behavior

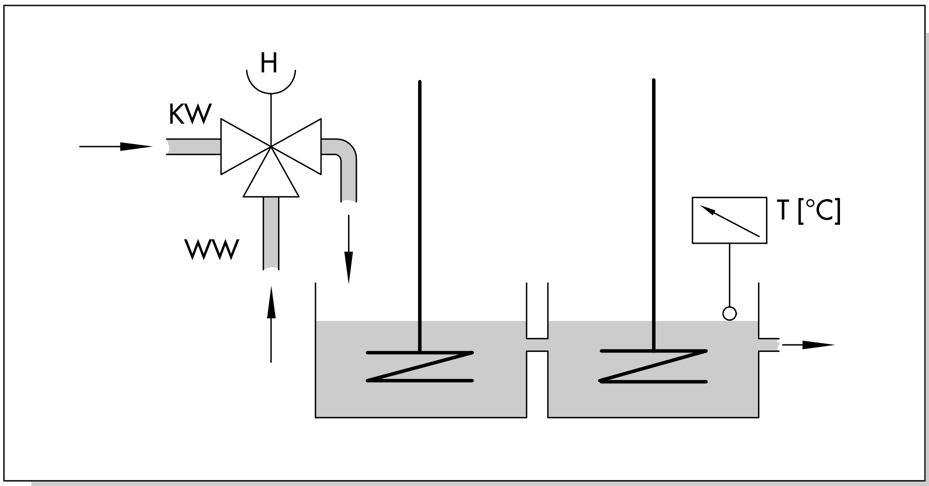

Fig. 10: Second-order controlled system; controlled variable: temperature

step response with inflection point...

The dynamic behavior of such a system is reflected by the characteristic curves shown in Fig. 11. The step response of the controlled variable shows an inflection point which is characteristic of higher-order systems (Figs. 11 and 12): initially, the rate of change increases up to the inflection point and then continuously decreases (compare to behavior of first-order systems: Fig. 8).

... and time constants of the individual PT_1 elements

Mathematically, the characteristic of a higher-order system is described by the time constants T_1, T_2, etc. of the individual systems. The characteristic curve for the step response is then derived as follows:

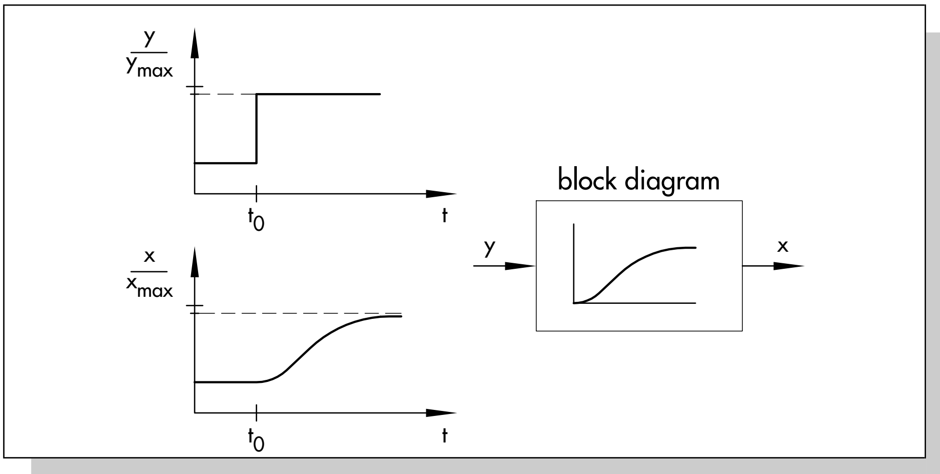

Fig. 11: Dynamic behavior of second- or higher-order controlled systems (y: valve position; x: medium temperature in the second tank)

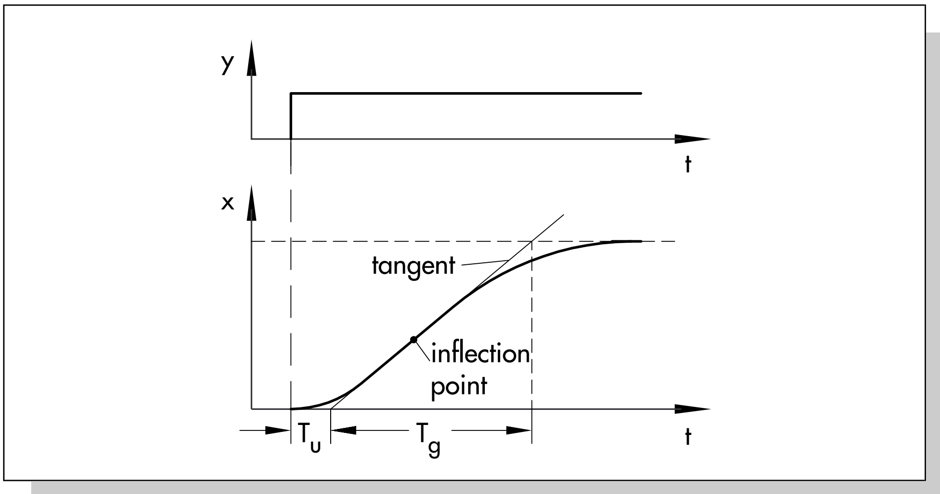

Fig. 12: Step response of a higher-order controlled system with the characteristic values T_u and T_g

$$x(t) = (1 - e^{-\frac{t}{T_1}})\,(1 - e^{-\frac{t}{T_2}})$$

T_u and T_g simplify the evaluation

For a simplified characterization of this behavior, the process lag T_u and the process reaction rate T_g are defined with the help of the inflection point tangents (Fig. 12). Since process lag has the same effect as dead time, a system is more difficult to control when T_u approaches the value of the process reaction rate T_g. The higher the system order, the less favorable does this relationship develop (Fig. 13).

time constants characterize the control response

The controllability improves, however, when the time constants T_1, T_2, etc. are as small as possible compared to the time required by the control loop for corrective action. Highly different time constants (factor 10 or higher) also simplify the controller adjustment since it can then be focused on the highest, the time determining value. It is therefore on the part of the practitioner to carefully consider these aspects already during the design phase of a process control system.

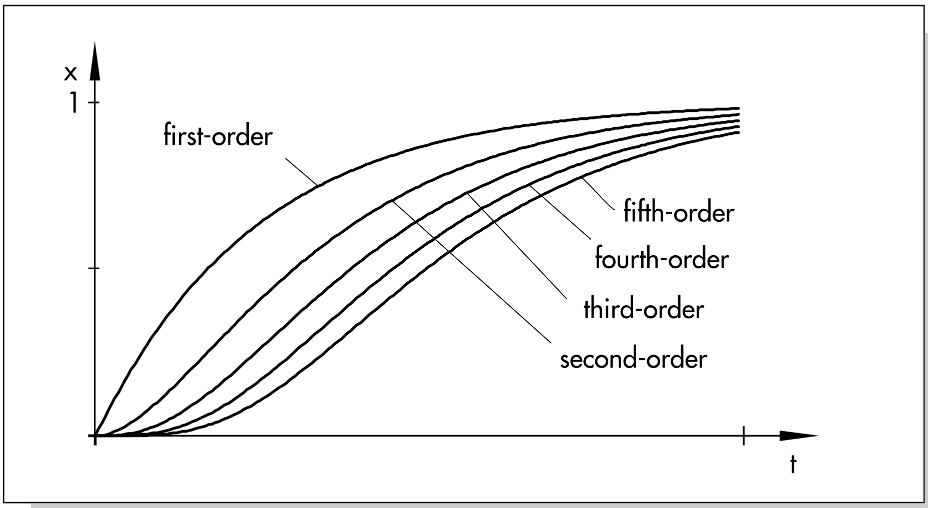

Fig. 13: Dynamic behavior of higher-order controlled systems

Characterizing Controlled Systems

System response

systems consist of several subsystems

A complex controlled system can be described through the combined action of several subsystems, each of which can be assigned with P, I, dead time or lag reaction. The system response is therefore a result of the combined action of these individual elements (Fig. 14: Actuator with internal clearance in its gears). In most cases, proportional or integral action occurs only after a certain lag and/or dead time has elapsed.

only time determining elements are important

The system-specific lags and/or dead times can also be so small that they do not have to be considered in the control process. In temperature controllers, for instance, the short time of opening the control valve can usually be neglected contrary to the much longer heating time.

Proportional-action coefficient

An important process variable in characterizing controlled systems with self-regulation is the factor K_{PS}. This factor indicates the ratio of change in the controlled variable x to the corresponding change in the manipulated

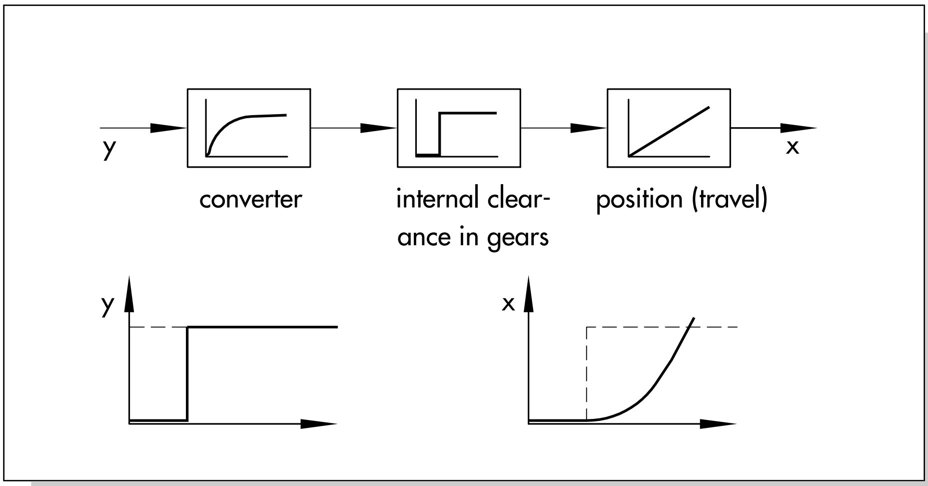

Fig. 14: Dynamic behavior of an actuator with internal clearance in its gears (lagging integral response with dead time)

variable y under balanced, steady-state conditions:

$$K_{PS} = \frac{\Delta x}{\Delta y} = \frac{x_2 - x_1}{y_2 - y_1}$$

K_{PS}: proportional-action coefficient of the system

To calculate K_{PS}, the system must reach a new equilibrium after a step change in the manipulated variable Δy. Since this requirement is only met by systems with self-regulation, K_{PS} is not defined for systems without self-regulation.

The factor K_{PS} is frequently referred to as system gain. This term is not quite correct. If K_{PS} is smaller than one, it does not have the effect of an amplification factor. Therefore, the proper term must be 'proportional-action coefficient'. To ensure that the above relationship applies irrespective of the nature of the variables, input and output signals are normalized by dividing them by their maximum values (100 % value).

Nonlinear response

dynamic behavior depends on the operating point

In many practical applications, K_{PS} is not constant over the complete range of the controlled variable, but changes depending on the corresponding operating point. Such a response is termed nonlinear which is often encountered in temperature control systems.

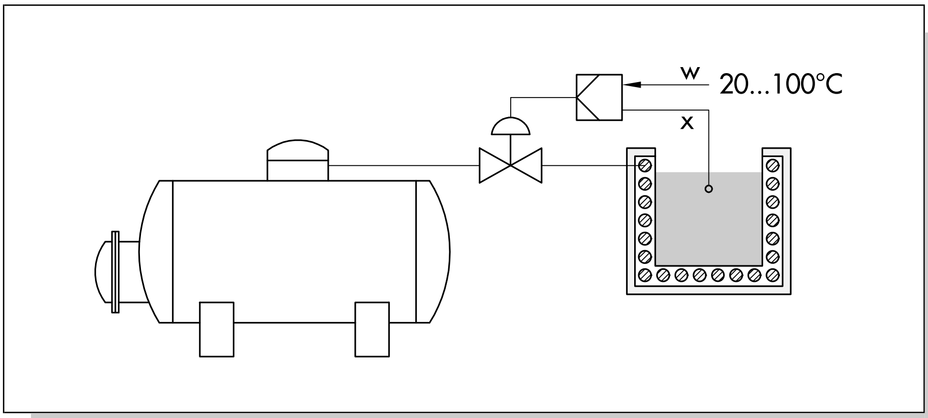

Fig. 15: Steam-heated tank

▸ Example: Heating a steam-heated tank (Fig. 15)

heat dissipation changes with the temperature difference

A steam-heated water bath is a controlled system with self-regulation. The water bath and the tank material in which the pipeline is embedded are two large heat storing components which can be considered a second-order controlled system. Since a body being heated will convey more and more heat into the environment as the heating temperature increases, the coefficient K_{PS} changes with the water bath temperature (Fig. 16). To increase the temperature at high temperatures, comparatively more energy must be supplied than at low temperatures. Therefore, the following applies:

$$K_{PS}(0°\,C) > K_{PS}(100°\,C)$$

Operating point (OP)

nonlinearity makes control more difficult

If the reaction of nonlinear systems is analyzed with the help of step responses, a different dynamic behavior of the controlled variable can be observed at each operating point. With the above illustration of water bath heating, entirely different values are obtained for K_{PS}, T_u and T_g that depend on the operating temperature. This behavior is a disadvantage for the controlled system, because it leads to an operating point-dependent control response of the system.

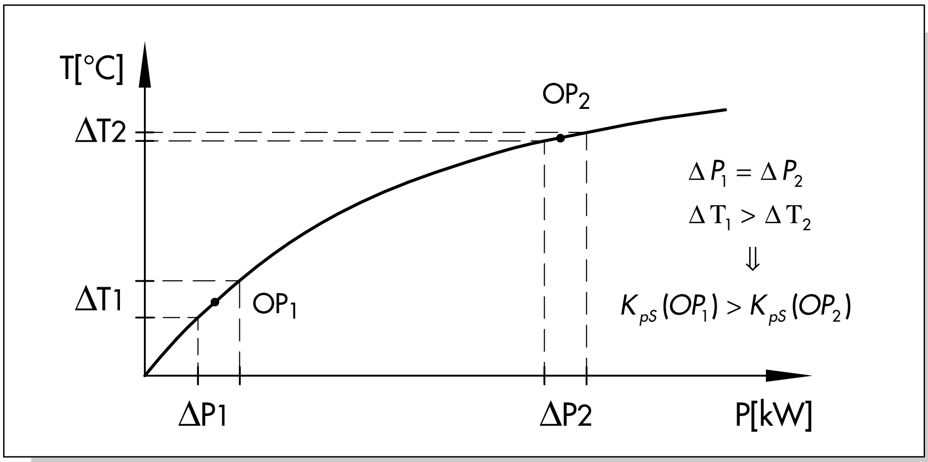

Fig. 16: Operating point-dependent behavior of the steam-heated tank

▸ Example: Nonlinearity of the steam-heated tank (Fig. 15 and 16)

The characteristic in Fig. 16 shows that the controlled system in the lower temperature range has a higher proportional-action coefficient than in the upper range. If the temperature controller of the bath is adjusted so that a favorable control action is obtained at low temperatures, there will be longer delays at high temperatures and vice versa: if the control action is favorable at high temperatures, oscillations might occur at low temperatures.

optimum control action is obtained at only one operating point

The adjustment of the controller is easier if a nonlinear system is operated at a fixed operating or working point. Since K_{PS} changes only very little in the immediate surrounding area of the operating point (see OP_1 and OP_2 in Fig. 16), the control action is consequently influenced very little as well.

tuning the controller to a fixed operating point...

If a nonlinear system is mostly or principally operated at one fixed operating point, the controller is tuned especially to this operating point. The system parameters (e.g. T_u/T_g) must therefore be determined for this operating point only and, if applicable, to its immediate surrounding area.

... or an entire operating range

If a fixed operating point cannot be defined, such as with follow-up control systems, the adjustment of the controller parameters remains a compromise. In that case, the controller is usually tuned to medium system gain.

Controllability of systems with self-regulation

assessing the controllability with T_g/T_u

For systems without integral-action component, the controllability can be assessed by means of the process reaction lag T_u and process reaction rate T_g (see also page 17). To do this, a simplified assumption is made, saying that the system response is described sufficiently accurate by one dead time and one lag.

T_u and T_g can best be determined graphically by using a series of measurements. In open loop control, the system response is determined after small step changes in the manipulated variable. In nonlinear systems, this measurement must be made at different operating points. The relationship between T_g and T_u, which is determined from the measuring curves, indicates which control response must be expected.

Ratio T_g/T_u	System is ...
$0 < \frac{T_g}{T_u} \leq 3$	difficult to control;
$3 < \frac{T_g}{T_u} < 10$	only just controllable;
$10 \leq \frac{T_g}{T_u}$	easy to control.

magnitude of T_u and T_g

Example: T_u and T_g for controlled systems in process engineering

Controlled variable	Type of controlled system	T_u	T_g
Temperature	Autoclaves Extruder	30 to 40 s 1 to 6 min	10 to 20 min 5 to 60 min
Pressure	Oil-fired boiler	0 min	2.5 min
Flow rate	Pipeline with gas Pipeline with liquid	0 to 5 s 0 s	0.2 s 0 s

Controllers and Control Elements

A controller's job is to influence the controlled system via control signal so that the value of the controlled variable equals the value of the reference value. Controllers consist of a reference and a control element (Fig. 17). The reference element calculates the error (e) from the difference between reference (w) and feedback variable (r), while the control element generates the manipulated variable (y) from the error:

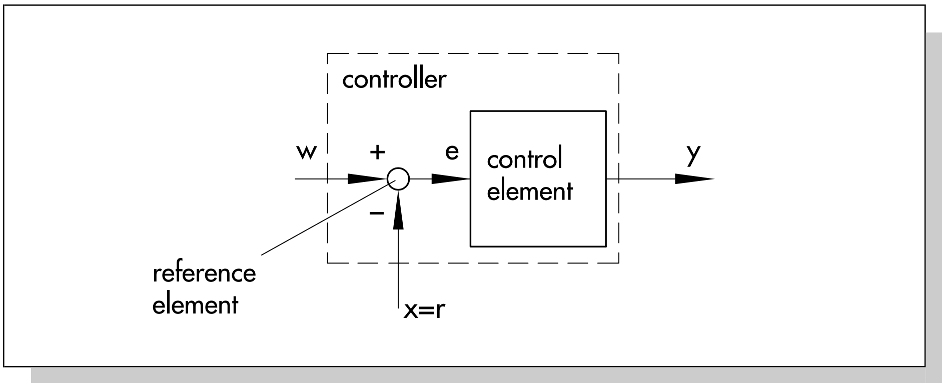

Fig. 17: Controller components

Classification

Control elements can be designed in many different ways. For instance, the manipulated variable y can be generated

functional principle

- mechanically or electrically,
- analog or digitally,
- with or without auxiliary energy

from the error e. Although these differences significantly influence the controller selection, they have (almost) no impact on the control response. First and foremost, the control response depends on the response of the manipulated variable. Therefore, controllers are classified according to their control signal response. Depending on the type of controller, the control signal can either be continuous or discontinuous.

control signal response ⇔ control response

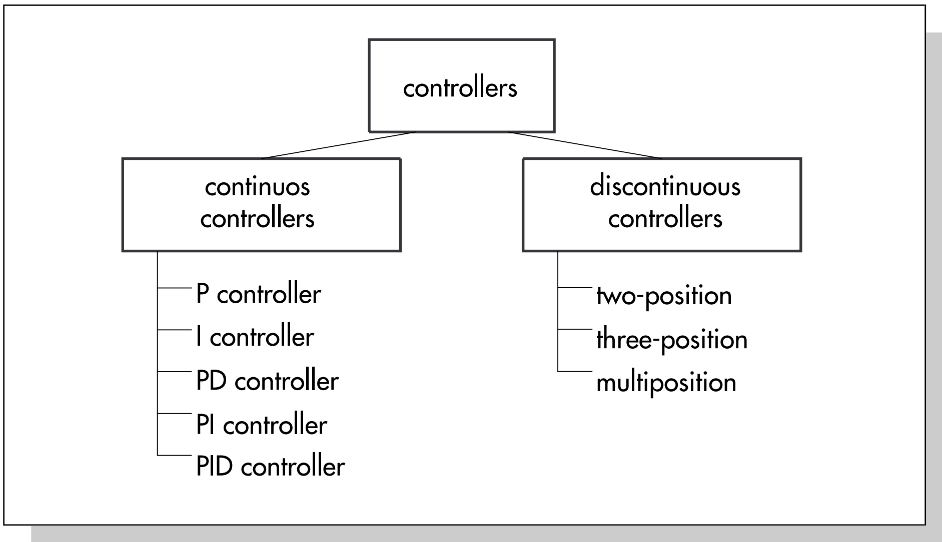

Fig. 18: Classification of controllers

Continuous and discontinuous controllers

continuous...

In continuous controllers, the manipulated variable can assume any value within the controller output range. The characteristic of continuous controllers usually exhibits proportional (P), integral (I) or differential (D) action, or is a sum of these individual elements (Fig. 18).

...or discrete range of the manipulated variable

In discontinuous controllers, the manipulated variable y changes between discrete values. Depending on how many different states the manipulated variable can assume, a distinction is made between two-position, three-position and multiposition controllers. Compared to continuous controllers, discontinuous controllers operate on very simple, switching final controlling elements. If the system contains energy storing components, the controlled variable responds continuously, despite the step changes in the manipulated variable. If the corresponding time constants are large enough, good control results at small errors can even be reached with discontinuous controllers and simple control elements.

Auxiliary energy

externally supplied energy or energy derived from the system

Any controller and final controlling element requires energy to operate. Controllers externally supplied with pneumatic, electric or hydraulic energy are classified as controllers with auxiliary energy. If no energy transfer medium is available at the point of installation, self-operated regulators should be

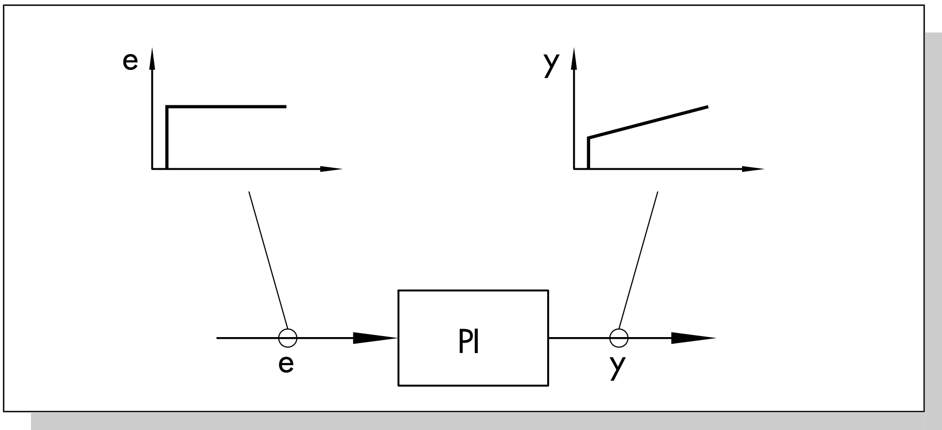

Fig. 19: Step response of a controller

used. They derive the energy they require to change the manipulated variable from the controlled system. These cost-effective and rugged controllers are often used for pressure, differential pressure, flow and temperature control. They can be used in applications where the point of measurement and the point of change are not separated by great distances and where system deviations caused by energy withdrawal are acceptable.

Determining the dynamic behavior

As with the controlled systems, the following chapters will illustrate the dynamic behavior of individual controllers based on step responses (Fig. 19). The resulting control response can be shown even more clearly in a closed control loop.

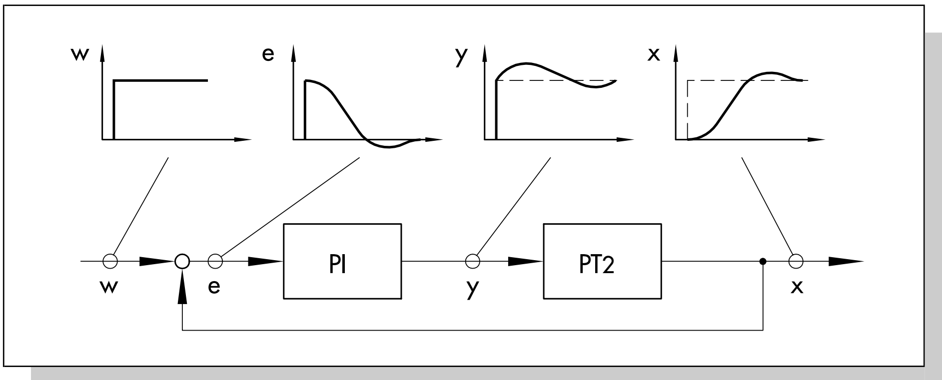

Fig. 20: Signal responses in a closed control loop

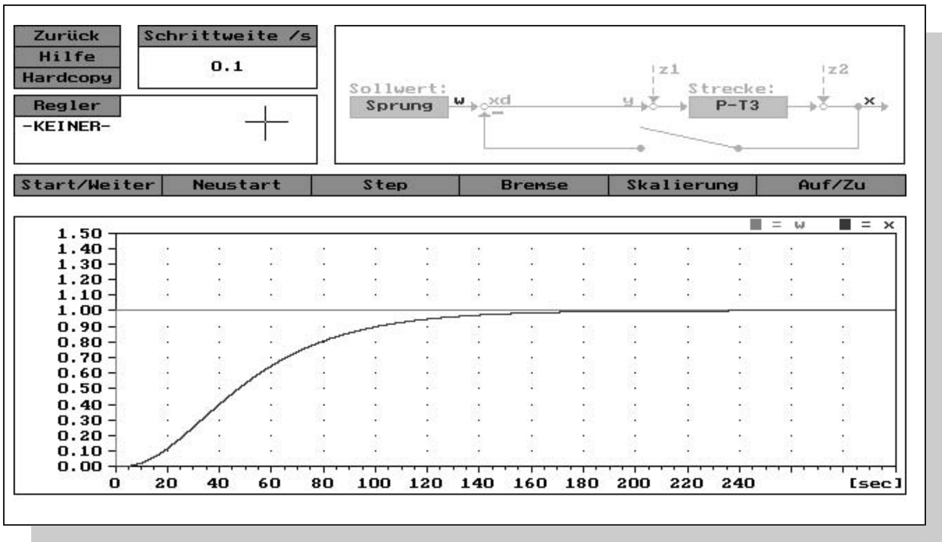

Fig. 21: Step response the third-order reference system

action flow in a closed control loop

In a closed control loop, a step change in the reference variable first results in a step increase in the error signal e (Fig. 20). Due to the control action and the feedback, the error signal will decrease in time. Finally, the controlled variable will reach a new steady state, provided that the control response is stable (Fig. 20: Controlled variable x).

comparison of control responses based on a ´reference system´

In order to be able to compare and analyze the response of different controllers, each controller will be discussed in regard to its interaction with the same 'reference system'. This is a third-order system with the following parameters:

Proportional-action coefficient: $K_P = 1$

System parameters: $T_1 = 30$ s; $T_2 = 15$ s; $T_3 = 10$ s .

The lag and the proportional-action of this system can be seen in Fig. 21. It shows the step response, i.e. the response of the output variable (controlled variable x) to a step change in the input variable (manipulated variable y).

Continuous Controllers

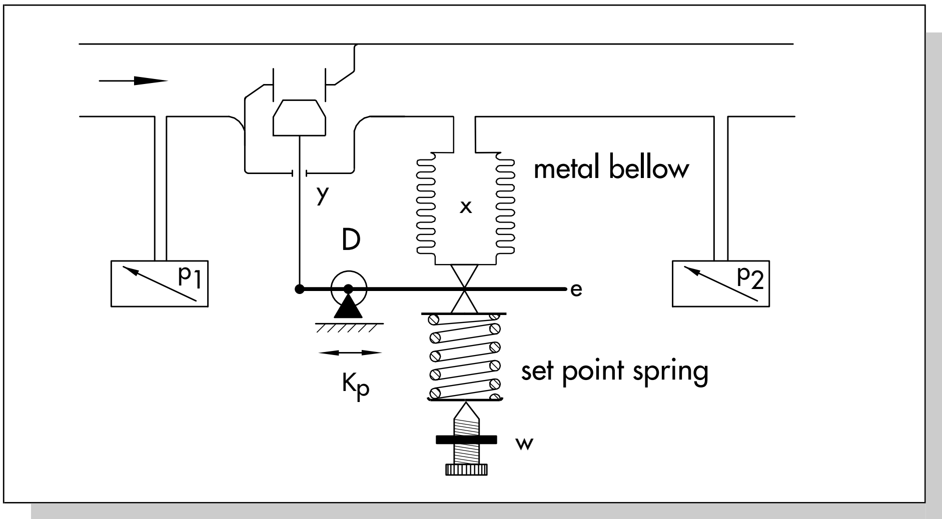

Fig. 22: Design of a P controller (self-operated regulator)

Proportional controller (P controller)

The manipulated variable y of a P controller is proportional to the measured error e. From this can be deducted that a P controller

- reacts to any deviation without lag and
- only generates a manipulated variable in case of system deviation.

manipulated variable changes proportional to error

The proportional pressure controller illustrated in Fig. 22 compares the force F_S of the set point spring with the force F_M created in the elastic metal bellows by the pressure p_2. When the forces are off balance, the lever pivots about point D. This changes the position of the valve plug – and, hence, the pressure p_2 to be controlled – until a new equilibrium of forces is restored.

- Proportional-action coefficient

The dynamic behavior of the P controller after a step change in the error variable is shown in Fig. 23. The amplitude of the manipulated variable y is determined by the error e and the proportional-action coefficient K_P:

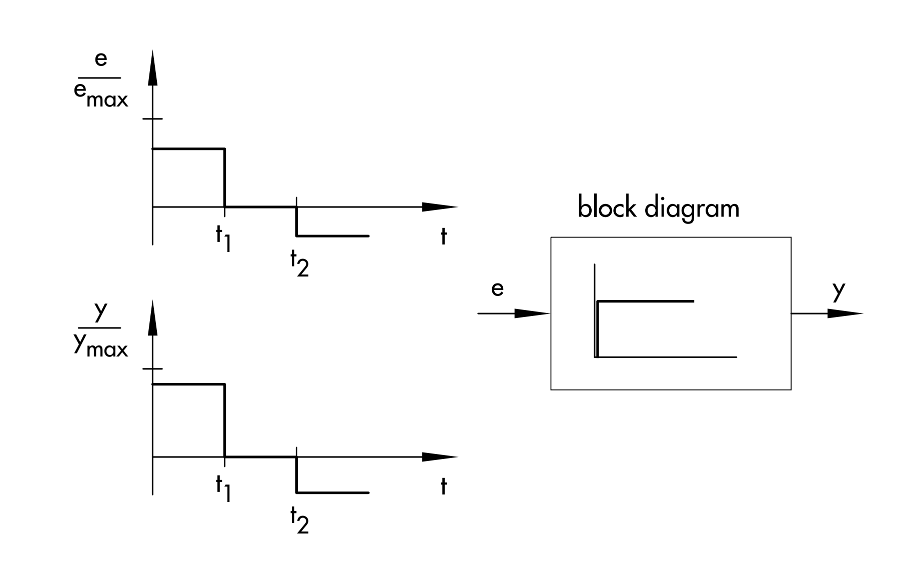

Fig. 23: Dynamic behavior of a P controller (e: system devitation; y: manipulated variable)

$$y = K_P \cdot e \qquad \text{with: } K_P \text{ as proportional-action coefficient}$$

high K_P causes strong control action

The term describes a linear equation whose gradient is determined by K_P. Fig. 24 clearly shows that a high K_P represents a strongly rising gradient, so that even small system deviations can cause strong control actions.

proportional-action *coefficient* or proportional band

Note: In place of the proportional-action coefficient K_P, the old term 'proportional band' is frequently used in literature which is represented by the parameter X_P[%]. The parameter is converted as follows:

$$X_P = \frac{100[\%]}{K_P} \qquad \text{or} \qquad K_P = \frac{100[\%]}{X_P}$$

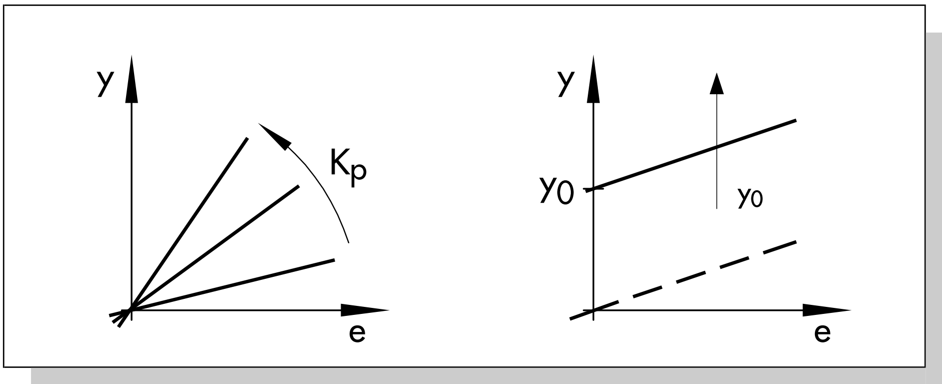

Fig. 24: Effect of K_P and operating point adjustment

- System deviation

Controllers compensate for the effect of disturbance variables by generating a corresponding manipulated variable acting in the opposite direction. Since P controllers only generate a manipulated variable in case of system deviation (see definition by equation), a permanent change, termed 'steady-state error', cannot be completely balanced (Fig. 25).

characteristic feature of P controllers: steady-state error

Note: Stronger control action due to a high K_P results in smaller system deviations. However, if K_P values are too high, they increase the tendency of the control loop to oscillate.

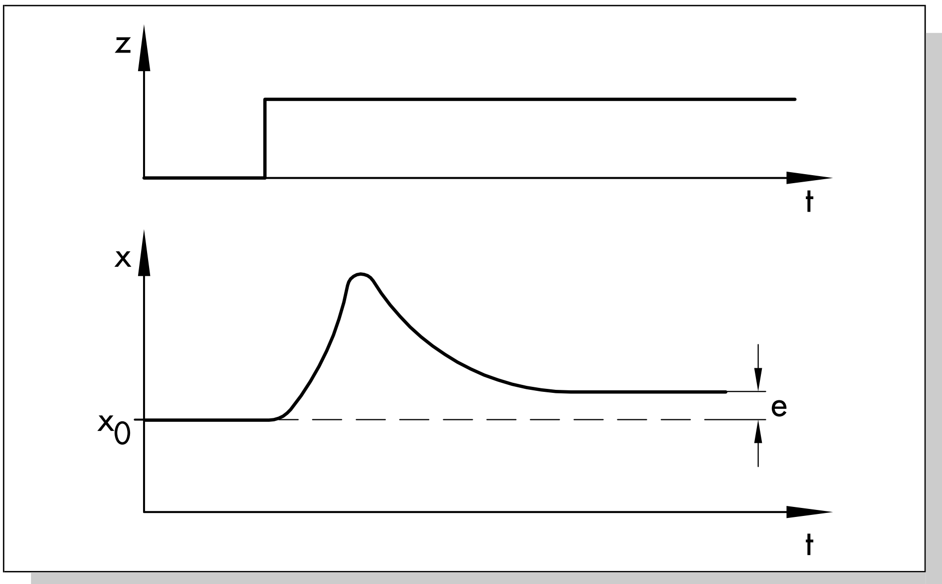

Fig. 25: Steady-state error in control loops with P controllers
x_0: adjusted operating point of the controller

- Adjusting the operating point

selection of the control amplitude at steady state

In the 'ideal' control situation, i.e. with zero error, proportional-only controllers do not generate control amplitudes (see above). This amplitude is required, however, if the controlled variable is to be kept at any level of equilibrium in a system with self-regulation. In order to achieve this anyhow, P controllers require an option for adjusting the operating point. This option is provided by adding a variable offset y_0 to the manipulated variable of the

$y = K_P \cdot e + y_0$	y_0 : manipulated variable at operating point

P controller:

This way, any control amplitude y_0 can be generated, even with zero error. In mathematical terms, this measure corresponds to a parallel displacement of the operating characteristic over the entire operating range (see Fig. 24).

Note: Selecting an operating point – y_0 nonzero – only makes sense for systems with self-regulation. A system without self-regulation will only reach steady state when the manipulated variable equals zero (example: motor-driven actuator).

▸ Example: Operating point and system deviation in pressure reducing valves

In a pressure control system (Fig. 26), p_2 lies within the range of 0 to 20 bar, the operating point (p_{OP}, q_{Op}) is p_{Op} = 8 bar.

If the proportional-action coefficient is set to K_P = 10, the valve passes through the entire travel range with a 10 percent error. If the spring is not preloaded (y_0 = 0), the pressure reducing valve is fully open at 0 bar (H_{100}) and fully closed at 2 bar (H_0). The operating point (p_{OP}, q_{OP}) is not reached; significant system deviation will occur.

operating point adjustment by preloading the spring

With the help of the operating point adjustment the spring can be preloaded in such a manner that the valve releases the cross-sectional area which is exactly equivalent to the operating point at p_2 = 8 bar => zero system deviation.

For instance, this would allow the following assignment (Fig. 26):

9,0 bar:	valve closed	H_0
8,0 bar:	valve in mid-position (q_{OP})	H_{OP}
7,0 bar:	valve fully open	H_{100}

high K_P reduces system deviation and increases the tendency to oscillate

There is a maximum system deviation of ≤ 0.5 bar over the entire valve travel range. If this is not tolerable, K_P must be increased: a K_P of 50 reduces the system deviation to ≤ 0.2 bar (20 bar/50 = 0.4 bar). However, K_P cannot be increased infinitely. If the response in the controller is too strong, the controlled variable will overshoot, so that the travel adjustment must be subsequently reversed for counteraction: the system becomes instable.

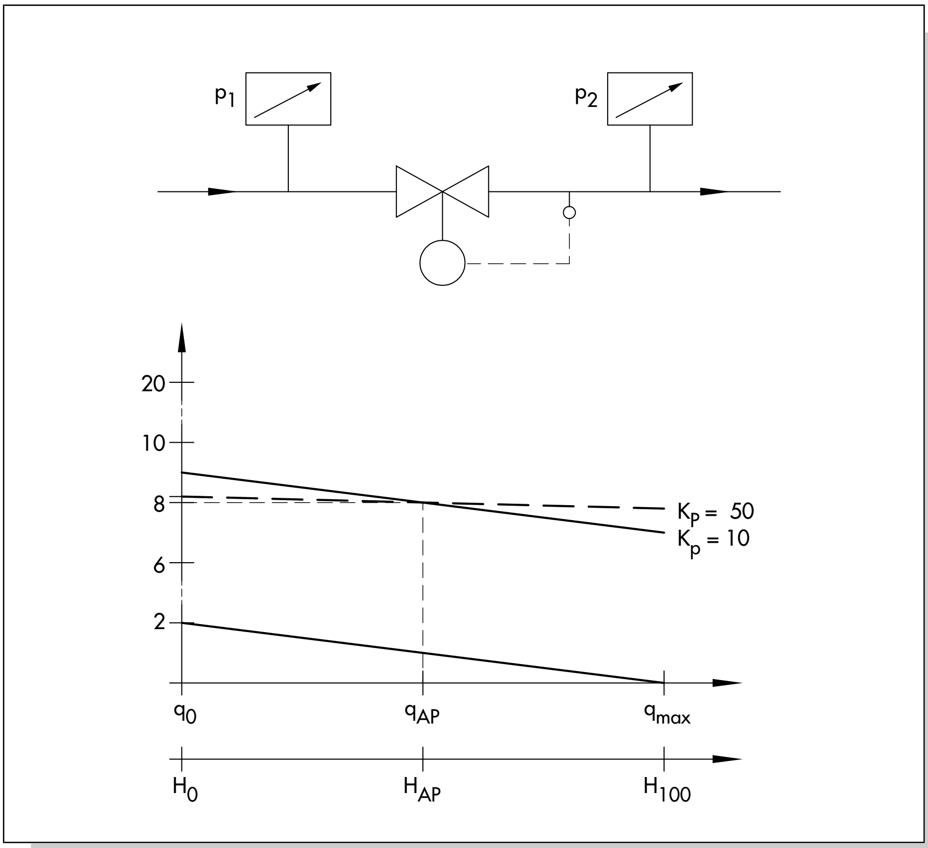

Fig. 26: Functional principle and characteristics of a pressure reducing valve

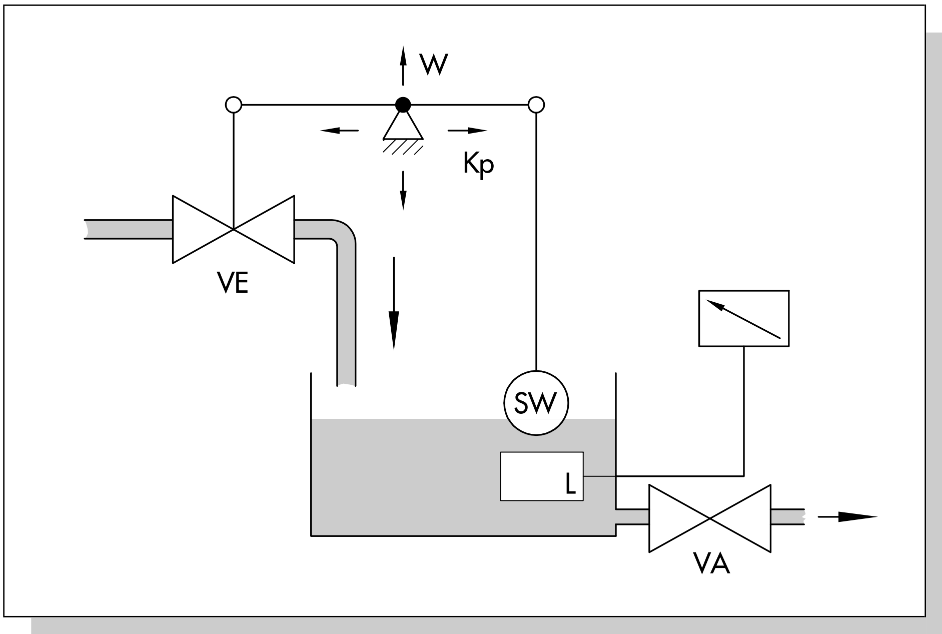

Fig. 27: Level control with a P controller (self-operated regulator)

- Example: Proportional level control

The water in a tank (Fig. 27) is to be kept at a constant level, even if the output flow rate of the water is varied via the drain valve (VA).

The illustrated controlling system is at steady state when the supplied as well as the drained water flow rates are equally large the liquid level remains constant.

level control: principle of operation

If the drain valve (VA) is opened a little further, the water level will start to fall. The float (SW) in the tank will descend together with the water level. This will cause the rigid lever connected to the float to open the inlet valve (VE). The increasing flow finally prevents the water level from dropping still lower so that the system reaches a new equilibrium level.

By displacing the pivot of the lever upward or downward, a different stationary water level can be adjusted. If the individual components are sized properly, this type of control process will prevent the tank from discharging or overflowing.

The above example shows the typical characteristics of proportional control action:

- In case of disturbances, steady-state error is always sustained: when the outlet flow rate permanently changes, it is urgently required for the liquid level to deviate from the originally adjusted set point to permanently change the position of the inlet valve (VE) as well.

steady-state error

- The system deviation decreases at high gain (high proportional action coefficient), but also increases the risk of oscillation for the controlled variable. If the pivot of the lever is displaced towards the float, the controller sensitivity increases. Due to this amplified controlling effect, the supply flow changes more strongly when the level varies; too strong an amplification might lead to sustained variations in the water level (oscillation).

limit values in adjusting K_P

Note: The illustrated level control system uses a self-operated regulator. The control energy derived from the system is characteristic of this controller type: the weight of the float and the positioning forces are compensated for by the buoyancy of the float caused by its water displacement.

self-operated regulators for simple control tasks

- Control response (based on the example of the PT_3 system)

Control of a PT_3 system ($K_P = 1$; $T_1 = 30$ s; $T_2 = 15$ s; $T_3 = 10$ s) with a P controller results in the control response shown in Fig. 28. As previously mentioned, the system's tendency for oscillation increases with increasing K_P, while the steady-state error is simultaneously reduced.

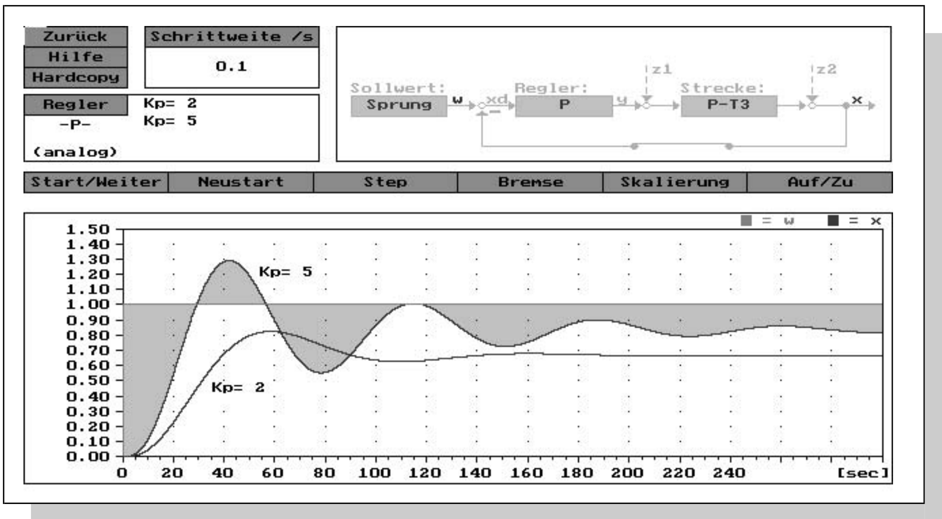

Fig. 28: Control response of the P controller based on a PT_3 system

P controllers exhibit the following advantages:

- Fast response to changes in the control process due to immediate corrective action when an error occurs.
- Very stable control process, provided that K_P is properly selected.

P controllers exhibit the following disadvantages:

- Steady-state error when disturbances occur, since only system deviation causes a change in the manipulated variable.

P controllers: fast and stable with steady-state error

P controller applications:
P controllers are suited to noncritical control applications which can tolerate steady-state error in the event of disturbances: e.g. pressure, flow rate, level and temperature control. P control action provides rapid response, although its dynamic properties can still be improved through additional control components, as described on page 38 ff.

Integral controller (I controller)

Integral control action is used to fully correct system deviations at any operating point. As long as the error is nonzero, the integral action will cause the value of the manipulated variable to change. Only when reference variable and controlled variable are equally large – at the latest, though, when the manipulated variable reaches its system specific limit value (U_{max}, p_{max}, etc.) – is the control process balanced. Mathematics expresses integral action as follows: the value of the manipulated variable is changed proportional to the integral of the error e.

no error in steady state

$$y = K_i \int e \, dt \qquad \text{with: } K_i = \frac{1}{T_n}$$

How rapidly the manipulated variable increases/decreases depends on the error and the integral time T_n (reciprocal of integral-action coefficient K_i). If the controller has a short integral time, the control signal increases more rapidly as for controllers with long integral time (small integral-action coefficient).

Note: The higher the integral action coefficient K_i, the greater the integral action of an I controller, or it is the lower, the higher the integral time value T_n.

high $T_n \Rightarrow$ slow control action

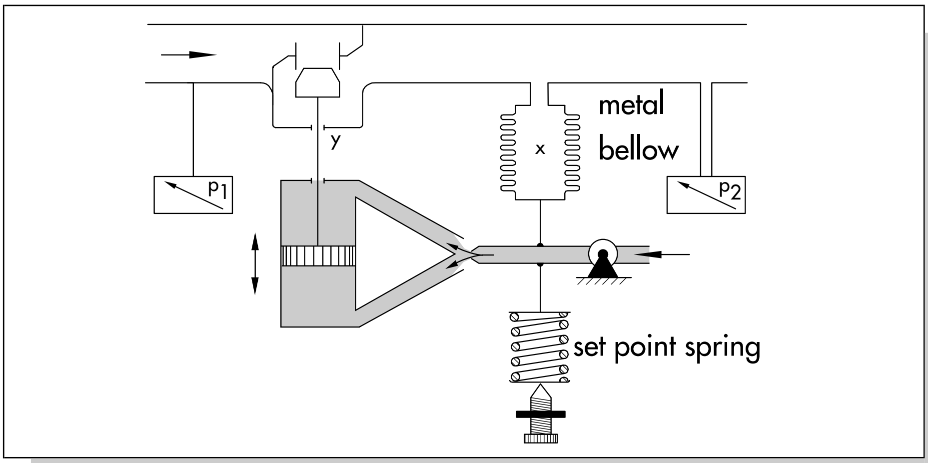

Fig. 29: I pressure controller

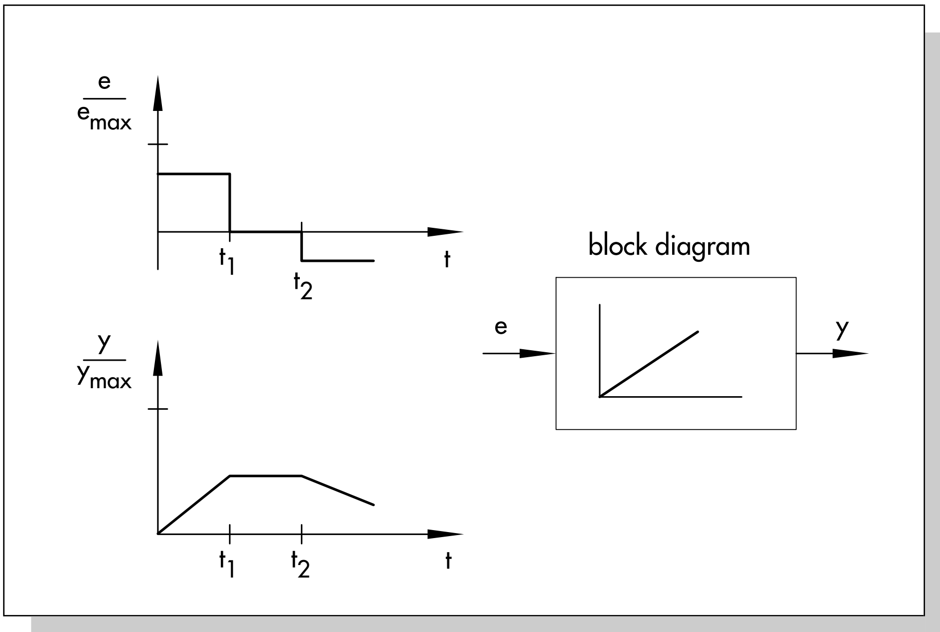

Fig. 30: Dynamic behavior of an I controller (e: system deviation; y: manipulated variable)

The pneumatic I controller illustrated in Fig. 29 operates with a piston actuator. When the supply nozzle in front of the jet divider is in mid-position, the piston remains where it is. In this position, error equals zero because the forces of the set point spring F_S and the pressure loaded metal bellows F_M cancel each other out completely.

functional principle of integral pressure controllers

A 'virtual' control cycle helps us recognize the functional principle:
When, due to an additional consumer, the pressure p_2 drops, the nozzle turns towards the upper piston chamber. The piston slides downward, opening the valve until the equilibrium of forces is restored. The nozzle is then again in mid-position, i.e. error equals zero and the valve plug remains in the new, wider open position.

I control action is comparatively slow

When comparing the dynamic behavior of a P and an I controller (Figs. 21 and 30), it shows that the manipulated variable y increases only slowly in I controllers, while it immediately reaches its final control value with P controllers. Therefore, the response of integral-only controllers to disturbances and step changes in the reference variable is only very sluggish. If the integral time is adjusted to be so short that it causes a rapid increase in the manipulated variable, oscillation will easily occur, making the control loop instable in the end.

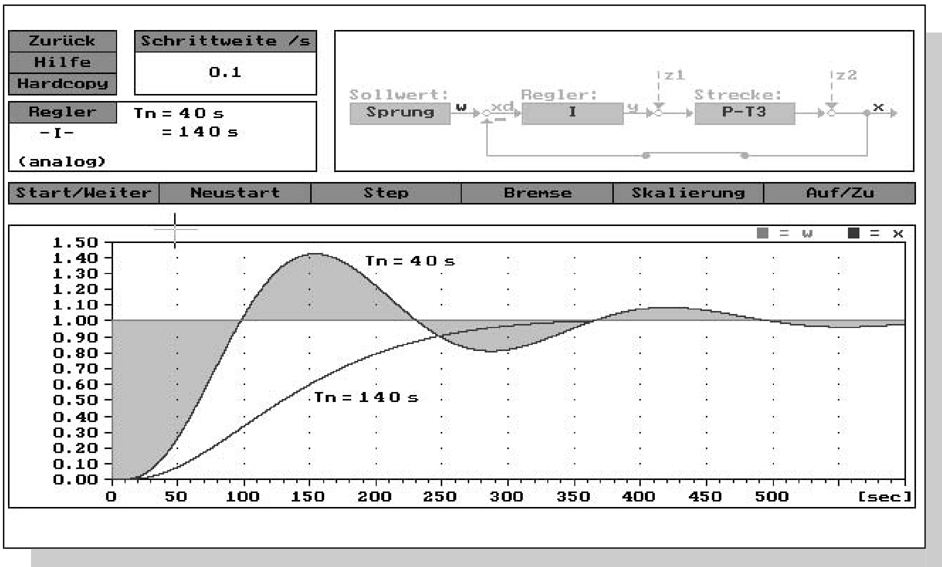

Fig. 31: Control response of the I controller with PT_3 system (double time scale)

- Control response (based on the example of the PT_3 system)

Fig. 31 shows how the PT_3 system ($K_P = 1$; $T_1 = 30$ s; $T_2 = 15$ s; $T_3 = 10$ s) is controlled with an I controller. Contrary to Fig. 28 which shows proportional-action control, the time scale was doubled in this illustration. It clearly shows that the I controller's response is considerably slower, while the control dynamics decreases with increasing T_n. A positive feature is the nonexistent error at steady state.

no steady-state error...

Note: Adjusting an operating point would not make any sense for I controllers, since the integral action component would correct any set-point deviation. The change in the manipulated variable until error has been eliminated is equivalent to an 'automated' operating point adjustment: the manipulated variable of the I controller at steady state (e=0) remains at a value which would have to be entered for P controllers via the operating point adjuster.

... by self-adaption to the operating point

I controllers exhibit the following advantages:

- No error at steady state

I controllers exhibit the following disadvantages:

- Sluggish response at high T_n
- At small T_n, the control loop tends to oscillate/may become instable

Derivative controller (D controller)

D controllers generate the manipulated variable from the rate of change of the error and not – as P controllers – from their amplitude. Therefore, they react much faster than P controllers: even if the error is small, derivative controllers generate – by anticipation, so to speak – large control amplitudes as soon as a change in amplitude occurs. A steady-state error signal, however, is not recognized by D controllers, because regardless of how big the error, its rate of change is zero. Therefore, derivative-only controllers are rarely used in practice. They are usually found in combination with other control elements, mostly in combination with proportional control.

rapid response to any change

In PD controllers (Fig. 32) with proportional-plus-derivative control action, the manipulated variable results from the addition of the individual P and D control elements:

combined P and D controllers

$$y = K_P \cdot e + K_D \frac{de}{dt} + y_0 \qquad \text{with: } K_D = K_p \cdot T_v$$

The factor T_V is the rate time, K_D is the derivative-action coefficient. Both variables are a measure for the influence of the D component: high values mean strong control action.

As with the P controller, the summand y_0 stands for the operating point adjustment, i.e. the preselected value of the manipulated variable which is issued by the controller in steady state when e = 0.

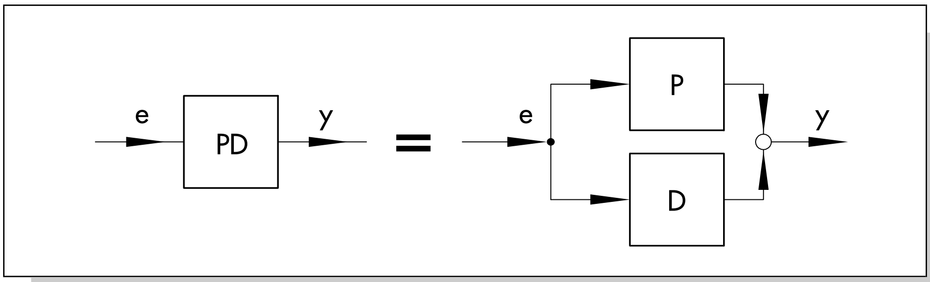

Fig. 32: Elements of a PD controller

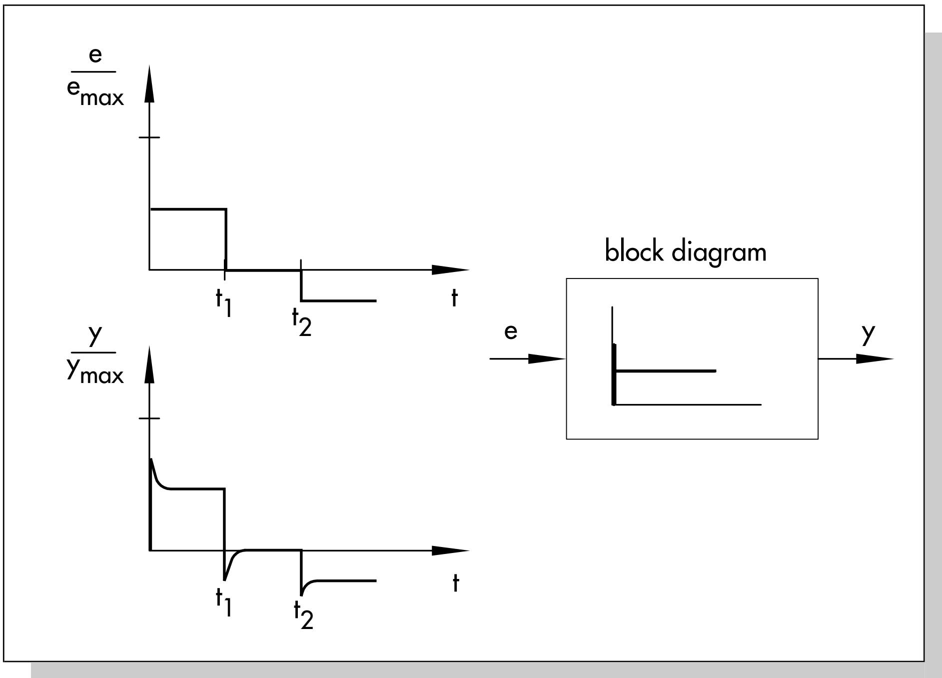

Fig. 33: Dynamic behavior of a PD controller
(e: system deviation; y: manipulated variable)

The course of the manipulated variable which can be seen in the step response shows the influence of the D component (see Figs. 23 and 32): any change in the error signal results in a short-term increase of the manipulated variable. Due to parasitical lags, this pulse has only a finite rate of change. An indefinitely short pulse, as required by the above equation, will not occur in practice.

small lags ´influence´ the control pulse

Note: The influence of the D component increases proportional to the rate time T_V or the derivative-action coefficient K_D.

high $T_V \Rightarrow$ great control action

- Control response (based on the example of the PT_3 system)

The control response in Fig. 34 shows that steady-state error occurs in PD controllers just as it occurs in P controllers. Due to the immediate control action whenever there is a change in the error signal, the control dynamics is higher than with P controllers. Despite the very rapid changes in the controlled variable (set point reached after 23 s), the tendency of the control loop to oscillate decreases. Due to this stabilizing effect of the D component, a higher K_P value can be chosen than for proportional-only controllers which reduces steady-state error.

D component improves control dynamics

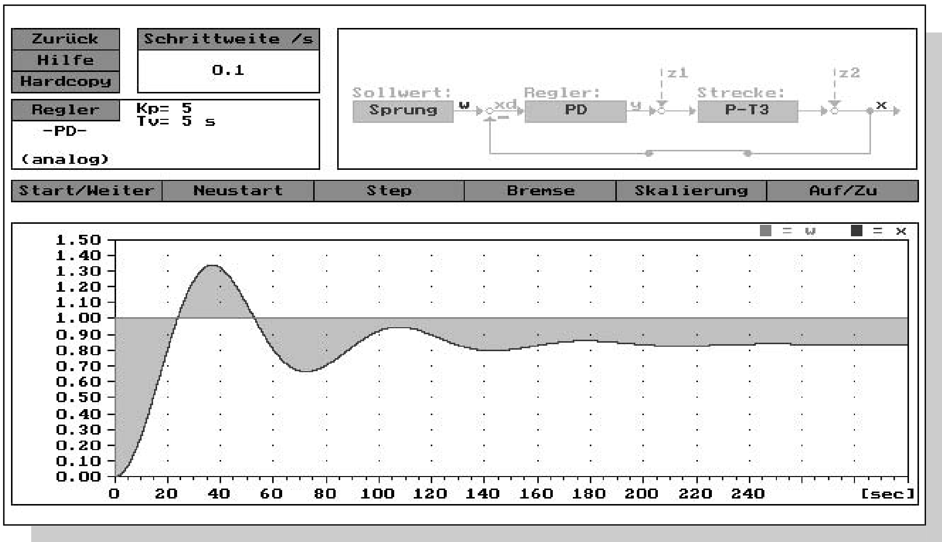

Fig. 34: Control response of the PD controller with PT_3 system

PD controllers are employed in all applications where P controllers are not sufficient. This usually applies to controlled systems with greater lags, in which stronger oscillation of the controlled variable – caused by a high K_P value – must be prevented.

PI controllers

suited to many control tasks

PI controllers are often employed in practice. In this combination, one P and one I controller are connected in parallel (Fig. 35). If properly designed, they combine the advantages of both controller types (stability and rapidity; no steady-state error), so that their disadvantages are compensated for at the same time.

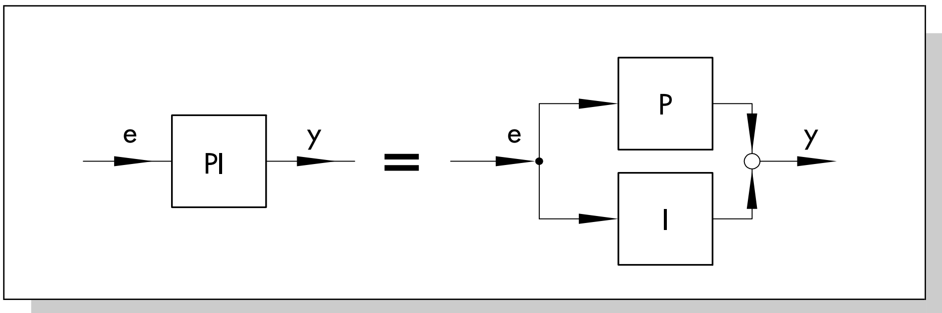

Fig. 35: Elements of a PI controller

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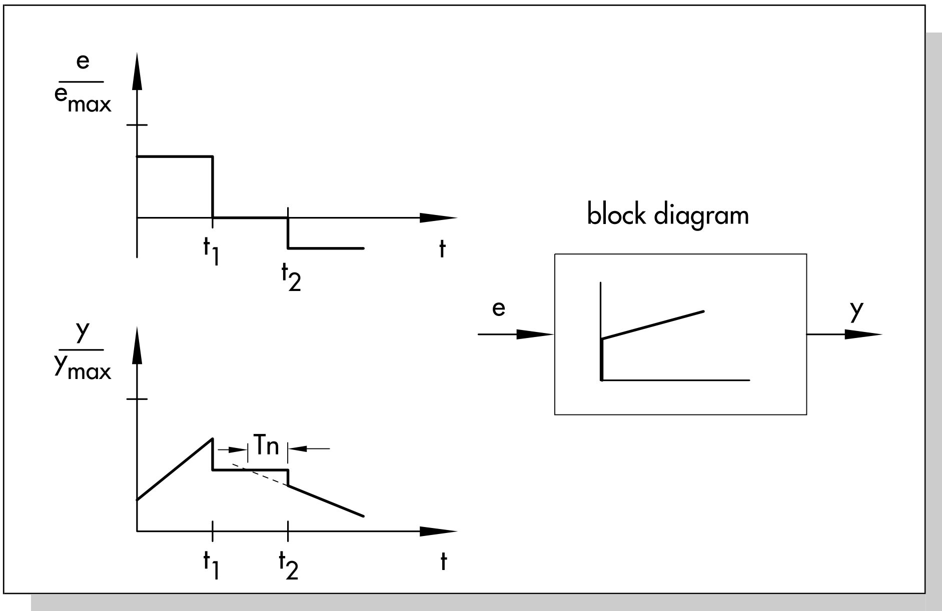

Fig. 36: Dynamic behavior of a PI controller (e: system deviation; y: manipulated variable)

The manipulated variable of PI controllers is calculated as follows:

$$y = K_p \cdot e + K_i \int e\,dt \qquad \text{with: } K_i = \frac{K_p}{T_n}$$

division of tasks between P and I controllers: fast and accurate

The dynamic behavior is marked by the proportional-action coefficient K_P and the reset time T_n. Due to the proportional component, the manipulated variable immediately reacts to any error signal e, while the integral component starts gaining influence only after some time. T_n represents the time that elapses until the I component generates the same control amplitude that is generated by the P component (K_P) from the start (Fig. 36). As with I controllers, the reset time T_n must be reduced if the integral-action component is to be amplified.

- Control response (based on the example of the PT_3 system)

As expected, PI control of the PT_3 system (Fig. 37) exhibits the positive properties of P as well as of I controllers. After rapid corrective action, the controlled variable does not show steady-state error. Depending on how

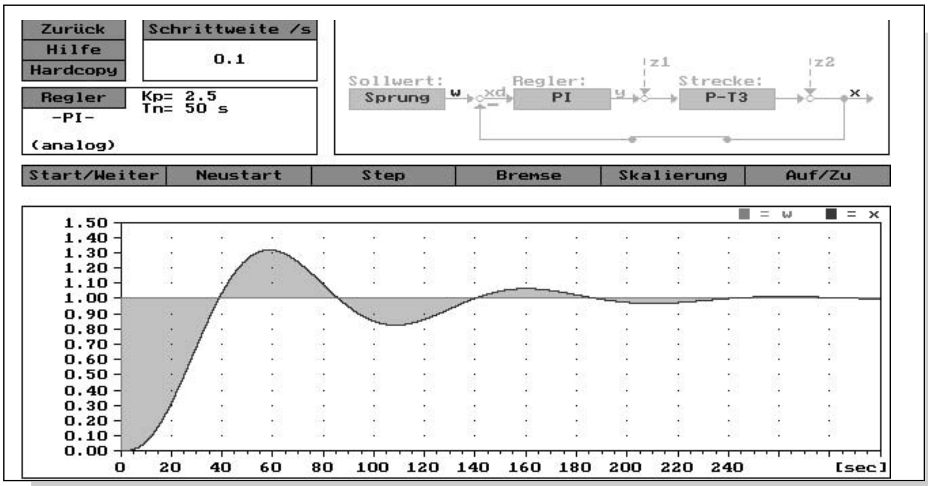

Fig. 37: Control response of the PI controller with PT_3 system

variable controller design

high the K_P and T_n values are, oscillation of the controlled variable can be reduced, however, at the expense of control dynamics.

PI controller applications:
Control loops allowing no steady-state error.
Examples: pressure, temperature, ratio control, etc.

PID controller

PI controller with improved control dynamics

If a D component is added to PI controllers, the result is an extremely versatile PID controller (Fig. 38). As with PD controllers, the added D component – if properly tuned – causes the controlled variable to reach its set point more quickly, thus reaching steady state more rapidly.

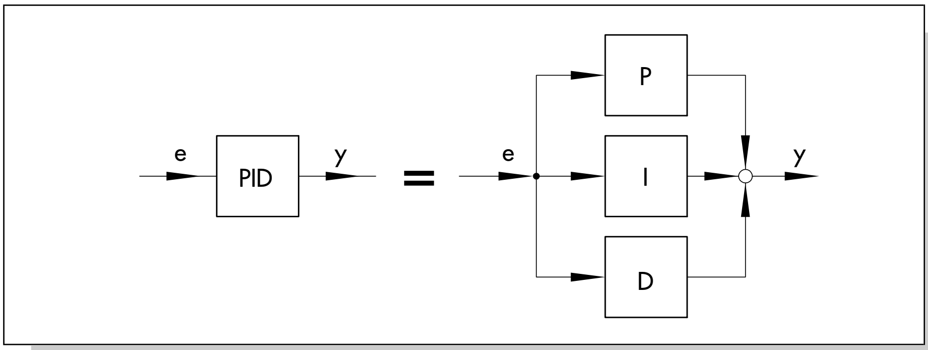

Fig. 38: Elements of a PID controller

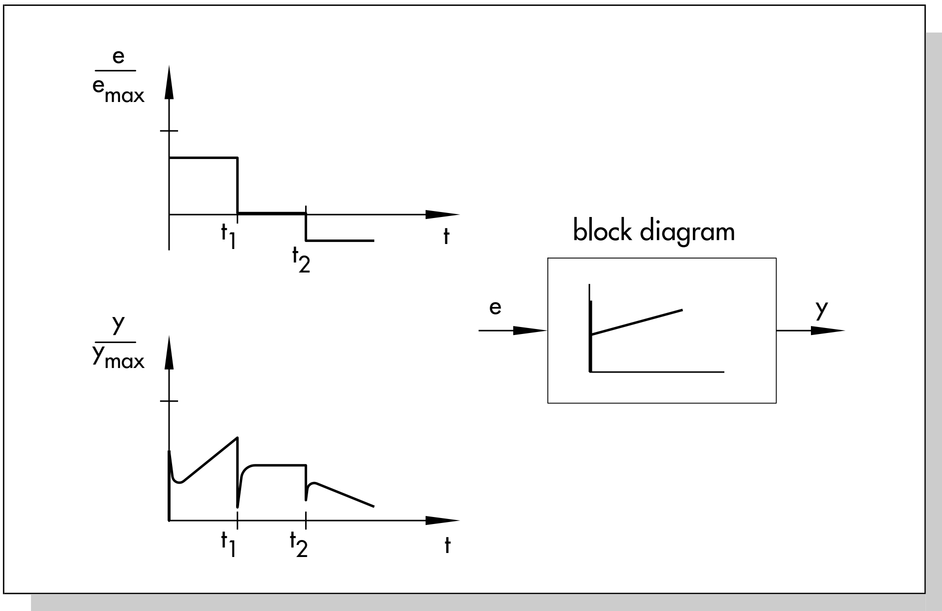

Fig. 39: Dynamic behavior of a PID controller (e: system deviation; y: manipulated variable)

In addition to the manipulated variable generated by the PI component (Fig. 36), the D component increases the control action with any change in error (Fig. 39). Thus, the manipulated variable y results from the addition of the differently weighted P, I and D components and their associated coefficients:

three control modes provide high flexibility..

$$y = K_p \cdot e + K_i \int e\,dt + K_D \frac{de}{dt} \qquad \text{with } K_i = \frac{K_P}{T_n};\, K_D = K_P \cdot T_V$$

- Control response (based on the example of the PT_3 system)

The control response of PID controllers is favorable in systems with large energy storing components (higher-order controlled systems) that require control action as fast as possible and without steady-state error.

Compared to the previously discussed controllers, the PID controller therefore exhibits the most sophisticated control response (Fig. 40) in the reference system example. The controlled variable reaches its set point rapidly, stabilizes within short, and oscillates only slightly about the set point. The three control parameters K_P, T_n and T_V provide an immense versatility in

accurate and highly dynamic control

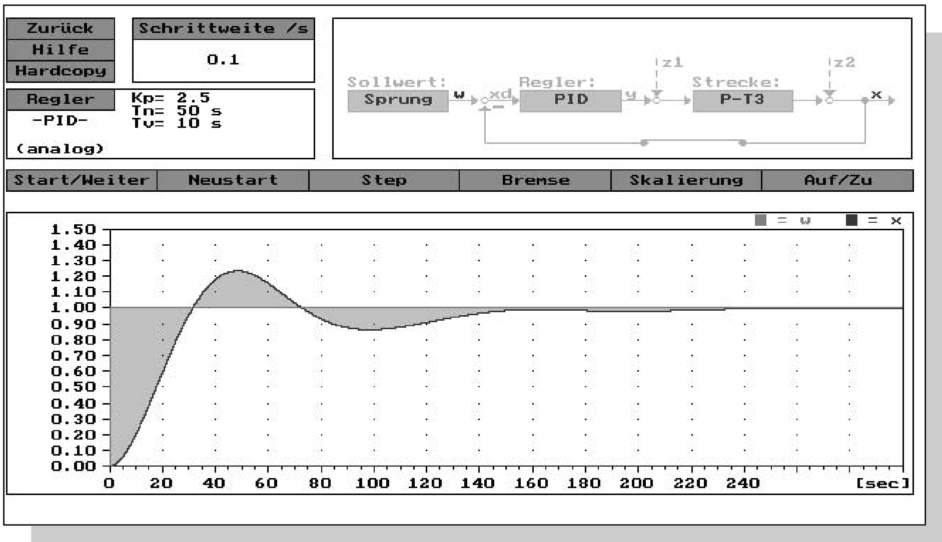

Fig. 40: Control response of the PID controller with PT_3 system

... and require careful tuning adjustments

adjusting the control response with respect to amplitude and control dynamics. It is therefore especially important that the controller be designed and tuned with care as well as be adapted to the system as good as possible (see chapter: Selecting a Controller).

PID controller applications:
Control loops with second- or higher-order systems that require rapid stabilization and do not allow steady-state error.

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Discontinuous Controllers

Discontinuous controllers are also frequently called switching controllers. The manipulated variable in discontinuous controllers assumes only a few discrete values, so that energy or mass supply to the system can be changed only in discrete steps.

only definite number of switching states

Two-position controller

The simplest version of a discontinuous controller is the two-position controller which, as the name indicates, has only two different output states, for instance 0 and y_{max} according to Fig. 41.

A typical application is temperature control by means of a bimetallic strip (e.g. irons). The bimetal serves as both measuring and switching element. It consists of two metal strips that are welded together, with each strip expanding differently when heated (Fig. 42).

example: temperature control via bimetal

If contact is made – bimetal and set point adjuster are touching – a current supplies the hot plate with electricity. If the bimetallic strip is installed near the hot plate, it heats up as well. When heated up, the bottom material expands more than the top material. This causes the strip to bend upward as the heat increases, and it finally interrupts the energy supply to the heating coil. If the temperature of the bimetal decreases, the electrical contact is made again, starting a new heating phase.

cyclic on/off switching

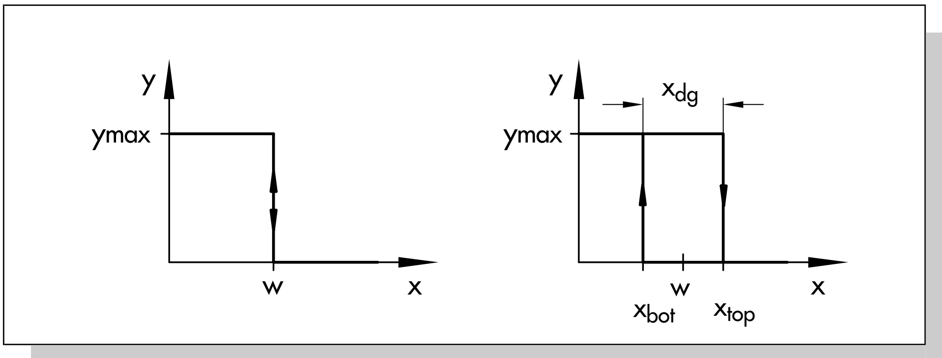

Fig. 41: Switching charakteristic of the two-position controller (without and with differential gap x_{dg})

differential gap reduces switching frequency

To increase the service life of the contacts, as shown in Fig. 42, a differential gap x_{dg} can be created by using an iron plate and a permanent magnet. The conditions for on/off switching are not identical anymore (x_{bot} and x_{top} according to Fig. 41), so that the switching frequency is reduced and spark generation is largely prevented.

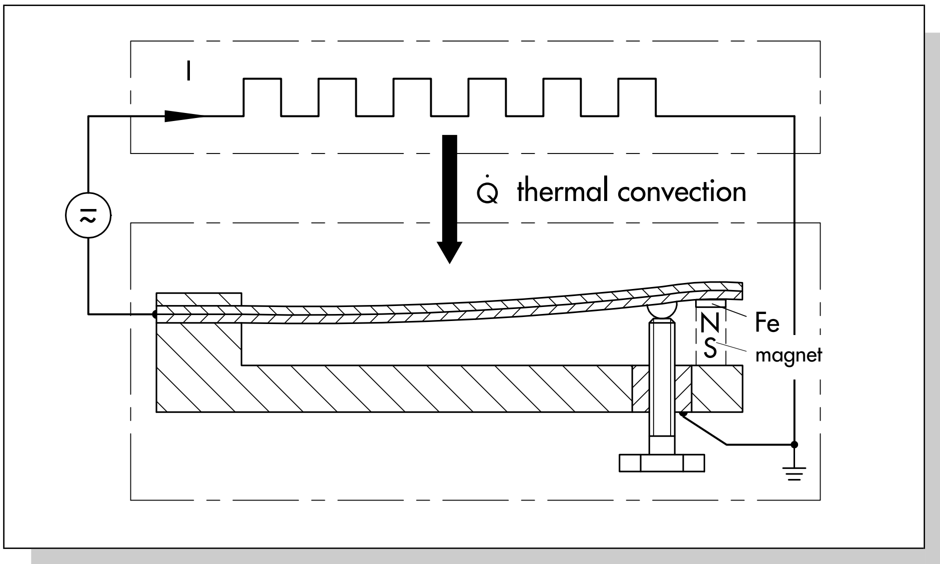

Fig. 43: Temperature control via bimetallic switch

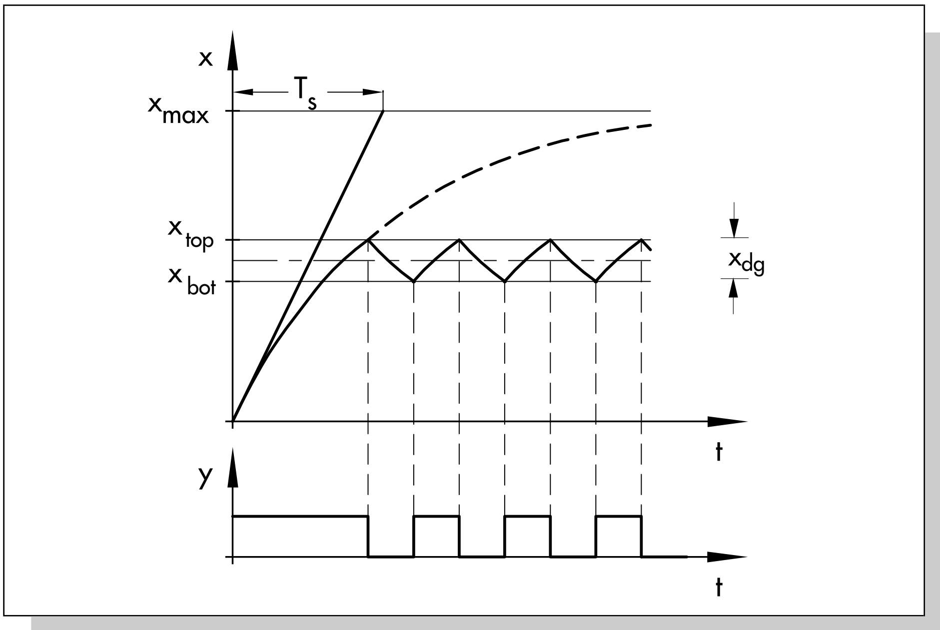

Fig. 42: Control cycle of a two-position controller with differential gap and first-order controlled system

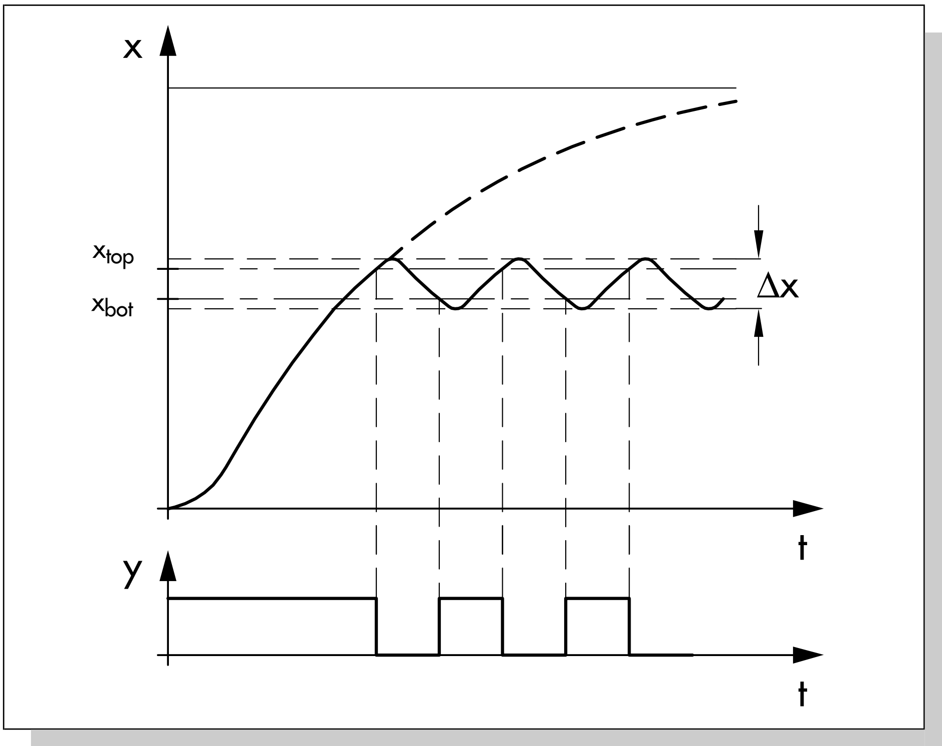

Fig. 44: Control cycle of a two-position controller with differential gap and higher-order controlled system

The typical behavior of manipulated and controlled variable as a function of time in a two-position controller can be seen in Fig. 43. The dotted characteristic shows that at higher set points the temperature increase takes longer than the cooling process. In this example we assume that the energy inflow (here: heating capacity) is sufficient to reach double the value of the selected set point. The capacity reserve of 100% chosen here has the effect that on/off switching periods are identical.

additional system deviation due to lag

The temperature curve shown in Fig. 43 identifies a first-order controlled system. In higher-order controlled systems, the controlled variable would follow the manipulated variable only sluggishly due to the lag. This causes the controlled variable to leave the tolerance band formed by the switching points x_{top} and x_{bot} (Fig. 44). This effect must be taken into consideration when tuning the controller by applying the measures described below.

Two-position feedback controller

Should the displacement of the controlled variable as shown in Fig. 44 not be tolerable, the differential gap can be reduced. This causes the switching frequency to increase, thus exposing the contacts to more wear. Therefore, a two-position feedback controller is often better suited to controlling sluggish higher-order systems.

feedback control improves the control quality

In a two-position feedback temperature controller, an additional internal heating coil heats up the bimetallic strip when the controller is switched on, thus causing a premature interruption of energy supply. If properly adjusted, this measure results in a less irregular amplitude of the controlled variable at an acceptable switching frequency.

Three-position controller and three-position stepping controller

Three-position controllers can assume three different switching states. In a temperature control system, these states are not only 'off' and 'heating' as in a two-position controller, but also 'cooling'. Therefore, a three-position controller fulfills the function of two coupled two-position controllers that switch at different states; this can also be seen in the characteristic of a three- position controller with differential gap (Fig. 45).

three-position controlled actuator motors

quasi-continuous control

In the field of control valve technology, three-position controllers are frequently used in combination with electric actuators. The three states of 'counterclockwise' (e.g. opening), 'clockwise' (e.g. closing) and 'off' can be used to adjust any valve position via relay and actuator motor (Fig. 46). Using a discontinuous controller with integrated actuator (e.g. actuator motor) and

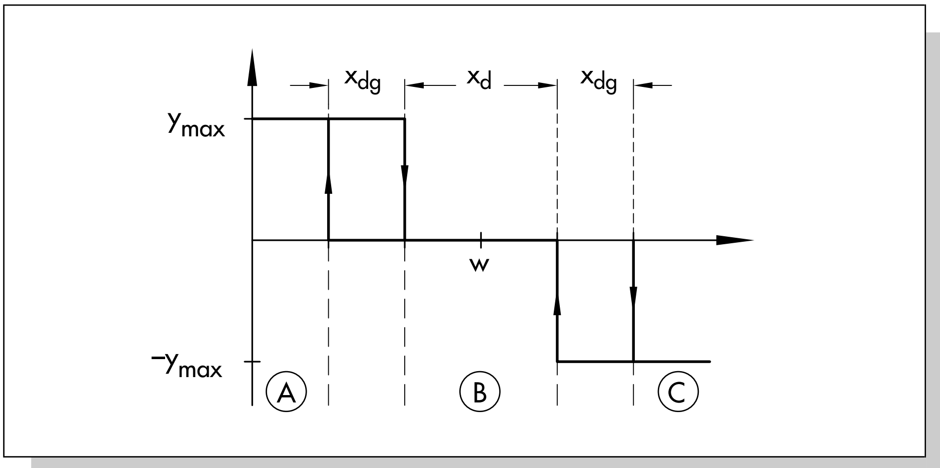

Fig. 45: Characteristic of a three-position controller with differential gap x_{dg} and dead band x_d

applying suitable control signals, the result is a quasi-continuous P, PI or PID control response. Such three-position stepping controllers are frequently used in applications where pneumatic or hydraulic auxiliary energy is not available, but electric auxiliary energy.

When properly adapted to the system, the control response of a three-position stepping controller can barely be differentiated from that of a continuous controller. Its control response may even be more favorable, for instance, when the noise of a controlled variable caused by disturbances is within the dead band x_d.

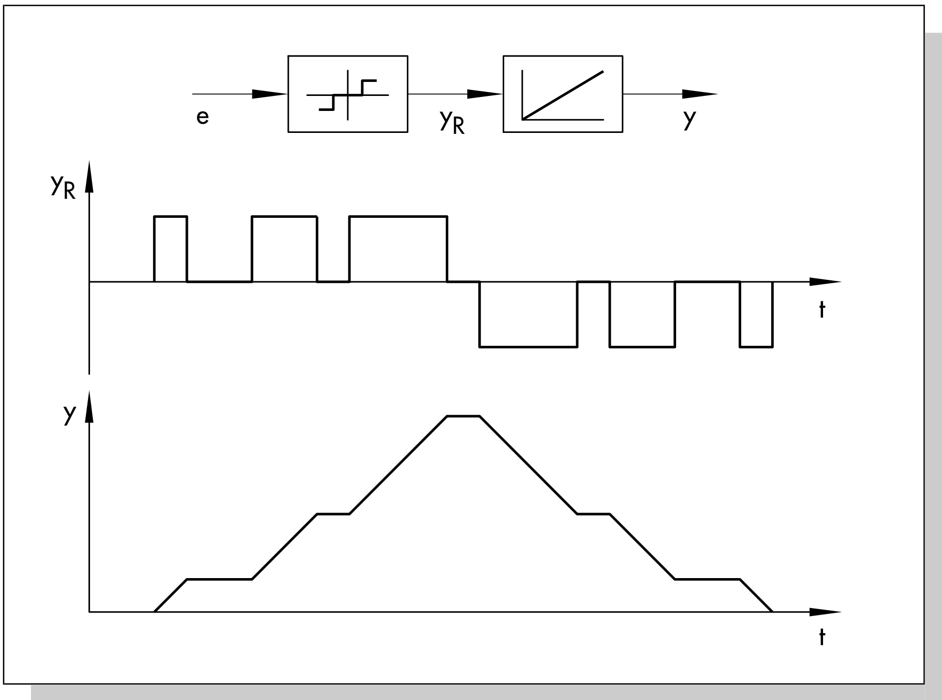

Fig. 46: Control signal of a quasi-continuous controller (three-position controller with actuator motor)

Selecting a Controller

Selection criteria

To solve a control task it is required that

- the controlled system be analyzed and
- a suitable controller be selected and designed.

The most important properties of the widely used P, PD, I, PI and PID control elements are listed in the following table:

Control element	Offset	Operating point adjustment	Speed of response
P	yes	recommended	high
PD	yes	recommended	very high
I	no	N/A	low
PI	no	N/A	high
PID	no	N/A	very high

what to consider when selecting a controller

Which controller to select depends on the following factors:

- Is the system based on integral or proportional control action (with or without self-regulation)?
- How great is the process lag (time constants and/or dead times)?
- How fast must errors be corrected?
- Is steady-state error acceptable?

According to the previous chapters (see also above table), controllers and systems can be assigned to each other as follows:

P controllers

P controllers are employed in easy-to-control systems where steady-state error is acceptable. A stable and dynamic control response is reached at minimum effort.

PD controllers

It makes sense to employ PD controllers in systems with great lag where offset is tolerable. The D component increases the speed of response so that control dynamics improve compared to P controllers.

I controllers

I controllers are suitable for use in applications with low requirements as to the control dynamics and where the system does not exhibit great lag. It is an advantage that errors are completely eliminated.

PI controllers

PI controllers combine the advantages of both P and I controllers. This type of controller produces a dynamic control response without exhibiting steady-state error. Most control tasks can be solved with this type of controller. However, if it is required that the speed of response be as high as possible regardless of the great lag, a PID controller will be the proper choice.

PID controllers

PID controllers are suitable for systems with great lag that must be eliminated as quick as possible. Compared to the PI controller, the added D component results in better control dynamics. Compared to the PD controller, the added I component prevents error in steady state.

The selection of an appropriate controller significantly depends on the corresponding system parameters. Therefore, the above mentioned applications should only be considered a general guideline; the suitability of a certain type of controller must be thoroughly investigated to accommodate the process it controls.

Adjusting the control parameters

objectives in tuning controllers

For a satisfactory control result, the selection of a suitable controller is an important aspect. It is even more important that the control parameters K_P, T_n and T_V be appropriately adjusted to the system response. Mostly, the adjustment of the controller parameters remains a compromise between a very stable, but also very slow control loop and a very dynamic, but irregular control response which may easily result in oscillation, making the control loop instable in the end.

adaptation to operating point or range

For nonlinear systems that should always work in the same operating point, e.g. fixed set point control, the controller parameters must be adapted to the system response at this particular operating point. If a fixed operating point cannot be defined, such as with follow-up control systems, the controller must be adjusted to ensure a sufficiently rapid and stable control result within the entire operating range.

In practice, controllers are usually tuned on the basis of values gained by experience. Should these not be available, however, the system response must be analyzed in detail, followed by the application of several theoretical or practical tuning approaches in order to determine the proper control parameters.

ultimate tuning method by Ziegler and Nichols

One approach is a method first proposed by Ziegler and Nichols, the so-called ultimate method. It provides simple tuning that can be applied in many cases. This method, however, can only be applied to controlled systems that allow sustained oscillation of the controlled variable. For this method, proceed as follows:

- At the controller, set K_P and T_V to the lowest value and T_n to the highest value (smallest possible influence of the controller).
- Adjust the controlled system manually to the desired operating point (start up control loop).
- Set the manipulated variable of the controller to the manually adjusted value and switch to automatic operating mode.
- Continue to increase K_P (decrease X_P) until the controlled variable encounters harmonic oscillation. If possible, small step changes in the set point should be made during the K_P adjustment to cause the control loop to oscillate.
- Take down the adjusted K_P value as critical proportional-action coefficient $K_{P,crit}$.

	K_P	T_n	T_v
P	$0{,}50 \cdot K_{p,crit.}$	-	-
PI	$0{,}45 \cdot K_{p,crit.}$	$0{,}85 \cdot T_{crit.}$	-
PID	$0{,}59 \cdot K_{P,crit.}$	$0{,}50 \cdot T_{crit.}$	$0{,}12 \cdot T_{crit.}$

Fig. 47: Adjustment values of control parameters acc. to Ziegler/Nichols: at $K_{P,crit.}$, the controlled variable oscillates periodically with $T_{crit.}$

- Determine the time span for one full oscillation amplitude as T_{crit}, if necessary by taking the time of several oscillations and calculating their average.
- Multiply the values of $K_{P,crit}$ and T_{crit} by the values according to the table in Fig. 47 and enter the determined values for K_P, T_n and T_V at the controller.
- If required, readjust K_P and T_n until the control loop shows satisfactory dynamic behavior.

Appendix A1: Additional Literature

[1] Terminology and Symbols in Control Engineering
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Figures

FIGURES

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