From Open Loop Control to Closed Loop Control

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1 From Open Loop Control to Closed Loop Control

As shown by calculation examples for the design of open loop control systems with proportional valves, the possible accuracy of the system depends on several factors resulting from overall system characteristics.

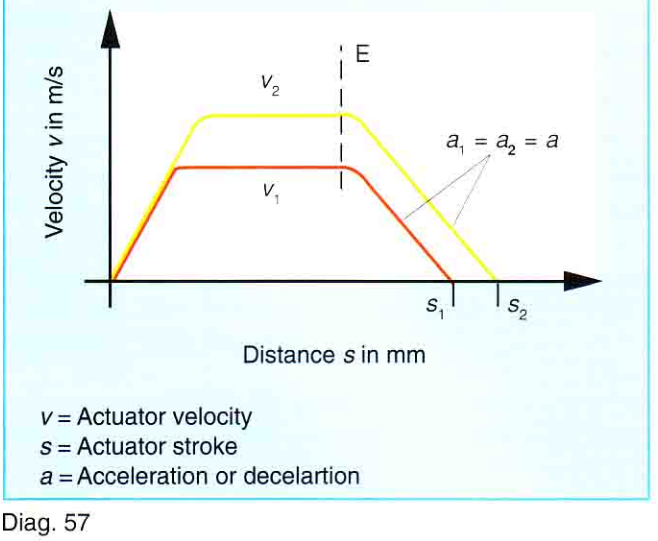
Before dealing with closed loop control in detail, two more types of open loop control will be discussed as an introduction:

- time dependent deceleration and
- stroke dependent deceleration

1.1 Time dependent Deceleration

The following occurs if an electrical time ramp is used for the purpose of deceleration in an open loop control system with proportional valves:

1.1.1 Deceleration via limit switch



Diag. 57

A cylinder moves at velocity v_1. On reaching the limit switch E the command velocity (deflection of the valve spool) is switched to v = 0 for example (i.e. cylinder stop). The command signal now changes with respect to the set ramp time. The displacement required for deceleration is thus determined.

Example:

v_1 = 0.8 m/s travel speed
t_{b1} = 0.2 s deceleration time (ramp setting)

$$a = \frac{v}{t}$$

Deceleration

$$a = \frac{0,8\ \text{m/s}}{0,2\ \text{s}} = 4\ \text{m/s}^2$$

Displacement required for deceleration

$$s_1 = \frac{v_1^2}{2 \cdot a} = \frac{0,8^2}{2 \cdot 4} = 0,08\ \text{m} = 80\ \text{mm}$$

If, depending on the operation, the velocity is changed, a different displacement is then required for the deceleration but the ramp setting remains the same.

Example:

v_2 = 1.2 m/s travel speed
t_{b2} = 0.3 s deceleration time (ramp dependent on command signal)

$$a = \frac{v}{t}$$

Deceleration

$$a = \frac{1,2\ \text{m/s}}{0,3\ \text{s}} = 4\ \text{m/s}^2$$

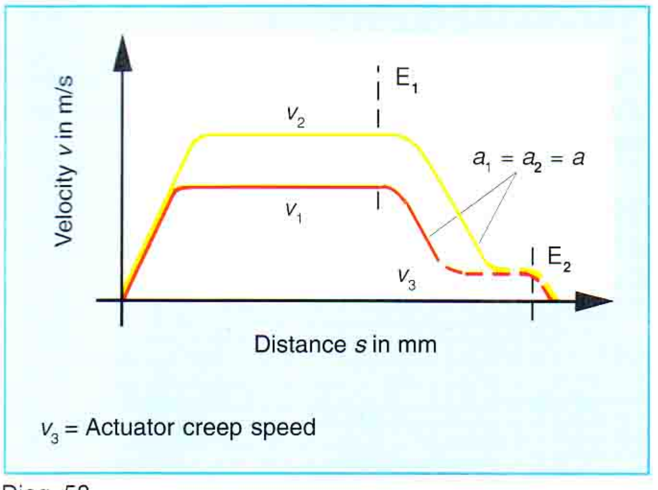
Displacement required for deceleration

$$s_2 = \frac{v_2^2}{2 \cdot a} = \frac{1,2^2}{2 \cdot 4} = 0,18\ \text{m} = 180\ \text{mm}$$

This, therefore, means that the cylinder may stop at various points. Unfortunately, this fact is often forgotten in practical applications, when the same stopping point is to be approached at various velocities.

1.1.2 Deceleration at low speed

One way of reaching the same stopping point at various velocities is to decelerate at a relatively low speed (limit switch E1). A stop signal is only sent via limit switch E2 at this very low velocity. *Diag. 58* shows this process. In this case the accuracy in stopping is good (see page 118).



Diag. 58

However, at velocities $v < v_{max}$ this leads to significant losses in time.

1.1.3 Individual ramps for each command velocity

An alternative is to assign a ramp to each command velocity. If the same stopping point is to be approached at various speeds, this may be achieved as follows.

Although the same displacement required for deceleration is obtained at a particular ramp setting, time is again lost as in example 1.1.2 *(see page 118).*

Example:

The previously calculated displacement required for deceleration of 180 mm (at v_2 = 1.2 m/s and a = 4 m/s²) will be used in this example.

This results in a deceleration of

$$a_1 = \frac{v^2 \cdot 10^3}{2 \cdot s} = \frac{0{,}8^2 \cdot 10^3}{2 \cdot 180} = 1{,}8 \text{ m/s}^2$$

and the time necessary for this deceleration of

$$t_b = \frac{v}{a} = \frac{0{,}8}{1{,}8} = 0{,}44 \text{ s}$$

(This is at v_1 = 0,8 m/s and s_b = 180 mm)

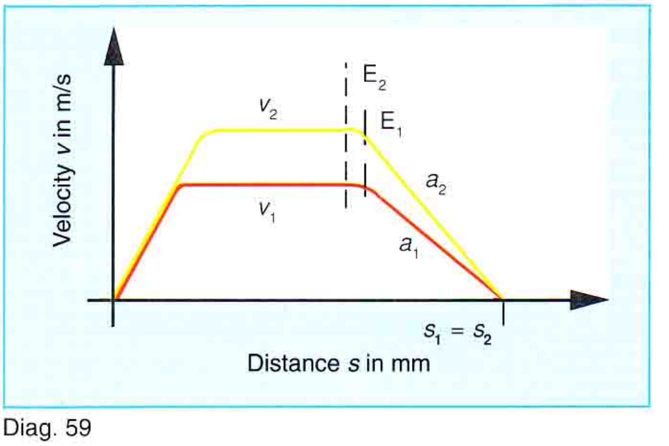
In practical applications, deviations from the end point are greater than in *example 1.1.2* as decelerations occur from different speeds.

The maximum possible accelerations/decelerations as specified on *pages 127/128* must also be remembered in this context.

The problems involved in accurately setting the ramp must also be taken into consideration. Hence, this solution is not really recommended for applications where an exact stopping point is important.

1.1.4 Individual limit switches for each velocity

In order to achieve a more reliable and higher system deceleration than that in *example 1.1.3*, it is necessary to use a further limit switch for the other velocity.



Diag. 59

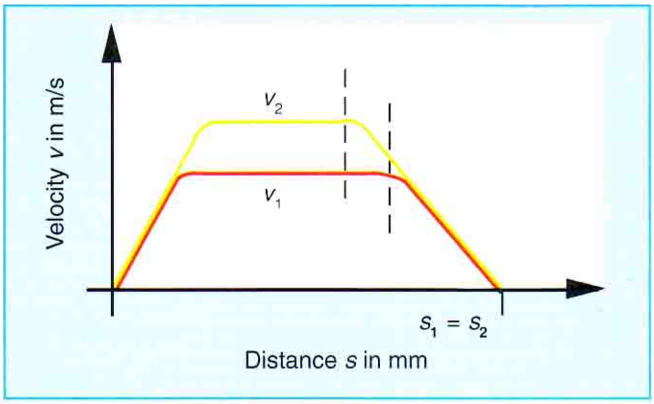
Due to the lower velocity v_1, the limit switch E1 is activated at a greater displacement. Therefore, for this solution one limit switch is assigned to each velocity.

A similar solution which does not require separate limit switches is **stroke dependent deceleration** *(see Diag. 60).*

1.2 Stroke dependent Deceleration

Clearly by definition, deceleration takes place dependent on the stroke of the actuator and not on an electrical ramp.

Diag. 61 clearly shows that the same stopping point is always reached irrespective of the velocity at the actuator.



Diag. 60

A version often used in practical applications for stroke dependent deceleration involves a deceleration cam and analogue initiator *(Fig. 172)*.

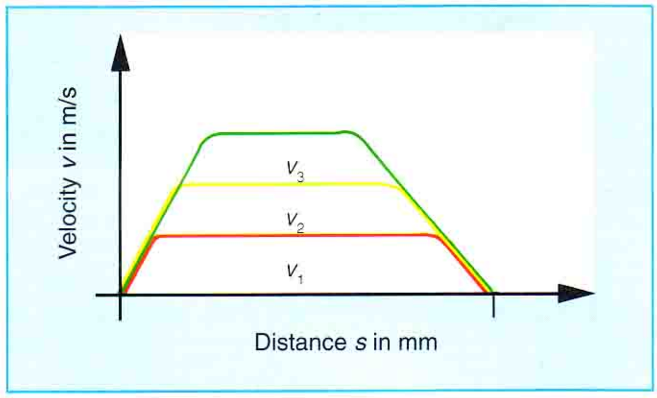
The analogue initiator is an electronic proximity switch. It produces a voltage proportional to the proximity of a metal component (i.e. cam). The closer the cam is to the initiator, the smaller the distance is between them, and hence the smaller the analogue output voltage becomes until it reaches 0 V. This voltage is fed to a specially designed amplifier and hence controls the proportional solenoids of the proportional directional valves.

The block diagram *(Fig. 173)* shows how a solenoid is controlled via an analogue initiator.

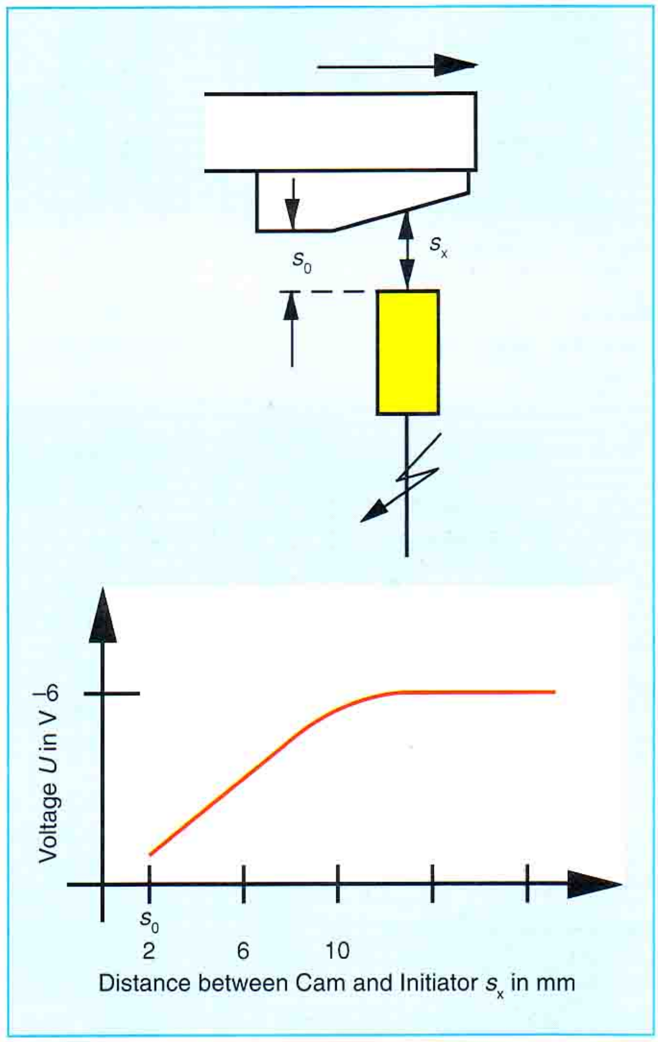
The minimum value evaluator only allows the smaller of the two input signals (E1 = command signal, E2 = from proximity switch) to be active at the output.

In addition, as shown in the block diagram *(Fig. 173)*, a root value generator is often used in conjunction with the analogue initiator. The advantage for practical applications is that the time necessary is reduced, as a position may be approached in the best possible manner, i.e. at the highest possible speed. (An example of an implemented system is on *pages 272 and 273*.)

If the analogue positional feedback is only required within the deceleration range (always the same end point) systems may be designed without full position feedback.



Diag. 61



Diag. 62

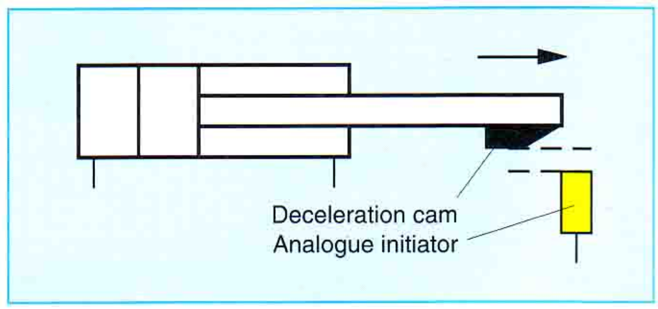


Fig. 172

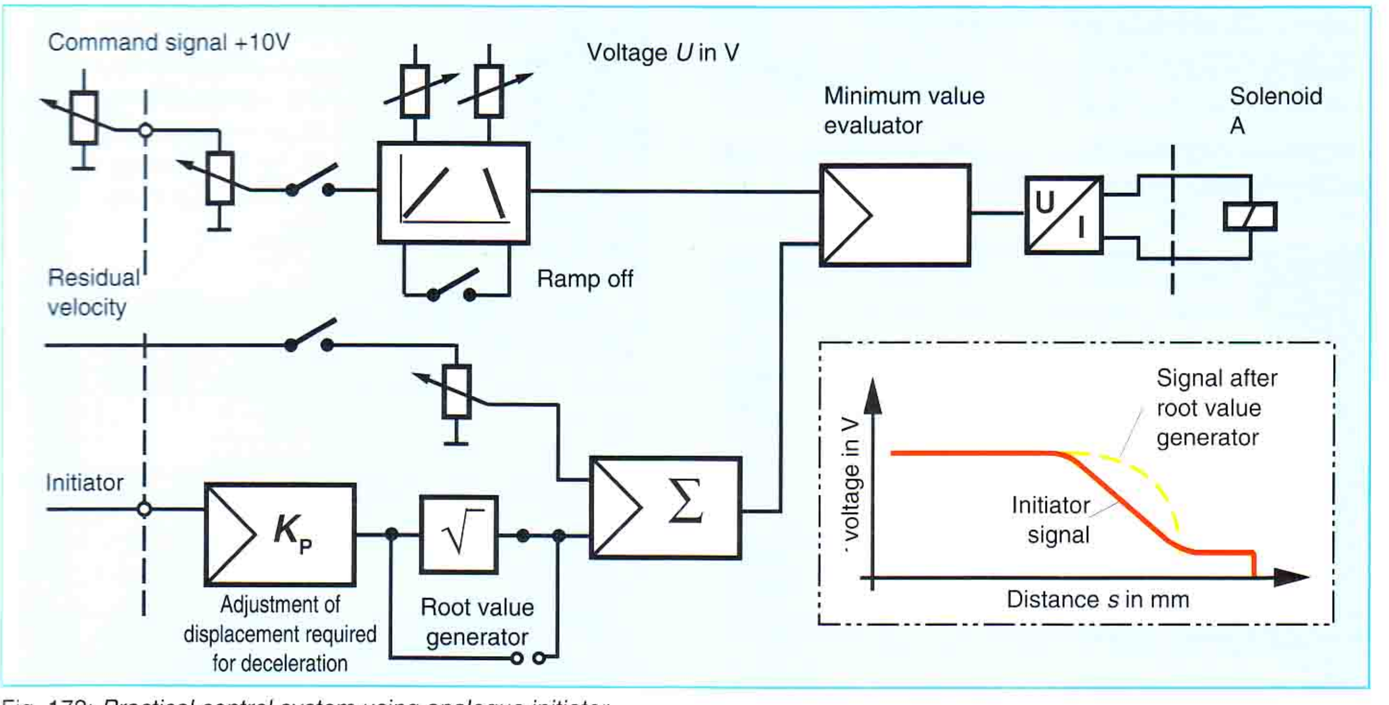


Fig. 173: *Practical control system using analogue initiator*

Another way of determining the stroke during stroke dependent deceleration is via a linear potentiometer *(Fig. 174)*.

Similarly, in this version, the stroke is measured via an analogue voltage and this signal is processed via an electronic amplifier.

Since, in this case, the entire stroke is converted to a signal, it is possible to select any stroke via the electrical amplifier.

The examples described so far are clearly all examples of open loop control.

This means that the actual value, e.g. velocity of a cylinder, is not measured and is not compared with the command signal.

Hence all external disturbances naturally have an effect on results.

If it is necessary to compensate for external disturbances, the system must be designed as a closed loop control circuit.

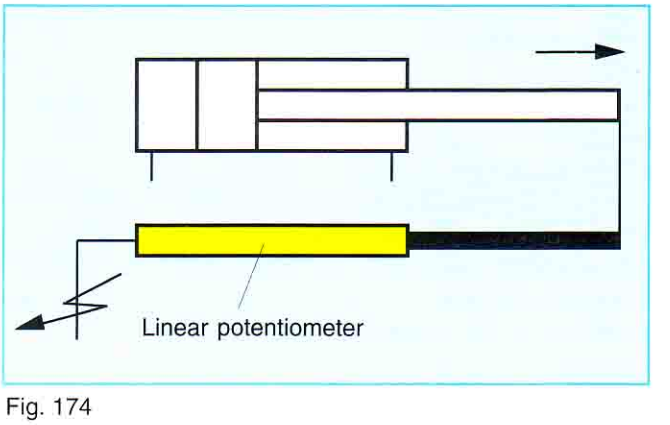


Fig. 174

2 Closed Loop Control

It is important to know some basic closed loop control conditions and definitions before it is possible to understand the relationships involved in a closed loop control circuit.

The most important relationships are summarised below.

Information relating to formulas and calculation methods will not be conveyed here, but instead the fundamental physical relationships involved in closed loop control will be described.

2.1 What is Closed Loop Control?

Fig. 175 shows the basic layout of a closed loop control circuit, from which the most important definitions may be deduced.

2.1.1 Definition of closed loop control

In a closed loop control system, the parameter being controlled is constantly measured and compared with a command signal. As soon as a difference occurs between the two signals in the closed loop control system, a suitable adjustment of the control parameter is implemented, so that it is forcibly re-aligned with the command signal again.

As in any other closed loop control system, the closed loop positional control circuit features a control device and a controlled system.

In the example shown in *Fig. 176* the control device includes:

- the regulator, which consists of a comparator which generates the command/feedback signal difference and a closed loop control amplifier
- the positional measuring system.

The controlled system includes:

- the hydraulic drive with hydraulic motor and valve
- the mechanical transmission elements, such as
  - gearbox
  - coupling and
  - lead screw

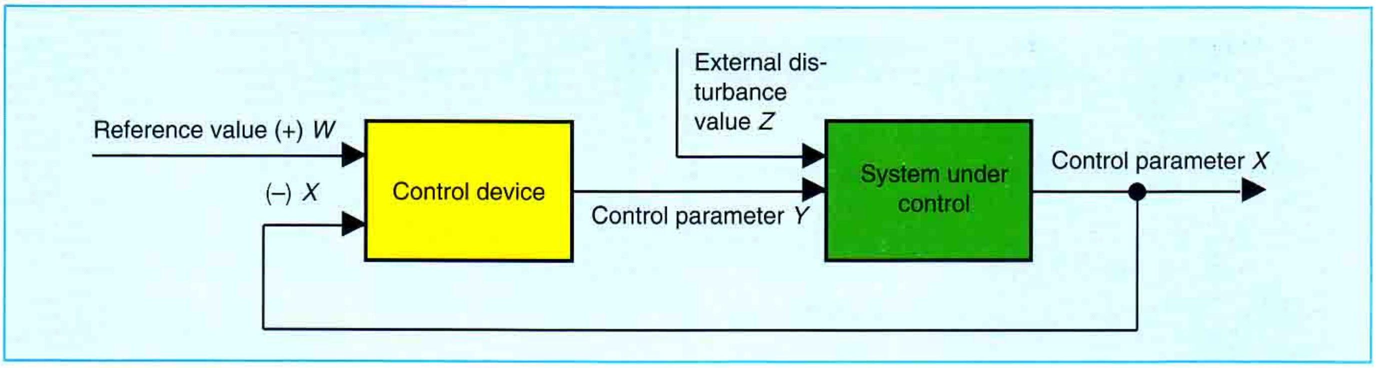


Fig. 175: *Basic layout of a closed loop control circuit*

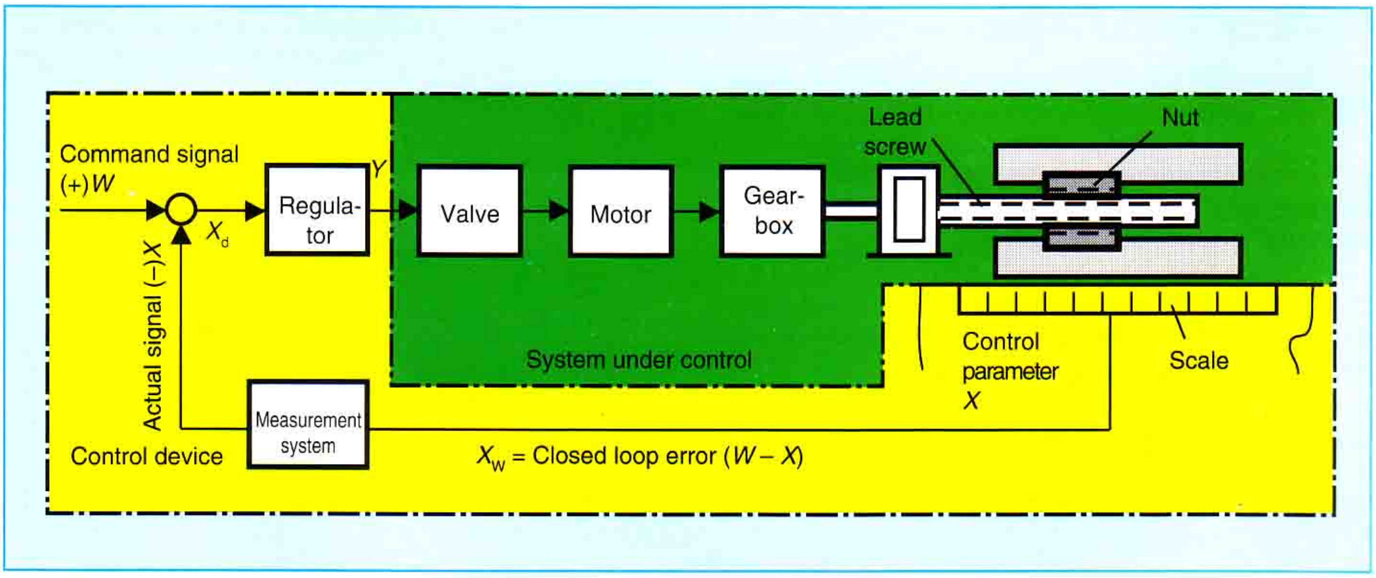


Fig. 176: *Example of closed loop positional control*

The characteristic feature of closed loop control circuits, is the closed loop which may be described as follows:

The position *X* of the slide (= control variable) is measured, using a scale and measuring amplifier. This measurement then represents the actual position. The command position is specified by the command signal *W* (= reference signal) which is produced by a command signal generator. The closed loop error X_d is the difference between the command and actual signals ($W - X$).

The closed loop error is fed to the regulator. The output signal from the regulator is the control variable *Y*. This control variable *Y* is fed as the input to the controlled system and hence actuates the valve. The rotation of the motor is converted by means of a lead screw drive into a linear motion of the slide. The position of the slide is then measured and hence the signal flow has come full circle, thus forming a closed loop positional control circuit.

2.1.2 Block Diagram

The individual elements of the closed loop control circuit such as "controlled system" and "control device" are known as "closed loop control elements". These closed loop control elements are usually represented as rectangular blocks.

The block diagram shows the connection between individual blocks and how they form an effective closed loop system.

The signal path is represented by lines and direction arrows.

2.1.3 Transfer Characteristic

Input signals or "input variables" X_e act on individual elements in a closed loop control circuit. "Output variables" X_a which depend on the "transfer function" of the element are derived from these inputs and then further processed.

The "transfer function" shows how the output changes with time, with respect to any change in input with time.

A characteristic change in input may be represented by the step function. The output signal obtained is a "step response" or "transfer function".

This transfer function is often shown in the block symbol to ensure that the transfer function of an element is clearly and correctly represented and understood.

In spite of the wide variety of components available from a technical point of view, the various transfer functions may be reduced to a few basic types.

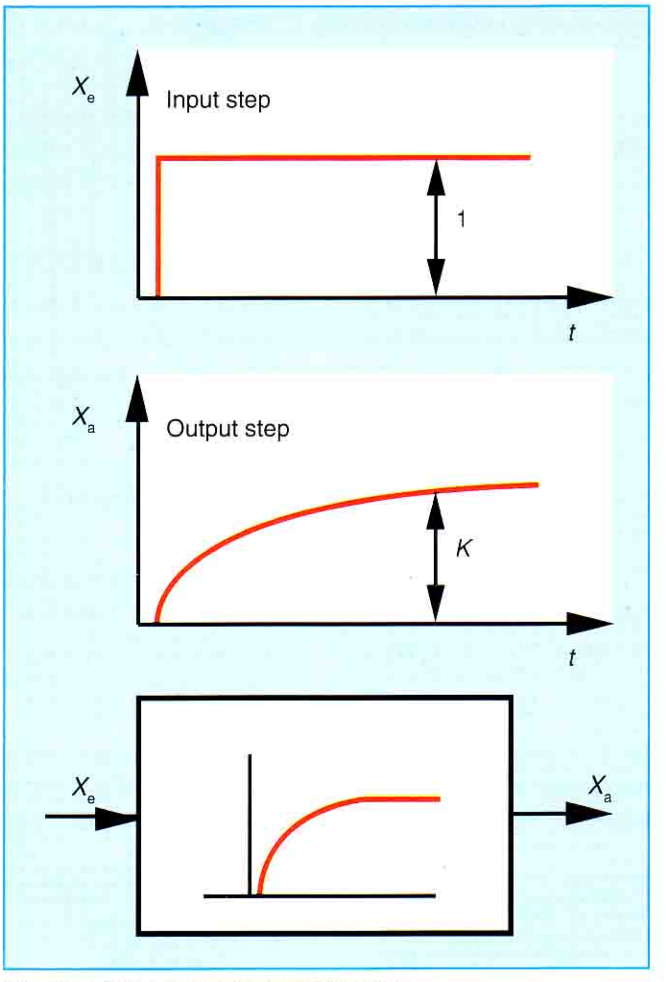


Fig. 63: *Example of a transfer function*

By disregarding the wide variety of components available for use in real systems in mathematical models, this facilitates examination of the dynamic processes. This enables general statements to be made about the behaviour of closed loop control circuits without needing to consider whether the circuit consists of electrical, mechanical or other elements.

The closed loop control elements may be categorized into "basic transfer elements" *(Fig. 177)* depending on their transfer characteristics.

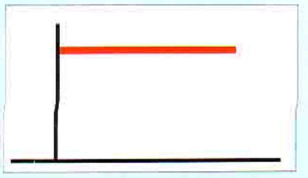
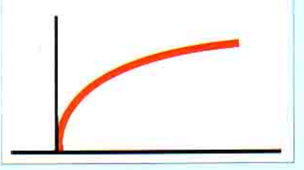
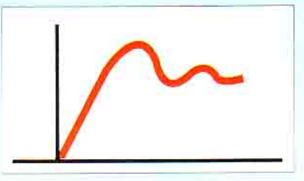
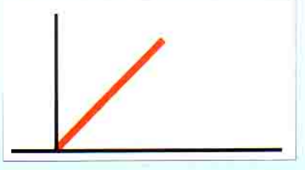
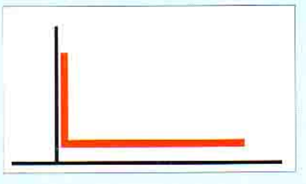
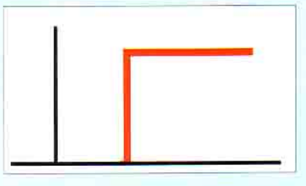
Proportional element		**P element**
Proportional element with 1st order delay		**PT_1 element**
Proportional element with 2nd order delay		**PT_2 element**
Integral element		**I element**
Differential element		**D element**
Time delay element		**T_t element**

Fig. 177: *Basic transfer elements*

2.2 Examples illustrating basic transfer functions

2.2.1 Proportional element (P element)

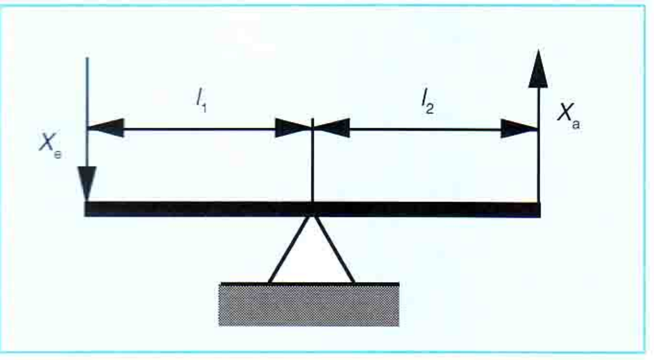


Fig. 178

If the input variable X_e is changed by a step function, the output X_a produces a similar step response.

The output is given by

$$X_a = \frac{X_e \cdot l_2}{l_1} = K \cdot X_e$$

with the gain of the proportional element (also known as the transfer constant) given by

$$K = \frac{l_2}{l_1} .$$

Hence the symbol for the P element is as shown:

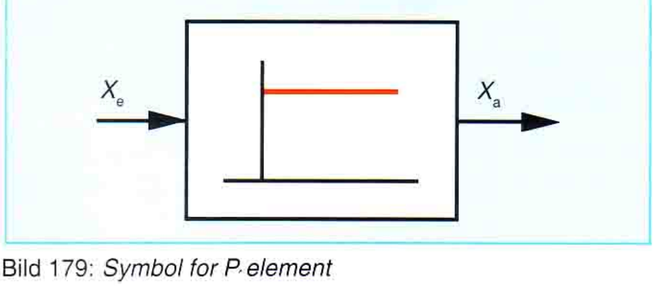


Bild 179: *Symbol for P element*

Some other examples involving the P element are the relationship U = R . I between current I and voltage U at a resistance R; the relationship F = m.a between acceleration a and force F on accelerated mass m; and the ideal amplifier with a resistance circuit (see "7 Appendix" for further details).

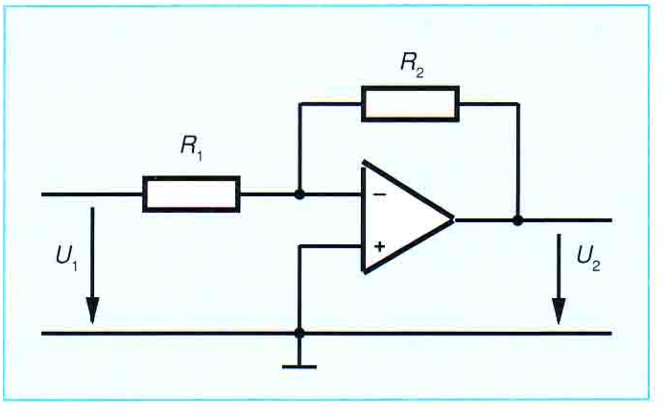


Bild 180: *Amplifier with resistance circuit*

The step response in the output voltage U_2 corresponds to a step change in the input voltage U_1.

The output voltage is given by

$$U_2 = \frac{-R_2}{R_1} \cdot U_1 = -K \cdot U_1$$

with gain

$$K = \frac{R_2}{R_1} .$$

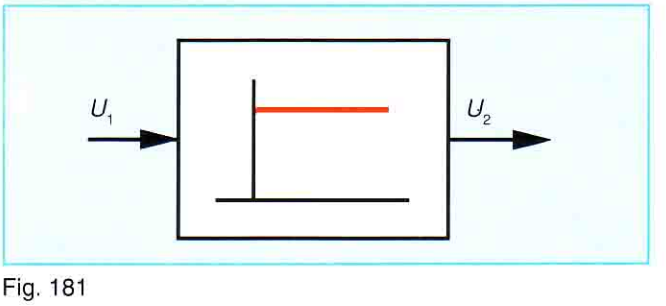


Fig. 181

2.2.2 Integral Element (I element)

The output signal increases linearly with respect to time.

$$X_a = K \cdot \int X_e(t) \cdot dt$$

Again K is the transfer constant or gain factor of the I element.

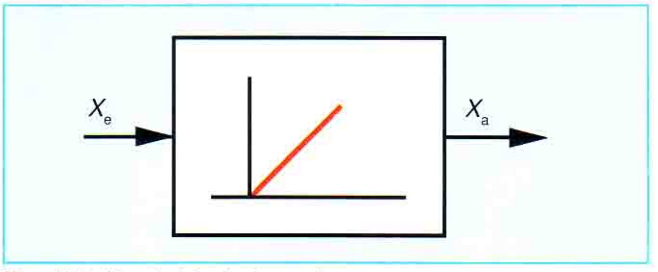


Fig. 182: *Symbol for I element*

Example involving the I element:

Hydraulic cylinder

Stroke s is dependent on the flow Q.

$$s = \frac{1}{A} \cdot \int q \cdot dt$$

$$K = \frac{1}{A}$$

A = effective area

Hydraulic motor

The angle of rotation of a motor shaft is dependent on the angular velocity.

$$\varphi = K_0 \cdot \int \omega \cdot dt$$

$$K = 1$$

Lead screw drive

A lead screw speed n is converted to a linear motion.

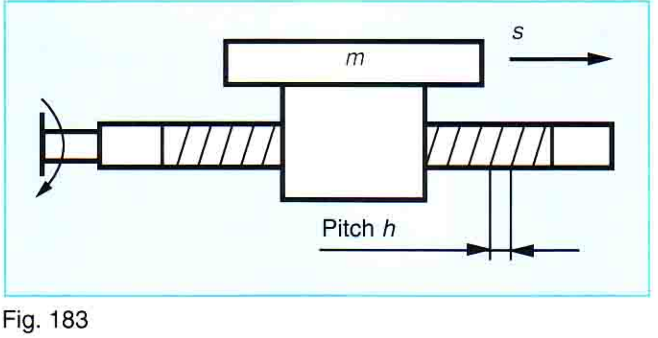


Fig. 183

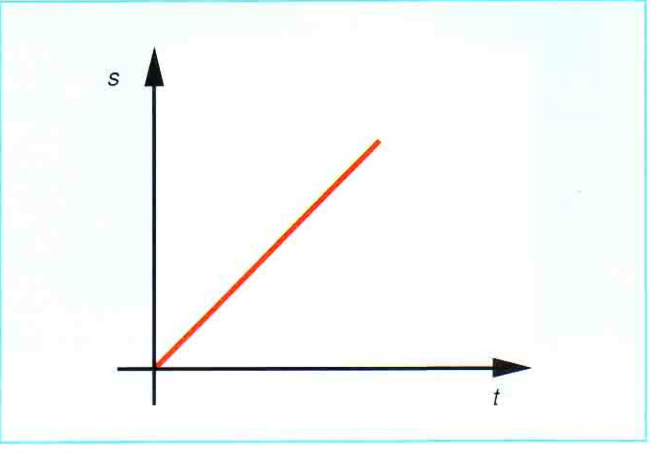
The output, which in this case is the stroke s is given by

$$s = h \cdot \int n \cdot dt$$

At constant lead screw speed n the stroke s is

$$s = h \cdot n \cdot t$$

i.e. stroke increases linearly with respect to time.



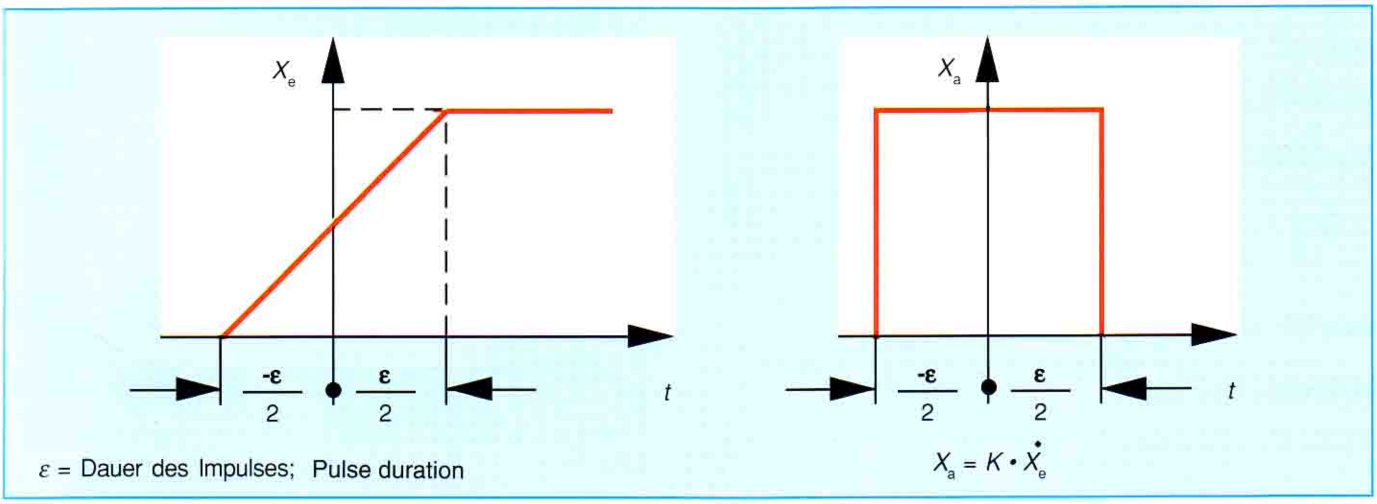
Diag. 64

2.2.3 Differential Element (D element)

The level of the output signal X_a depends on the rate of change of the input signal X_e.

$$X_{a(t)} = K \cdot \dot{X}_e$$

$$\dot{X}_e = \frac{dx_e}{dt}$$



Diag. 65: *Step response*

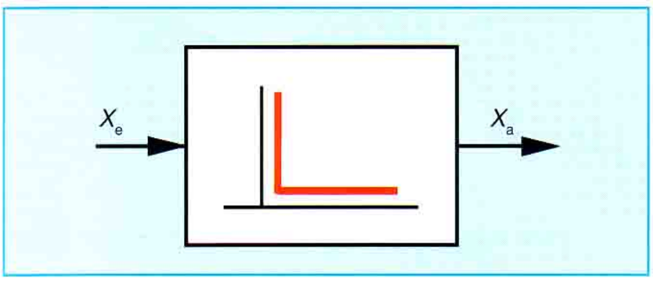


Fig. 184: *Symbol for D element*

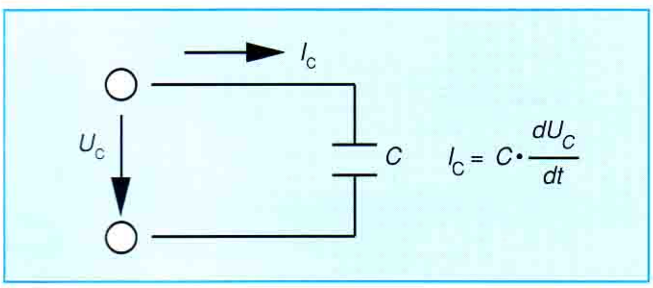


Fig. 185

Examples of the D element are the relationship $U = L \cdot \dot{I}$ of the voltage U with respect to current I at inductance L; the charging current of a capacitor, dependent on the capacitance C, and applied voltage U_c or the relationship $F = m \cdot \dot{v}$ ($\dot{v} = a$) i.e. of force F on the rate of change $\dot{v}$.

2.2.4 Time Delay Element

The amount of material at the beginning of belt is X_e, and the amount discharged at the end of the belt is X_a. At time t, the quantity at the start of the belt is $X_e = X_{e(t)}$. The time required for this quantity to be conveyed to the end of the belt is $T_t = l/v$.

At time t, at the end of the belt is the quantity which was at the beginning of the belt at T_t earlier i.e. at time ($t - T_t$)

Therefore: $\boldsymbol{X_a(t) = X_e\,(t - T_t)}$

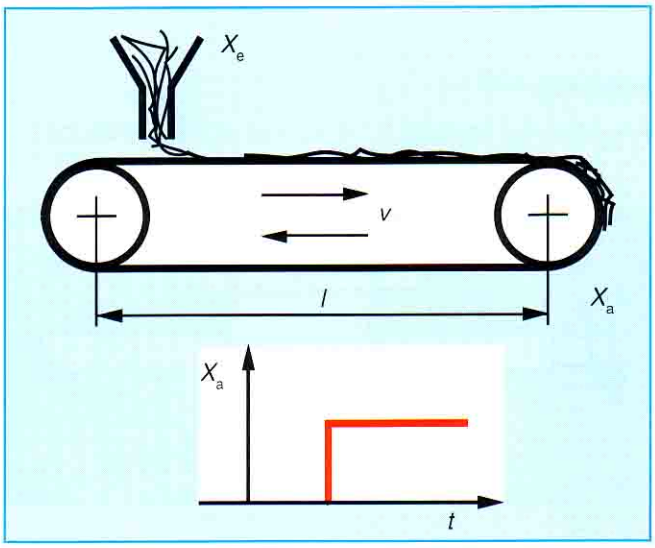


Fig. 186: *conveyor belt*

2.2.5 Proportional element with 1st order delay – PT_1 element

$$T \cdot \dot{X}_a + X_a = K \cdot X_e$$

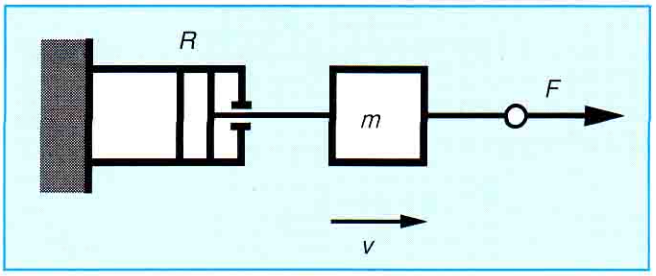
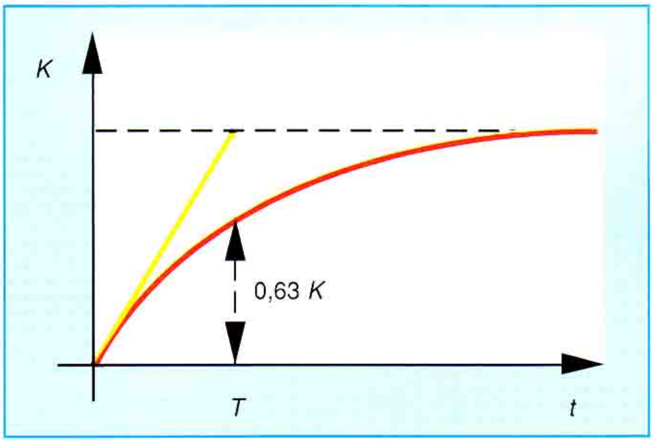


Fig. 187: *Example of PT_1 element*

The external force F and the fluid friction $-R \cdot v$ which is proportional to velocity act on mass m.

Therefore: $m \cdot \dot{v} = F - R \cdot v$ or $\frac{m}{R} \cdot \dot{v} + v = \frac{F}{R}$



Diag. 66: *Step response of PT_1 element*

The final value K is only reached after a certain time. The dynamic behaviour of the PT_1 element is due to the delay *Xe(t)*.

The tangent of the step response at $t = 0$ assumes the final value K at the time $t = T$.

T is therefore referred to as the time constant of the PT_1 element.

The time constant T hence determines the rate of increase.

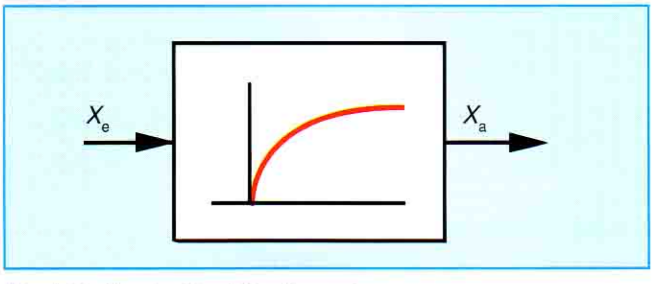


Fig. 188: *Symbol for PT_1 element*

2.2.6 Proportional element with 2nd order delay – PT_2 element

The PT_2 element is defined by the equation

$$T^2 \cdot \ddot{X}_a + 2 \cdot D \cdot T \cdot \dot{X}_a + X_a = K \cdot X_e$$

The constant T is again known as the time constant, the dimensionless number D represents the damping, and K is the transfer constant of the PT_2 element.

The relationship between the force F and the displacement X of a mechanical system is shown in *Fig. 189*.

$$m \cdot \ddot{X} = F - R \cdot \dot{X} - C \cdot X$$

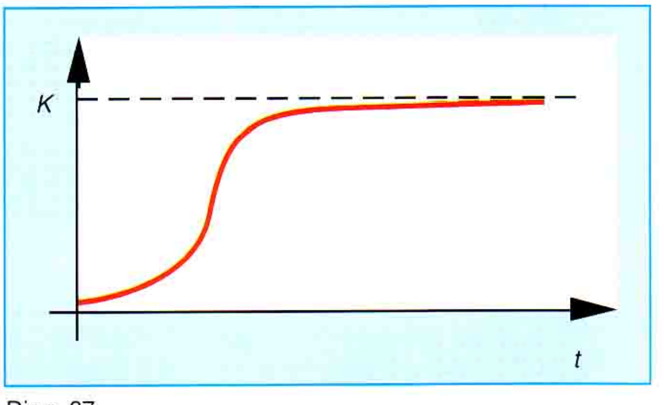
or

$$\underbrace{\frac{m}{C}}_{T^2} \cdot \ddot{X} + \underbrace{\frac{R}{C}}_{2\,D\,T} \cdot \dot{X} + X = \underbrace{\frac{1}{C}}_{K} \cdot F$$

$$T = \sqrt{\frac{m}{c}} \qquad D = \frac{R}{2 \cdot \sqrt{m \cdot c}} \qquad K = \frac{1}{c}$$

Step response of the PT_2 element

In the limiting case, for $D > 1$ there is no oscillation *(Fig. 67)*



Diag. 67

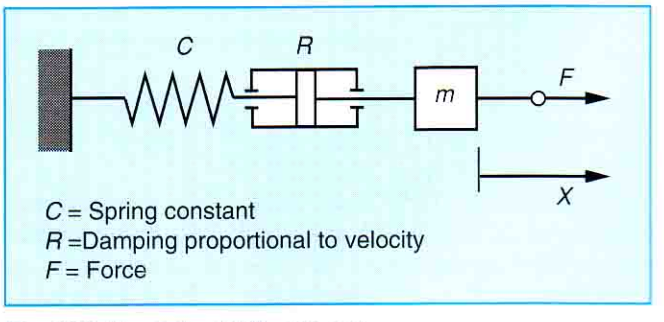
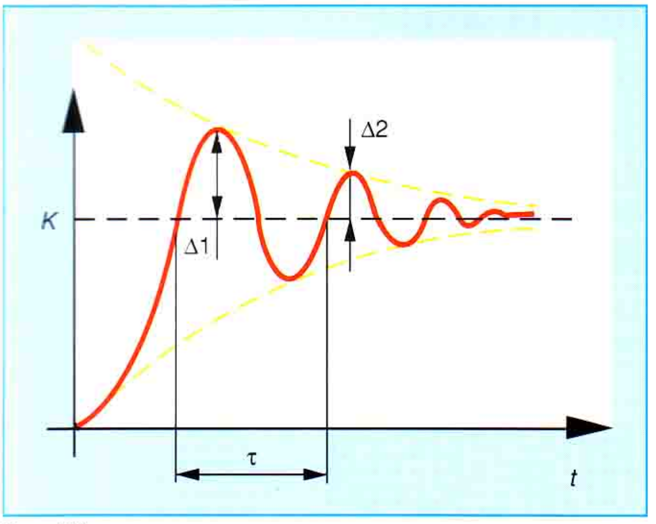


Fig. 189: *Example of PT_2 element*

For $D < 1$ the step response takes the form of a damped oscillation.



Diag. 68

Its frequency is

$$\omega_N = \sqrt{1 - D^2} \cdot \omega_0 = \frac{\sqrt{1 - D^2}}{T} \qquad \omega_0 = \frac{1}{T}$$

This is termed a periodical case and hence the PT_2 element is also known as an oscillation element.

Derived from this step response is the symbol for the PT_2 element, applicable for all cases.

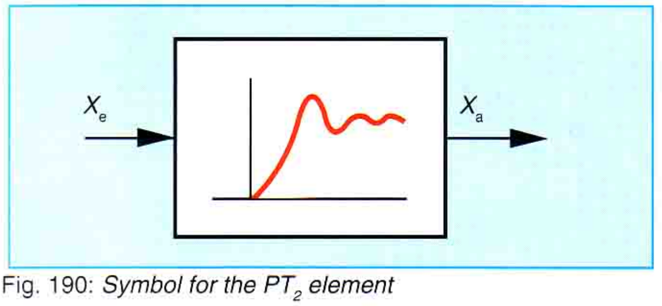


Fig. 190: *Symbol for the PT_2 element*

The parameters *K*, *D* and *T* may be determined from the oscillation diagram *(Diag. 68)*

The transfer constant K is the final value in the step response.

In order to determine the damping *D*, the amounts by which the final value *K* is exceeded by in the first peak Δ*1* and second peak Δ*2* are measured. These form a "logarithmic decrement":

$$\delta = \ln \frac{\Delta 1}{\Delta 2} = 2{,}303 \log_{10} \frac{\Delta 1}{\Delta 2}$$

and hence

$$D = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}$$

To determine T, the period for one oscillation is required, which may be read off the step response.

Given $\tau = \frac{2\pi}{\omega_N} = 2\pi \frac{T}{\sqrt{1 - D^2}}$

then $T = \frac{\tau}{2\pi} \sqrt{1 - D^2}$

2.2.7 Summary of the Basic Transfer Elements

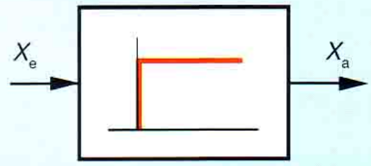
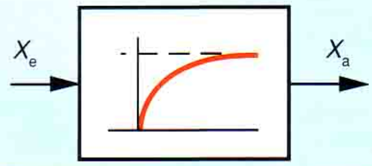
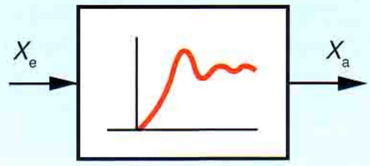
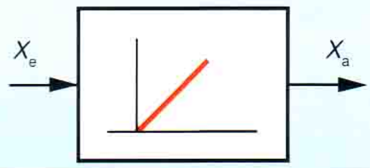
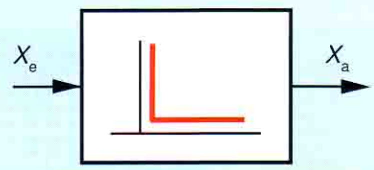
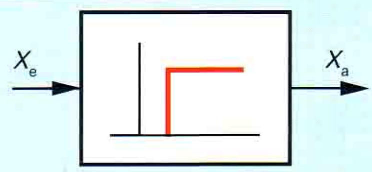
P element	$X_a = K_p \cdot X_e$	
PT$_1$ element	$T_1 \cdot \dot{X}_a + X_a = K_p \cdot X_e$	
PT$_2$ element	$T^2 \cdot \ddot{X}_a + 2 \cdot D \cdot T \cdot \dot{X}_a + X_a = K_p \cdot X_e$	
I element	$X_a = K_I \cdot \int X_e(t) \cdot dt$	
D element	$X_a = K_D \cdot \dot{X}_e$	
T$_t$ element	$X_a(t) = K \cdot X_e(t - T_t)$	

Fig. 191: *Basic transfer elements*

As already mentioned, the main task of closed loop control is to eliminate effects of external disturbances on control parameters.

However, this arrangement is also suitable for when changes in the command signal occur. The actual value of the control variable may be easily aligned with the new command signal.

Closed loop control therefore has two tasks:

- Elimination of external disturbances
- Adjustment to the reference value

Influencing the control variable after a change in input or external disturbance generally requires a certain period of time (refer to transfer function).

If the external disturbance increases by a step, closed loop control responds by readjustment of the changed control variable. This always occurs with a delay irrespective of the physical nature of the closed loop system.

For example, moment of inertia and friction are of importance in a mechanical system, whilst charges may be reversed in electrical systems etc.

How the control variable behaves with time is, however, of significance for the closed loop control characteristic.

For example, the system may begin to oscillate if attempts are made to keep this delay as short as possible by allowing the regulator to intervene too much in the case of changes in disturbance variables.

If any initial oscillation is self-damping, then the closed loop control is considered to be stable. If the oscillation does not abate, i.e. a constant oscillation is taking place in the closed loop control circuit, then the closed loop control is said to be unstable.

If the closed loop control is stable, another feature it must maintain is a closed loop error below a preset value.

These requirements with respect to stability and maintaining preset closed loop errors are essential for a closed loop control circuit.

Often, even further demands are placed on closed loop control.

For example, the adjustment time after a change in input or external disturbance may be required to be within a certain time.

These requirements are by no means achieved by adding arbitrary measuring, comparing or positioning devices to the controlled system and hence closing the control loop.

The closed loop control circuit would almost certainly be either unstable, extremely inaccurate or very slow.

To ensure that the closed loop control circuit meets specific requirements, particular fundamental rules must be taken into consideration, particularly concerning the selection of the regulator itself.

An accurate description of the dynamic behaviour of all closed loop control elements is necessary to ensure the correct selection of a regulator.

At this point, the many criteria for stability will not be discussed, but the relevant literature on closed loop control technology may be referred to for further information.

Reference is, however, made to general suitability of particular regulators to given controlled systems.

As shown in Fig. 192, a regulator is matched to a control system dependent on its time characteristic, otherwise stable closed loop control circuits are not produced. For this reason, regulators are necessary with varying time characteristics.

Note to Fig. 192:

Reference means:
Used for changes in reference values.

External disturbance means:
Used to compensate external disturbances.

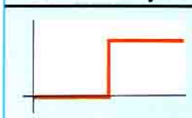
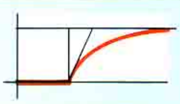
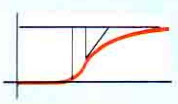
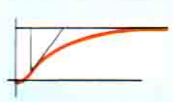
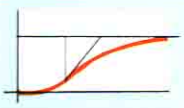
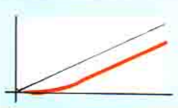
Controlled system / Regulator		P	I	PI	PD	PID
	Pure time delay	Not applicable	Not quite as good as PI	Reference + external disturbance	Not applicable	Not applicable
	Time delay + 1st order delay	Not applicable	Not quite good as PI	Not quite as good as PID	Not applicable	Reference + external disturbance
	Time delay + 2nd order delay	Not suitable	Poor	Not quite good as PID	Poor	Reference + external disturbance
	1st order + extremly short time delay	Reference	Not suitable	external disturbance	Reference at time delay	external disturbance at time delay
	Higher order	Not suitable	Not quite good as PID	Not quite as good as PID	Not suitable	Reference + external disturbance
	Integral behaviour	Reference (without delay)	Not applicable unstable structure	external disturbance (without delay)	Reference	external disturbance

Fig. 192: *Selection of a suitable regulator for a given controlled system*

3 Summary of Applicable Regulator Functions

The following regulators are appropriately connected operational amplifiers.

3.1 P regulator

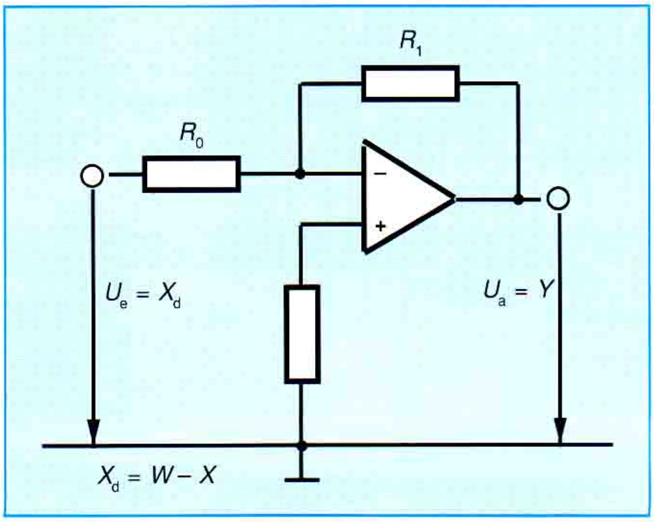


Fig. 193

Closed loop proportional control means that the output U_a is proportional to the input U_e.

For the circuit in *Fig. 193*

$$Y = \frac{R_1}{R_0} \cdot X_d$$

where R_1/R_0 = gain factor = K_P

The behaviour of a closed loop control amplifier may be determined by observing the response to a step input. This refers to how the output voltage U_a proceeds with time when an input voltage U_e is stepped from zero to a set value.

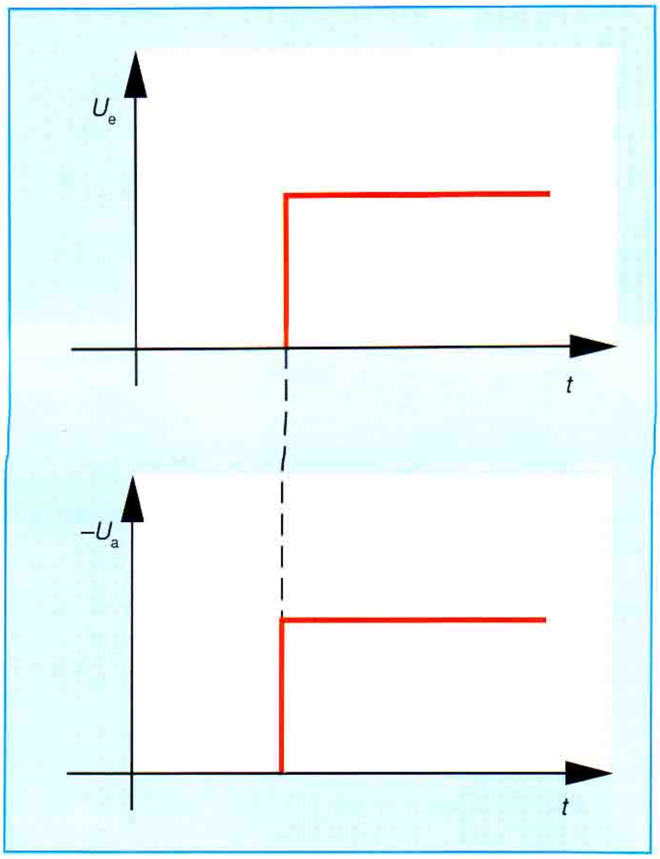
The P regulator hence responds to a step change in the input X_d with a step change in the output Y (control variable).

Features of the P regulator:

- Simple construction
- Easy adjustment
- Fast response to change in control variable

Basically, the control variable never quite equals the input variable using a P regulator. A closed loop error dependent on the gain factor always exists and must be accepted.

This is due to the fact that the P regulator requires a closed loop error to function.



Diag. 69: *Step response of P regulator*

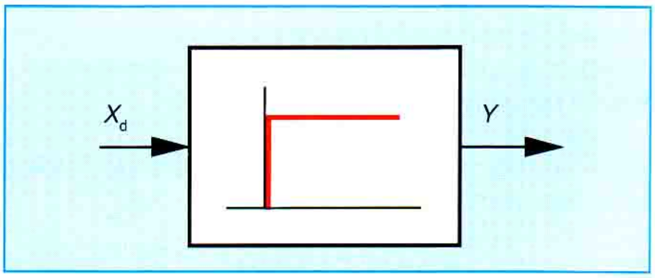


Fig. 194: *Block representation of P regulator*

5.2 I regulator

A regulator with an integrating function produces the time integral of the input variable.

This is characterized by the integration time constant

(The integration time constant is the time required by the integrator to achieve an output voltage U_a at a stepped input voltage U_e.)

$$T_I = R_0 \cdot C$$

or its reciprocal:

$$K_I = \frac{1}{T_I} \cdot$$

The input voltage U_e is the closed loop error $X_d = W - X$.

The output voltage is the control variable

$$Y(t) = U_a(t) = \frac{-1}{T_I} \int_0^t X_d(t)\, dt$$

The output signal is inverted if required by the circuit. An input voltage step produces a linear output voltage with respect to time.

Hence, a special feature of an I element is that the output continues changing for as long as the input is not equal to zero. The output voltage does not change once the input voltage is zero *(Diag. 71)*.

In comparison to the P regulator, the control variable generated by the I regulator is not proportional to the closed loop error, but rather the rate of change of the control variable is proportional to the closed loop error *(Diag. 70)*.

In principle, the integral regulator completely eliminates all closed loop errors since in time even the smallest input signals become large output signals.

The advantage of eliminating closed loop errors is offset by certain disadvantages.

As may be seen from the time diagram for the I regulator, the I regulator reacts relatively slowly to a change in the control variable. This results in long control times and possible large overshoots of the closed loop control variable.

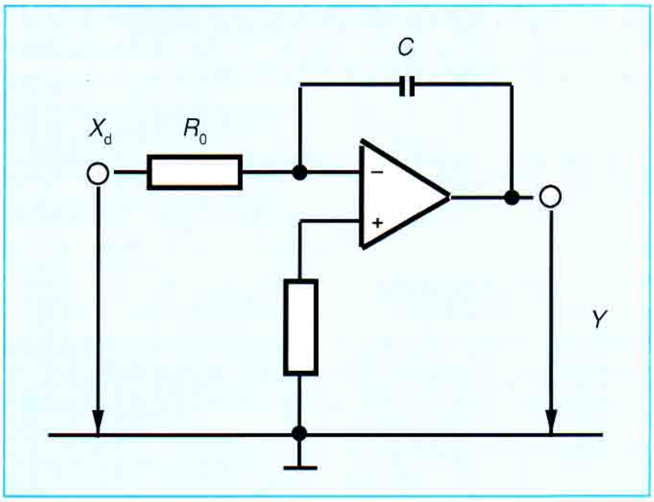


Fig. 195

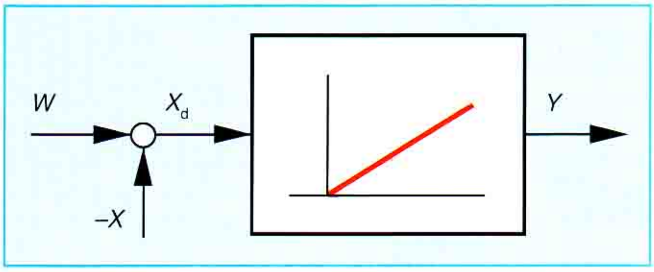
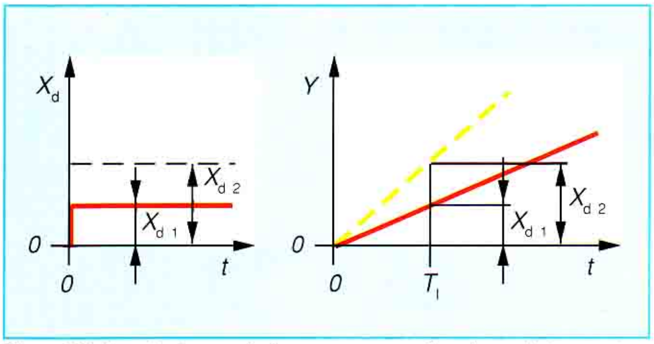
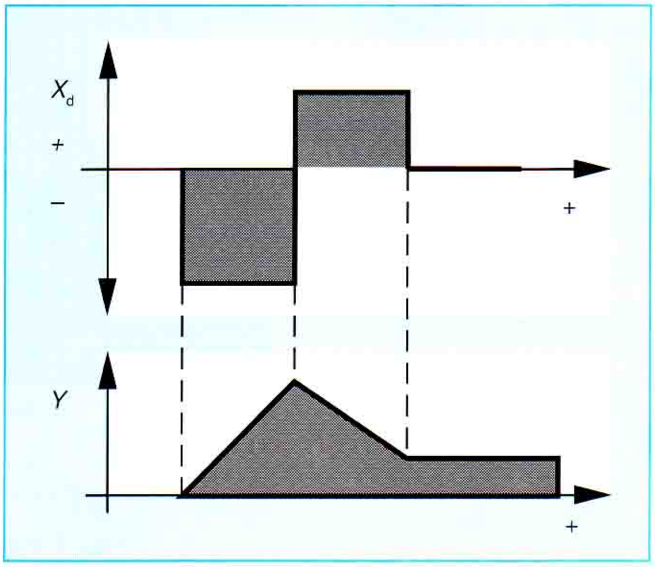


Fig. 196: *Block representation of I regulator*



Diag. 70: *Input step and step response of an I regulator system*



Diag. 71: *Time diagram of an I regulator*

3.3 PI regulator

The PI regulator combines the good characteristics of the P regulator (fast response) with those of the I regulator (accuracy).

The proportional and integral components are added together.

This regulator is used in effect in such a way that the proportional component quickly removes external disturbance (but not accurately) by regulation and then the integral component ensures that accurate closed loop control is carried out.

The adjustment time is the time T_n taken by the integral component, to produce the same change in output as the proportional component produced instantaneously for the same input step.

The behaviour of the PI regulator is hence the same as that of an I regulator. However, it effectively becomes active earlier, i.e. by the adjustment time T_n *(Diag. 72).*

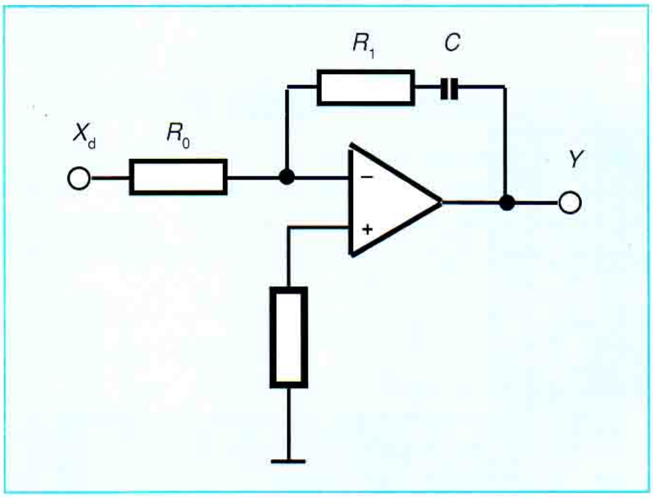


Fig. 197: *PI regulator*

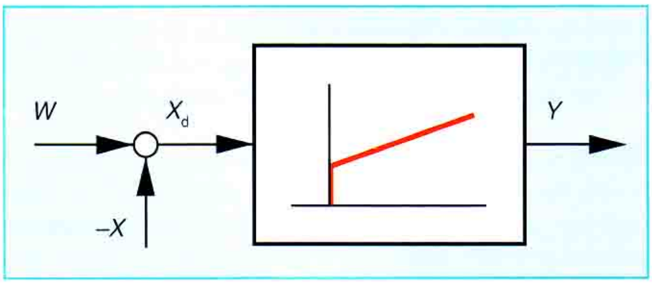
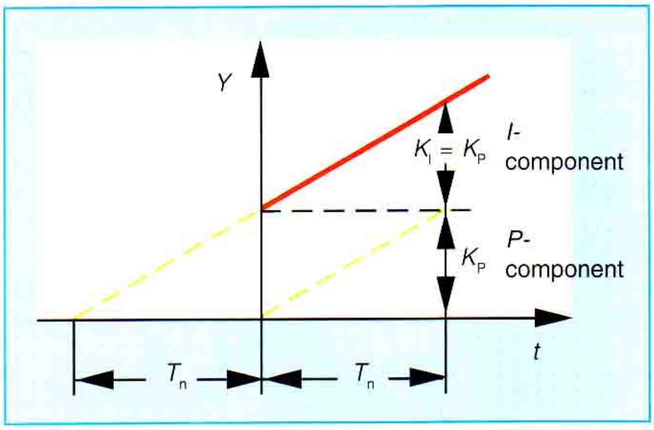


Fig. 198: *Block representation of PI regulator*



Diag. 72: *Behaviour of PI regulator*

The output of a PI regulator is equal to the outputs of P and I regulators added together.

$$Y = K_P \cdot X_d\ (t) + K_I \int X_d\ (t)\ dt$$

Here it is more practical to use the time constant as $T_n = K_p / K_I$ rather than parameter K_I.

$$Y = K_P \left(X_d\ (t) + \frac{1}{T_n} \int X_d\ (t)\ dt \right)$$

Here K_p, the proportional factor, and T_n, the adjustment time, are the parameters of the regulator which which may be selected.

$$K_P = \frac{R_1}{R_0} \qquad T_n = R_1 \cdot C = \frac{K_P}{K_I}$$

$$T_I = R_0 \cdot C = \frac{1}{K_I}$$

As R_1 effects both K_p and T_n, K_p is altered via R_1, but T_n is altered via C.

3.4 D regulator

The differential regulator responds to the rate of change $\Delta X_d/\Delta t$.

This regulator is not suitable to be used on its own for closed loop control.

The *D* behaviour may be combined with other time characteristics to produce either a PD or PID regulator.

Using only a *D* component the output *Y* is proportional to changes in the velocity of the input X_d.

$$Y(t) \approx \frac{\Delta X_d}{\Delta t}$$

$$Y(t) = K_D \cdot \frac{dX_d(t)}{dt} = -T_D \frac{dX_d(t)}{dt}$$

K_d is the differential factor and T_D the differential time constant.

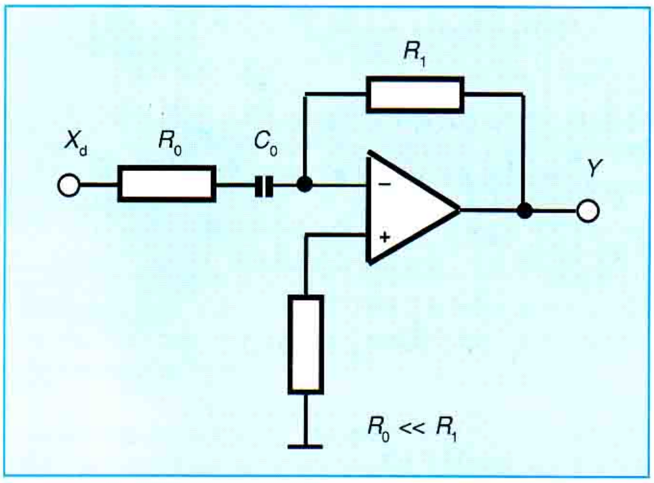
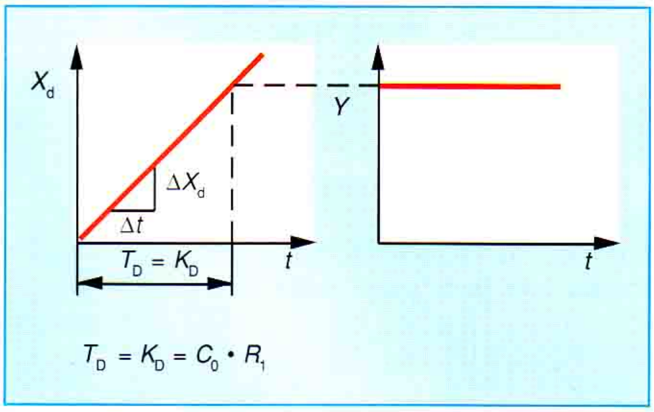


Fig. 199: *D regulator*

The behaviour of this regulator is examined using a ramp input signal, instead of a step input signal.



Diag. 73: *Behaviour of D regulator*

3.5 PD Regulator

By adding a differential stage, the rate of change of the closed loop error also effects the output signal.

Hence, closed loop control is accelerated.

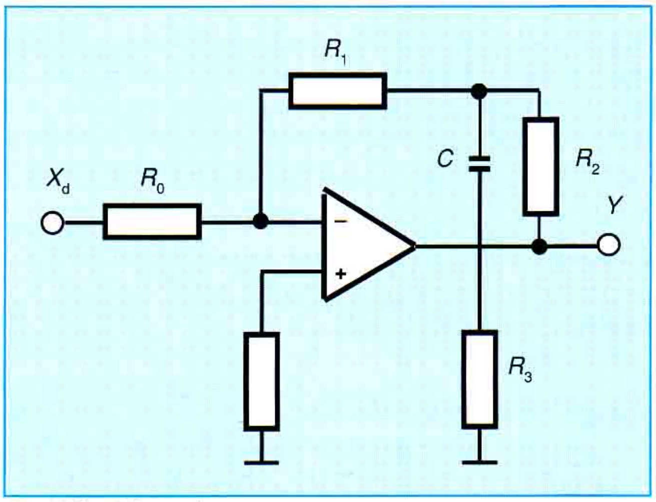
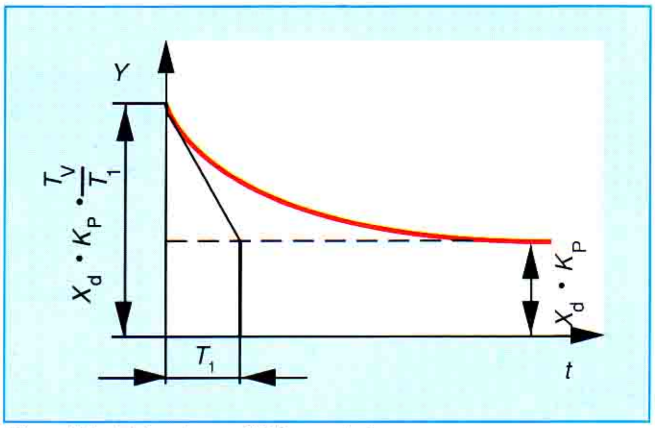


Fig. 200: *PD regulator*



Diag. 74: *Behaviour of PD regulator*

The output from a PD regulator is equal to the outputs of P and D regulators added together.

Hence

$$Y(t) = K_P \cdot X_d(t) + K_D \frac{dX_d(t)}{dt}$$

$$Y(t) = K_P \left(X_d(t) + \frac{K_D}{K_P} \frac{dX_d(t)}{dt}\right)$$

$$Y(t) = K_P \left(X_d(t) + T_V \frac{dX_d(t)}{dt}\right)$$

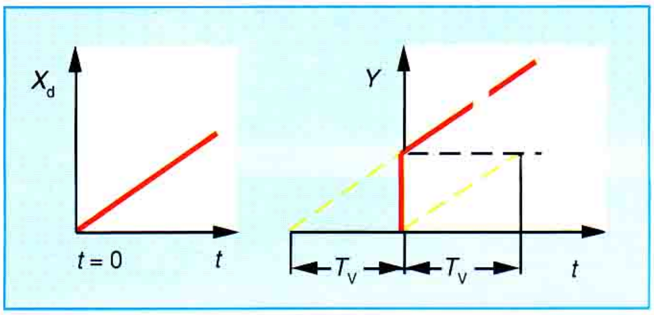
$$K_P = \frac{R_1 + R_2}{R_0}; \quad T_V = \left(\frac{R_1 \cdot R_2}{R_1 + R_2} + R_3\right) \cdot C$$

K_P	proportional factor
K_D	differential factor
$K_D / K_P = T_V$	derivation action time

Time delay $T_1 = R_3 \cdot C << T_V$

The time delay T1 dampens the output signal and limits it to $t = 0$ auf $Y = X_d \cdot K_P \ (T_V / T_1)$.

As with the D regulator the ramp is also used as a test signal for the PD regulator.



Diag. 75: *Behaviour of PD regulator*

The derivative action time TV is the time it takes, after the ramped input signal, for the output of the proportional component to reach the same level as the output of the D component which was produced immediately.

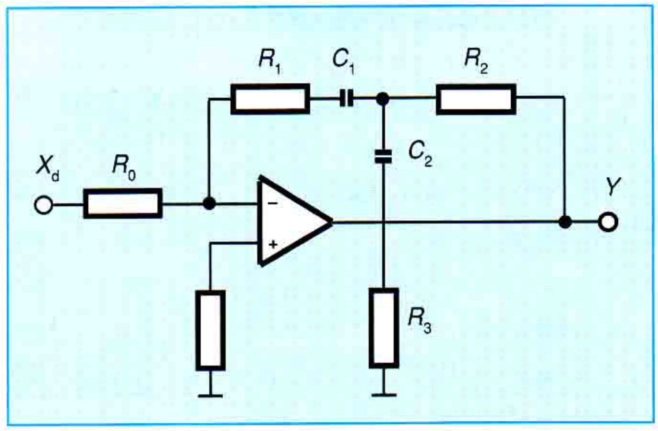
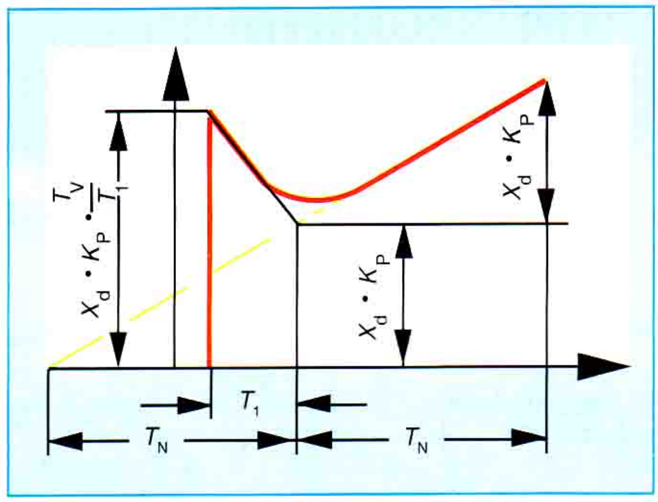


Fig. 201



Diag. 76

3.6 PID regulator

The PID regulator is a combination of all three types of regulator, i.e. P, I and D.

Such a regulator with adjustable control constants may be adapted to suit any control system.

In addition to the good dynamic properties of the PD regulator, the static closed loop errors are removed.

First, the control variable changes by an amount dependent on the change in velocity of the input dX_d/d_t (D component). After the derivative action time has elapsed, the control variable returns to a value in the proportional range and it then changes with respect to the value of the I component.

The control variable Y is equal to the outputs of P, I, and D regulators added together.

$$Y = K_P \cdot X_d(t) + K_I \int X_d(t)\, dt + K_D \frac{dX_d(t)}{dt}$$

$$Y = K_P \left(X_d(t) + \frac{K_I}{K_P} \int X_d(t)\, dt + \frac{K_D}{K_P} \frac{dX_d(t)}{dt}\right)$$

Using the known time constants

$T_n = K_P / K_I$ and $T_V = K_D / K_P$

where $Y = K_P \left(X_d(t) + \frac{1}{T_n} \int X_d(t)\, dt + T_V \frac{dX_d(t)}{dt}\right)$

$K_P = \frac{R_1 + R_2}{R_0}$	proportional constant
$T_n = (R_1 + R_2) \cdot C_1$	readjustment time
$T_V = \left(\frac{R_1 \cdot R_2}{R_1 + R_2} + R_3\right) \cdot C_2$	derivation action time
$T_1 = R_3 \cdot C_2$	delay

4 Principles of Closed Loop Control

4.1 Closed Loop Position Control, Motor Drive

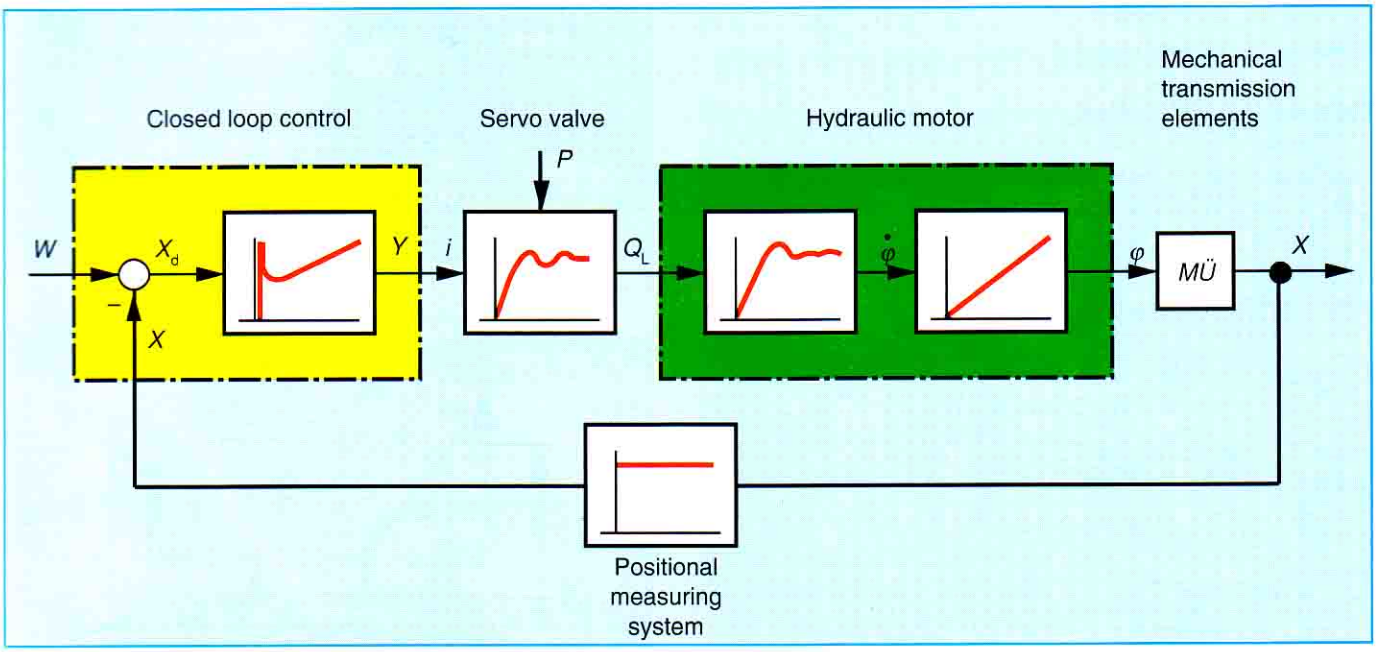


Fig. 202: *Block diagram of a closed loop position controlled motor drive*

Transfer Behaviour of Closed Loop Control Elements

The servo valve and positioning motor under load are considered to be 2nd order systems connected in series (proportional element with 2nd order delay, PT_2 element).

Due to integration during the transfer of angular velocity to angle of rotation, the controlled system is then considered to be a 5th order system (The 5th order system is produced by multiplication of the frequency response equations of the individual elements. Refer to relevant literature on closed loop control technology).

Depending on the regulator selection criteria for the control system *(Fig. 192)*, the regulator chosen will be a PID regulator.

The positional measuring system may be considered as a P element without delay, i.e. it responds to a change in the input without delay.

The hydraulic motor behaves as a proportional element with respect to the angular velocity and as an integral element with respect to the angle of rotation.

4.2 Closed Loop Position Control, Cylinder Drive

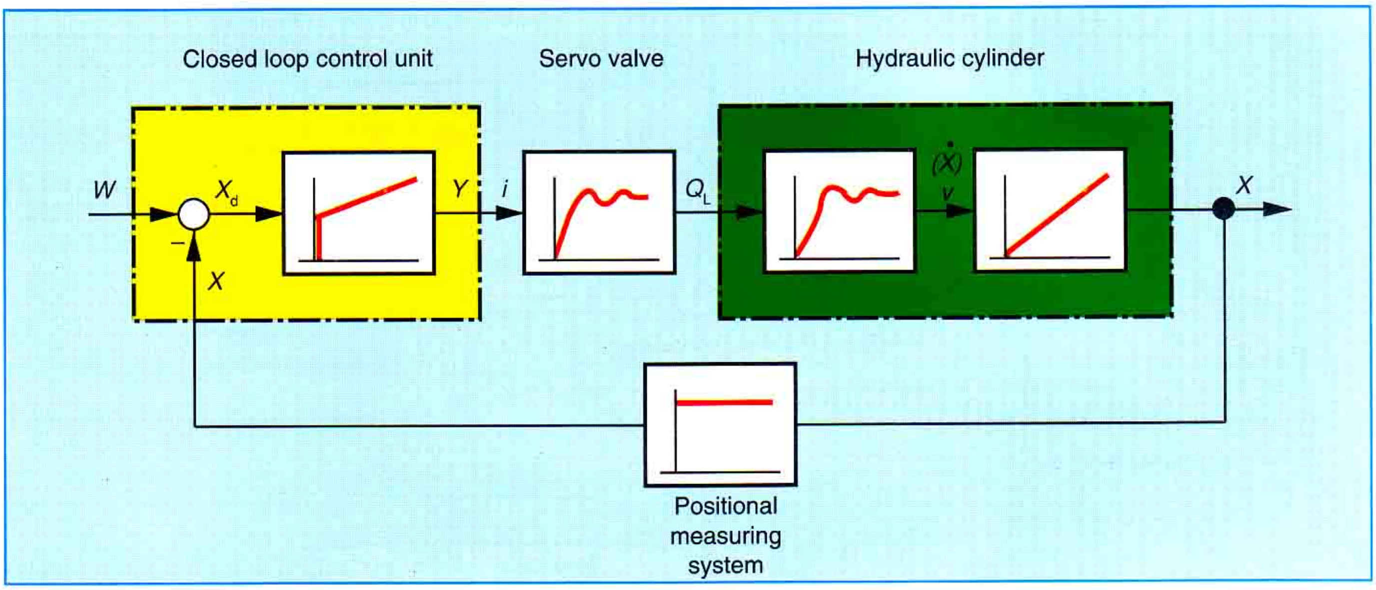


Fig. 203: *Block diagram of a closed loop positional controlled cylinder drive*

Transfer Behaviour of Closed Loop Control Elements

The servo valve and cylinder may be considered as 2nd order systems connected in series.

In this case, the integration represents the transfer of cylinder velocity to stroke.

Again, a 5th order system is produced.

It is clear that these two block diagrams are almost identical. Hence, the statement on *page 162* is confirmed, i.e. if substituting a theoretical model for a real technical system the wide variety of technical components may be ignored.

The hydraulic cylinder behaves as a proportional element with respect to the travel speed and as an integral element with respect to the cylinder stroke.

4.3 Closed Loop Positional Control
(Servo Control)

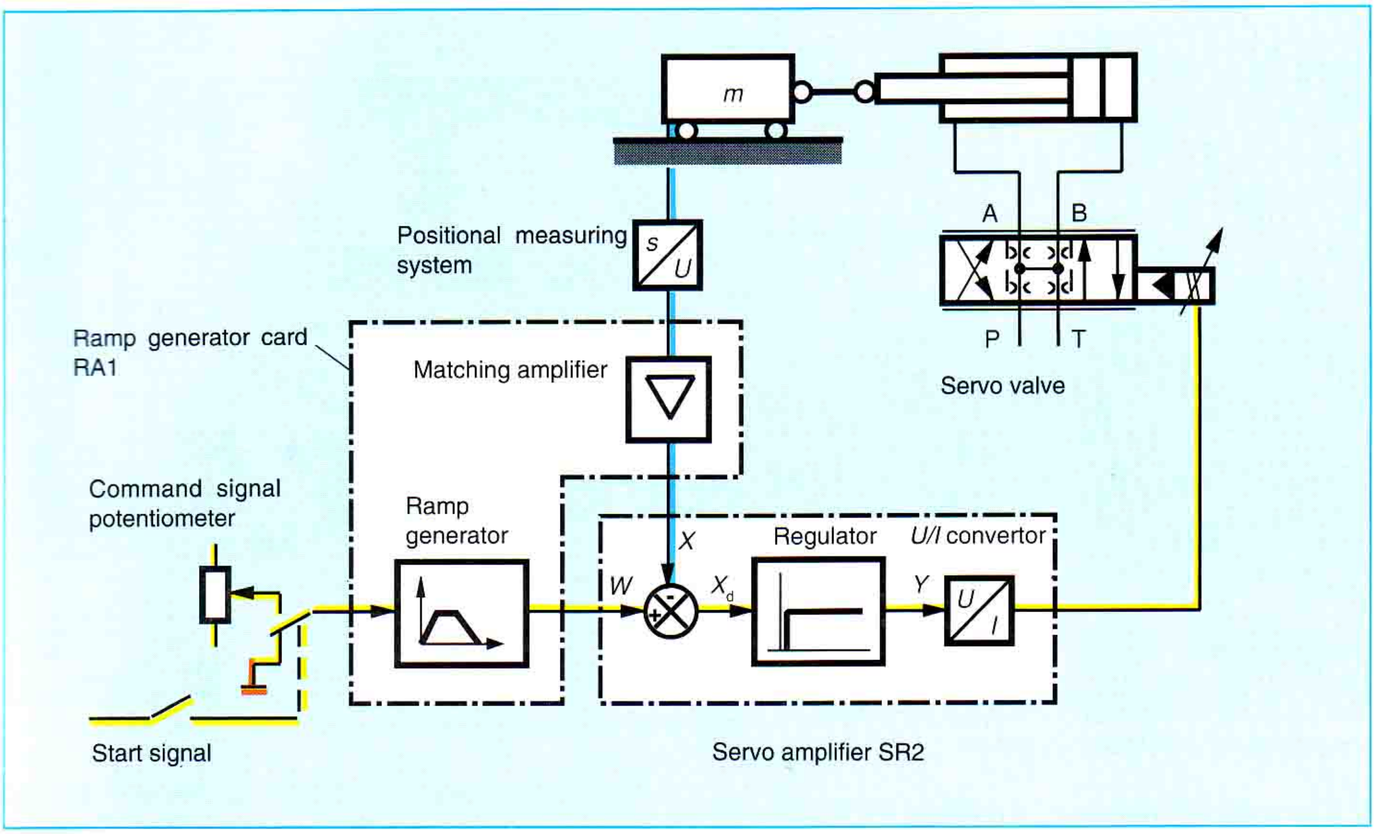


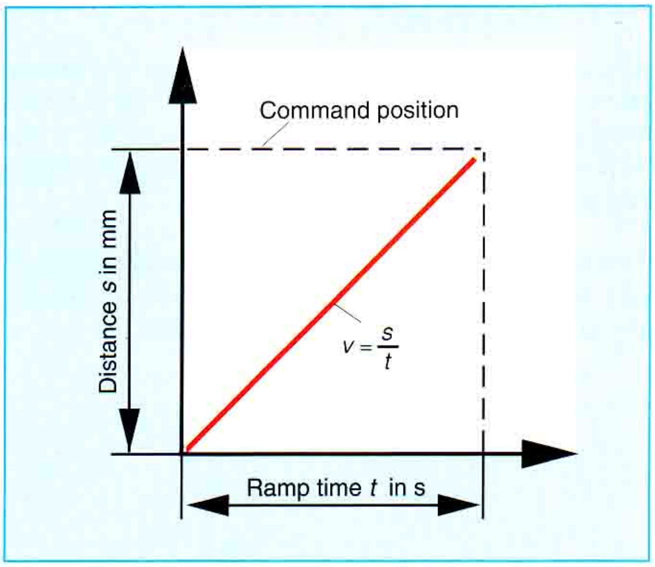
Fig. 204: *Example of closed loop positional control circuit*

Both the position of the cylinder and the travel speed may be controlled using this circuit.

Signal Sequence

The control signal is fed to the ramp generator via a start signal. During the set ramp time, the output from the ramp generator increases from 0 V to the voltage set at the command signal potentiometer.

In this case, the set ramp time corresponds to the travel speed.



Diag. 77

4.4 Closed Loop Speed Control
(Velocity Control)
with Integration of Reference Values

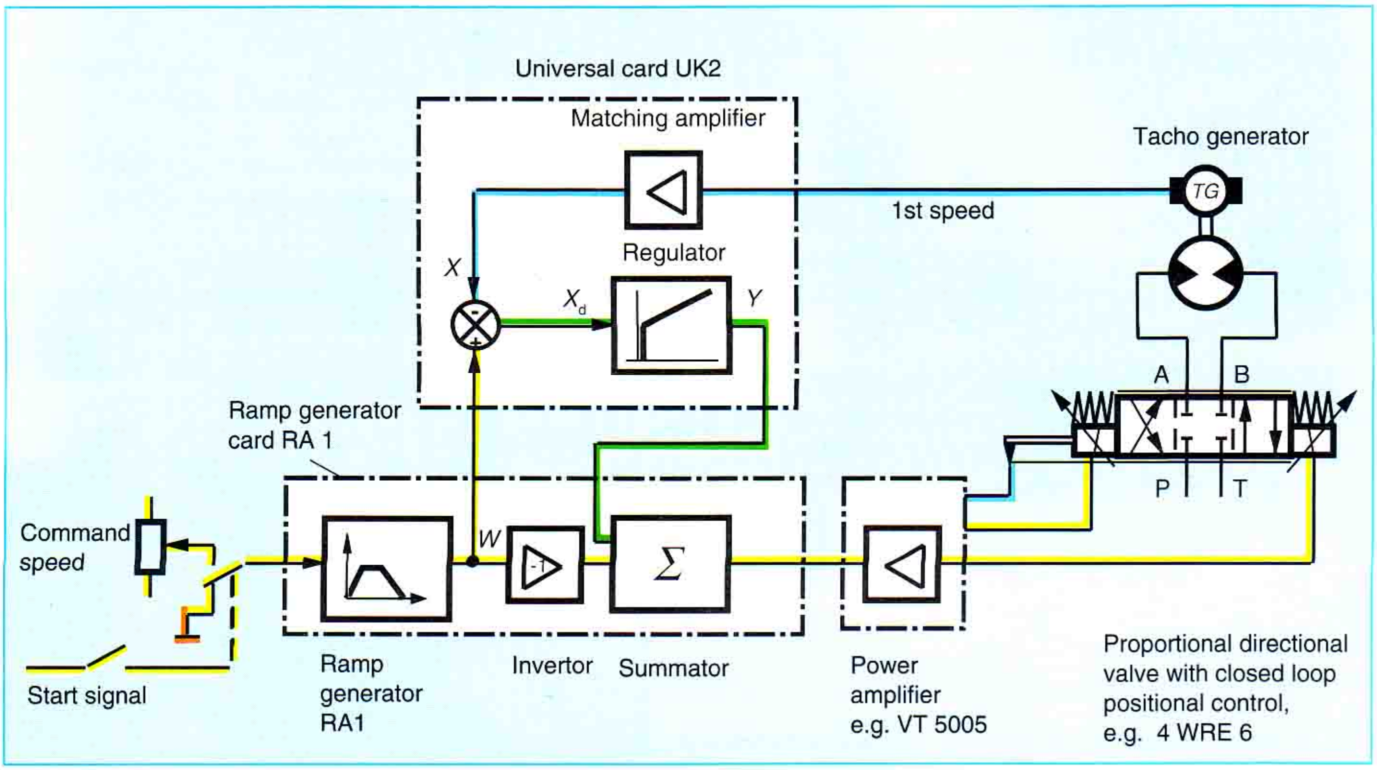


Fig. 205: *Example of a closed loop speed control circuit*

The set command speed is fed to the ramp generator via a start signal.

The command output from the ramp generator increases with respect to the set ramp time.

This signal is fed directly to the power amplifier via the invertor and summator. Hence, the valve is directly controlled by this command signal. At the same time, the command signal is compared with the control variable (current actual speed) and the difference is then fed to the regulator.

The control signal from the regulator is fed to the summator where it effects the control signal fed to the power amplifier and hence controls the servo valve.

Using this circuit, the closed loop control can be given a faster response, as the regulator is only activated when command/actual signal differences occur.

4.5 Closed Loop Velocity Control

Using the closed loop control shown in *Fig. 207*, only velocity may be controlled.

It is not possible to reach the command position.

Signal Sequence

The command velocity signal set via the command signal potentiometer is fed to the ramp generator RA 1 via a start signal. During the set ramp time, the ramp generator output signal is increased from 0 V to the command signal fed in at the input. The ramp time corresponds to the acceleration.

The ramp generator output signal is fed to the SR servo amplifier. The cylinder velocity is measured by means of a velocity transducer. The velocity signal is matched to the command signal via a matching amplifier which is also on the ramp generator card.

The command signal in the control loop is normally between 0 and10 V. Matching of the actual value means that the actual signal is 10 V at the maximum required velocity.

This matched actual signal is also fed to the servo amplifier.

Command/actual signal comparison is carried out via the SR servo amplifier. The closed loop error X_d is fed to the PI regulator. This regulator generates the control signal Y, which directly actuates the servo valve, such that the actual velocity is matched to the command velocity.

The PI regulator continues changing its output voltage until the command/actual signal difference is zero *(see PI regulator, page 173)*.

To prevent the PI regulator from drifting and to ensure that the capacitor is not charged at the start, the regulator is released by a start signal from a switching amplifier.

If the relay K1 is closed, the PI regulator carries out its normal closed loop control function. On the other hand, if relay d1 is open, the operational amplifier feedback is short-circuited so that the output signal Y equals zero (as the gain equals zero).

The regulator is released by a switching amplifier (1) dependent on the applied command signal. (Release means K1 is closed.) The switching amplifier is set so that the regulator starts carrying out the closed loop control at a command signal of approx. 100 mV.

A second switching amplifier (2) is connected, which effects the release of the regulator dependent on the actual velocity.
If, for example, the command velocity signal is stepped down to zero, the switching amplifier coupled to the command signal switches off.

However, the control function is retained by the second switching amplifier (coupled to the actual value), so that the controlled movement of the cylinder may continue until it reaches the neutral position.

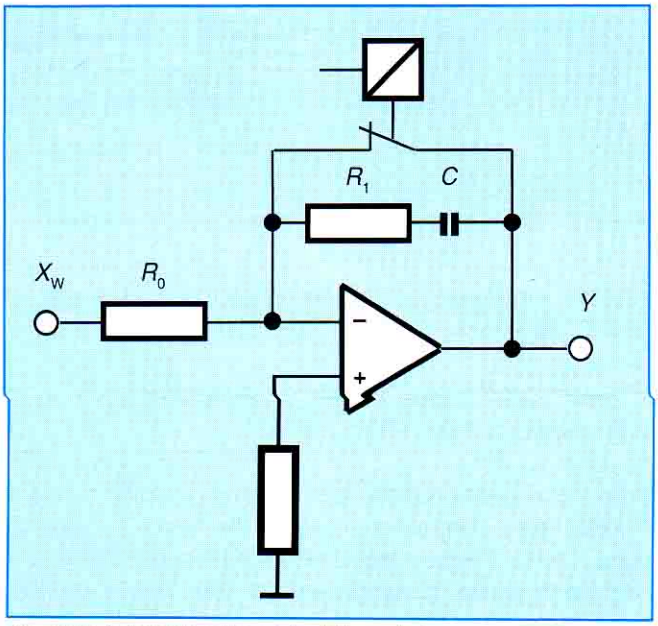


Fig. 206: *Interlock release for PI regulator*

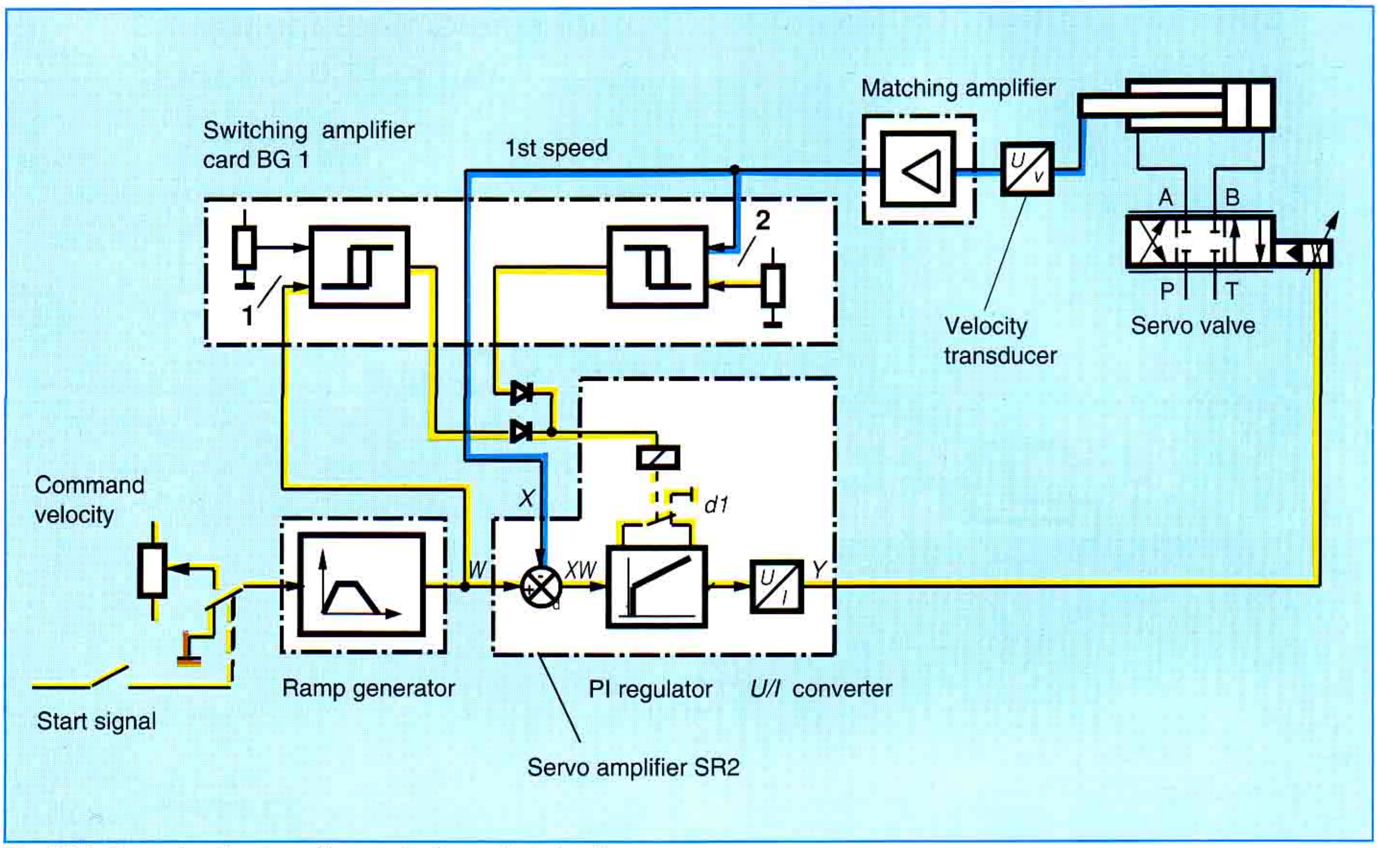


Fig. 207: *Example of a closed loop velocity control circuit*

4.6 Closed Loop Pressure Control

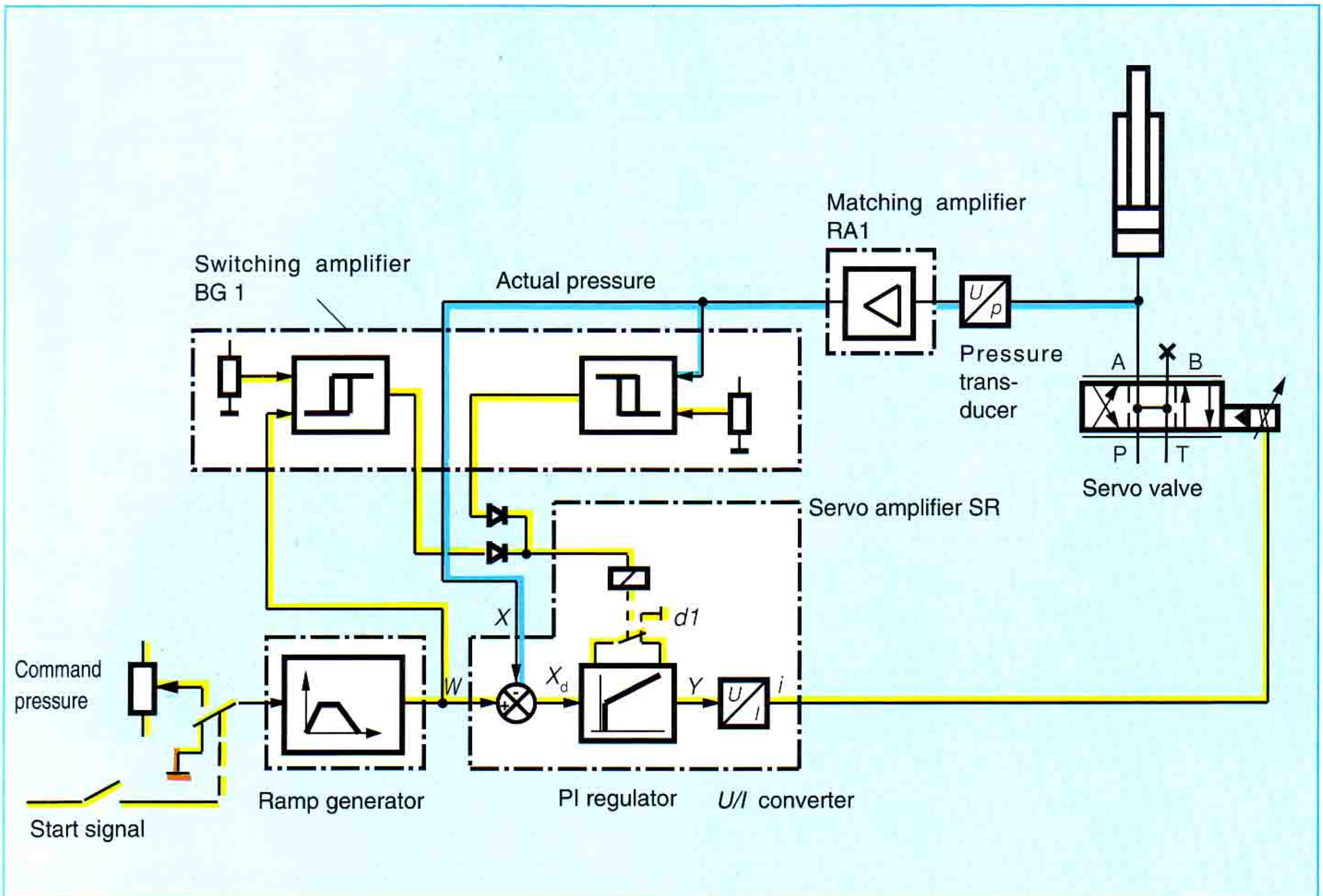


Fig. 208: *Example of a closed loop pressure control circuit*

Closed loop pressure control is the third type of basic closed loop control.

The block diagram for this closed loop control circuit is very similar to the previous block diagrams, so there is no need to describe the signal sequence in this case.

4.6.1 General information on closed loop pressure control with a directional servo valve

The valve operates about its neutral point so long as disturbance flows are not present. The possible loop gain is hence determined by the servo valve.

Pressure chamber characteristics also have an influence on the system and must be considered via a time constant T.

4.6.2 Estimation of loop gain

The critical loop gain is almost proportional to the product

$$V_{Crit} = 2 \cdot D_V \cdot \omega_V \cdot T$$

D_V = Damping factor of the valve

ω_V = Natural frequency of the valve (1/s) (frequency at-90° phase offset)

T = Pressure chamber time constant

If the amplitude drop at the valve at the natural frequency (-90°) is defined as A_v (specified in dB) then:

$$A_V = 20 \cdot \log \frac{1}{2\ D_V}.$$

Hence degree of damping Dv is given by

$$D_V = \frac{10^{-\left(\frac{A_V}{20}\right)}}{2}.$$

The time constant T is given by

$$T = \frac{V}{E \cdot K_{pq}}.$$

where

V = Oil volume which is clamped or to be compressed

E_{oil} = Modulus of elasticity (1,4 • 10^5 N/cm²)

K_{pq} = Pressure flow gain of the valve (V_q/V_p)

The optimum loop gain is therefore

$$K_{V\ opt} = \frac{1}{3}\ V_{Crit}.$$

5 Equipment for Implementing Closed Loop Control

Universal electronics cards have been developed to achieve the various closed loop control circuits by relatively simple means.

Any analogue closed loop control circuit may be produced by suitably linking these cards.

This is illustrated in the individual examples of closed loop control shwon in the block diagrams:

Fig. 204 Closed loop positional control circuit

Fig. 205 Closed loop speed control circuit

Fig. 207 Closed loop velocity control circuit

Fig. 208 Closed loop pressure control circuit.

5.1 Servo Amplifier SR

Servo amplifiers are used to actuate servo valves or proportional directional valves with servo valve pilot control.

The main function of a servo amplifier is to amplify an analogue input signal (command signal, control variable) so that the output signal can actuate the servo valve (gain e.g. 1 mA : 60 mA).

Depending on the application, the amplifiers are chosen as follows.

Servo amplifier SR1

For servo valves or proportional valves with servo valve pilot control and electrical positional feedback of the main spool. Output current is $I_{max} = \pm 60$ mA.

Servo amplifier SR2

For servo valves with mechanical feedback. Output current is $I_{max} = \pm 60$ mA.

Due to the maximum output current of ±60 mA, valves are controlled via flapper jet systems.

Servo amplifier SR4

For servo valves without electrical feedback. Output *current is* $I_{max} = \pm 700$ *mA.*

Amplifier SR4 with $I_{max} = \pm 700$ mA is used to actuate a single-stage control valve.

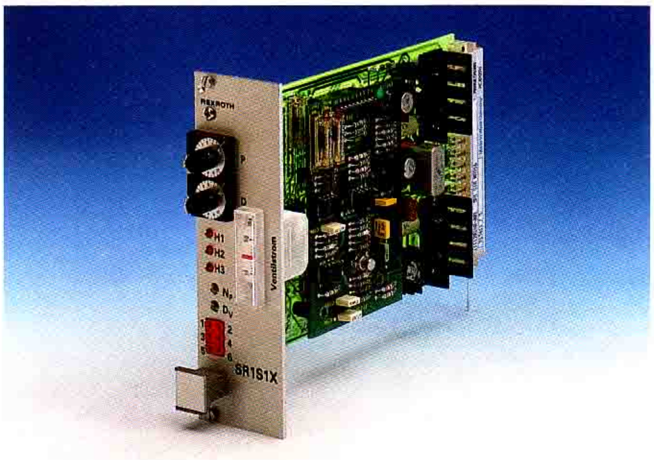


Fig. 209: *Servo amplifier SR1*

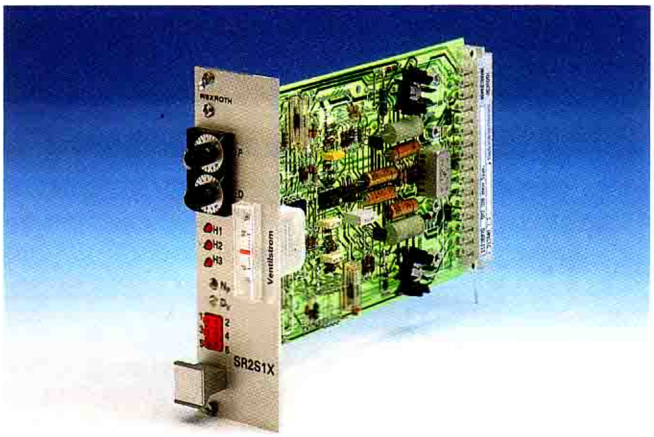


Fig. 210: *Servo amplifier SR2*

The circuit for the servo amplifier is shown in the block diagram *(Fig. 212)*.

A smoothed DC voltage (1) of between ±20 V and ±28 V is necessary as the supply.

The power supply unit NE1S30 may be used for this purpose. The smoothed output voltage is ±22 to 30 V, the supply voltage 220 V/50-60 Hz or 110 V/50-60 Hz.

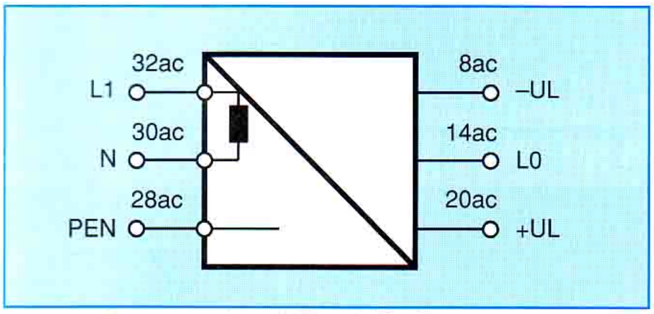


Fig. 211: *Power supply unit Type NE 1 S 30*

A stabilized voltage (2) of ±15 V is then produced from the supply voltage for the amplifier card.

This voltage is used for:

– the supply of external actuators such as potentiometers (tapping point at 12c (+15 V) and at 22c (-15 V)

and

– the supply of internal operational amplifiers.

Furthermore, two basic function groups should be considered:

a) Control for servo valve with output stage (4) and PD regulator 3).

In the version without electrical feedback (SR2 and SR4), the command signal is fed directly to the PD regulator (3).

If the card is used for valves with electrical feedback (6), then the PD regulator is used for the closed loop positional control of the valve itself. The inductive positional transducer measures the position of the valve spool. An oscillator/demodulator (5) provides the AC voltage supply for the transducer and also converts the signal for feedback. The positional transducer produces an AC voltage signal which varies in amplitude, dependent on the position of the valve spool. The demodulator (5) converts this AC signal into a corresponding DC signal *(see page 83)*.

The valve position regulator (3) then compares the command signal at 28a (optionally at 30a) with the feedback from the valve spool (measured at test point (2) or terminal 32a). Depending on the difference between the command signal and actual signal, the regulator (3) sends the output stage (4) a relevant signal which it converts into a proportional current.

For example, depending on system pressure, the signal from the output stage (4) may be fed to the contact at (7) and relay K2. This prevents the flapper jet system in the servo valve from being damaged.

The flapper jet system may be damaged, if the servo valve is actuated without system pressure being present. Hence, it is good practice to interlock the servo valve by means of a pressure switch in the hydraulic system (via input 6a).

Other system dependent connections may be linked to this input.

A dither current is superimposed upon the valve current by the oscillator (8).

Through this, hysteresis is decreased and response sensitivity of the valve increased.

The measuring instrument (9) on the front panel of the amplifier indicates the valve current.

b) A second regulator (PID) (10) for a superimposed closed loop control circuit.

This may be added on request. By using a suitable circuit, the control characteristic is achieved as required.

The function sequence is briefly as follows: The PID regulator (10) compares the command signal applied at 30c (e.g. command velocity) with the actual value at 28c (e.g. actual velocity). Depending on the difference, the regulator (at 32c) produces a relevant voltage signal. This signal may then be used to control the servo valve via 28c.

Relay K1 is used to release the regulator (10) which may be selected at terminal 2a.

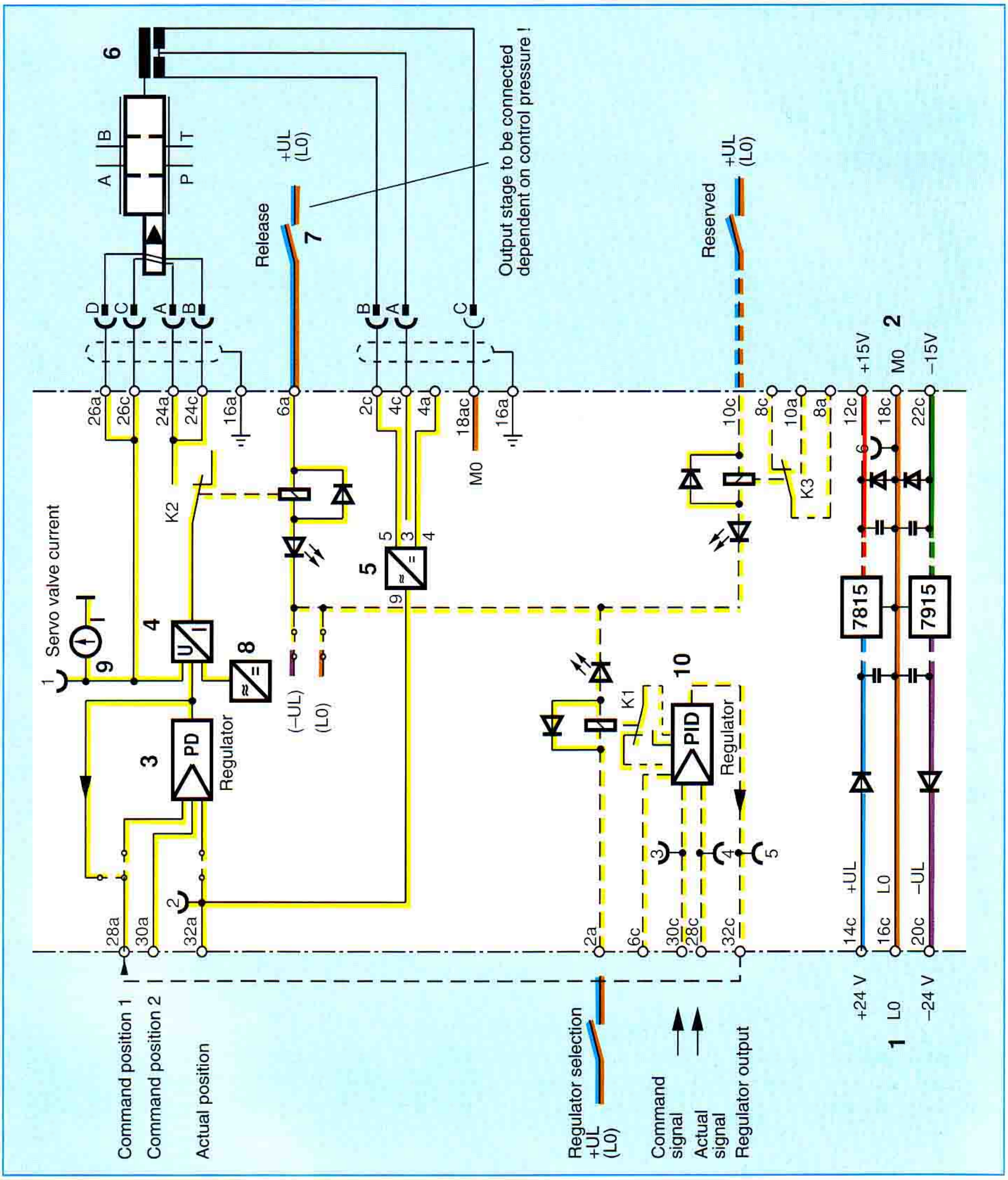


Fig. 212: *Block diagram of servo amplifier SR 1 S 3X (Relays K1 and K3 as well as the PID regulator are defined separately for each application.)*

5.2 Universal Card UK2

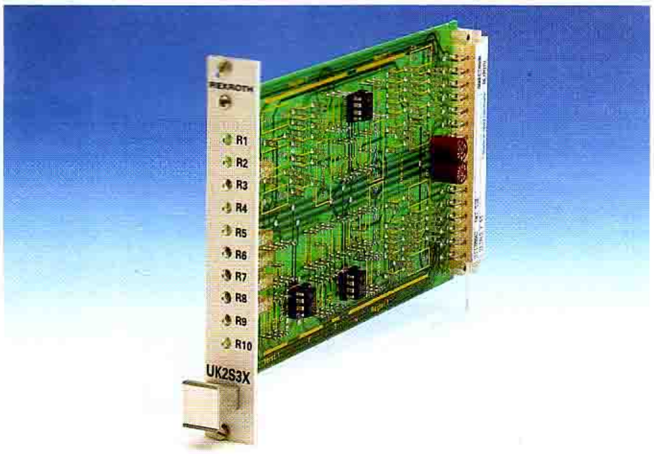


Fig. 213: *Universal board UK2*

This card is used for the connection of several operational circuits. It consists of 3 double operational amplifiers and 5 null point potentiometers.

Circuits to suit individual requirements are achieved via electrical components connected together via soldered junctions.

The power supply for the card and hence for the 6 operational amplifiers (3 x double operational amplifiers) must be provided by a stabilized voltage of ±15 V *(see Fig. 219)*.

The following functions may be produced:

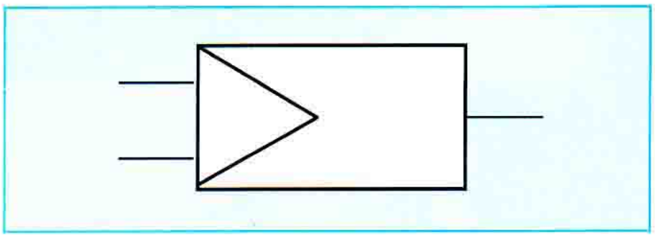


Fig. 214: *General regulators*

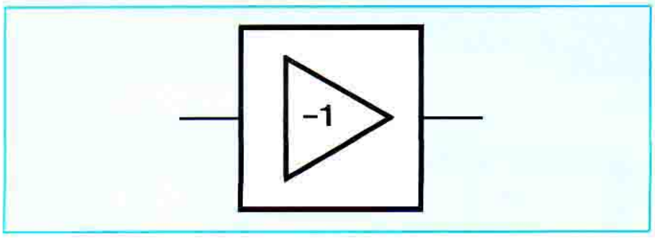


Fig. 215: *Invertor*

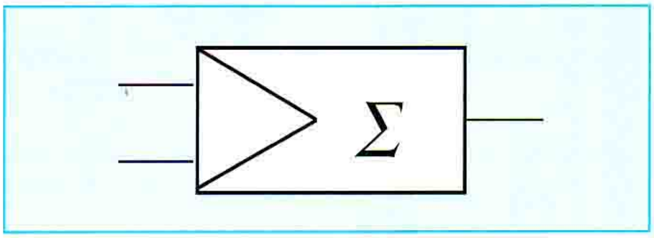


Fig. 216: *Summator*

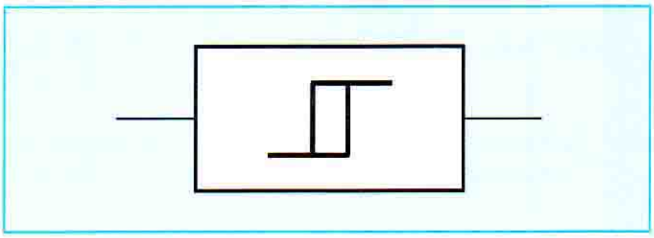


Fig. 217: *Schmitt-trigger*

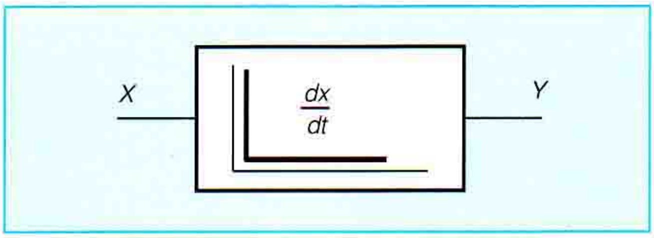


Fig. 218: *Differentiator*

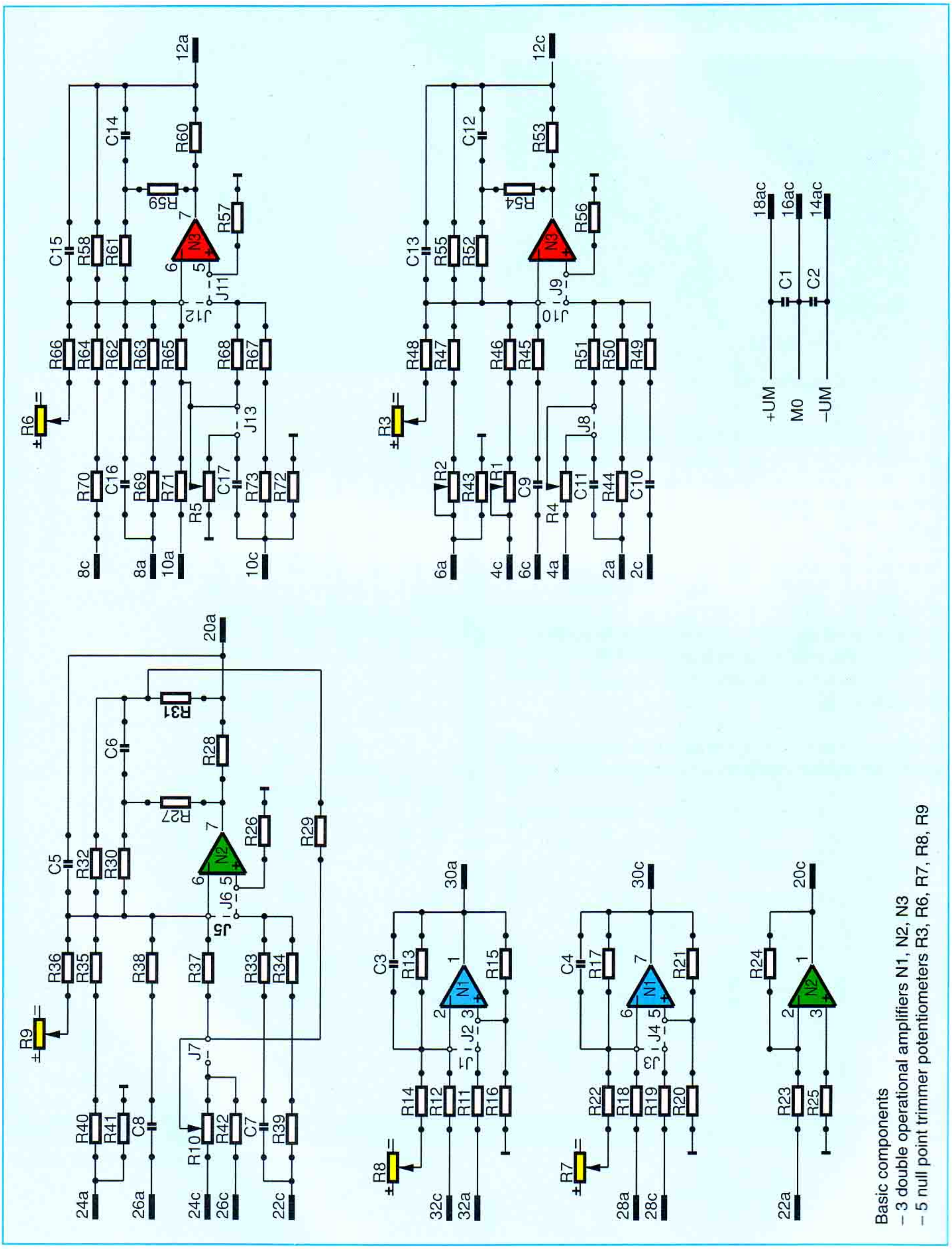


Fig. 219: *Terminal connections of the universal card UK 2 S 30*

5.3 Card with Ramp Generator RA 1

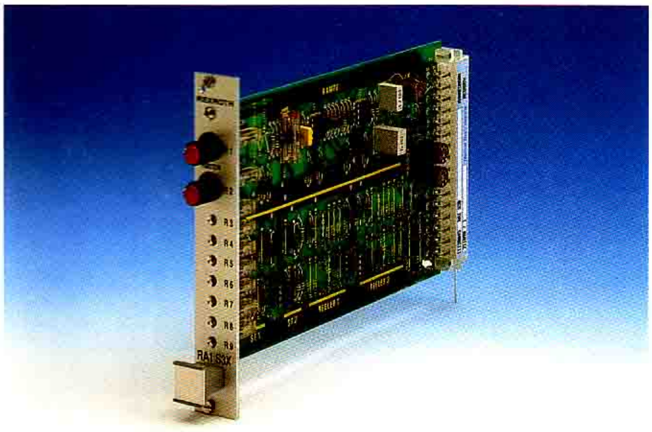


Fig. 220: *Ramp generator RA 1 S 30*

The basic component on this card is an analogue ramp generator. Depending on requirements, one of the following three ramp time ranges may be selected for a voltage change of 10V:

0,01 to 0,1 s

0,1 to 1 s

1 to 10 s

The ramp times for "ramp up" and "ramp down" may be separately adjusted via potentiometers R1 and R2 (Fig. 221). The ramp time may also be set via external potentiometers.

In addition to this ramp generator, the card also has 5 further operational amplifiers for optional use (Fig. 221).

Depending on components supplied, the card may be used to provide:
- 2 regulators (P, PI or PID)
- 1 invertor
- 2 switching amplifiers
  with separately adjustable switching point.

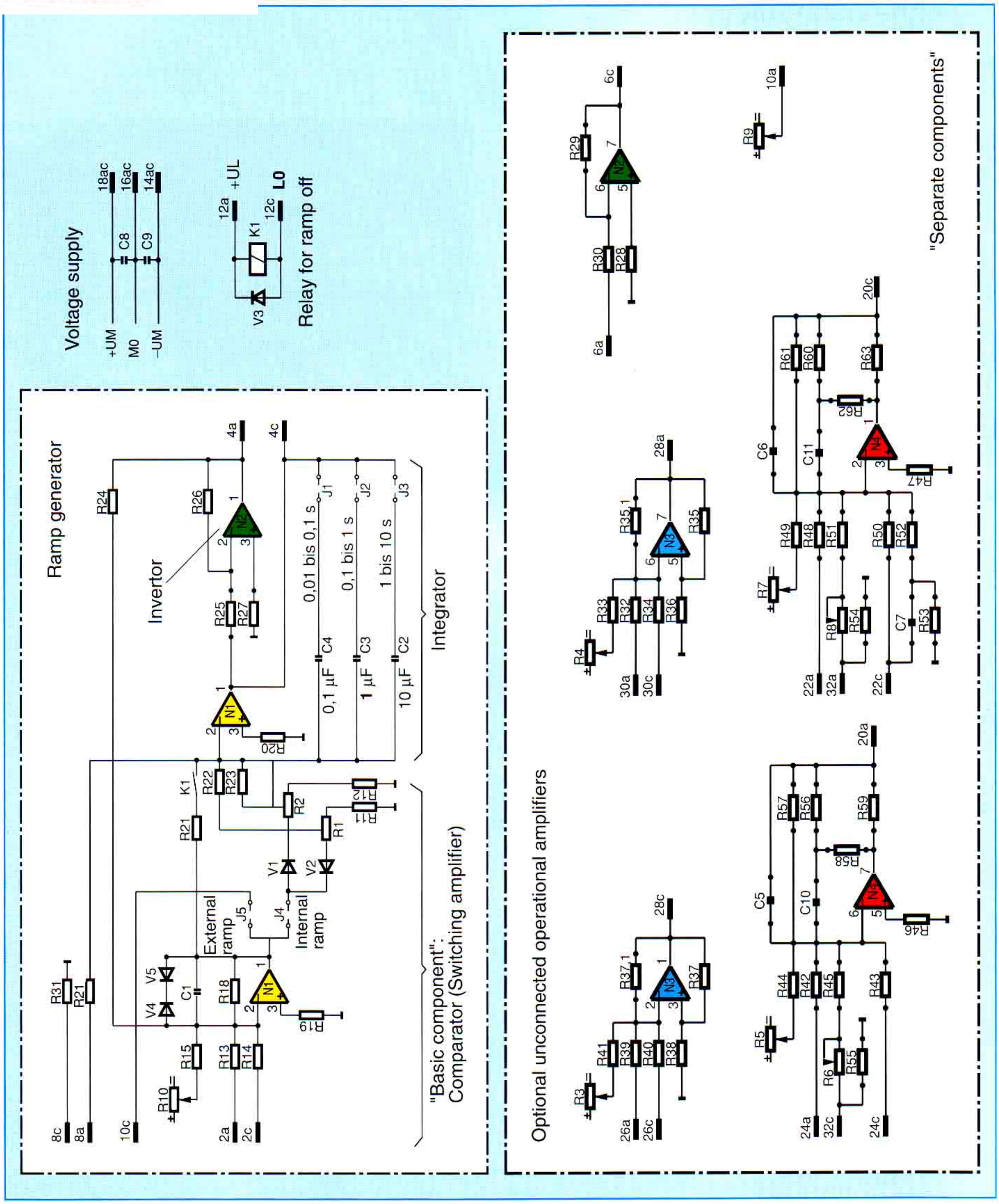


Fig. 221: *Terminal connections of ramp generator RA 1 S 30*

In addition to the cards already described a wide variety of other standard cards are also available, for processing analogue signals.

5.4 Limiting amplifier BG 1

The limiting amplifier may be used as a:

- Limiting amplifier
- Switching amplifier

These functions may be subdivided as follows:

- Analogue signal limiting

  This enables (depending on the circuit) unipolar or bipolar limiting functions to be achieved.

- If selected values are exceeded (depending on the circuit), differential signals may be used as error signals to activate the amplifier (positive or negative).

- Switching amplifier for absolute signal recognition

  The inputs E1 and E2 are added together, whereby the absolute value or inverted absolute value (depending on circuit) is compared with the preset switching point.

- The signals may be stored and later cleared via a reset.

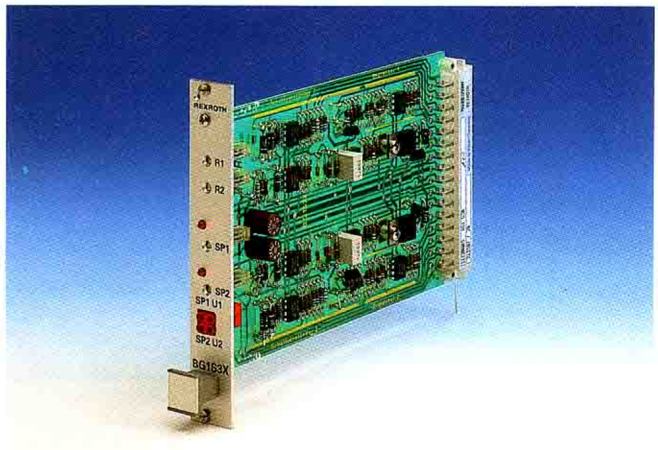


Fig. 222: *Limiting amplifier BG 1 S 30*

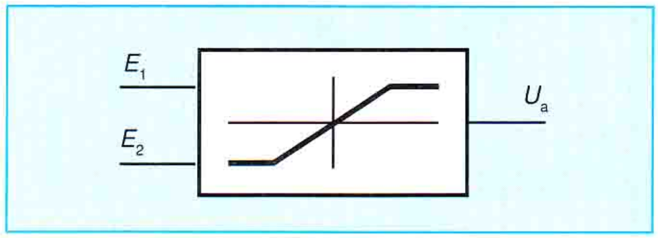


Fig. 223

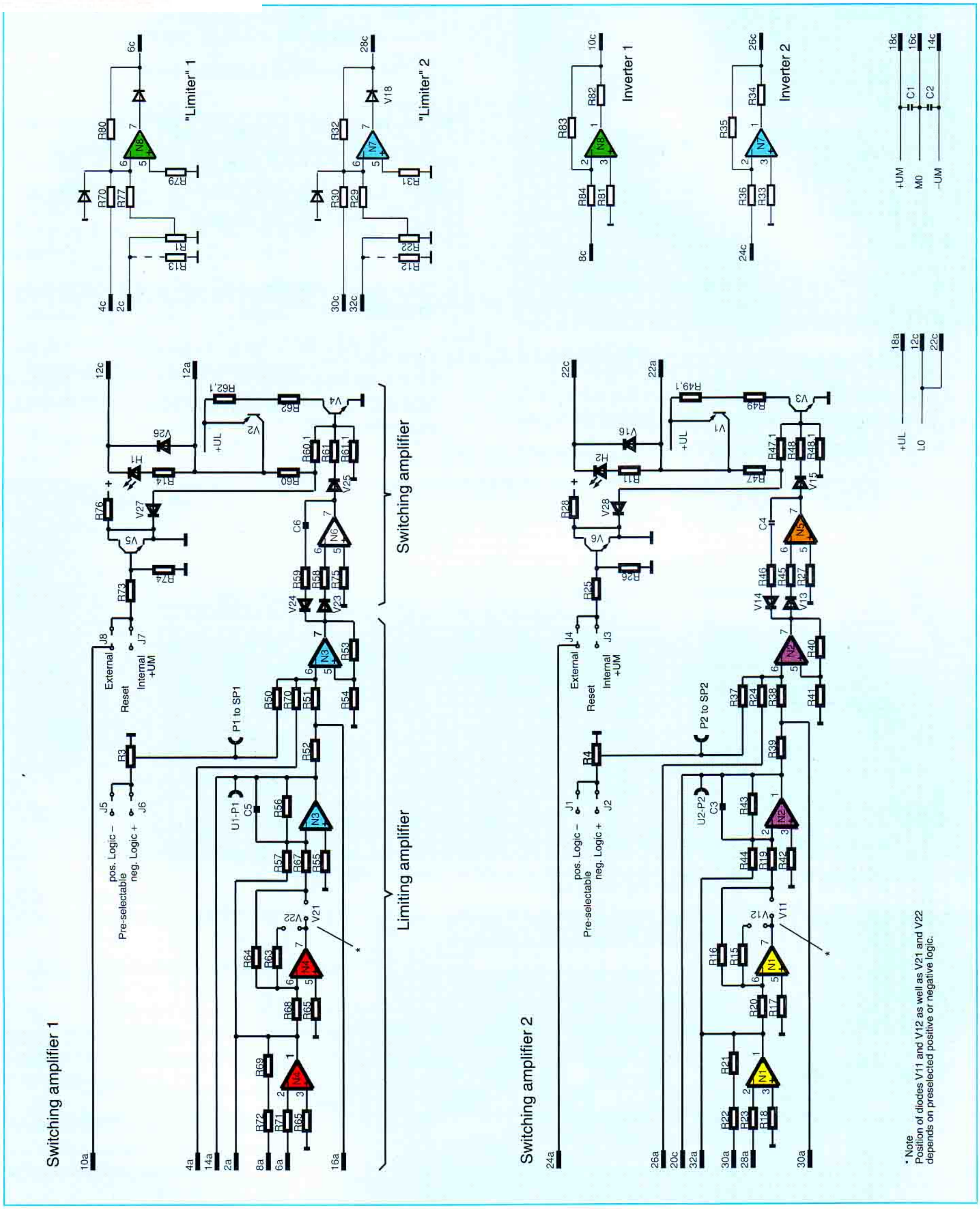


Fig. 224: *Terminal connections of limiting amplifier BG 1 S 30*

6 Measurement of actual values

A particularly important function in closed loop control is the measurement of the actual or feedback value.

It is obvious that the system can only be as accurate as the measurement of the actual value.

Hence measuring instruments should have an accuracy 10 times higher than that required by the system. With respect to the degree of accuracy achievable, the behaviour of the control system (time delay) must be taken into consideration.

Measurements may be either digital (figures) or analogue (relative).

The terms digital and analogue are explained via a positional measurement example:

- Digital
  Measurements are made in unit steps of a defined length
- Analogue
  Measurements are provided in the form of a different but relative analogue variable (e.g. voltage)

The difference between incremental and absolute measurements must also be clarified.

- Incremental
  Incremental changes are added or subtracted from a variable.
- Absolute
  Direct representation of a variable as an absolute digital code (i.e. coded in figures) (from an absolute reference point).

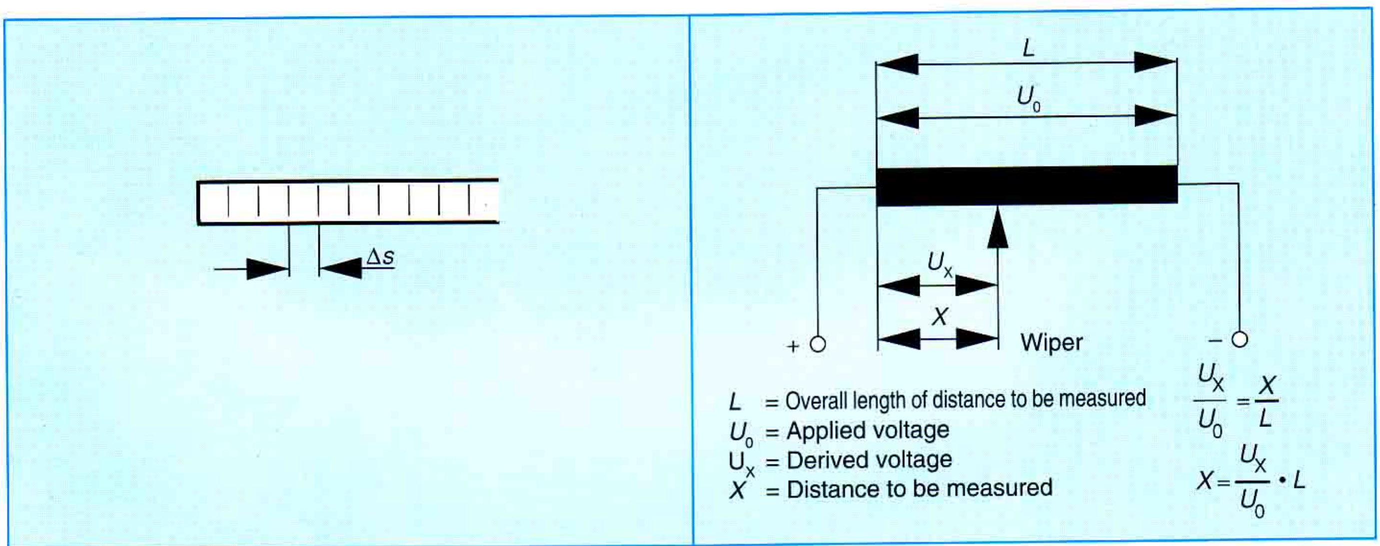


Fig. 225: *Digital positional measurement (left) and analogue positional measurement (right)*

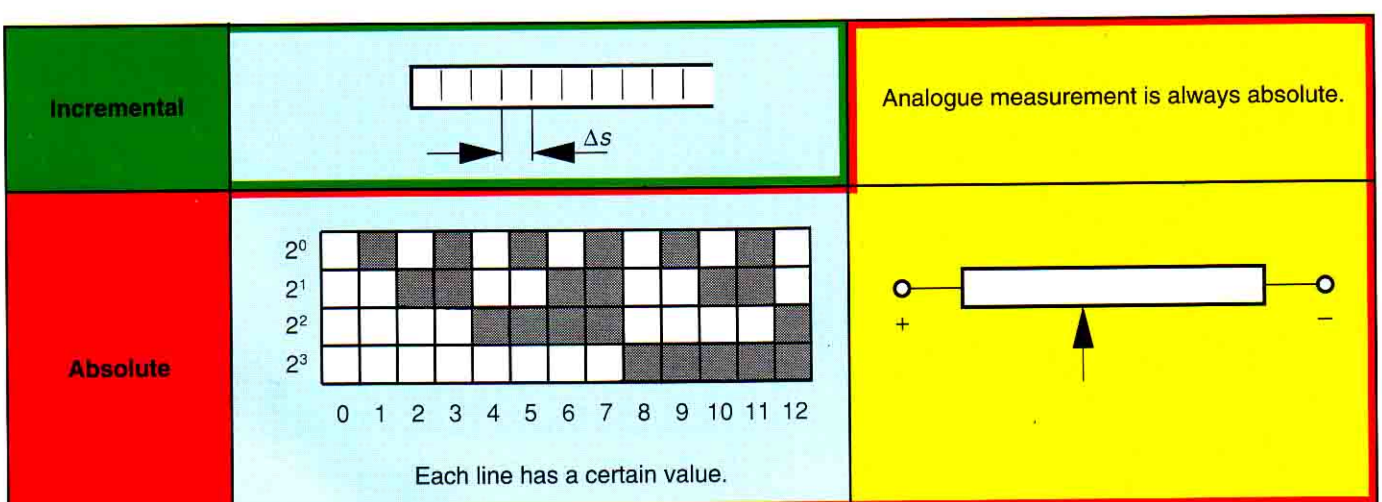


Fig. 226: *Digital measurement (left) and analogue measurement (right).*

6.1 Position Measurement

6.1.1 Linear wire-wrapped potentiometer

Distances are measured directly as analogue variables in the form of voltages. These voltages are usually between ±10 V and ±20 V. The smallest usable signal is 20 mV. This, however, depends on the quality of the voltage supply, i.e. on fluctuations which may occur. Hence 30 to 50 mV is considered to be the lowest useful voltage signal.

Lengths to be measured may sensibly be up to 500 mm

Example of measuring accuracy: 500 mm ≙ 20 V

- Minimum length to be measured

$X = 500\ (\text{mm}) \cdot 0{,}02\ (\text{V}) / 20\ (\text{V})$

$X = 0{,}5$ mm

6.1.2 Conductive Plastic Potentiometer for Analogue Measurement

This is a positional transducer with resistor and collector lines made of conductive plastic (analogue measurement).

Lengths to be measured: up to 1000 mm

Resolution: 0.01 mm

The degree of accuracy which may be obtained depends on the useful signal as described in 6.1.1. The advantages of this positional transducer are the low wear and improved signal resolution (no winding jumps).

6.1.3 Inductive Positional Transducer

In this measurement system, a moveable round bar made of magnetic soft iron is moved in a coil or coil system. The inductance of the measurement coil changes with respect to the distance.

Measurement is carried out using AC in a bridge circuit. (inductive positional transducers, page 83).

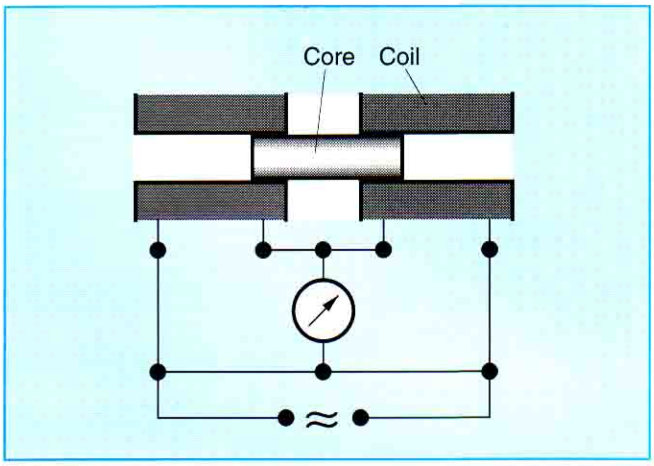


Fig. 227

Differential coils with immersed core (Fig. 227) are suitable for measuring extremely small distances.

The sensitivity in this case is approx. 2 µm.

6.1.4 Glass Scale (NC distance measurement system, photoelectric)

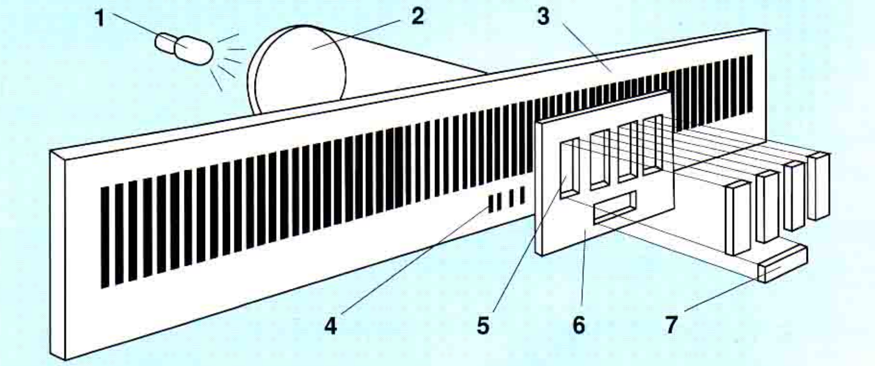
Incremental digital measurements are carried out in that the grid graduations on the scale are scanned photoelectrically *(Fig. 228)*.

The photo-elements generate periodical, almost sinusoidal signals as the scale moves relative to the scanning unit. The signals are then evaluated in the electronic circuit.

Since, if the measurement system is switched off or the power fails, the assignment of measured value to position is lost, the scale also features one or more reference marks. An additional signal (reference signal) is generated when passing such a reference mark.

Length to be measured: 10 mm to 30 m (depending on system)

Accuracy: Up to ±1 µm



1 Miniature lamp
2 Condensor
3 Glass scale
4 Reference mark
5 Scanning grid
6 Scanning plate
7 Silicon photo-element

Fig. 228: *Glass scale*

6.1.5 Inductive Positional Transducer, Integrated into the Hydraulic Cylinder

This positional measuring system is incorporated into the pressure chamber of a hydraulic cylinder.

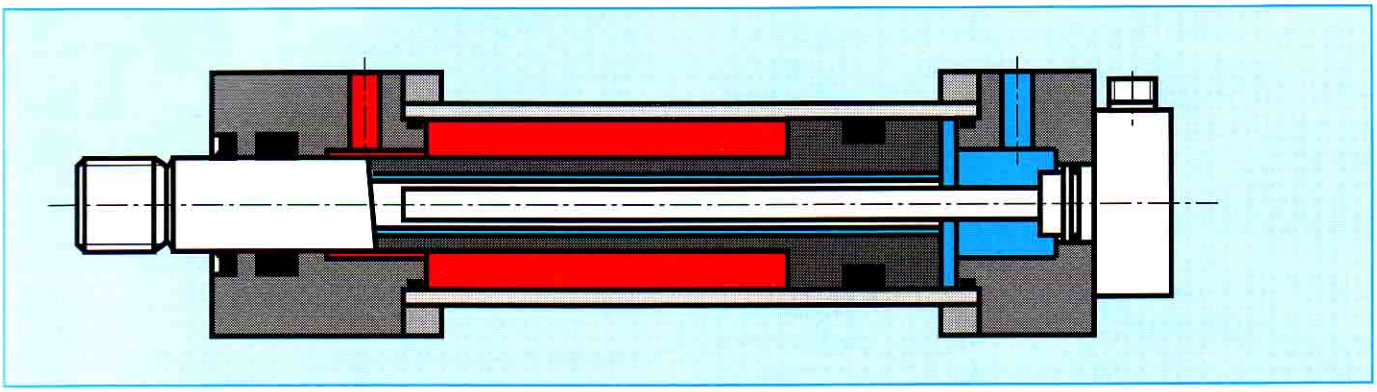


Fig. 229

Dependent on type of cylinder and on piston dimensions, lengths of up to 1000 mm may be measured.

Voltage output: ±10V.

6.1.6 Ultrasonic Positional Transducer, Integrated into the Hydraulic Cylinder

The measured, absolute distance may be accessed as often as necessary without it being corrupted by interruptions in operation, mains failure or other malfunctions.

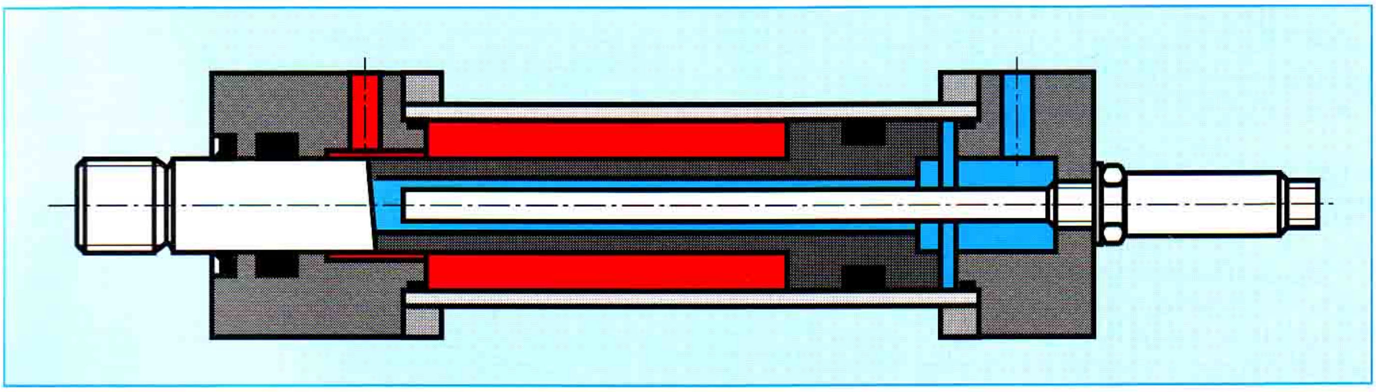


Fig. 230

The required positioning accuracy is determined by the type of output signal:

- Analogue: 0 to 10 V or ±10V
- Digital: Resolution 0.1 mm

Length to be measured: up to 2500 mm.

6.1.7 Laser Measuring System

This measurement system is used for determining workpiece dimensions or edge positions.

A transmitter generates a narrow band of laser light which is directed towards a receiver in the detector. As this band of light consists of a fine, parallel beam, a workpiece placed in the measurement field throws a shadow with respect to time. The receiver determines the distances with respect to time between the edges of the shadow and transfers this data to the microprocessor evaluator which in turn determines the workpiece dimensions (for example).

Measuring accuracy: ±0.25 μm

Measures absolute size and deviation from nominal size.

Application examples for the laser measurement system:

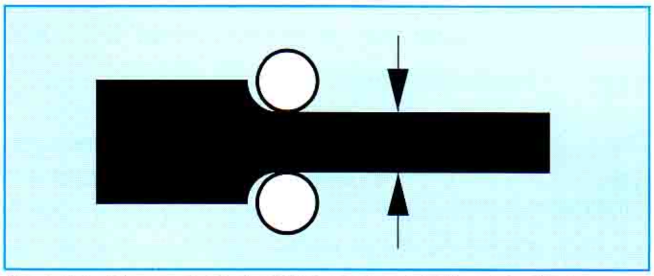


Fig. 231: *Measurement of the distance between rollers*

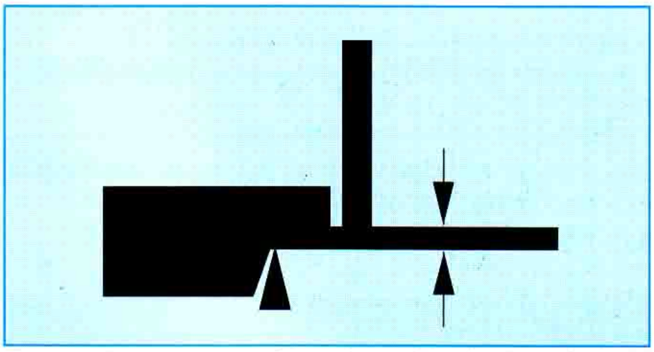


Fig. 232: *Determination of the edge position (tool position) with reference to a reference edge*

6.1.8 Measurement Strain Gauge (Fig. 233)

Measurement strain gauges are sensors in which a length and cross section of wire or film change as the strain load changes. The resistance also changes as a result of this.

Normal length of a strain gauge is between 3 and 60 mm. The gauges may be used to measure changes in length of up to ±5‰ of their length.

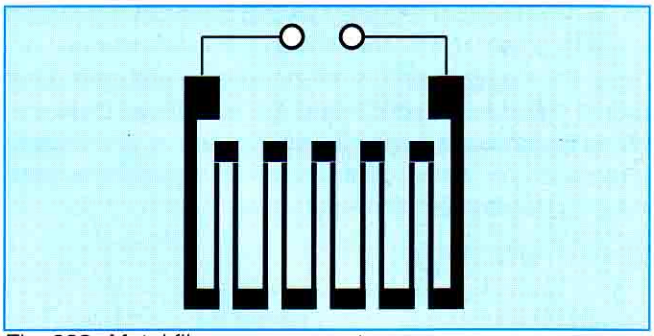


Fig. 233: *Metal film measurement gauge*

6.1.9 Angle Encoder, Rotation Encoder

Angle encoders may also be used to measure distances. The distance is represented as an angle by means of a rack and pinion, lead screw and nut or measuring disc. Theoretically, the distance to be measured is unlimited.

6.2 Angle Measurement

6.2.1 Ring Potentiometer

The angle of rotation is represented as an analogue voltage. The potentiometer may be wire wrapped or a conductive plastic resistor.

The effective angle is up to 350°, the maximum displacement velocity up to 10000 rpm.

The potentiometer is a supplied with ±10 V (preferably from the output of an operational amplifier).

Minimum angle: $\omega = 350(°) \cdot 0.02\ (V) / 20\ (V) = 0.35\ (°)$ (at minimum useful signal of 20 mV).

6.2.2 Incremental Angle Encoder

An incremental angle encoder generates a certain number of pulses per revolution. The number of pulses is a measure of the distance covered (angular or linear).

An encoder disc is mounted onto a shaft. It is subdivided into individual segments which are alternately transparent and non-transparent to light. The segments are scanned by infra-red photo cells.

Since incremental angle encoders produce pulses continuously irrespective of the number of revolutions, large distances may be measured without any problems.

Supply voltage: normally + 5 V =

Minimum step: 10 μm

e Encoders (Digitizer)

Digitizers may be used in measurement and open loop control systems in which angular and linear displacements are to be measured. In such a system, the digitizer converts rotary motions into electrical signals which are used for display or control purposes.

Minimum step: 10 µm.

Basically measurements may be analogue or digital. The resolution of an analogue system is generally limited to 10^{-3} or 10^{-4} of the measuring range, whereas digital measurement systems may have a much higher measuring accuracy. Furthermore, the result produced by the digital system is definitive and may easily be further processed.

Two types of digitizers are available: incremental and absolute. Incremental digitizers (pulse generators) generate periodical signals and require a memory (counter) to create a measurement value. The memory defines the measurement range. Measurement errors, spurious external pulses and similar effects result in corruption of measurements, which cannot be corrected. When operation is interrupted or if the power fails, the memory is cleared and the measurement is lost.

In contrast to the incremental system, absolute digitizers are designed as coded measurement systems. In this case, a certain value is absolutely assigned to each angular increment. This value is read out as a numerical value via the scanning element. This means a measurement is not generated using auxiliary devices but instead it is represented unchanged as a code pattern. Without loss of time, this absolute value may be further processed. Also no measurement errors are produced due to operation interruptions or power failures. In this way, each position in a certain area (angle of rotation) is given a code which may be selected as often as required without errors occuring in the information.

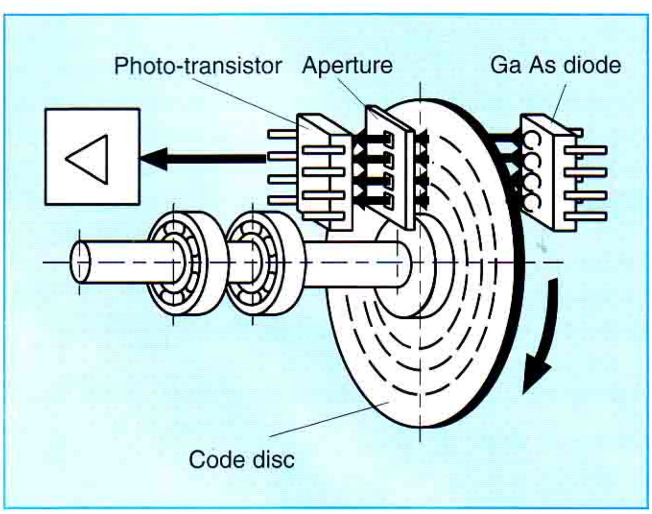


Fig. 234: *Absolute digital digitiser*

The function is shown in *Fig. 234.* A rotating drive shaft carries a code disc which is positioned opposite to a stationary aperture disc. The code disc has alternate light dark fields. The signals produced by the diode (acting as a light transmitter) are evaluated by the photo-transistor (acting as receiver). Depending on the version, a resolution of up to 4000 signals (data items) per revolution may be achieved.

6.2.4 Incremental Rotary Regulator

They are used to measure angles of rotation and angular velocities.

The version with a glass scale corresponds to the system described under 6.1.4 for measurement of length. Depending on the type of selected rotation encoder, the maximum resolution of up to 100,000 measuring increments per revolution is possible.

6.3 Velocity Measurement

6.3.1 Tacho-generator

The tacho-generator produces a voltage dependent on speed which then acts as a measure of rotary speed or if a rack and pinion is used, as a measure of linear speed.

Example:

Traverse speed $v_{max} = 1$ m/s

Ratio of the tacho-generator to cylinder:
1 m cylinder stroke ≙ 10 revolutions of the tacho-generator.

The ratio is selected so that the tacho-generator is operated at the level of its nominal data.
e.g. 100 V at 1000 rpm = 16.67 1/s

At $v_{max} = 1$ m/sec, the tachogenerator produces an output voltage of

$$U = \frac{10\,(1/s)}{16{,}67\,(1/s)} \cdot 100\ V = 60\ V$$

6.3.2 Incremental Rotary Encoder

They are used to measure angular velocities. As already described in connection with positional measurements in 6.1.9 (also see 6.2.4 and 6.1.4), they are used in conjunction with rack/pinion, lead screw/nut, lead screw or measuring wheel for velocity measurements. The increments are evaluated per unit of time.

6.3.3 Positional Signal Differentiation

A further possibility of converting the velocity into a signal is to differentiate the position measurement.

The analogue positional signal may be produced as a velocity signal via a differential element (D element).

Accuracy is approx. 2-3% with respect to maximum stroke voltage.

6.4 Pressure Measurement, Force Measurement

6.4.1 Pressure Transducer with Strain Gauge (Pressure Sensor)

In this device, pressures are transformed into electrical signals via strain gauges which, for example, are attached to the work-piece (e.g. membrane) in the form of a thin film.

The measuring range is from 0 to well above 1000 bar. The accuracy lies in the range of ±0.2% to ±0.5%, dependent on and with reference to the measurement range limits.

Basically, it is possible to measure force indirectly via any pressure measurement with reference to an effective area, e.g. a cylinder.

Depending on the frequency range (depending on the type of pressure transducer, e.g. up to 500 Hz or up to several thousand Hz) changes in pressure and hence pressure peaks may be measured in the ms range and below.

6.4.2 Pressure Cell with Inductive Positional Transducer

The movement of a membrane bending under load may also be converted into an electrical signal via an inductive positional transducer. Movement of the membrane is proportional to the effective pressure.

6.4.3 Quartz Pressure Sensor, Piezo-electric Load Cells

Pressure measurements with quartz crystals are particularly suitable for dynamic processes, i.e. for determining pulse rate and pressure peaks. However, static pressure measurements are only possible over a few minutes.

The operating principle is basically the piezo-electric effect. If a force is applied to a quartz crystal in the direction of one of its three axes, then an electrical charge is produced at the surface perpendicular to the axis under load. This charge is proportional to the force applied. The voltage obtained is then amplified and converted to a force or pressure value. As the voltage follows changes in force or pressure without any noticeable delay, these transducers are particularly suitable for dynamic measurements.

The frequency range is between 10 Hz and 200 kHz.

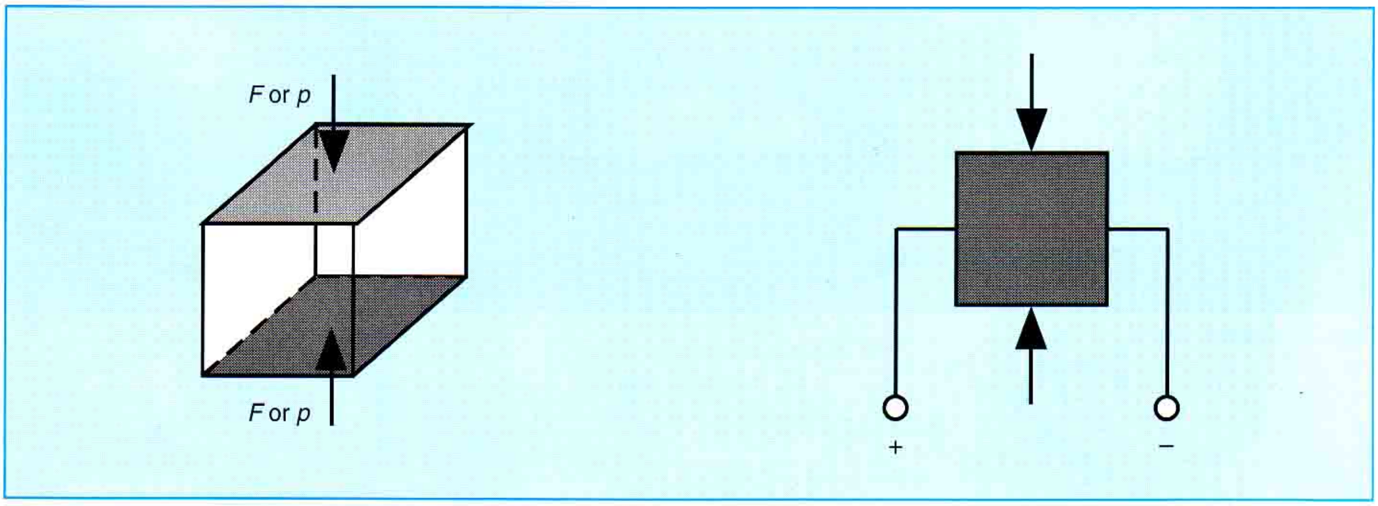


Fig. 235: *Principle of piezo-electric measurements*

7 Appendix

The most important electronic components often found in open loop control circuits and particularly in closed loop control circuits are briefly described in the following.

7.1 Potentiometer

The potentiometer is basically a variable resistor. If, for example, voltages of 0 V and 10 V are applied to the ends of a potentiometer, then any value between 0 and 10 V may be tapped off at the wiper.

Example:

At a setting of 60%, a voltage of 6 V can be tapped off at the wiper.

A potentiometer is used for:

- Selecting a command signal

  i.e. the level of the tapped voltage corresponds to the required actual distance, force or pressure.

- Measurement of actual values

  i.e. the tapped voltage represents a distance and, therefore, a position.

7.2 Operational Amplifier

The operational amplifier is a classic example of integrated circuit technology. It is a multi-stage analogue amplifier with an extremely high gain factor and may be adapted for various tasks by means of external circuitry.

For example, by means of suitable circuitry the following functions may be obtained: ramp generator, amplifier, invertor, summator, differentiator, limiter, various regulators etc.

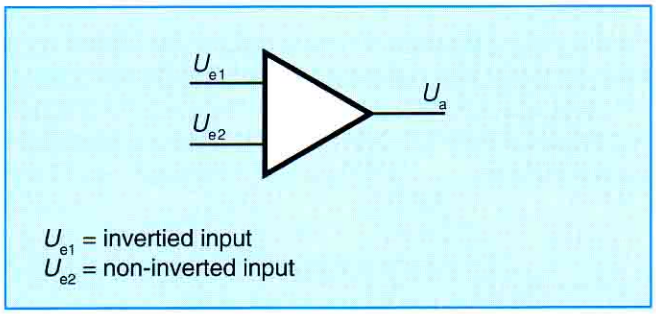
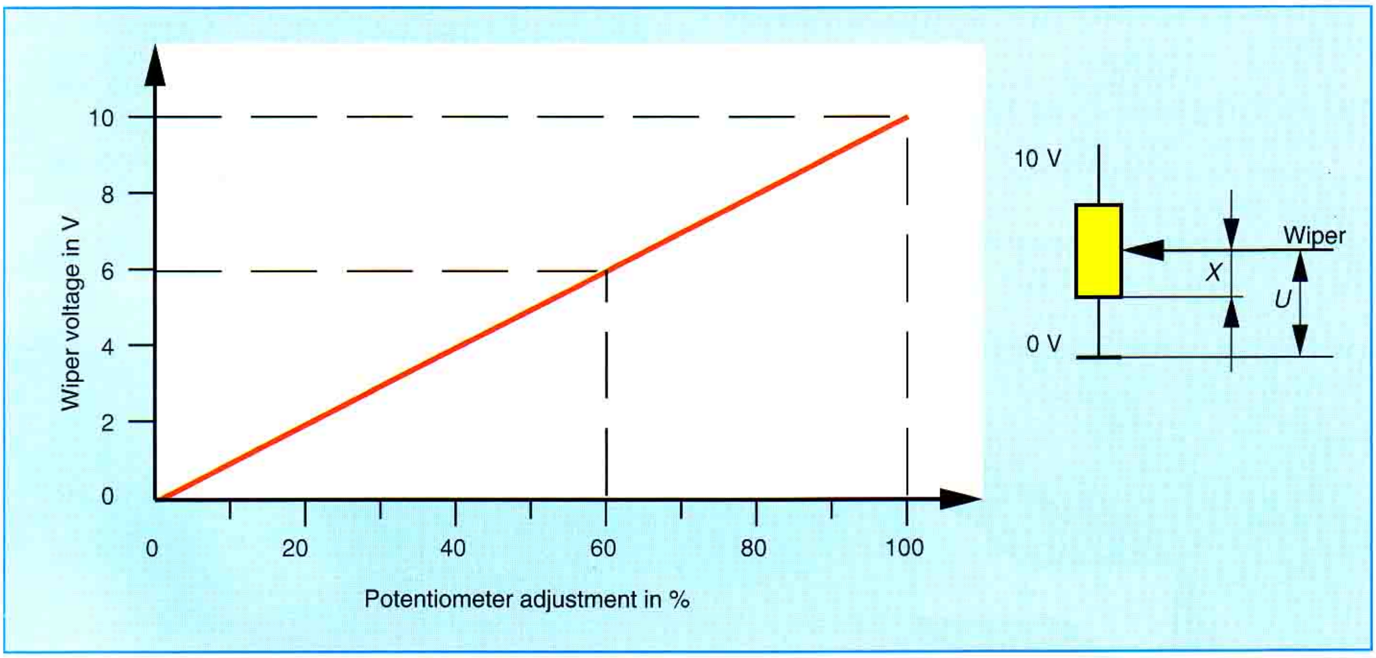


Fig. 236: *Symbol for an operational amplifier*



Diag. 78: *Potentiometer*

7.3 Ramp, Ramp Generator *(Fig. 237)*

The ramp generator produces a slowly rising or falling output signal from a step input signal. The change with respect to time of the output signal may be adjusted via a potentiometer.

The ramp generator makes use of the fact that capacitor C is charged slowly so that the output signal changes at a slow, steady rate, in response to a step input signal.

The rise of the output signal is determined by the charging rate of the capacitor and dependent on the variable resistor R.

The set ramp time is always with respect to 100% command signal (step input signal).

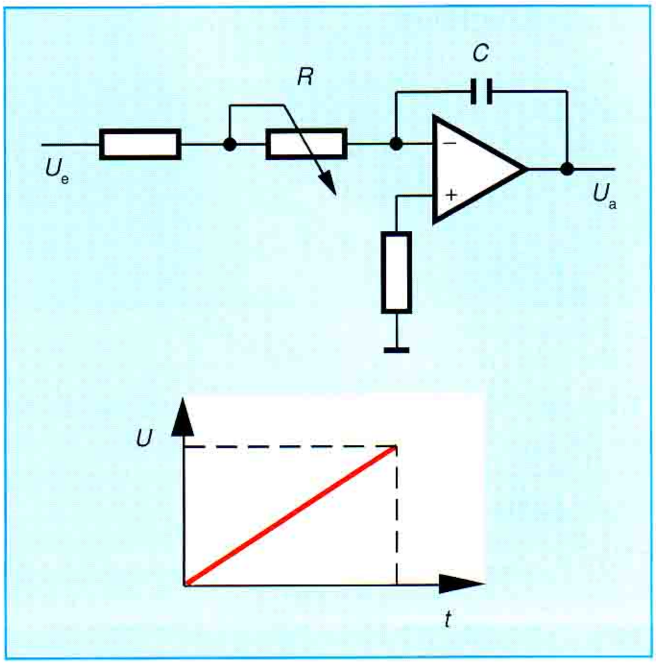
Example:

Set ramp time of max. 5 sec at 100% command signal. If, a command signal of 60% is set then this is reached after approx. 3 sec.

In this way, the speed increase (acceleration) in a closed loop velocity control circuit or the speed in a closed loop position control circuit may be preset via a ramp generator. In a closed loop position control circuit, the set ramp time corresponds to the travel speed of the cylinder as the preset position is reached in this time.

7.4 Limiter *(Fig. 239)*

The applied input voltage is limited to a preset value as the output voltage. Limitation takes place via two connections 1 (limiting of negative voltages) and 2 (limiting of positive voltages).



Diag. 78: *Potentiometer*

7.5 Regulator *(Fig. 238)*

A regulator refers to a device or component which carries out the essential processing of closed loop errors. The regulator therefore compares the command signal with the actual signal and produces an output signal which is dependent on the difference between the two signals.

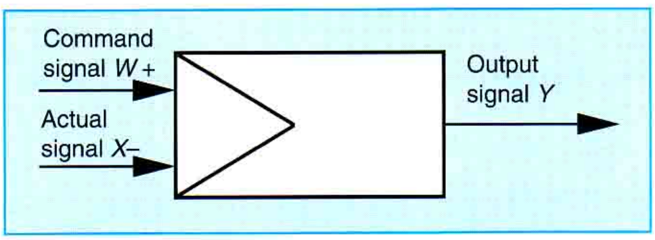


Fig. 237: *Ramp generator*

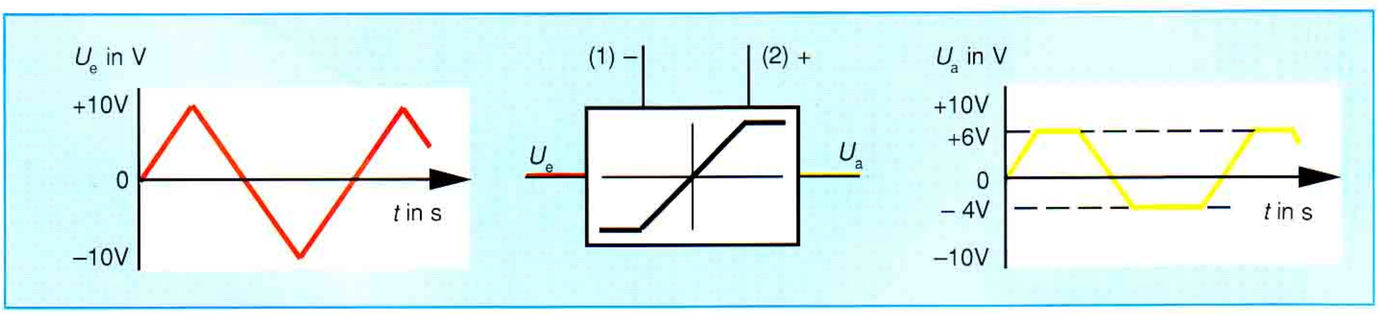


Fig. 238

7.6 Amplifier

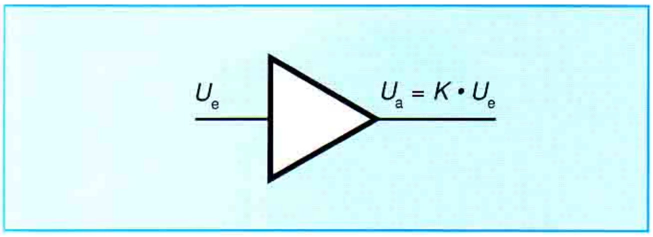


Fig. 240: *Amplifier*

The output voltage Ua is changed with respect to the input voltage Ue by a gain factor K. Depending on the circuit, the polarity of the output voltage is reversed with respect to the input voltage.

7.7 Invertor

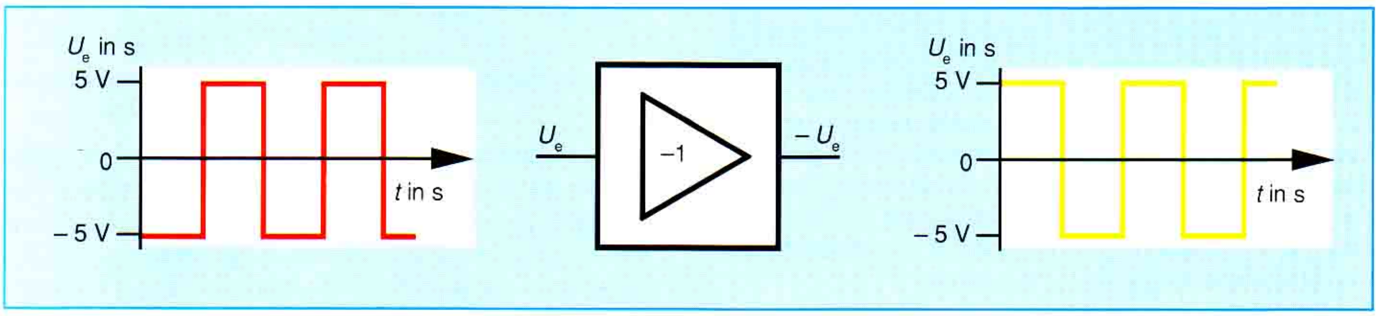


Fig. 242: *Matching amplifier*

The invertor reverses the polarity of the input voltage.

e.g.	$U_e = + 5$ V	at output	$-U_e = - 5$ V
or	$U_e = - 3$ V	at output	$-U_e = + 3$ V

It is an amplifier with gain factor of -1.

7.8 Matching Amplifier

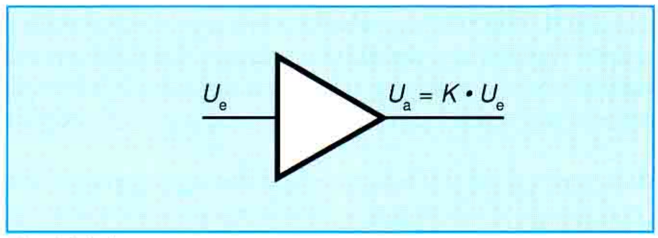


Fig. 241: *Invertor*

With the aid of a matching amplifier, the voltage produced by a measuring element (e.g. max. 60 V output voltage from a tacho-generator at maximum speed) is converted to 10 V after the matching amplifier. This 10 V then corresponds to a certain rotational speed of a motor or travel speed of a cylinder. Matching is necessary in order to be able to further process the signal in a closed loop control circuit.

7.9 Power Amplifier

The input signal U_e is converted in the power amplifier into an output current which is proportional to U_e.

e.g. U_e = 0 to 10 V, I in mA ≙ solenoid current

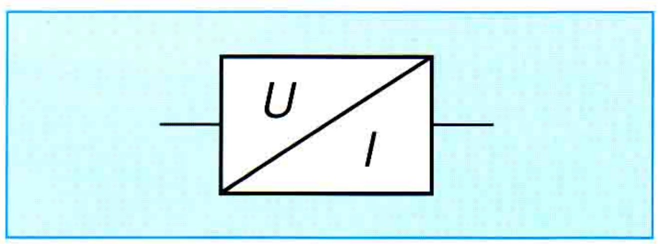


Fig. 243: *Power amplifier*

7.10 Schmitt-Trigger

Schmitt-triggers are used as threshold value switches. The two diagrams for input and output signal illustrate their function. If U_e exceeds a certain value (U1), then U_a jumps from one value to another. Correspondingly, the output signal jumps back to the previous value (e.g. 0) as soon as U_e drops below a certain value (U2).

This results in two clearly defined switching points so that no switching takes place at intermediate values.

For example, if oscillations occur in signals to a system, then these would be eliminated.

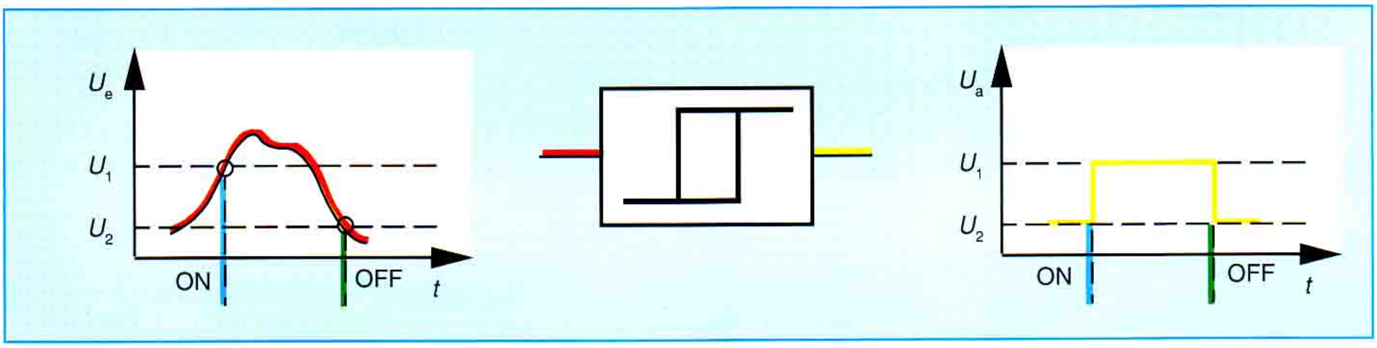


Fig. 244: *Schmitt-trigger*

7.11 Summator (Adder)

With a summator, two signals may be added taking into account their signs. It should be noted that the resulting output signal is inverted.

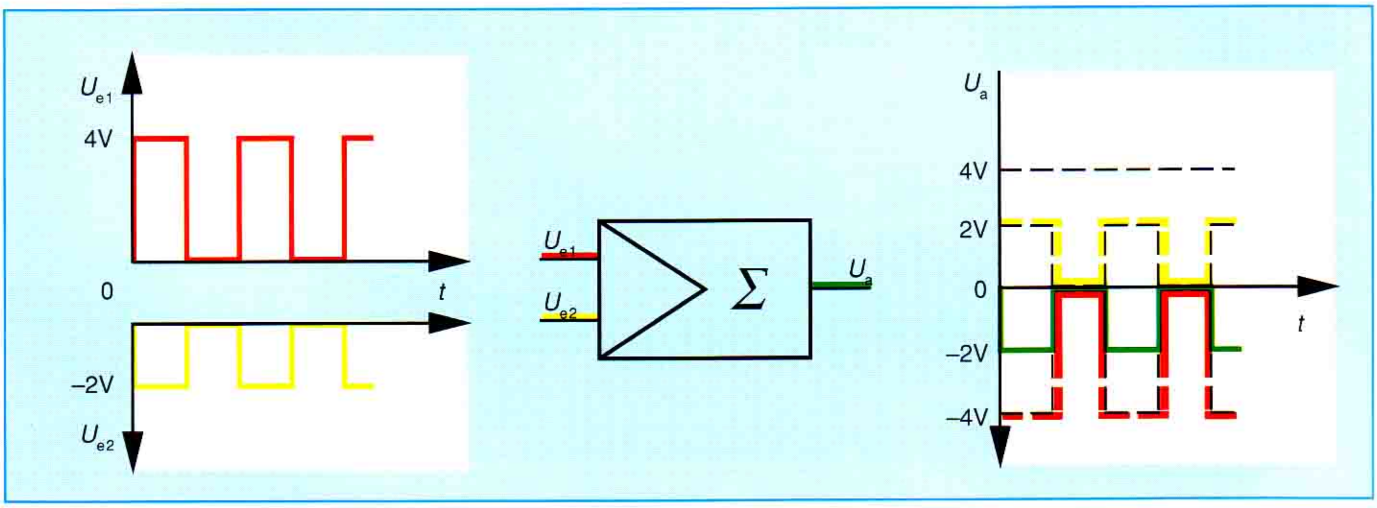


Fig. 245: *Summator*