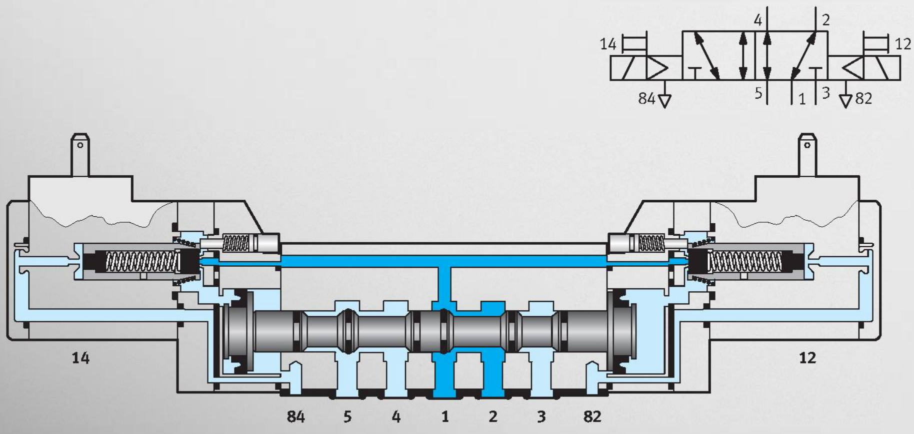
# Pneumatics
# Electropneumatics
## Fundamentals

FESTO

Textbook




Festo Didactic
573030 EN

Order No.: 573030
Edition: 12/2009
Authors: Frank Ebel, Siegfried Idler, Georg Prede, Dieter Scholz
Graphics: Doris Schwarzenberger
Layout: 05.11.2010, Frank Ebel


Internet: www.festo-didactic.com
E-mail: did@de.festo.com

# Contents

# Foreword

The use of air as a working medium can be traced back over thousands of years. Everyone is familiar with wind as a driving force for sailing ships and windmills.

The word pneumatics comes from the Greek word pneuma, meaning breath or breeze. Pneumatics is generally understood as the study of air movements and air processes.

Pneumatics and electropneumatics are successfully used in many areas of industrial automation. Throughout the world, electropneumatic control systems are used to operate production, assembly and packaging systems. In addition, technological advances in materials, design and production methods have improved the quality and variety of the pneumatic components and in this way helped to extend their use.

Changing requirements and technical developments have dramatically altered the appearance of control systems. In the signal control section, the relay has increasingly been replaced by the programmable logic controller in many fields of application in order to meet the increased requirement for flexibility. And in the power section of electropneumatic control systems new concepts have been included that are tailored to the demands of industrial practice. Examples of these new concepts include valve terminals, bus networking and proportional pneumatics.

We invite readers of this manual to send us their tips, feedback and suggestions for improving the book. Please send these to did@de.festo.com or Festo Didactic GmbH & Co. KG, P.O. Box 10 07 10,
73707 Esslingen, Germany.

The authors

# 1 Applications in automation technology

## 1.1 Overview

Pneumatics play a major role in the automated work environment and are still gaining in importance. Many production processes would be inconceivable without them. Pneumatics are an inherent part of almost every production system in the following industry sectors:

- Automotive industry
- Chemical industry
- Petrochemical industry
- Pharmaceutical industry
- Printing and paper industry
- Machine building
- Food industry
- Drinking water and wastewater technology
- Packaging industry

In these industries, pneumatics are used to perform the following functions:

- Detecting states by means of input elements (sensors)
- Processing information using processing elements (processors)
- Switching operating elements by means of control elements
- Doing work using operating elements (drives)

Controlling machines and systems requires a rather complex logical chain of states and switching conditions to be set up. This is done through the interaction of sensors, processors, control elements and drives in pneumatic or partially pneumatic systems.

The technological advances in materials, design and production methods have helped to improve the quality and variety of pneumatic components, which has contributed to them being used more extensively.

Below are some examples of areas of application for pneumatics:

- Generally in handling technology:
  - Clamping workpieces
  - Moving workpieces
  - Positioning workpieces
  - Orienting workpieces
  - Branching material flows

- General use in various fields
  - Packaging
  - Filling
  - Metering
  - Locking
  - Material transport
  - Turning workpieces
  - Separating workpieces
  - Stacking workpieces
  - Embossing and pressing workpieces

## 1.2 Characteristics of pneumatics

| Parameter | Comment |
|---|---|
| Quantity | Air is available virtually everywhere in unlimited quantities. |
| Transport | Air can be very easily transported over long distances in ducts. |
| Storage ability | Compressed air can be stored in a reservoir and supplied from there. The reservoir (bottle) can also be transported. |
| Temperature | Compressed air is virtually insensitive to temperature fluctuations. This guarantees reliable operation even under extreme conditions. |
| Safety | Compressed air does not represent a hazard in terms of fire or explosion. |
| Cleanliness | Leaks of unlubricated compressed air do not cause environmental pollution. |
| Design | The operating elements have a simple setup and are therefore inexpensive. |
| Speed | Compressed air is a fast working medium. It facilitates high piston speeds and fast switching times. |
| Overload protection | Pneumatic tools and operating elements can be loaded until they give out and are therefore overload-proof. |

Table 1.1: Features and advantages of pneumatics

| Parameter | Comment |
|---|---|
| Preparation | Compressed air must be prepared as otherwise there is a risk of increased wear of the pneumatic components by dirt particles and condensed water. |
| Compression | It is not possible to achieve uniform and constant piston speeds with compressed air. |
| Force | Compressed air is only economical up to a certain force requirement. With a normal operating pressure of 600 to 700 kPa (6 to 7 bar) and depending on the stroke and speed, this limit is between 40,000 and 50,000 N. |
| Exhaust air | Escaping air makes a lot of noise. This problem can be solved to a large extent by means of sound-absorbing materials and silencers. |

Table 1.2: Disadvantages of pneumatics

The comparison with other forms of energy is an important prerequisite for using pneumatics as a control or working medium. This assessment covers the overall system from the input signals (sensors) and the control section (processor) to the control elements and drives. In addition, the following factors must be considered:

- Preferred control media
- Available equipment
- Available knowledge
- Existing systems

### 1.2.1 Criteria for working media

Working media are:

- Electric current (electrics)
- Fluids (hydraulics)
- Compressed air (pneumatics)
- Combination of the above media

Selection criteria and system properties that must be taken into consideration for working media:

- Force
- Stroke
- Type of movement (linear, swivelling, rotary)
- Speed
- Service life
- Reliability and precision
- Energy costs
- Operability
- Storage ability

### 1.2.2 Criteria for control media

Control media area:

- Mechanical connections (mechanics)
- Electric current (electrical, electronics)
- Fluids (hydraulics)
- Compressed air (pneumatics, low-pressure pneumatics)

Selection criteria and system properties that must be taken into consideration when using the control media:

- Reliability of the components
- Sensitivity to environmental influences
- Ease of maintenance and repair
- Switching time of the components
- Signal speed
- Space requirement
- Service life
- Alterability of the system
- Training requirements

### 1.3 Development of pneumatic control systems

The following product groups are available within pneumatics:

- Drives
- Sensors and input devices
- Processors
- Accessories
- Complete control systems

The following considerations must be taken into account when developing pneumatic control systems:

- Reliability
- Ease of maintenance
- Spare part costs
- Assembly and connection
- Maintenance costs
- Interchangeability and versatility
- Compact design
- Economy
- Documentation

# 2 Basic concepts of pneumatics

## 2.1 Physical principles

Air is a gaseous mixture with the following composition:

- approx. 78% nitrogen
- approx. 21% oxygen

It also contains traces of carbon dioxide, argon, hydrogen, neon, helium, krypton and xenon.

To help you understand the nature of air, the physical variables that are used in this context are listed below. All specifications are in the "International System of Units", or SI for short.

| Variable | Symbol | Unit |
|---|---|---|
| Length | $l$ | Metre (m) |
| Mass | $m$ | Kilogram (kg) |
| Time | $t$ | Second (s) |
| Temperature | $T$ | Kelvin (K, 0 °C = 273.15 K) |

Table 2.1: Basic units

| Variable | Symbol | Unit |
|---|---|---|
| Force | $F$ | Newton (N) |
| Area | $A$ | Square metre ($m^2$) |
| Volume | $V$ | Cubic metre ($m^3$) |
| Flow rate | $q_v$ | Cubic metre per second ($m^3/s$) |
| Pressure | $p$ | Pascal (Pa)<br>1 Pa = 1 $N/m^2$<br>1 bar = $10^5$ Pa |

Table 2.2: Derived units

### 2.1.1 Newton's law

Newton's law describes the relationship between force, mass and acceleration:
Force = mass · acceleration

$$F = m \cdot a$$

In the case of free fall, $a$ is replaced by gravitational acceleration $g = 9.81\ m/s^2$.

### 2.1.2 Pressure

1 Pa corresponds to the pressure exerted by a vertical force of 1 N on an area of 1 $m^2$.

The pressure against/on the earth's surface is referred to as atmospheric pressure ($p_{amb}$). This pressure is also called reference pressure. The range above this pressure is called the excess pressure range ($p_e > 0$), while the range below is called the vacuum range ($p_e < 0$). The atmospheric pressure differential $p_e$ is calculated according to the formula:

$$p_e = p_{abs} - p_{amb}$$

This is illustrated in the following diagram:

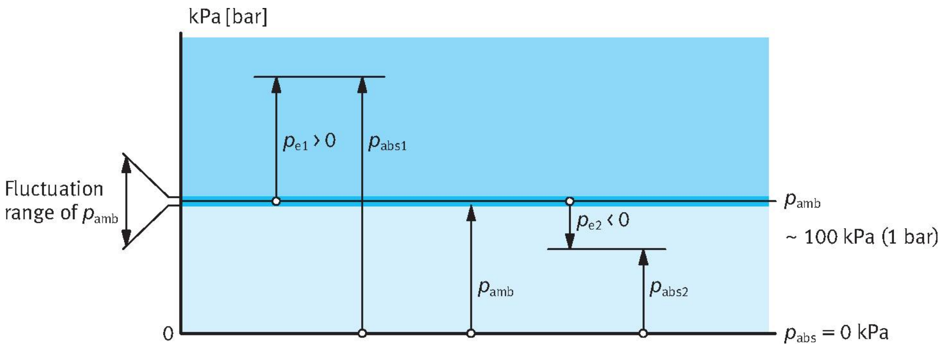



Figure 2.1: Air pressure

Atmospheric pressure is not constant. Its value changes with the geographical position and the weather.

Absolute pressure $p_{abs}$ is the value referred to zero pressure (vacuum). It is equal to the sum of the atmospheric pressure and excess pressure or vacuum. The pressure gauges most often used in practice are those that display only the excess pressure $p_e$. The absolute pressure value $p_{abs}$ is approximately 100 kPa (1 bar) higher.

In pneumatics, all specifications relating to air quantities are usually referred to as the so-called normal condition. The normal condition according to DIN 1343 is the condition of a solid, liquid or gaseous material defined by means of standard temperature and standard pressure.

- Standard temperature $T_n = 273.15$ K, $t_n = 0$ °C
- Standard temperature $p_n = 101{,}325$ Pa $= 1.01325$ bar

## 2.2 Properties of air

Air is characterised by very low cohesion, i.e. the forces between the air molecules are negligible in the operating conditions usual in pneumatics. Like all gases, air therefore does not have a specific form. It changes its shape with the least application of force and occupies the maximum space available to it.

### 2.2.1 Boyle's law

Air can be compressed and attempts to expand. Boyle's law describes these properties as follows: the volume of a fixed amount of gas is inversely proportional to the absolute pressure at constant temperature; or, to put it another way, the product of volume and absolute pressure is constant for a fixed amount of gas.

$$p_1 \cdot V_1 = p_2 \cdot V_2 = p_3 \cdot V_3 = \text{constant}$$

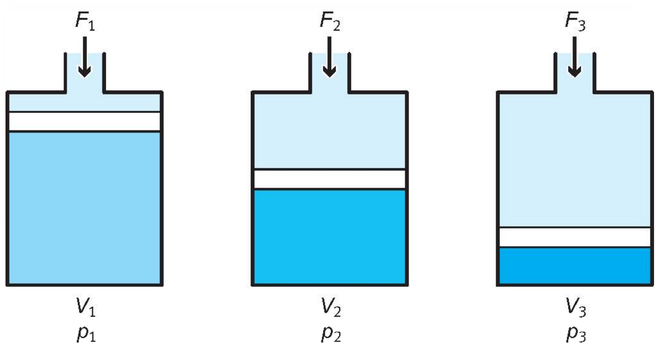



Figure 2.2: Boyle's law

**Calculation example**

Air is compressed to 1/7 of its volume at atmospheric pressure. What is the pressure if the temperature remains constant?

$$p_1 \cdot V_1 = p_2 \cdot V_2$$

$$p_2 = p_1 \cdot \frac{V_1}{V_2}, \text{ note: } \frac{V_2}{V_1} = \frac{1}{7}$$

$p_1 = p_{amb} = 100$ kPa = 1 bar

$p_2 = 1 \cdot 7 = 700$ kPa = 7 bar absolute

This means: $p_e = p_{abs} - p_{amb}$ = (700 – 100) kPa = 600 kPa = 6 bar

A compressor that generates an excess pressure of 600 kPa (6 bar) has a compression ratio of 7:1.

### 2.2.2 Gay-Lussac's law

Air expands by 1/273 of its volume at constant pressure, a temperature of 273 K and a rise in temperature of 1 K. Gay-Lussac's law states that the volume of a fixed amount of gas is proportional to the absolute temperature as long as the pressure is not changed.

$\frac{V_1}{V_2} = \frac{T_1}{T_2}$, $V_1$ = volume at $T_1$, $V_2$ = volume at $T_2$

or

$$\frac{V}{T} = constant$$

The change in volume $\Delta V$ is: $\Delta V = V_2 - V_1 = V_1 \cdot \frac{T_2 - T_1}{T_1}$

The following holds for $V_2$: $V_2 = V_1 + \Delta V = V_1 + \frac{V_1}{T_1} \cdot (T_2 - T_1)$

These equations only apply if the temperatures in K are used. The following formula must be used to convert to °C:

$$V_2 = V_1 + \frac{V_1}{273\ °C + T_1} \cdot (T_2 - T_1)$$

**Calculation example**
0.8 m³ of air with the temperature $T_1$ = 293 K (20 °C) is heated to $T_2$ = 344 K (71 °C). By how much does the air expand?

$$V_2 = 0.8\ \text{m}^3 + \frac{0.8\ \text{m}^3}{293\ \text{K}} \cdot (344\ \text{K} - 293\ \text{K})$$

$$V_2 = 0.8\ \text{m}^3 + 0.14\ \text{m}^3 = 0.94\ \text{m}^3$$

The air expands by 0.14 m³ to 0.94 m³.

If the volume is kept constant during the heating process, the increase in pressure can be expressed using the following formula:

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}$$

or

$$\frac{p}{T} = \text{constant}$$

### 2.2.3 General gas equation

The general gas equation fulfils all the laws:

$$\frac{p_1 \cdot V_1}{T_1} = \frac{p_2 \cdot V_2}{T_2} = \text{constant}$$

With a fixed amount of gas, the product of pressure and volume divided by the absolute temperature is constant.

The above-mentioned laws can be derived from this general gas law, when one of the three factors p, V or T is kept constant.

- Pressure $p$ constant ➔ isobaric change
- Volume $V$ constant ➔ isochoric change
- Temperature $T$ constant ➔ isothermic change

# 3 Compressed air generation and compressed air supply

## 3.1 Preparing the compressed air

To be able to guarantee the reliability of a pneumatic control system, compressed air of adequate quality must be supplied. This is determined by the following factors:

- Correct pressure
- Dry air
- Cleaned air

If these requirements are not met, this can result in increased machine downtime coupled with higher operating costs.

Compressed air generation starts with compression. The compressed air flows through a whole series of components before it reaches the consuming device. The compressor type and its location more or less influence the amount of dirt particles, oil and water that get into a pneumatic system. The following components should be used for preparing compressed air:

- Inlet filter
- Compressor
- Air reservoir
- Air dryer
- Compressed air filter with water separator
- Pressure regulator
- Lubricator (if required)
- Drain points for the condensate

### 3.1.1 Consequences of poorly prepared compressed air

Poorly prepared air increases the number of malfunctions and shortens the service life of pneumatic systems. This is indicated by:

- Increased wear on seals and moving parts in valves and cylinders
- Oil-fouled valves
- Dirty silencers
- Corrosion in pipes, valves, cylinders and other components
- Lubrication of moving components flushed out

If there are leaks, escaping compressed air can impair the materials (e.g. foodstuffs) to be processed.

### 3.1.2 Pressure level

Pneumatic components are usually designed for a maximum operating pressure ranging between 800 and 1,000 kPa (8 to 10 bar). However, a pressure of 600 kPa (6 bar) is sufficient for economical operation. Due to flow resistances in the individual components (e.g. flow control valves) and in the piping, a pressure loss between 10 and 50 kPa (0.1 and 0.5 bar) is to be expected. The compressor system should therefore supply a pressure of 650 to 700 kPa (6.5 to 7 bar) to ensure the desired operating pressure of 600 kPa (6 bar).

## 3.2 Compressors

The choice of a compressor depends on the working pressure and the quantity of air required. Compressors are differentiated based on their design.

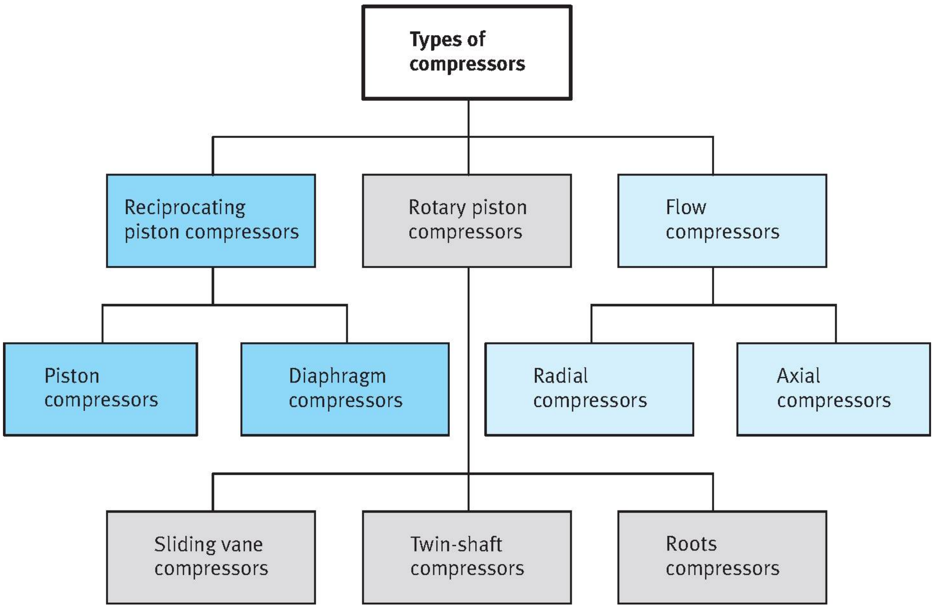



Figure 3.1: Compressor designs

### 3.2.1 Reciprocating piston compressor

A piston compresses the air taken in via an intake valve. The air is passed on via an exhaust valve.

Reciprocating piston compressors are frequently used as they are available for large pressure ranges. For generating higher pressures, multi-stage compressors are used. With these, the air is cooled between the individual compressor stages.

The optimum pressure ranges for reciprocating piston compressors are:

| | | |
|---|---|---|
| Up to 400 kPa | (4 bar) | One stage |
| Up to 1,500 kPa | (15 bar) | Two stages |
| Above 1,500 kPa | (> 15 bar) | Three or more stages |

The following pressure ranges are possible, but not always economical:

| | | |
|---|---|---|
| Up to 1,200 kPa | (12 bar) | One stage |
| Up to 3,000 kPa | (30 bar) | Two stages |
| Above 3,000 kPa | (> 30 bar) | Three or more stages |

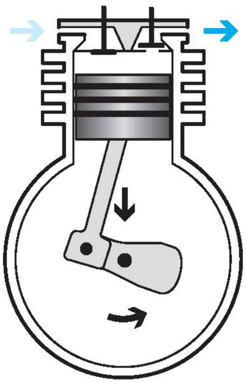


Figure 3.2: Sectional view of a single-stage reciprocating piston compressor

### 3.2.2 Diaphragm compressor

The diaphragm compressor belongs to the group of reciprocating piston compressors. The compressor chamber is separated from the piston by a diaphragm. This has the advantage that no oil from the compressor can get into the air flow. The diaphragm compressor is therefore frequently used in the food industry and in the pharmaceutical and chemical industry.

### 3.2.3 Rotary piston compressor

With a rotary piston compressor, the air is compressed using rotary pistons. During the compression process, the compression chamber is continuously constricted.

### 3.2.4 Screw compressor

Two shafts (slides) with helical profiles turn against each other. The interlocking profile delivers and compresses the air.

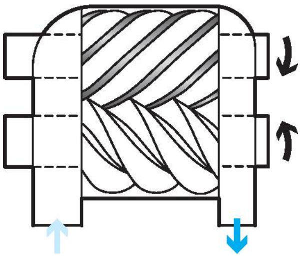


Figure 3.3: Sectional view of a screw compressor

### 3.2.5 Flow compressor

Flow compressors are especially suitable for high delivery rates. They can have an axial or radial design. Air flow is created using one or more turbine wheels. The kinetic energy is converted into pressure energy. With an axial compressor, the air is accelerated in axial flow direction by the vanes.

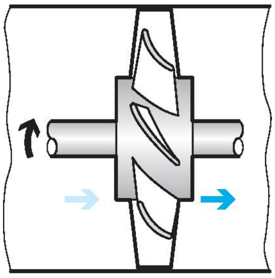


Figure 3.4: Sectional view of an axial compressor

### 3.2.6 Regulation

The compressor needs to be regulated to adapt the delivery rate of the compressor to fluctuations in demand. The delivery rate is regulated between variable limits for maximum and minimum pressure. There are different types of regulation:

- Idling regulation
  - Exhaust regulation
  - Shut-off regulation
  - Gripper regulation
- Partial load regulation
  - Speed regulation
  - Suction throttle regulation
- Intermittent regulation

**Idling regulation**

With exhaust regulation, the compressor works against a pressure-relief valve. If the set pressure is reached, the pressure-relief valve opens and the air is exhausted into the open. A non-return valve prevents the reservoir from being emptied. This type of regulation is only used with very small systems.

With exhaust regulation, the suction side is shut off. The compressor cannot take in air. This type of regulation is primarily used with rotary piston compressors.

Gripper regulation is used with larger piston compressors. A gripper keeps the suction valve open; the compressor cannot compress any air.

**Partial load regulation**

With speed regulation, the speed of the compressor's drive motor is regulated as a function of the achieved pressure.

With suction throttle regulation, regulation takes place by means of a restriction in the compressor's suction nozzle.

**Intermittent regulation**

With this type of regulation, the compressor assumes the operating states full load and idle. The compressor's drive motor is turned off when $p_{max}$ is reached and turned on when $p_{min}$ is reached.

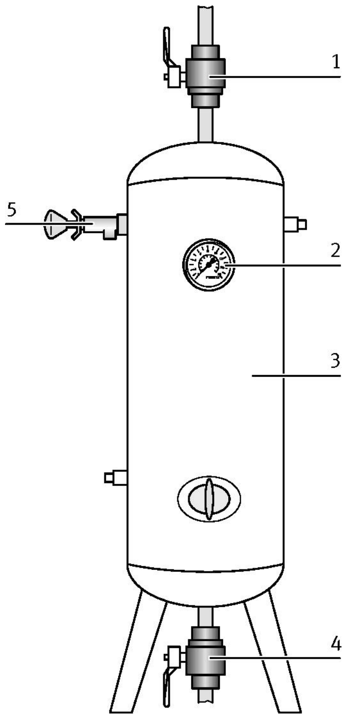
### 3.2.7 Duty cycle

It is recommended to achieve a duty cycle of approx. 75% for a compressor. To do this it is necessary to determine the average and maximum air requirement of a pneumatic system and to tailor the choice of compressor to this. If it is expected that extensions to the system will mean an increase in the air requirement, the compressed air supply unit should be designed bigger since subsequent extension is always associated with high costs.

### 3.3 Air reservoirs

An air reservoir is placed downstream of the compressor to stabilise the compressed air. The air reservoir compensates pressure fluctuations when compressed air is removed from the system. If the pressure in the air reservoir falls below a certain value, the compressor fills it until the set upper pressure value is reached again. This has the advantage that the compressor does not have to work continuously.

The compressed air in the air reservoir is cooled by the relatively large surface of the reservoir. This produces condensed water, which must be regularly drained via a drain cock.




1: On-off valve; 2: Pressure gauge; 3: Air reservoir; 4: Drain cock; 5: Pressure-relief valve

Figure 3.5: Air reservoir

The size of the air reservoir depends on the following criteria:

- Delivery rate of the compressor
- Air requirement of the system
- Network (in case of additional volume)
- Regulation of the compressor
- Permissible pressure fluctuations in the network

**Example: Storage capacity of an air reservoir**

| | | | | |
|---|---|---|---|---|
| Specifications: | Delivery rate | $q_D$ | = | 20 $m^3$/min |
| | Differential pressure | $\Delta p$ | = | 100 kPa (1 bar) |
| | Switching cycles/h | $z$ | = | 20 $h^{-1}$ |
| Result: | Reservoir size | $V_R$ | = | 15 $m^3$ |
| | (see dashed line in Figure 3.6) | | | |

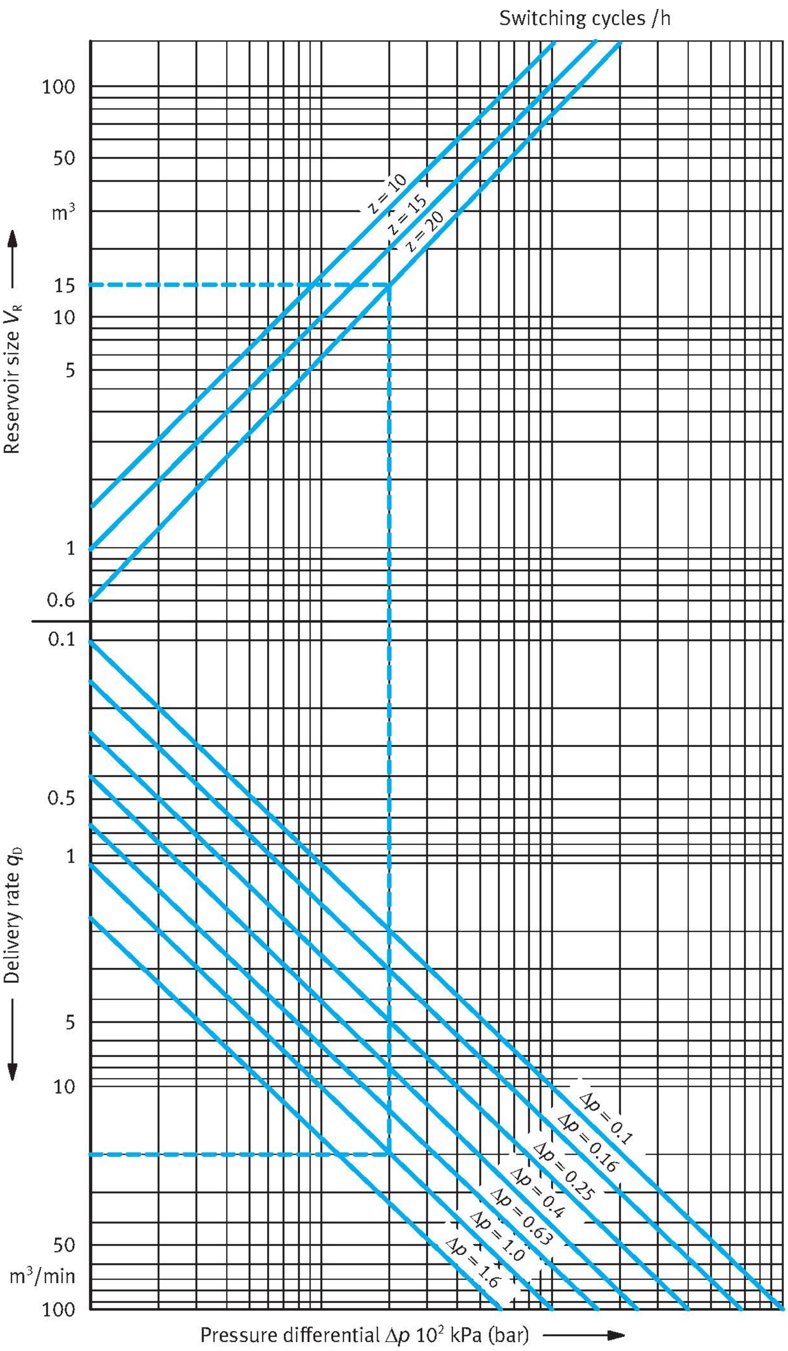



Figure 3.6: Determining the storage capacity

## 3.4 Air dryers

Moisture (water) gets into the air network via the air taken in by the compressor. The amount of moisture primarily depends on the relative air humidity. The relative air humidity is dependent on the air temperature and the weather conditions.

The absolute humidity is the amount of water vapour contained in one $m^3$ of air. The saturation quantity is the maximum amount of water vapour that one $m^3$ air can absorb at a specific temperature.

If the relative air humidity is specified in percent, the formula is as follows:

$$\text{relative humidity} = \frac{\text{absolute humidity}}{\text{saturation quantity}} \times 100\ \%$$

As the saturation quantity is dependent on temperature, the relative air humidity changes with the temperature even if the absolute air humidity stays constant. If the dew point is reached, the relative air humidity increases to 100%.

### Dew point

The dew point refers to the temperature at which the relative air humidity reaches 100%. If you reduce the temperature further, the water vapour in the air begins to condense. The further the temperature is reduced, the more water vapour condenses.

Excessive amounts of moisture in the compressed air reduce the service life of pneumatic systems. That is why air dryers should be interposed to reduce the moisture content of the air. These are the methods available for drying air:

- Refrigeration drying
- Adsorption drying
- Absorption drying

### Pressure dew point

To be able to compare different dryer systems, the operating pressure of the system must be taken into consideration. The concept of the pressure dew point is used for this. The pressure dew point is the air temperature reached in a dryer at operating pressure.

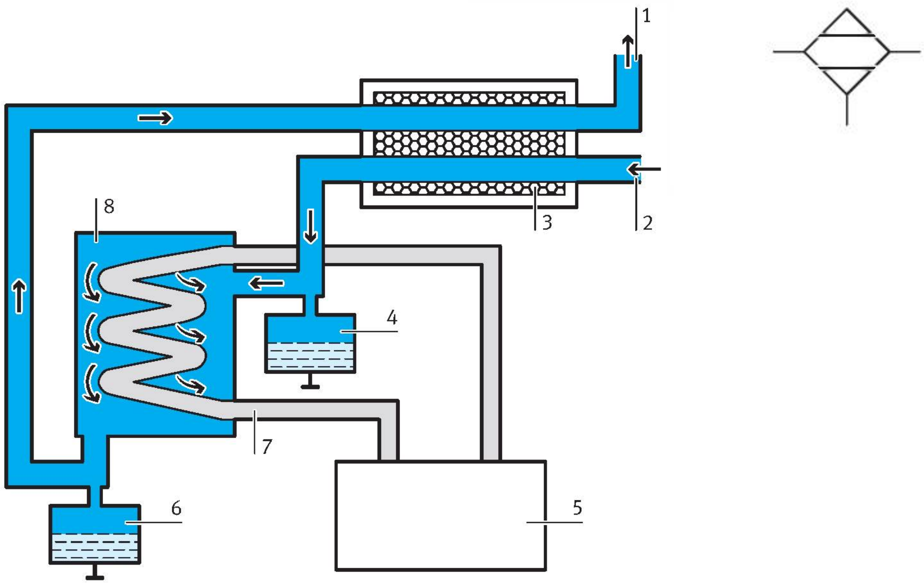
The pressure dew point of the dried air should be approx. 2 to 3 °C lower than the coolest ambient temperature. Due to the reduced maintenance costs, shorter downtimes and increased system reliability the additional costs for an air dryer are amortised relatively quickly.

### 3.4.1 Refrigeration dryer

The most frequently used air dryer is the refrigeration dryer. The air flowing through is cooled in a heat exchanger. The moisture in the air flow is removed and collected in a separator.

The air entering the refrigeration dryer is precooled in a heat exchanger by the cold air exiting the dryer. It is then cooled to temperatures between + 2 and + 5 °C in the cooling unit. The dried compressed air is filtered. When it exits the refrigeration dryer, the compressed air is heated once again in the heat exchanger by the warm air entering the dryer.

Refrigeration drying enables pressure dew points + 2 and + 5 °C to be achieved.



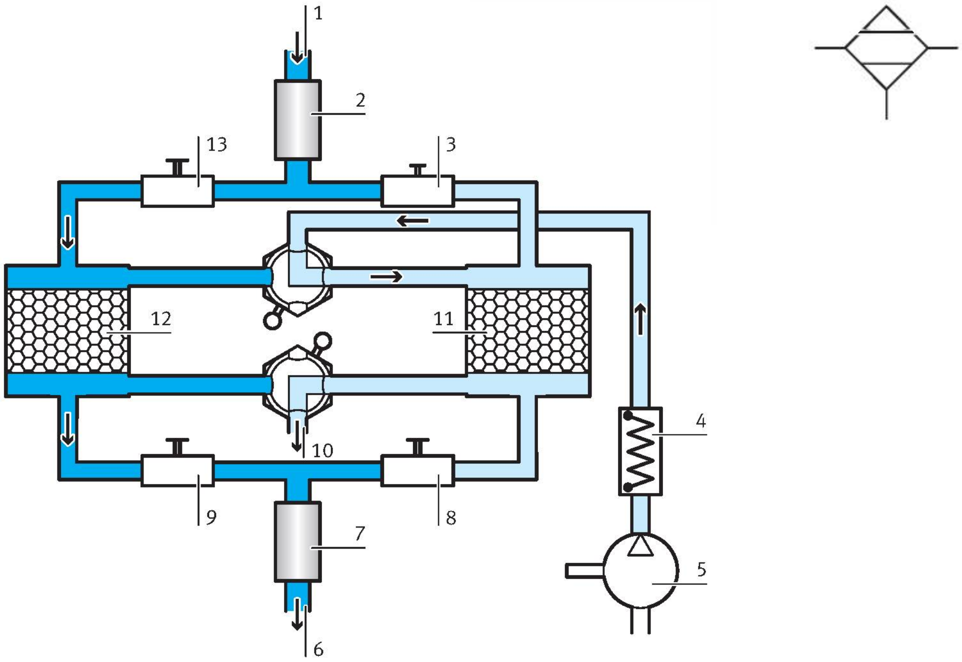

1: Air outlet; 2: Air inlet; 3: Air/air heat exchanger; 4: Separator; 5: Refrigerator; 6: Separator; 7: Cooling agent; 8: Cooling unit

Figure 3.7: Refrigeration dryer – sectional view and symbol

### 3.4.2 Adsorption dryer

Adsorption: Substances are deposited on the surface of solid bodies.
The drying agent, also called gel, is a granulate that consists mostly of silicon dioxide.
Adsorbers are always used in pairs. Once the gel is saturated in the first adsorber, a switch is made to the second adsorber. The first adsorber is then regenerated by means of hot-air drying.

Pressure dew points down to -90 °C can be reached by means of adsorption drying.



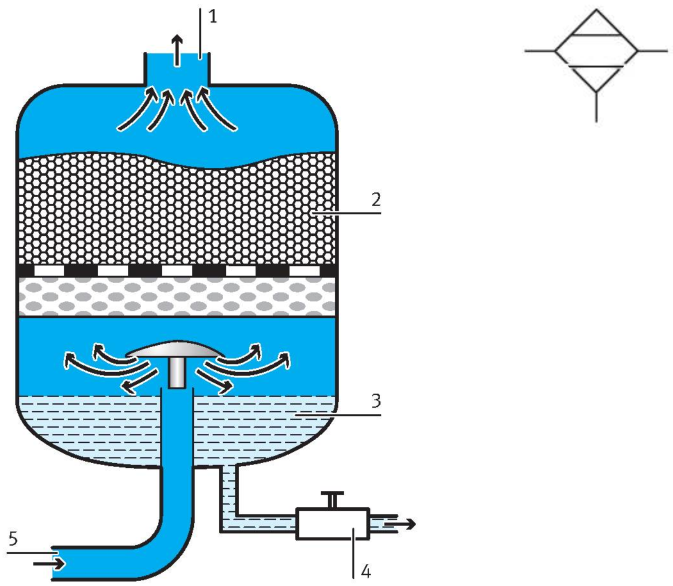

1: Wet air; 2: Prefilter (oil filter); 3: On-off valve (closed); 4: Heating element; 5: Ventilator; 6: Dry air; 7: Secondary filter; 8: On-off valve (closed); 9: On-off valve (open); 10: Hot air; 11: Adsorber 2; 12: Adsorber 1; 13: On-off valve (open)

Figure 3.8: Adsorption dryer – sectional view and symbol

### 3.4.3 Absorption dryer

Absorption: A solid or liquid substance absorbs a gaseous substance.

Absorption drying is a purely chemical process. This type of drying is rarely used due to the high operating costs.




1: Outlet for dry air; 2: Flux; 3: Condensate; 4: Condensate drain; 5: Outlet for wet air

Figure 3.9: Absorption dryer – sectional view and symbol

Large drops of water and oil are removed from the compressed air in a prefilter. When it enters the dryer, the compressed air spins around and flows through the drying chamber, which is filled with a flux (drying compound). The moisture bonds with the flux and dissolves it. This liquid compound then enters the lower collecting chamber.

The mixture must be regularly drained and the flux regularly replaced.

The absorption method is characterised by:
- Easy installation of the system
- Minimal mechanical wear (no moving parts)
- No outside energy requirement

A dust filter must be provided downstream of the dryer to collect flux dust that is carried along.
Pressure dew points below 0 °C can be achieved.

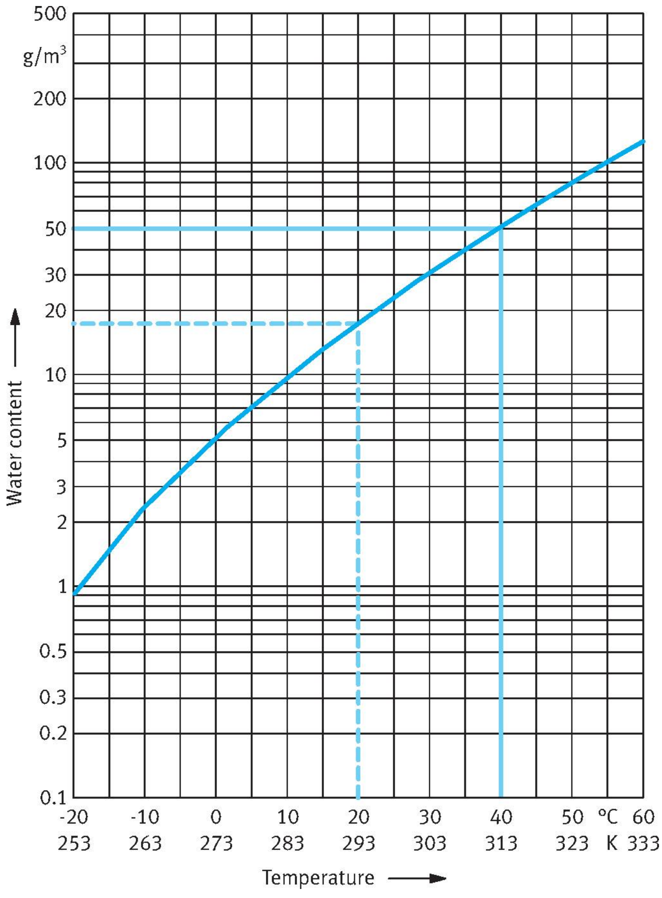



Figure 3.10: Dew point curve

**Example:**

| | |
|---|---|
| Suction capacity | 1,000 $m^3$/h |
| Absolute pressure | 700 kPa (7 bar) |
| Compressed quantity per hour | 143 $m^3$ |
| Suction temperature | 293 K (20 °C) |
| Temperature after compression | 313 K (40 °C) |
| Relative humidity | 50% |

Water volume before compression:
The water content at 293 K (20 °C) is as follows:

$$100\% = 17.3 \text{ g/m}^3$$

(see dashed line in Figure 3.10)

This means: $50\% = 8.65 \text{ g/m}^3$
This gives: $8.65 \text{ g/m}^3 \cdot 1{,}000 \text{ m}^3\text{/h} = 8{,}650 \text{ g/h}$

Water volume after compression:
The saturation quantity is as follows at 313 K (40 °C):

$$51.1 \text{ g/m}^3$$

(see solid line in Figure 3.10)

This gives: $51.1 \text{ g/m}^3 \cdot 143 \text{ m}^3\text{/h} = 7{,}307 \text{ g/h}$

The discharged amount of water downstream of the compressor is therefore:

$$8{,}650 \text{ g/h} - 7{,}307 \text{ g/h} = 1{,}343 \text{ g/h}.$$

## 3.5 Air distribution

To guarantee reliable and trouble-free air distribution, several points must be observed. Correct sizing of the pipe system is as important as the pipe material used, the flow resistance, the pipe layout and maintenance.

### 3.5.1 Sizing of the piping

Any future extension of the compressed air network should always be taken into consideration in new installations. For example, the main line should be made bigger than is needed for the current system requirements. It is also recommended to attach additional plugs and on-off valves for any potential future extension.

Pressure losses due to flow resistances occur in all pipes, particularly at narrowings in the pipes, corners, branches and fittings. These losses must be compensated by the compressor. The pressure drop in the network as a whole should then be minimal.

To calculate the pressure drop, the total pipe length must be known. For fittings, branches and corners, equivalent pipe lengths must be determined. The choice of the correct inner diameter also depends on the operating pressure and the quantity of air supplied and is best calculated with the help of a nomogram.

### 3.5.2 Flow resistance

Every manipulation of or change in direction in the air flow within a piping system is interference and means an increase in the flow resistance. This results in a constant pressure drop within the piping system. Since branches, corners and fittings have to be used in all compressed air networks, pressure drops cannot be avoided. They can, however, be significantly reduced by installing appropriate fittings, choosing the right material and assembling the fittings correctly.

### 3.5.3 Pipe material

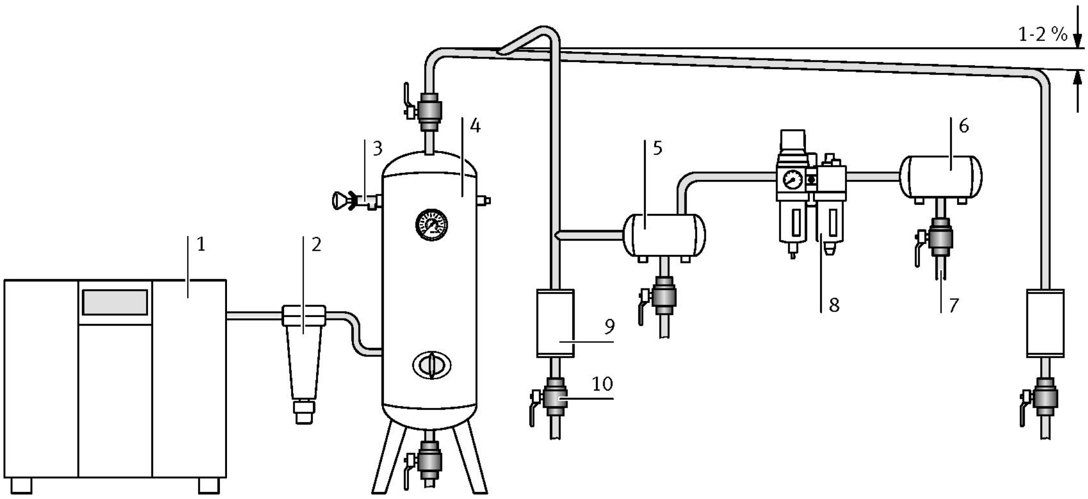
A modern compressed air system places particular demands on the quality of the pipes. They have to ensure

- low pressure losses,
- leak tightness,
- resistance to corrosion and
- extendability.

It is not just the costs of the materials but also the costs of installation that must be considered. Plastic pipes are very cheap to install, can be joined with completely air-tight connections through the use of adhesives and are also easy to extend.

Copper and steel pipes, on the other hand, cost less but have to be soldered, welded or joined via threaded connections. If this is not done carefully, chips, residues from welding work, deposits or sealants can get into the system. This can result in serious malfunctions. For small and medium diameters, plastic pipes are superior to all other materials in terms of price, assembly, maintenance and extendability.

Pressure fluctuations in the network demand reliable assembly of the pipes as otherwise leaks can occur at screwed and soldered joins.




1: Compressor; 2: Water/oil separator; 3: Pressure-relief valve; 4: Air reservoir; 5: Buffer for several consuming devices; 6: Air reservoir within the pneumatic system; 7: To the consuming device; 8: Service unit; 9: Condensate collector; 10: Drain cock

Figure 3.11: Air supply system

### 3.5.4 Pipe layout

In addition to correct sizing of the pipes and the quality of the pipe material, a correct pipe layout is also critical for economical operation of the compressed air system. The compressor supplies the system with compressed air at intervals. It is therefore frequently the case that the compressed air consumption only increases in the short term. This can result in unfavourable conditions in the compressed air network. It is recommended to design the compressed air network in the form of a ring main line as this guarantees relatively constant pressure conditions.

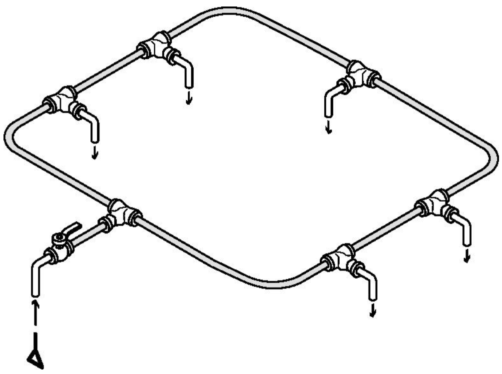


Figure 3.12: Ring line

It is advisable to divide the network into individual sections so that maintenance work, repairs or extensions to the network can be carried out without interrupting the entire air supply.

Branches with T-connectors and manifold blocks with plug-in couplings should be provided for this. The branch lines should be fitted with on-off valves or standard ball valves.

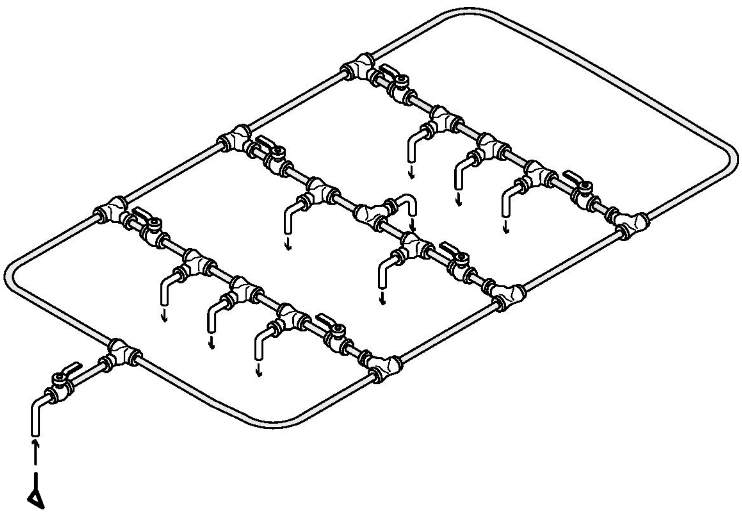


Figure 3.13: Network

Despite good water separation in the pressure generation system, pressure drops and surface cooling can result in condensate residues in the piping system. The branch lines should be laid with a 1 to 2% gradient in the direction of flow to enable this condensate to be drained. They can also be installed in a stepped configuration. The condensate can then be drained at the lowest point via water separators.

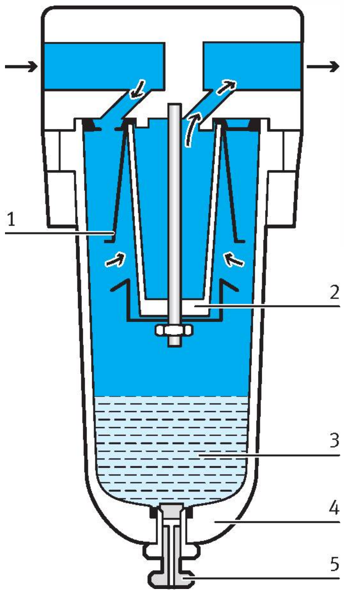
### 3.6 Service unit

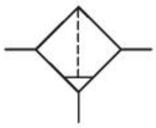
The individual functions in compressed air preparation of filtering, regulation and lubrication can be fulfilled with individual components. These functions have often been grouped together into one unit, the service unit. Service units are placed upstream of every pneumatic system.

The use of a lubricator is generally no longer required in modern systems. It should only be used when needed, primarily in the power section of a system. The compressed air in the control section should not be lubricated.

#### 3.6.1 Compressed air filter

Condensed water, contaminants and excessive oil can result in wear of moving parts and seals of pneumatic components. These substances can escape through leaks. If compressed air filters were not used, the products to be processed in the food, pharmaceutical and chemical industry, for example, could become contaminated and therefore be rendered unusable.



1: Spin disc; 2: Sintered filter; 3: Condensate; 4: Filter bowl; 5: Drain screw

Figure 3.14: Compressed air filter – sectional view and symbol

The choice of a compressed air filter plays an important role in supplying the pneumatic system with good quality compressed air. The characteristic for the compressed air filter is the pore size. It determines the smallest particle size that can still be filtered from the air flow.

The collected condensate must be drained before an upper boundary mark is reached as otherwise it will be reabsorbed by the air flow.

With a constant amount of condensed water it is advisable to use an automatic bleeder instead of the manual drain cock. However, the cause of the condensed water must also be investigated. It can, for example, be due to a poor system layout.

The automatic bleeder consists of a float that opens a compressed air nozzle via a lever mechanism when the maximum condensate level is reached. The inward flow of compressed air opens the drain port via a diaphragm. When the float reaches the minimum condensate level, the nozzle is closed and bleeding is stopped. The collector can also be drained via a manual override.

When it enters the air filter, the compressed air flows against a spin disc and is set in rotation. The centrifugal force separates water particles and solid foreign matter from the air flow. They are hurled against the inner wall of the filter bowl, from where they drain off into the collecting chamber. The pretreated air flows through the filter insert. The dirt particles that are bigger than the pore size are filtered out at this point. The pore sizes of regular filters are between 5 μm and 40 μm.

A filter's degree of filtration describes the percentage of particles of a specific size that are filtered out of the air flow. For example a degree of filtration of 99.99% refers to a particle size of 5 μm. With micro filters, 99.999% of particles bigger than 0.01 μm can be filtered out.

The filter insert must be replaced after an extended period of operation as the dirt particles that are filtered out can clog it. As the dirt increases, the filter offers greater flow resistance to the air flow. This increases the pressure drop at the filter.

A visual inspection or a differential pressure measurement must be carried out to determine when the filter needs to be changed.

**Maintenance**
The length of the maintenance interval for replacing the filter insert is dependent on the condition of the compressed air, the air requirement of the connected pneumatic components and the filter size.
Maintenance of the filter should include the following:
- Replacing or cleaning the filter insert
- Draining condensate

The manufacturer's specifications with regard to the cleaning agent must be observed during cleaning work.

### 3.6.2 Pressure regulator
The compressed air generated by the compressor is subject to fluctuations. Pressure fluctuations in the piping system can negatively influence the switching characteristics of valves, cylinder operating times and time regulation of flow control and double pilot valves.

Smooth operation of a pneumatic system calls for a constant working pressure. To guarantee a constant pressure level, pressure regulators are connected centrally to the compressed air network and, independent of the pressure fluctuations in the main control circuit (primary pressure), ensure a constant pressure supply in the system (secondary pressure). The pressure reducer or pressure regulator is connected downstream of the compressed air filter and keeps the working pressure constant. The pressure level should always be adapted to the requirements of the respective system section.

A working pressure of
- 600 kPa (6 bar) in the power section and
- 300 to 400 kPa (3 to 4 bar) in the control section

has proven the best economical and technical compromise between compressed air generation and performance of the components in practice.

A higher operating pressure would result in poor energy utilisation and greater wear while a lower pressure would reduce efficiency, particular in the power section.

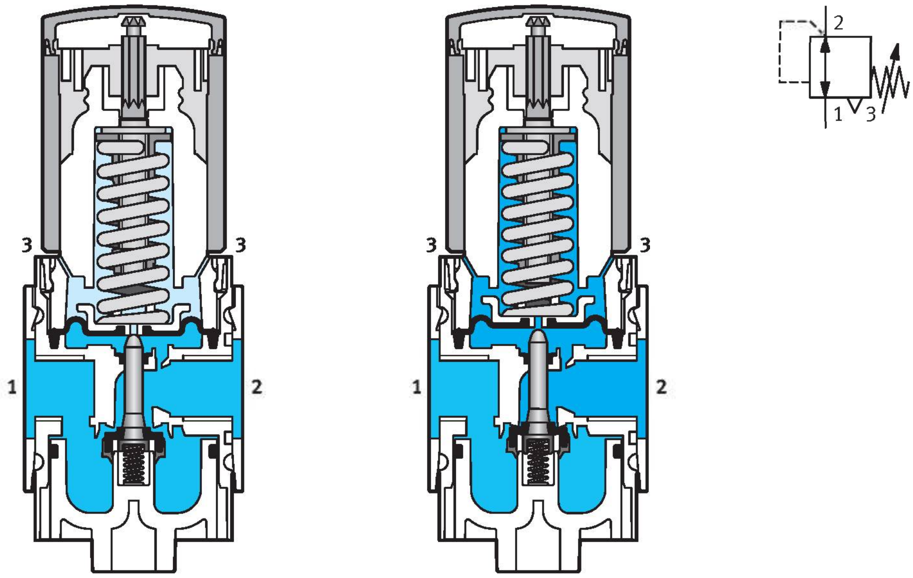



Figure 3.15: Pressure regulator with relief port – sectional views and symbol

**Pressure regulator with relief port – how it works**

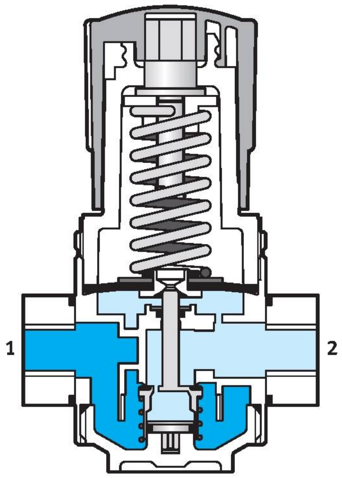
The supply pressure (primary pressure) at the pressure regulator must always be higher than the output pressure (secondary pressure). Pressure regulation itself takes place via a diaphragm. The output pressure acts on one side of the diaphragm, the force of a spring on the other side. The spring force can be set via an adjusting screw.

If the pressure on the secondary side increases, for example during a load change at the cylinder, the diaphragm is pressed against the spring and the outlet cross-sectional area at the valve seat is reduced or closed. The valve seat of the diaphragm opens and the compressed air can escape into the atmosphere through the relief ports in the housing.

If the pressure on the secondary side decreases, the spring force opens the valve. Regulating the air pressure to the preset operating pressure therefore means constant opening and closing of the valve seat, triggered by the air volume flowing through. The operating pressure is displayed on a measuring device.

**Pressure regulator without relief port – how it works**

If the operating pressure (secondary pressure) is too high, the pressure in the valve seat increases and presses the diaphragm against the force of the spring. At the same time, the outlet cross-sectional area at the seal seat is reduced or closed. The air flow is reduced or cut off. The compressed air can only start flowing again when the operating pressure is less than on the primary side.



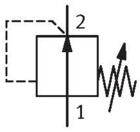



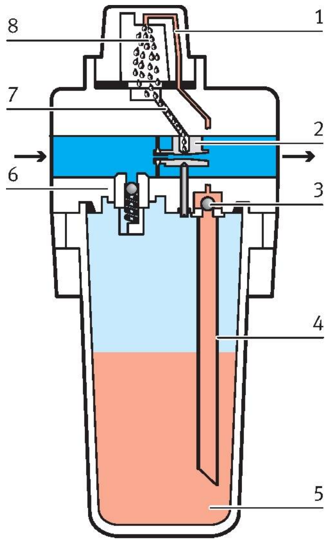

Figure 3.16: Pressure regulator without relief port – sectional view and symbol

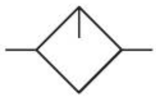
### 3.6.3 Lubricator

The generated compressed air should generally not be lubricated. If moving parts in valves and cylinders need external lubrication, the compressed air must be sufficiently and continuously enriched with oil. Lubrication of the compressed air should always be restricted to the sections of a system where lubricated air is needed. The oil added to the compressed air by the compressor is not suitable for lubricating pneumatic components.

Cylinders with heat-resistant seals should not be operated with lubricated compressed air as the oil can flush out the special grease.

If systems that were operated with lubrication are switched over to unlubricated compressed air, the original lubrication of the valves and cylinders must be renewed as it may have been flushed out.



1: Riser line; 2: Valve throttle point; 3: Ball seat; 4: Riser pipe; 5: Oil; 6: Non-return valve; 7: Duct; 8: Drip chamber

Figure 3.17: Lubricator – sectional view and symbol

The compressed air should only be lubricated if:
- Extremely fast motion sequences are required
- Cylinders with large diameters are used
  (the lubricator should be directly upstream of the cylinder in this case)

Excessive lubrication can result in the following problems:
- Malfunctioning components
- Increased environmental pollution
- Components seizing up after extended idle periods

**Operational principle**
The compressed air flows through the lubricator and generates a vacuum when it passes through a restriction/restricted passage. This vacuum sucks oil from the reservoir via a riser pipe. The oil reaches a drip chamber, is atomised by the oil flow and then transported onwards.

**Setting the lubricator**
The correct metering can be checked as follows: hold a piece of white card approx. 10 cm away from the discharge port of the control element on the cylinder furthest away from the lubricator. Allow the system to work for some time; the card should show a pale yellow colouration. Dripping oil is a sign of overlubrication.

**Lubricator maintenance**
The oil deposited by the compressor cannot be used as lubricant for the drive components. The heat generated in the compressor burns up and cokes the oil. It would have an abrasive effect on cylinders and valves and significantly reduce their performance.

A further problem when maintaining systems operated with lubricated compressed air is the oil deposits on the inner walls of the supply line pipes. These oil deposits can be absorbed uncontrolled into the air flow and increase the amount of dirt in the compressed air lines. Maintaining dirty systems of this type is extremely time-consuming as a pipe soiled by oil deposits can only be cleaned by dismantling it.

Oil deposits can also result in components seizing up, particularly after long idle times. After a weekend or holiday, lubricated components may no longer work properly.

Lubrication of the compressed air should be restricted to those system parts that really do need to be lubricated. Lubricators are best installed directly upstream of the consuming components. Components with self-lubrication should be chosen for the control section of a pneumatic system.

The basic rule should therefore be: compressed air should be prepared unlubricated.

In summary, the following points should be noted:
- Compressor oils should not get into the compressed air network (install oil separators).
- Only components that can also be operated with unlubricated air should be installed.
- Once a system has been operated with oil, it must continue to be operated with oil as the original lubrication of the components is flushed out over time.

### 3.6.4 Service unit combinations
The following must be noted when combining the individual components into a service unit:
- The size of the combined components is determined by the air flow rate ($m^3/h$). An excessive air flow rate results in a high pressure drop in the devices. The manufacturer's specifications must therefore be observed.
- The operating pressure must not exceed the value specified at the service unit. The ambient temperature should be no more than 50 °C (max. value for plastic bowls).

Figure 3.18: Service unit – manual on-off valve, filter regulator, lubricator

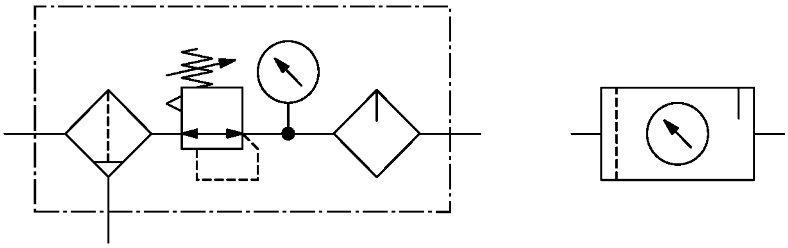


Figure 3.19: Service unit with lubricator – symbols; left: detailed representation; right: simplified representation

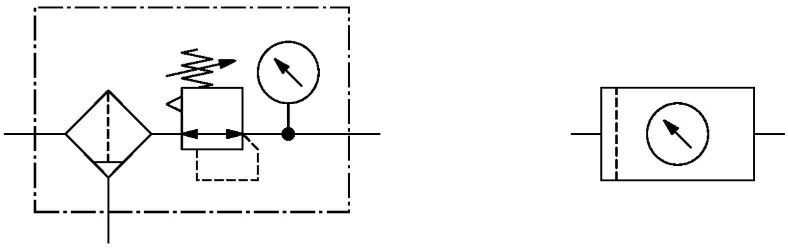


Figure 3.20: Service unit without lubricator – symbols; left: detailed representation; right: simplified representation

### Maintaining the service units

The following maintenance measures must be carried out regularly:

- Compressed air filter:
  The condensate level must be checked regularly as the level specified at the sight glass must not be exceeded. Exceeding the level can result in the collected condensate being sucked into the compressed air lines. The superfluous condensate can be drained via the drain cock at the sight glass. The filter cartridge must also be checked for dirt and if necessary cleaned or replaced.
- Pressure regulator:
  This needs no maintenance, provided there is an upstream compressed air filter.
- Lubricator:
  The level display must be checked at the sight glass here too and if necessary oil topped up. Only mineral oils may be used. Plastic filters and oil pans must not be cleaned with trichlorethylene.

# 4 Drives and output devices

A drive or operating element converts supply energy into work. The movement is controlled via the controller, the drive responds to the control signals via the control elements. Another type of output device are elements that indicate the status of the control system or the drives, for example a pneumatically actuated visual indicator.

Pneumatic operating elements can be divided into two groups, those with linear movements and those with rotary movements:

- Linear movement
  - Single-acting cylinder
  - Double-acting cylinder
- Rotary movement
  - Air motor
  - Rotary cylinder
  - Semi-rotary drive

## 4.1 Single-acting cylinders

Single-acting cylinders are pressurised from one side only and can only work in one direction. The return movement of the piston rod is effectuated by an integrated spring or application of external force. The spring force of the integrated spring is rated so that it returns the piston without load to its initial position with sufficient speed.

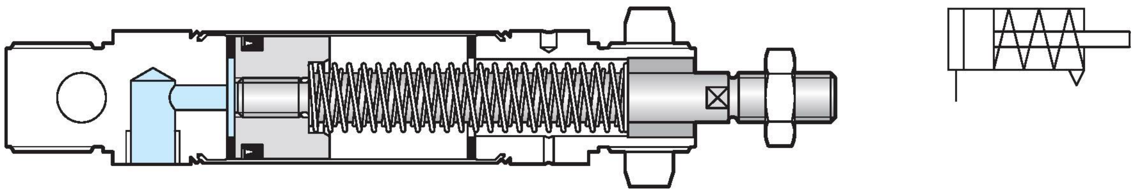


Figure 4.1: Single-acting cylinder – sectional view and symbol

With single-acting cylinders with integrated spring, the stroke is limited by the overall length of the spring. That is why single-acting cylinders have a stroke length of up to approx. 80 mm.

The design means that single-acting cylinders can carry out different movements relating to feeding, for example:

- Transferring
- Branching
- Merging
- Allocating
- Clamping
- Ejecting

### 4.1.1 Design
The single-acting cylinder has a simple piston seal on the air supply side. The seal is made of flexible material (perbunan) that is embedded in a metal or plastic piston to produce a seal. During movement, the sealing edges slide over the cylinder bearing surface. The different designs of single-acting cylinders include:
- Diaphragm cylinders
- Bellows cylinders

With the diaphragm cylinder, a built-in diaphragm made of rubber, plastic or even metal performs the task of the piston. The piston rod is mounted centrally on the diaphragm. There is no sliding seal, only friction caused by the expansion of the material.

Bellows cylinders function as a drive component by providing supply and exhaust functions. When bellows cylinders are supplied with permanent pressure, they act as a cushioning component. The design consists of two metal plates with a ribbed rubber bellows. There are no sealing components and no moving mechanical parts. Bellows cylinders are single-acting drives; the cylinder is returned through application of external force.

These cylinders are used in short-stroke applications for clamping, pressing and lifting.

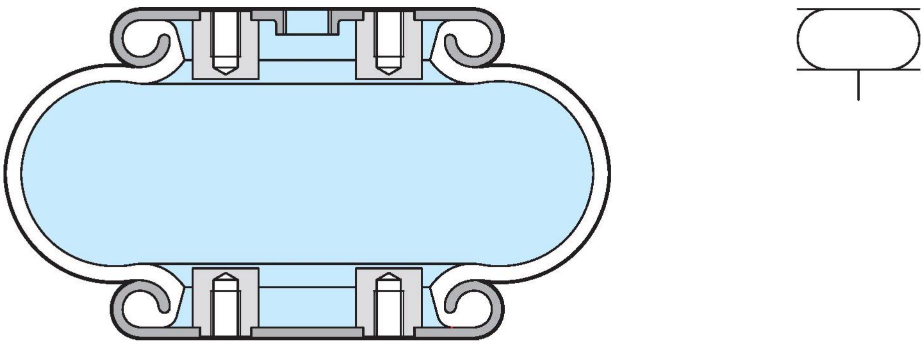


Figure 4.2: Diaphragm filter – sectional view and symbol

### 4.1.2 Fluidic muscle
The fluidic muscle is a membrane contraction system. An impervious and flexible tube is covered with tightly woven fibres in a diamond-shaped pattern. This results in a three-dimensional grid structure. The air flowing inwards deforms the grid structure; a tensile force is generated in axial direction which causes the muscle to contract due to increasing internal pressure.

The fluidic muscle develops up to ten times more force in stretched condition than a conventional pneumatic cylinder and uses only 40% of the energy while offering the same force. A third of the diameter is sufficient for the same force, while the stroke is shorter for the same overall length.

Figure 4.3: Fluidic muscle designs

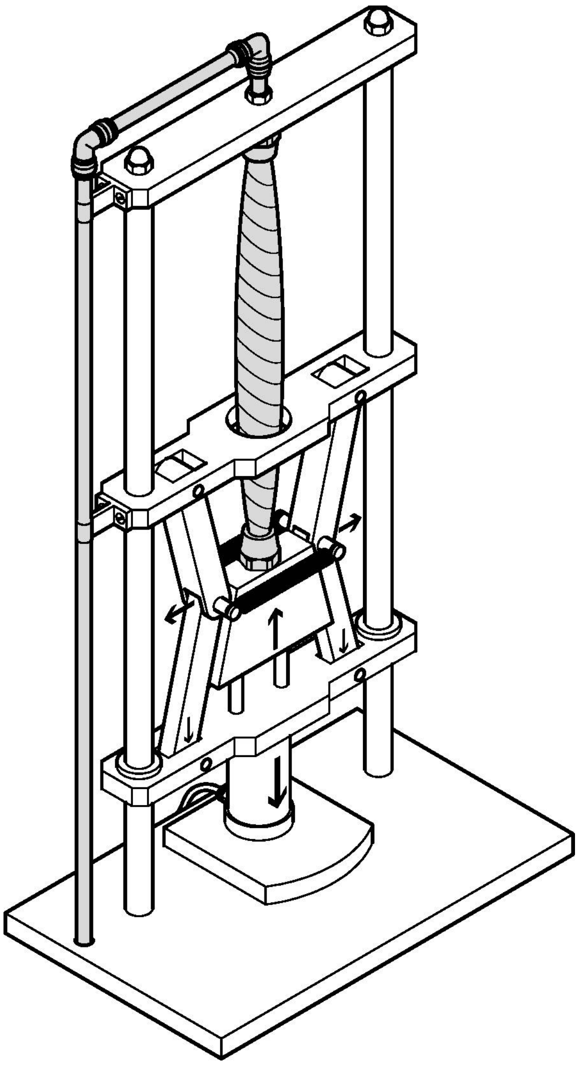


Figure 4.4: Sample application with fluidic muscle – press with double toggle lever system

## 4.2 Double-acting cylinders

The design is similar to that of the single-acting cylinder. However, there is no return spring and the two ports are used for supply and exhaust. The double-acting cylinder has the advantage that it can carry out work in both directions. It therefore has a wide range of applications. The force transferred to the piston rod is slightly greater for the forward stroke than for the return stroke as the pressurised area is greater on the piston side than on the piston rod side.

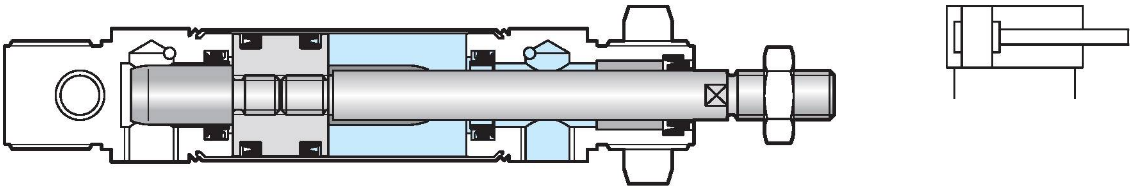


Figure 4.5: Double-acting cylinder – sectional view and symbol

### Development trends

Pneumatic cylinders have developed in the following directions:

- Contactless sensing – using magnets on the piston rod for reed switches
- Stopping heavy loads
- Rodless cylinders in confined spaces
- Other production materials like plastic
- Protective coating/casing against harmful environmental influences, for example resistance to acids
- Higher load capacity
- Robotic applications with special features such as non-rotating piston rods or hollow piston rods for vacuum suction cups

### 4.2.1 Cylinder with end-position cushioning

If a cylinder is moving heavy loads, cushioning in the end positions is used to avoid hard impacts and damage to the cylinder. Before the end position is reached, a cushioning piston interrupts the air's direct flow path into the open. Only a very small, often adjustable vent cross section remains open. The cylinder speed is progressively reduced during the last part of the stroke travel. Make sure that the adjusting screws are never completely tightened as the piston rod would not be able to reach the respective end position.

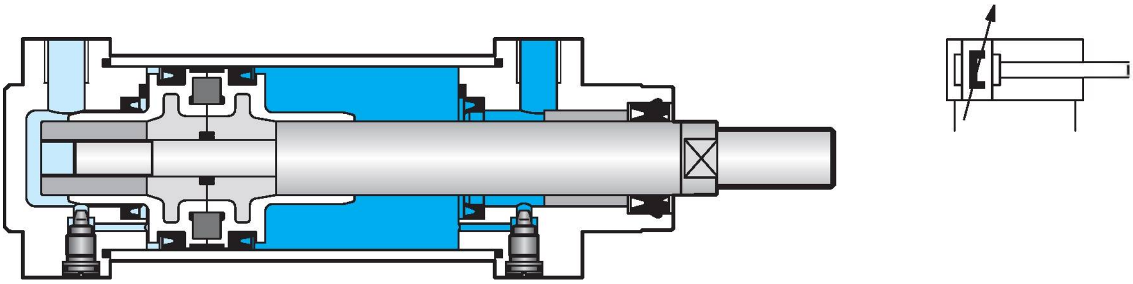


Figure 4.6: Double-acting cylinder with end-position cushioning – sectional view and symbol

Special precautions must be taken with very high forces and high acceleration. External shock absorbers can be attached to boost the deceleration effect.

The correct deceleration is achieved by:
- Tightening the adjusting screw.
- Gradually loosening the adjusting screw again until the required value is set.

### 4.2.2 Tandem cylinder
This design consists of two double-acting cylinders combined into one unit. With this construction and the common pressurisation of the two pistons the force on the piston rod is almost doubled. This type of cylinder is used wherever high force is needed and cylinder diameter is an issue.

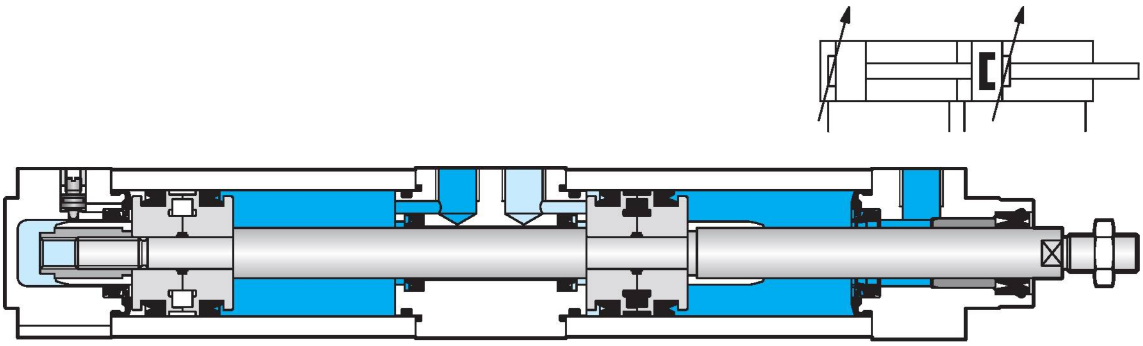


Figure 4.7: Tandem cylinder – sectional view and symbol

### 4.2.3 Cylinder with through piston rod

This cylinder has a piston rod on both sides. The piston rod is a through piston rod. Guidance of the piston rod is better as there are two bearing points. The force is identical in both directions of movement.

The through piston rod can be hollow. This means it can be used to feed through different media, for example compressed air. A vacuum connection is also possible.

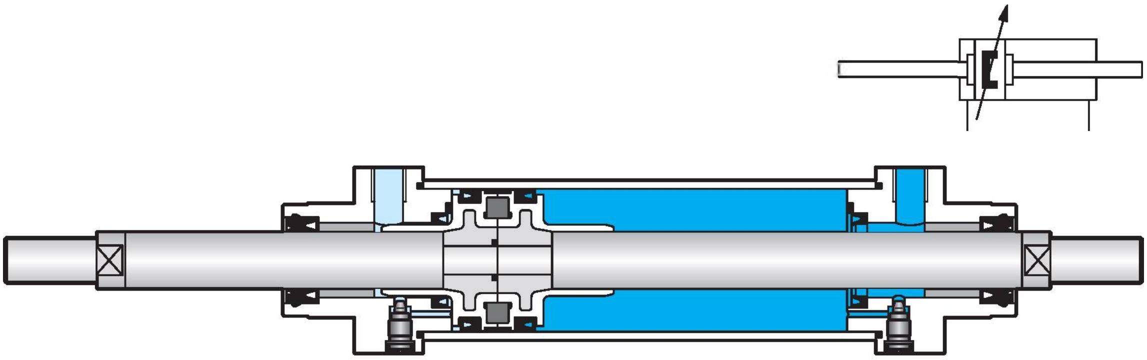


Figure 4.8: Cylinder with through piston rod – sectional view and symbol

### 4.2.4 Multi-position cylinder

The multi-position cylinder consists of two or more double-acting cylinders which are connected. The individual cylinders advance as pressure is applied. Two cylinders with different stroke lengths give four positions.

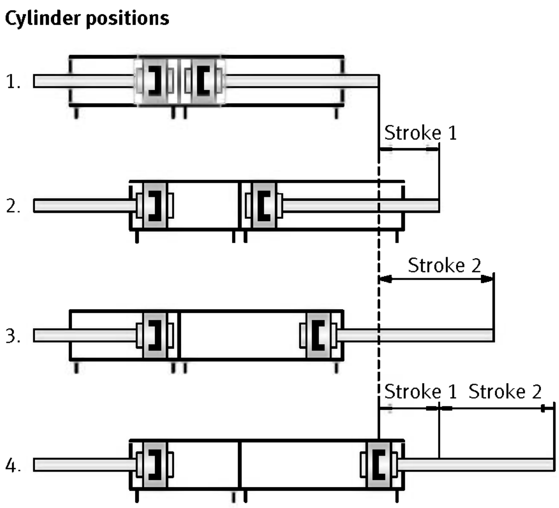
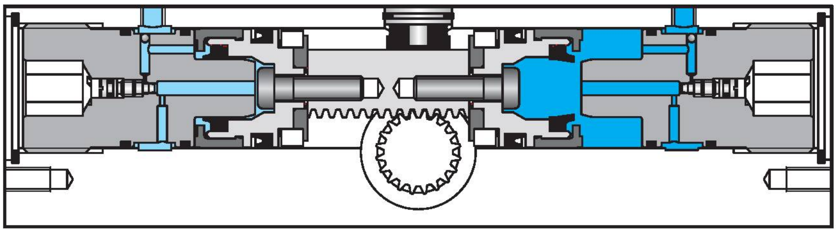



Figure 4.9: Multi-position cylinder

### 4.2.5 Rotary cylinder

With this type of double-acting cylinder, the piston rod has a toothed profile. The piston rod drives a gear wheel and a linear movement is translated into a rotary movement. The range of rotation varies from 45°, 90°, 180°, 270° to 360°. The torque is dependent on pressure, piston area and gear ratio; values up to approx. 150 Nm are possible.



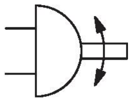
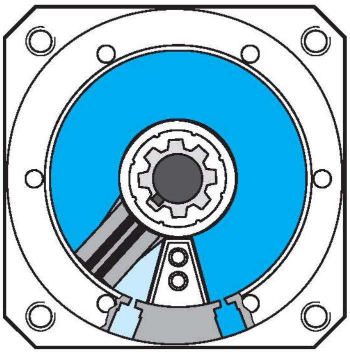


Figure 4.10: Rotary cylinder – sectional view and symbol

### 4.2.6 Semi-rotary drive

With the semi-rotary drive, force is transmitted directly to the drive shaft via the rotary vane. The swivel angle is infinitely adjustable from 0° to 180°. Torque should not exceed 10 Nm.



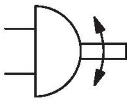


Figure 4.11: Semi-rotary drive – sectional view and symbol

Properties of semi-rotary drives:

- Small and sturdy
- Available with contactless sensors
- Adjustable rotation angle
- Easy to install

## 4.3 Rodless cylinders

Three different operational principles are used to construct rodless cylinders:

- Band or cable cylinder
- Sealing band cylinder with slotted cylinder barrel
- Cylinder with magnetically coupled slide

Rodless cylinders have a shorter installation length compared with conventional double-acting cylinders. There is no risk of the piston rod buckling and the movement can be guided across the entire stroke length. This cylinder design can be used for extremely long stroke lengths of up to 10 m. Devices, loads and other components can be attached directly to the mounting surface provided for this purpose on a slide or outer carriage. The force is identical in both directions of movement.

### 4.3.1 Band cylinder

With band cylinders, the piston force is transferred to a slide by a circulating band. When it emerges from the piston chamber, the band passes through a seal. The band is reversed in the end caps via guide rollers. Wiper seals make sure that no contaminants reach the guide rollers via the band.

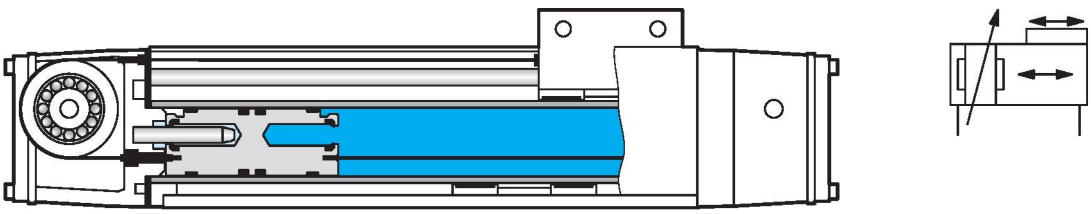


Figure 4.12: Band cylinder – sectional view and symbol

### 4.3.2 Sealing band cylinder

With this type of cylinder, the barrel has a slot along its entire length. Force is transmitted via a slide that is connected to the piston. The connection from the piston to the slide is guided to the outside through the slotted cylinder barrel. The slot is sealed by a steel strip that covers the inside of the slot. The strip is passed between the piston's seals and under the slide. A second strip covers the slot from the outside to prevent the ingress of dirt.

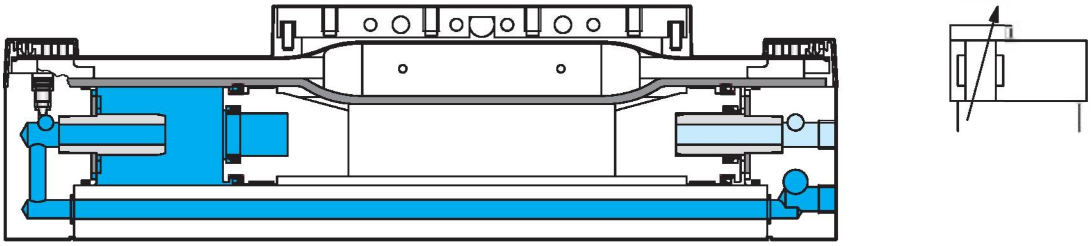


Figure 4.13: Sealing band cylinder – sectional view and symbol

### 4.3.3 Cylinder with magnetic coupling

This double-acting pneumatic linear drive consists of a cylinder barrel, a piston and a moving outer slide on the cylinder barrel. The piston and outer slide are equipped with permanent magnets. Movement is transferred from the piston to the outer slide via the magnetic coupling. As soon as the piston is pressurised, the slide moves synchronously with the piston. The cylinder chamber is hermetically sealed from the outer slide as there is no mechanical connection. There is no leakage loss.

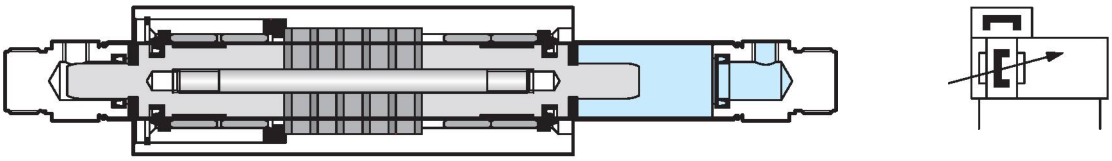


Figure 4.14: Cylinder with magnetic coupling – sectional view and symbol

## 4.4 Handling technology

Handling and assembly applications often require components that can carry out movements in two or three directions. Custom designs were most often used in these situations. Today, standard handling modules that can be combined as appropriate to the application are increasingly used. The modular concept has the following advantages:

- Easy to mount
- Specially adapted drives and mechanical guides
- Integrated energy supply line, for example for grippers or suction cups

### 4.4.1 Swivel/linear drive unit

The swivel/linear drive unit can, for example, be used to reposition workpieces. The bearing of the piston rod is designed so that it can absorb high lateral loads. The unit can be mounted in different ways, for example via a flange on the front or via slot nuts inserted into the linear profile. If necessary, the energy for the gripper or the suction cup is supplied through the hollow piston rod.

Figure 4.15: Swivel/linear drive unit (Festo)

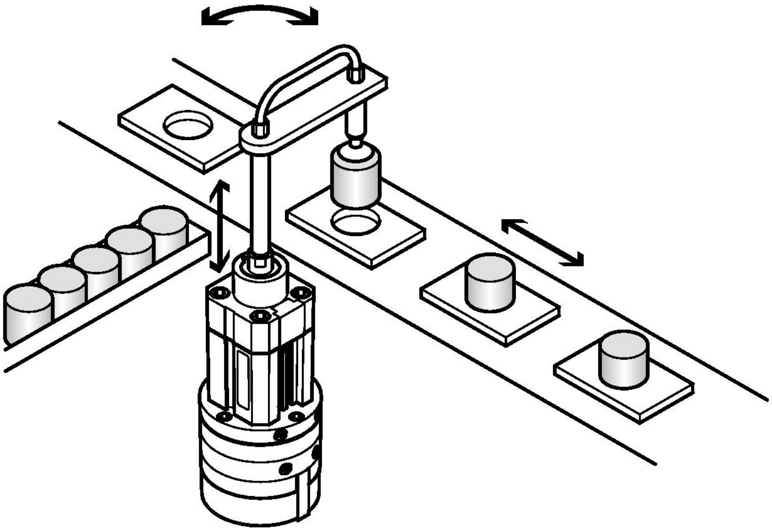


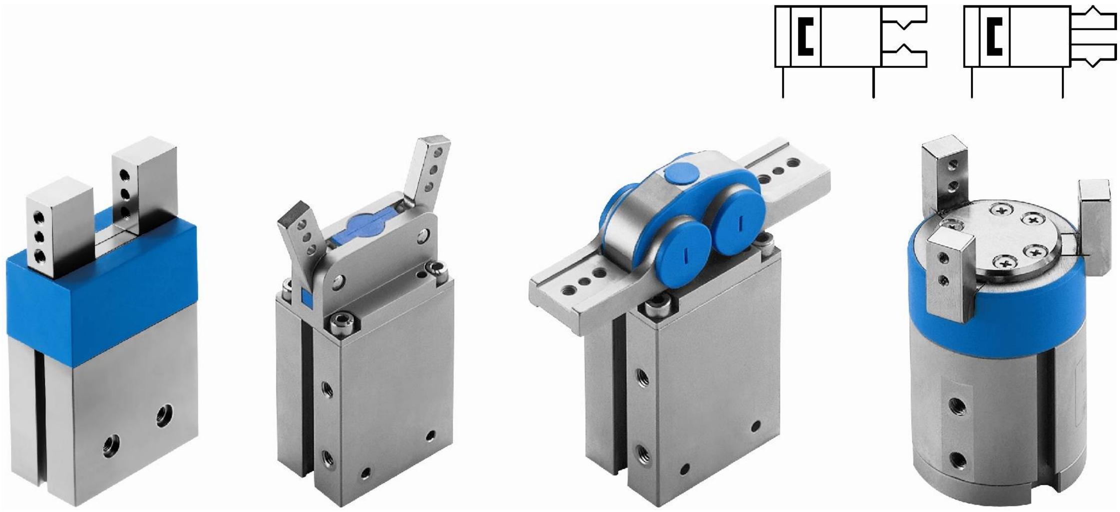
Figure 4.16: Sample application: repositioning workpieces

### 4.4.2 Pneumatic grippers

Handling units must have grippers that can grip, move and release a workpiece. Grippers either establish a force-locking or positive-locking connection with the part.

Figure 4.17 shows different gripper types. All gripper types have a double-acting piston drive and are self-centring. Contactless position sensing is possible via proximity sensors. Thanks to external gripper fingers, the grippers can be used for a variety of applications.

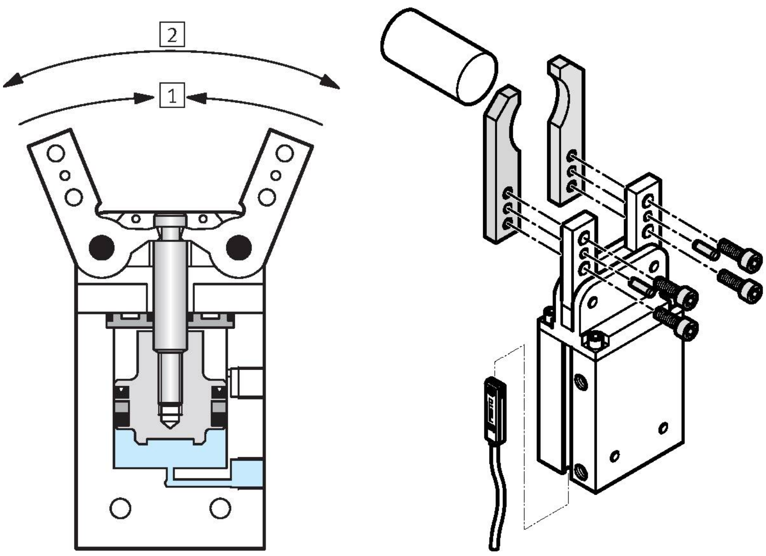


Parallel gripper, angle gripper, radial gripper, three-point gripper

Figure 4.17: Pneumatic grippers – symbols and photos

Figure 4.18 shows a sectional view of an angle gripper. It is driven by a double-acting cylinder. It clearly shows how gripper jaws (here: for cylindrical workpieces) and proximity sensors are attached to the gripper.

The choice of gripper type, size and jaw depends on the shape and weight of the workpieces.




1: Open; 2: Closed

Figure 4.18: Angle gripper – sectional view, gripper jaw and proximity sensor

### 4.4.3 Suction cups

Suction cups are generally a simple, cost-effective and operationally safe handling solution.

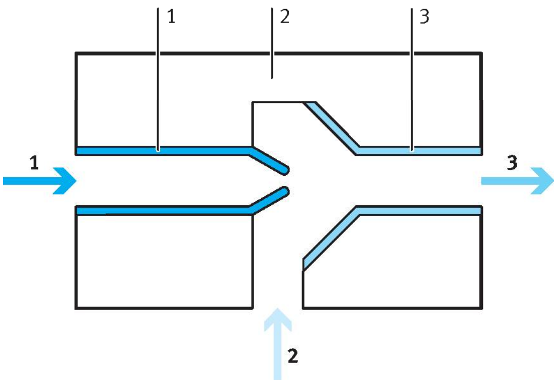
Suction cups enable different workpieces with weights ranging from just a few grams to several hundred kilograms to be handled. They come in different shapes, such as universal, flat or bellows suction cups.

Flat suction cups, bellows suction cups

Figure 4.19: Suction cups

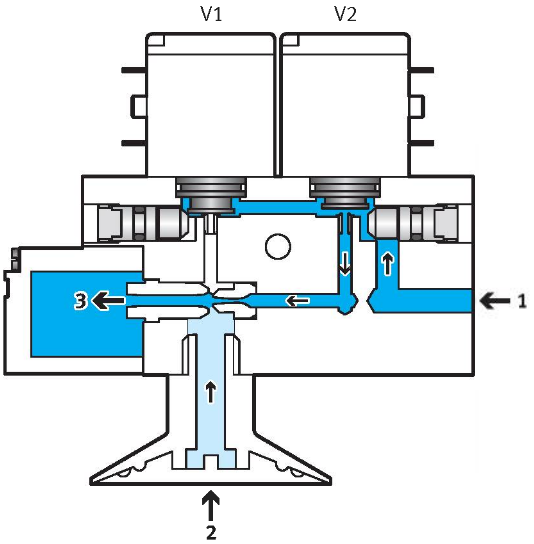
### 4.4.4 Vacuum generators

Figure 4.20 illustrates the principle of vacuum generation using ejectors. The compressed air flows through a jet nozzle where it is accelerated to high speed. Behind the jet nozzle a pressure builds up that is less than the ambient pressure. As a result air is sucked in from port U, so that here too a vacuum is created. The vacuum suction cup is connected at port U.

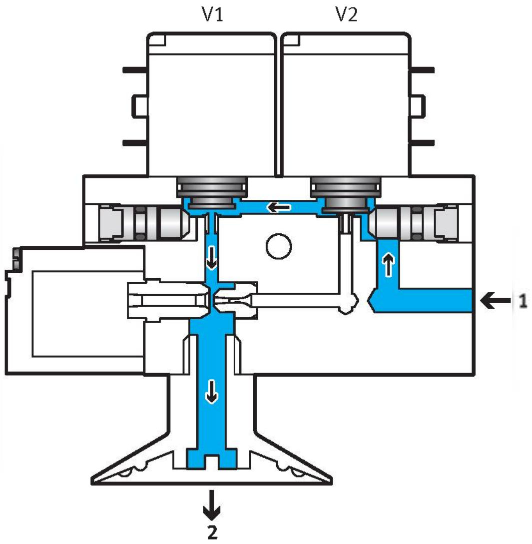



1: Jet nozzle; 2: Basic body; 3: Receiver nozzle

Figure 4.20: How an electropneumatic vacuum generator works – ejector principle




"Suction" operation




"Ejecting" operation condition

Figure 4.21: How an electropneumatic vacuum generator works

Figure 4.21 shows how a vacuum generator based on the ejector principle works. The picture on the left shows the "suction" operation. The solenoid actuated 2/2-way valve 1 is open. The compressed air flows from port 1 through the jet nozzle to silencer 3. This generates a vacuum at suction cup 2 and the workpiece is picked up.

The picture on the right shows the "ejecting" operation. Directional control valve 2 is opened and the compressed air is fed directly to the suction cup. The picked-up parts are ejected quickly from the suction cup by an ejector pulse from port 1 via valve 2.

## 4.5 Cylinder properties

The performance characteristics of cylinders can be calculated theoretically or with the help of the manufacturer's data. Both methods are possible; however the manufacturer's data is generally more relevant for a specific version and application.

### 4.5.1 Piston force

The piston force exerted by an operating element is dependent on the air pressure, the cylinder diameter and the frictional resistance of the sealing elements. The theoretical piston force is calculated using the following formula:

$$F_{\mathrm{th}} = A \cdot p$$

$F_{\mathrm{th}}$ Theoretical piston force (N)
$A$ Usable piston area ($m^2$)
$p$ Working pressure (Pa)

In practice it is the effective piston force that is important. When calculating it, the frictional resistance must be taken into consideration. Under normal operating conditions (pressure range: 400 to 800 kPa/4 to 8 bar), the friction forces can be assumed as being approx. 10% of the theoretical piston force.

**Single-acting cylinders**

$$\mathrm{F}_{\mathrm{eff}} = (A \cdot p) - (F_R + F_F)$$

**Double-acting cylinders**

$$\text{Forward stroke: } \mathrm{F}_{\mathrm{eff}} = A \cdot p - F_R$$

$$\text{Return stroke: } \mathrm{F}_{\mathrm{eff}} = A' \cdot p - F_R$$

$F_{\mathrm{eff}}$ Effective piston force (N)
$A$ Usable piston area ($m^2$) = $\frac{D^2 \cdot \pi}{4}$
$A'$ Usable piston ring area ($m^2$) = $(D^2 - d^2) \cdot \frac{\pi}{4}$
$p$ Working pressure (Pa)
$F_{\mathrm{R}}$ Friction force (approx. 10% of $F_{th}$) (N)
$F_{\mathrm{F}}$ Return spring force (N)
$D$ Cylinder diameter (m)
$d$ Piston rod diameter (m)

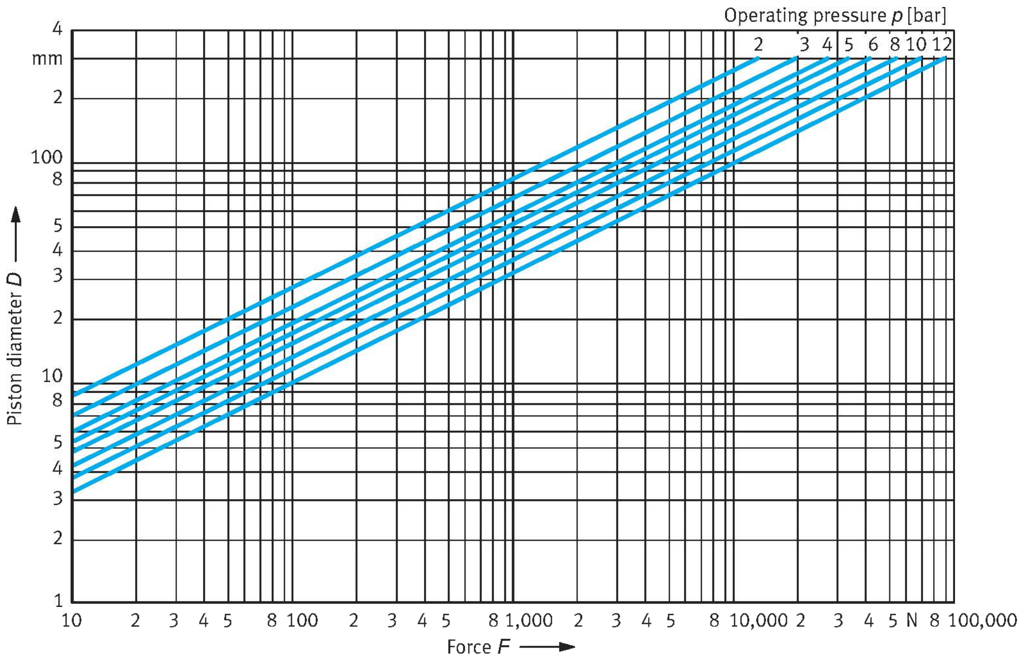



Figure 4.22: Pressure/force graph

## 4.5.2 Stroke length

The stroke length of pneumatic cylinders should not be greater than 2 m; with rodless cylinders it should not exceed 10 m. A longer stroke results in too large a mechanical load on the piston rod and the guide bearings. To avoid buckling of the piston rod in the case of longer stroke lengths, the buckling stress graph should be observed.

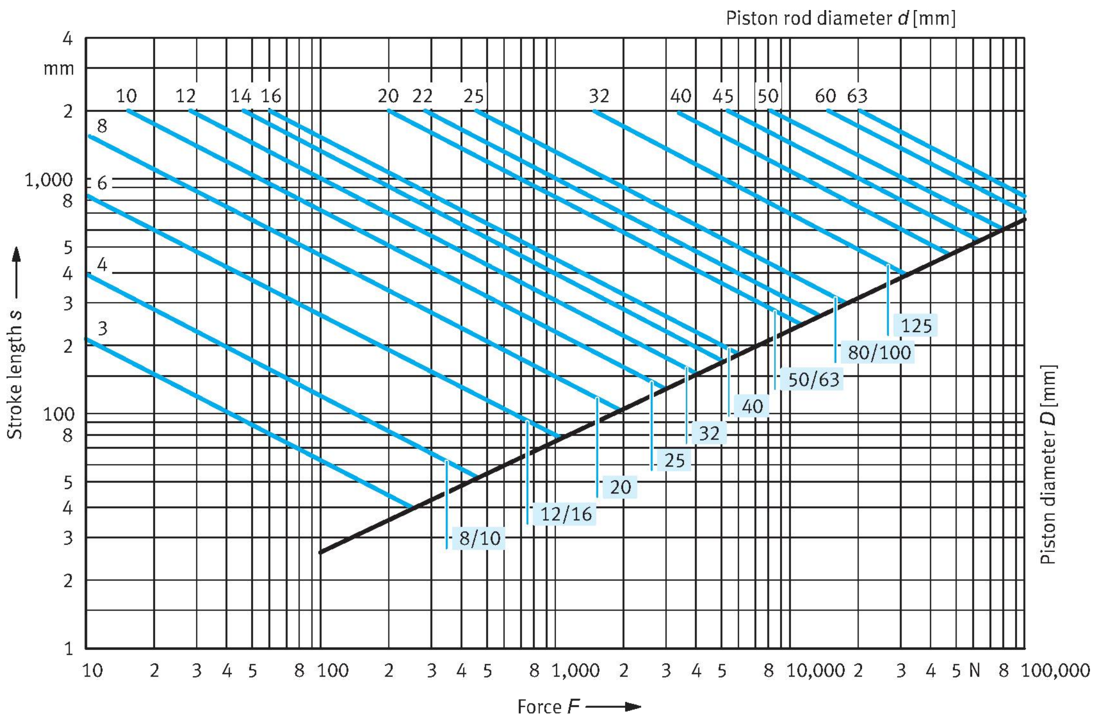



Figure 4.23: Buckling stress graph

### 4.5.3 Piston speed

The piston speed of pneumatic cylinders is dependent on the counteracting force, the prevailing air pressure, the tube length, the tube cross section between the control element and the operating element as well as the flow rate through the control component. Furthermore, the speed is influenced by end-position cushioning.

The average piston speed of standard cylinders is approx. 0.1 to 1.5 m/s. Speeds of up to 10 m/s are achieved with special cylinders (impact cylinder). The piston speed can be reduced using one-way flow control valves and it can be increased using quick exhaust valves.

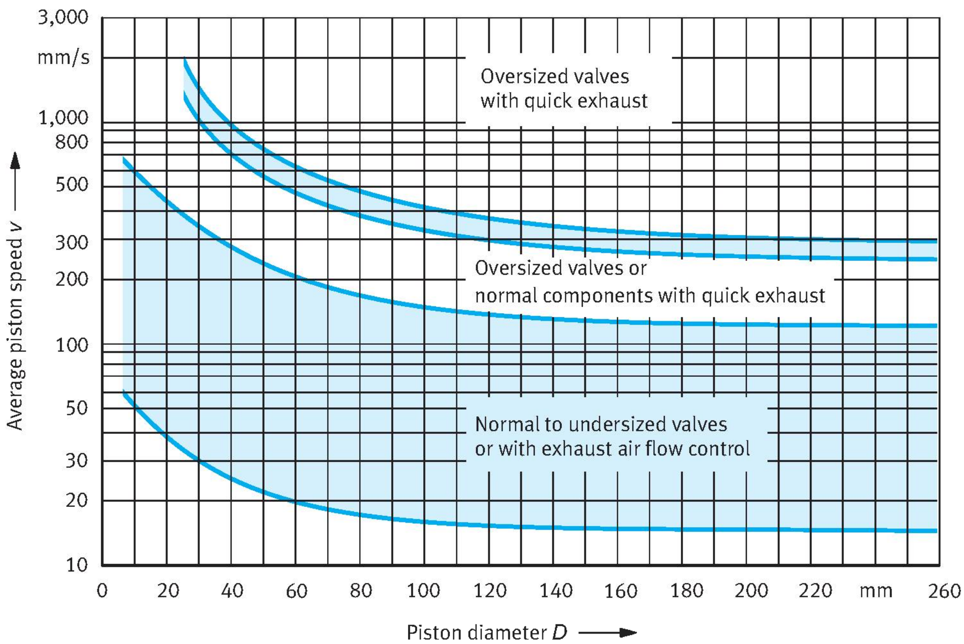



Figure 4.24: Average piston speed of a piston without load

### 4.5.4 Air consumption

It is important to know the air consumption of the system in order to generate air or calculate energy costs. The air consumption is specified in litres of air per minute. With specific values for working pressure, piston diameter, stroke and number of strokes per minute, the air consumption is calculated as follows:

$$\text{Air consumption} = \text{compression ratio} \times \text{piston area} \times \text{stroke} \times \text{strokes per minute}$$

$$\text{Compression ratio} = \frac{101.3 + \text{working pressure (in kPa)}}{101.3}$$

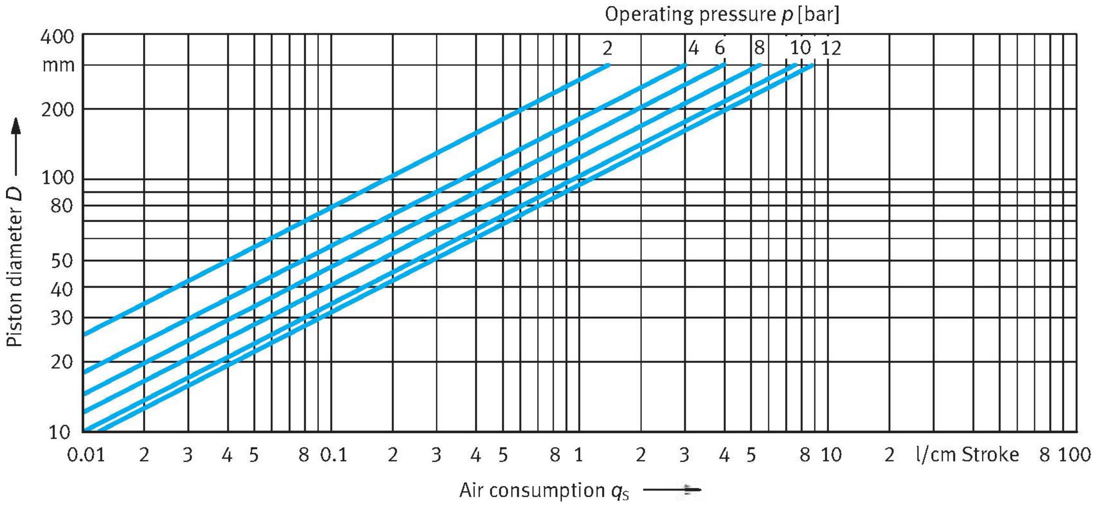



Figure 4.25: Air consumption graph

The formulae for calculating the air consumption according to the air consumption graph are:

**For single-acting cylinders**

$$q_B = s \cdot n \cdot q_S$$

**For double-acting cylinders**

$$q_B = 2 \cdot s \cdot n \cdot q_S$$

| | |
|---|---|
| $q_B$ | Air consumption (l/min) |
| $s$ | Stroke (cm) |
| $n$ | Number of strokes per minute (1/min) |
| $q_S$ | Air consumption per cm of stroke (l/cm) |

These formulae do not take into consideration the different air consumption of double-acting cylinders during the forward stroke and return stroke. It can be disregarded due to different tolerances in tubing and valves.

The total air consumption of a cylinder also includes filling dead spaces. The air consumption for filling the dead spaces can be as much as 20% of the working air consumption. Dead spaces in a cylinder are compressed air supply lines in the cylinder itself and spaces in the piston's end positions that cannot be used for the stroke.

| Piston diameter in mm | Cover side in $cm^3$ | Base side in $cm^3$ | Piston diameter in mm | Cover side in $cm^3$ | Base side in $cm^3$ |
|---|---|---|---|---|---|
| 12 | 1 | 0.5 | 70 | 27 | 31 |
| 16 | 1 | 1.2 | 100 | 80 | 88 |
| 25 | 5 | 6 | 140 | 128 | 150 |
| 35 | 10 | 13 | 200 | 425 | 448 |
| 50 | 16 | 19 | 250 | 2,005 | 2,337 |

Table 4.1: Dead spaces in cylinders (1,000 $cm^3$ = 1 l)

### 4.6 Motors

Devices that transform pneumatic energy into mechanical rotary movement that can also be continuous are called compressed air motors. The compressed air motor is one of the most frequently used elements in the assembly area. Compressed air motors are broken down according to their structure into:

- Piston motors
- Vane motors
- Geared motors
- Turbine motors (flow motors)

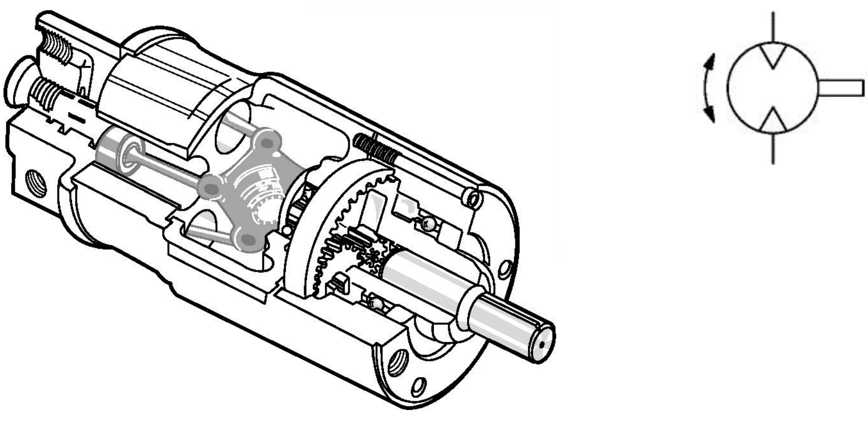


Figure 4.26: Air motor

Properties of compressed air motors:

- Infinite regulation of speed and torque
- Wide choice of speeds
- Compact design (weight)
- Overload-proof
- Insensitive to dust, water, heat, cold
- Explosion-proof
- Low maintenance
- Direction of rotation can be easily reversed

### 4.6.1 Piston motors

This design can be further divided into radial and axial piston motors. The compressed air drives the crank shaft of the motor via a connecting rod through the reciprocating motion of the piston. Several cylinders are required to guarantee jerk-free operation. The performance of the motors is dependent on the supply pressure, the number of pistons, the piston area and the stroke and piston speed.

The mode of operation of the axial piston motors is similar to that of the radial piston motors. The force in five axially arranged cylinders, the force is converted to a rotary movement via a swash plate. Two pistons are pressurised simultaneously so that a balanced torque produces the smooth operation of the motor.

These compressed air motors are available in clockwise and anticlockwise versions. The maximum speed is approx. 5,000 rpm; the performance range with normal pressure is between 1.5 and 19 kW (2 and 25 hp).

### 4.6.2 Vane motors

The simple design and low weight mean that compressed air motors are usually designed as rotary machines with vanes.

A rotor with slots is eccentrically mounted in a cylindrical chamber. Vanes are inserted into the slots in the rotor and are pressed outwards against the inner wall of the cylinder by the centrifugal force. In other designs, springs are used to press the vanes against the inner wall of the cylinder. This seals the individual chambers.

The rotor speed is between 3,000 and 8,500 rpm. Clockwise and anticlockwise units are also available, while performance ranges from 0.1 to 17 kW (0.14 to 24 hp).

### 4.6.3 Geared motors

With this design, the torque is generated by pushing the air against the tooth profile of two meshed gears. One of the gears is permanently connected to the motor shaft. Geared motors are manufactured with spur or helical gearing. These geared motors can be used as high-performance drive machines (up to approx. 44 kW/60 hp). With these motors the direction of rotation can also be reversed.

### 4.6.4 Turbine motors (flow motors)

Turbine motors can only be used for low performance rates. The speed range, however, is very high (a pneumatic drill at the dentist's operates at 500,000 rpm). Its mode of operation is the reverse of the flow compressor principle.

# 5 Directional control valves

## 5.1 Applications

Directional control valves control the path of compressed air. The direction of flow is indicated by an arrow. They can be actuated manually, mechanically, pneumatically or electrically. The main applications of directional control valves include:

- Connecting or shutting off the compressed air supply
- Retracting and advancing pneumatic drives

### 5.1.1 Solenoid valves

An electropneumatic control system works with two different energy media:

- With electrical energy in the signal control section
- With compressed air in the power section

The solenoid actuated directional control valves or solenoid valves form the interface between the two parts of an electropneumatic control system. They are switched by means of the output signals from the signal control section and shut off or open connections in the pneumatic power section.

### 5.1.2 Actuating a single-acting cylinder

Figure 5.1 shows a directional control valve that controls the movement of a single-acting cylinder. It has three ports and two switching positions.

- When the directional control valve is in its initial position, the cylinder chamber is exhausted via the directional control valve. The piston rod is retracted.
- When the directional control valve is actuated, the cylinder chamber is pressurised. The piston rod advances.
- When the directional control valve returns, the cylinder chamber is exhausted and the piston rod retracts.

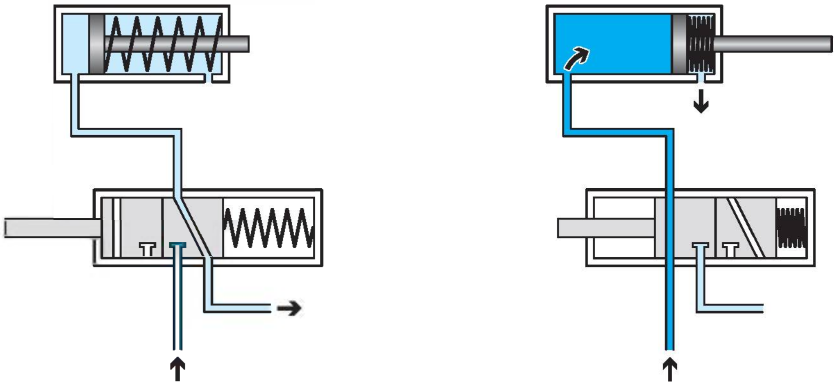


Figure 5.1: Actuating a single-acting cylinder

### 5.1.3 Actuating a double-acting cylinder

The double-acting cylinder is actuated by a directional control valve with five ports and two switching positions.

- When the directional control valve is in its initial position, the left cylinder chamber is exhausted and the right cylinder chamber is pressurised. The piston rod is retracted.
- When the directional control valve is actuated, the left cylinder chamber is pressurised and the right cylinder chamber is exhausted. The piston rod advances.
- When the directional control valve returns, the piston rod retracts.

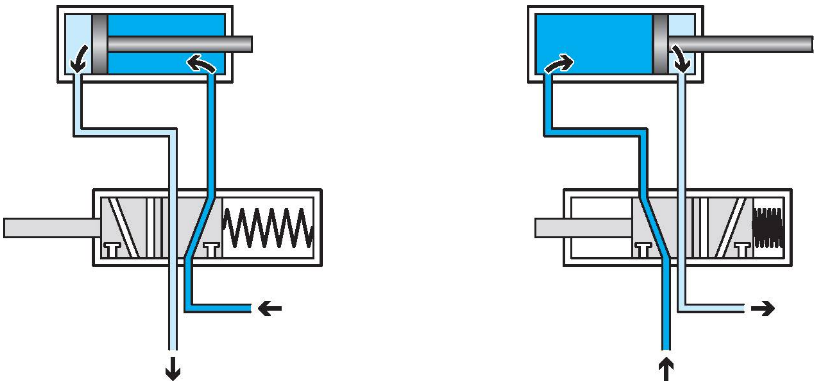


Figure 5.2: Actuating a double-acting cylinder

## 5.2 Design

Directional control valves can be divided into two groups:

- Valves with spring return only hold the actuated switching position as long as they are actuated.
- Bistable valves hold the mostly recently assumed switching position even if they are no longer being actuated.

Other distinguishing features are the number of valve ports and the number of switching positions. The valve designation is determined by the actuation method as well as the number of ports and switching positions, for example

- 3/2-way pneumatic valve with spring return
- 5/2-way double solenoid valve

The design principle of a directional control valve is also an important factor for the service life, switching time, actuation method, connection method and size. These are the different design types of directional control valves:

- Poppet valves
  - Ball poppet valves
  - Disc poppet valves
- Slide valves
  - Longitudinal slide valves (piston valves)
  - Longitudinal flat slide valves
  - Flat slide valves

### 5.2.1 Poppet valves

With poppet valves, the connections are opened or closed using balls, discs, flat slides or cones. The valve seats are generally sealed using rubber seals. Poppet valves have very few wearing parts and therefore have a long service life. They are insensitive to dirt and hard-wearing. The required actuating force is, however, relatively high since the force of the integrated return spring and the air pressure must be overcome.

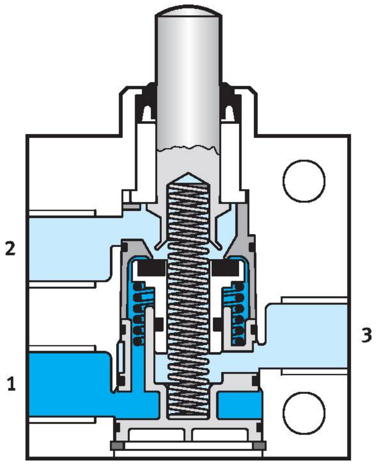



Figure 5.3: 3/2-way valve, mechanically actuated (stem), disc seat

### 5.2.2 Slide valves

With slide valves, the individual ports are connected or closed by means of longitudinal slides, longitudinal flat slides or flat slides.

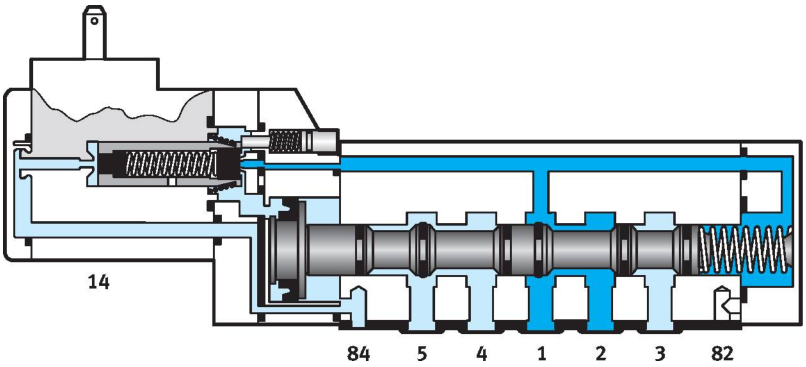



Figure 5.4: 5/2-way solenoid valve, solenoid actuated (coil), longitudinal slide (piston)

### 5.2.3 Pneumatic performance data

Directional control valves are manufactured in numerous variants and sizes to meet the different requirements of industrial applications.

A step-by-step approach is advisable when selecting a suitable valve.

1. First, the valve type is determined based on the performance requirements and required behaviour in the event of power failure (e.g. 5/2-way valve with spring return).
2. Next, the valve that meets the specified requirements with the lowest possible overall costs is determined based on the performance data listed in the manufacturers' catalogues. Not only the costs of the valve, but also the costs for installation, maintenance, storing spare parts, etc. must be taken into consideration.

Table 5.1 and Table 5.2 summarise the most frequently used valve types, their symbols and their applications.

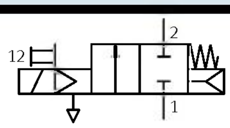
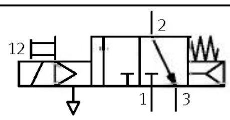
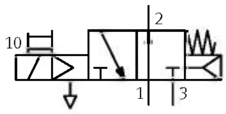
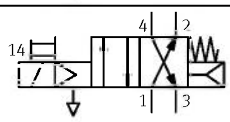
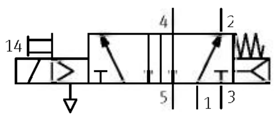
| Valve type | Symbol | Applications |
|---|---|---|
| Piloted 2/2-way valve with spring return |  | Shut-off function |
| Piloted 3/2-way valve with spring return (normally closed)<br><br>Piloted 3/2-way valve with spring return (normally open) | <br> | Single-acting cylinders<br><br>Switching the compressed air on and off |
| Piloted 4/2-way valve with spring return<br><br>Piloted 5/2-way valve with spring return | <br> | Double-acting linear or swivel cylinder |

Table 5.1: Applications and symbols for solenoid actuated directional control valves with spring return

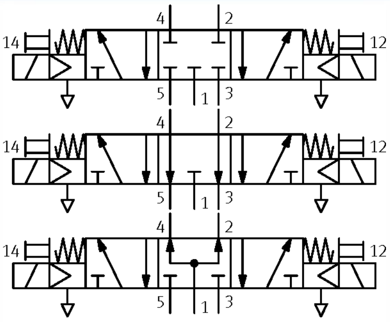
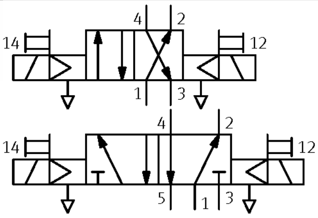
| Valve type | Symbol | Applications |
|---|---|---|
| Piloted 5/3-way solenoid valve with spring return (normally closed, exhausted or pressurised) |  | Double-acting linear or swivel cylinder with intermediate stop/with special requirements for the response in the event of a power failure |
| Piloted 4/2-way double solenoid valve<br><br>Piloted 5/2-way double solenoid valve |  | Double-acting linear or swivel cylinder |

Table 5.2: Applications and symbols for solenoid actuated directional control valves with spring return and solenoid actuated double solenoid valves

Table 5.3 summarises the pneumatic performance data and operating conditions of three 5/2-way directional control valves.

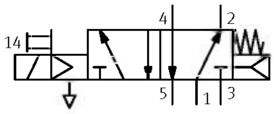
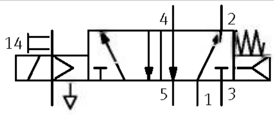
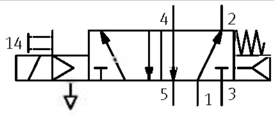
| | | | |
|---|---|---|---|
| **Valve type** | Piloted 5/2-way valve with spring return | Piloted 5/2-way valve with spring return and auxiliary pilot air | Piloted 5/2-way valve with spring return |
| **Port layout** | Sub-base valve | Sub-base valve with auxiliary pilot air | Individual valve |
| **Symbol** |  |  |  |
| **Nominal size** | 4.0 mm | 4.0 mm | 14.0 mm |
| **Nominal flow rate** | 500 l/min | 500 l/min | 2,000 l/min |
| **Pressure range** | 250 - 800 kPa | 90 - 800 kPa<br>(auxiliary pilot air: 250 - 800 kPa) | 250 - 1,000 kPa |
| **Switching times (on/off)** | 20/30 ms | 20/30 ms | 30/55 ms |

Table 5.3: Pneumatic performance data for solenoid actuated directional control valves (Festo)

### 5.2.4 Actuation methods for directional control valves

The actuation method of the directional control valves depends on the system requirements. They can include:

- Manually operated
- Mechanically actuated
- Pneumatically actuated
- Solenoid actuated
- Combinations of these

A complete representation of a directional control valve in the pneumatic circuit diagram includes

- Basic actuation method of the valve
- Reset method
- Pilot control (if present)
- Additional actuation options (e.g. manual override, if present)

Each actuation symbol is drawn on the side of the switching positions that corresponds to its direction of action.

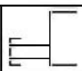
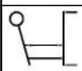
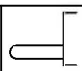
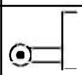
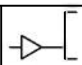
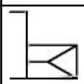
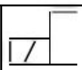
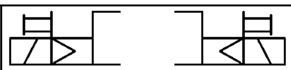
| Function | Symbol |
|---|---|
| **Manual operation** | |
| By pressing |  |
| By lever |  |
| **Mechanical operation** | |
| By stem |  |
| By roller |  |
| **Pneumatic operation** | |
| By compressed air |  |
| Pneumatic spring return |  |
| **Solenoid actuation** | |
| By solenoid coil |  |
| **Combined actuation** | |
| Piloted valve, electromagnetically actuated at both sides, manual override |  |
| **Mechanical components** | |
| Spring return |  |

Table 5.4: Actuation methods of directional control valves

### 5.3 2/2-way valves

The 2/2-way valve has two ports and two switching positions (open, closed). This valve does not have an exhaust function in the closed switching position (unlike the 3/2-way valve). The most frequent design is the ball seat.

The 2/2-way valve can be manually, mechanically or pneumatically actuated.

### 5.4 3/2-way valves

The 3/2-way valve can be used to set and reset signals. It has three ports and two switching positions.

The 3/2-way valve can be manually, mechanically, solenoid or pneumatically actuated. The actuation method is determined by the control requirements.

#### 5.4.1 3/2-way hand slide valve

This manually operated valve has a simple design. It is operated by sliding the grip sleeve (1) in longitudinal direction. This valve is used as an on-off valve, mainly for pressurising and exhausting control systems or parts of systems.

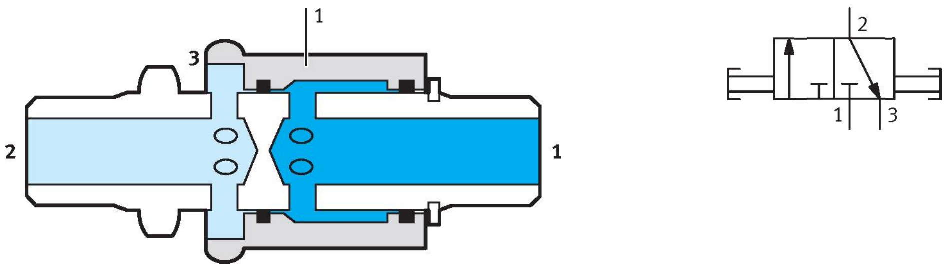



Figure 5.5: 3/2-way hand slide valve – sectional view and symbol

### 5.4.2 3/2-way stem actuated valve

The design of this mechanically operated valve is based on the disc seat principle. The seal is simple and effective. The response time is short. A small opening movement permits a large cross section for the air to flow through. Like the ball poppet valves, these valves are also insensitive to dirt and therefore have a long service life. 3/2-way valves are used for control systems with single-acting cylinders or for actuating control elements.

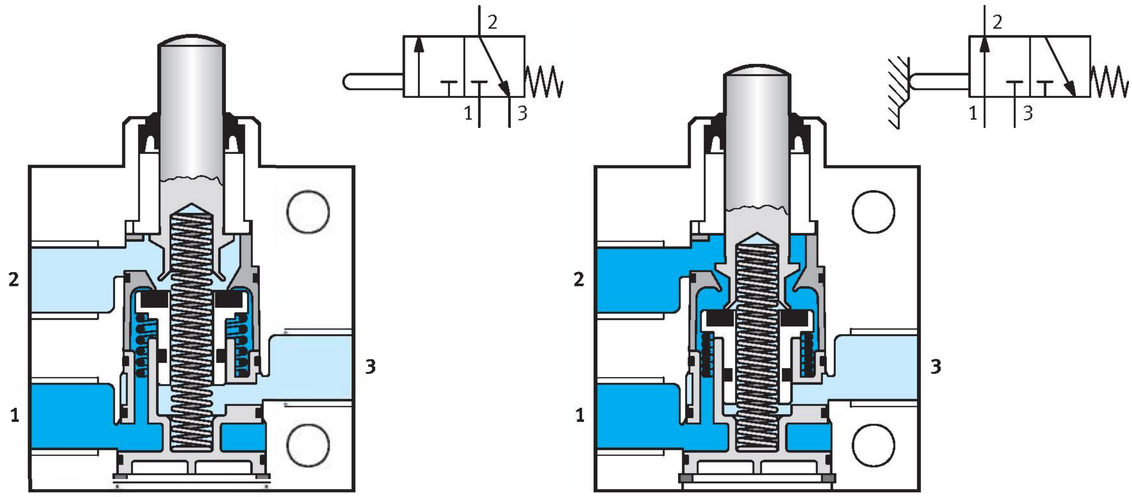



Figure 5.6: 3/2-way stem actuated valve, normally closed, disc seat; left: unactuated; right: actuated

In a valve with normally open position, port 1 to 2 is open in the normal position. The valve disc seat closes port 3. When the valve stem is actuated, supply port 1 is closed by the stem and the valve disc is lifted away from the seat. The exhaust air can then escape from 2 to 3. When the valve stem is no longer actuated, the return spring returns the valve stem and the valve disc to their initial position. The compressed air flows again from 1 to 2.

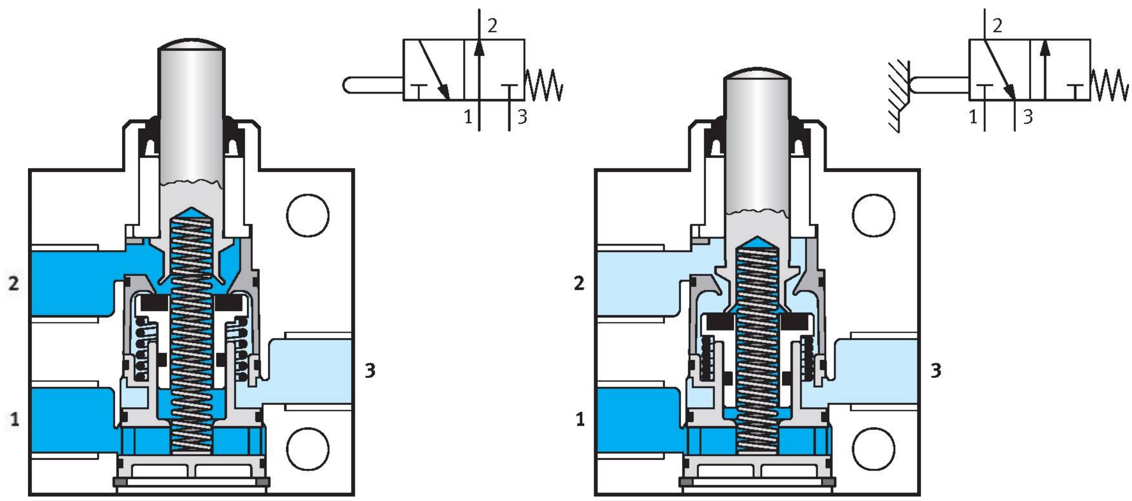



Figure 5.7: 3/2-way valve, normally open, disc seat; left: unactuated; right: actuated

### 5.4.3 3/2-way pneumatic valve

The 3/2-way pneumatic valve is actuated via a pneumatic signal at inlet port 12. Figure 5.8 shows a pneumatically actuated valve with spring return in closed position.

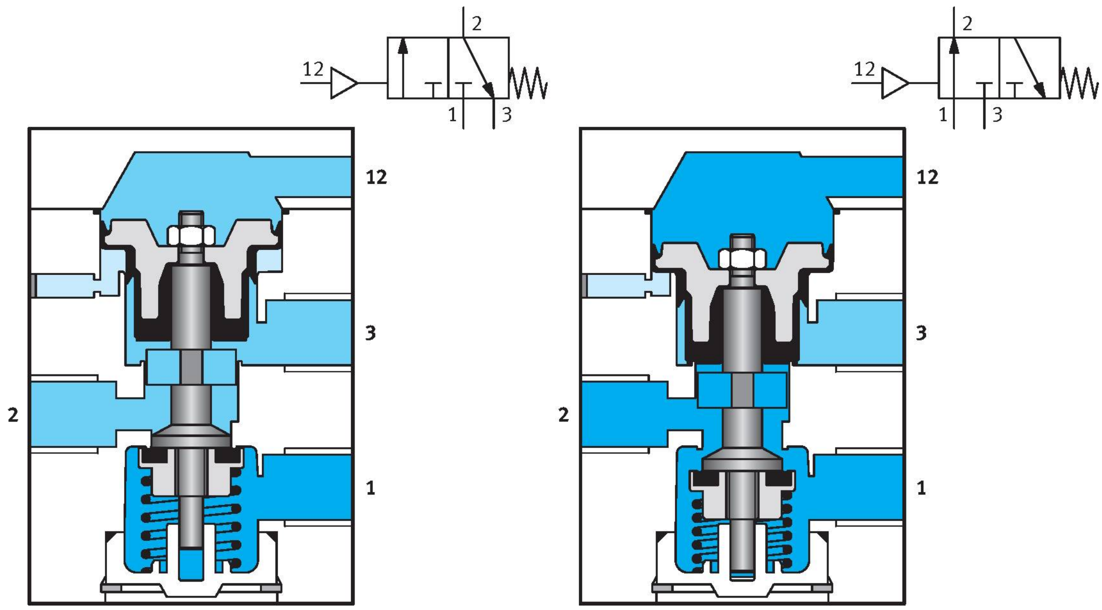
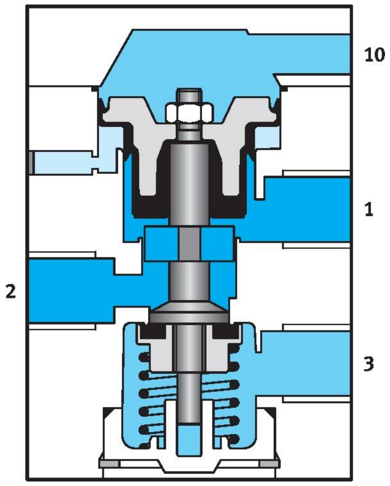



Figure 5.8: 3/2-way pneumatic valve, normally closed, pneumatically actuated, with spring return; left: unactuated; right: actuated

The valve stem is reversed against the return spring by pressurising the control piston at port 12. Ports 1 and 2 are connected. After pilot port 12 is exhausted, the control piston is returned to its initial position by the integrated spring. The disc closes off 1 from 2. The exhaust air from working line 2 can be exhausted via 3. The 3/2-way pneumatic valve with spring return can be used in closed position and open position.

A pneumatically actuated valve can be used as a control element for indirect actuation. The signal for advancing the cylinder 1A1 is triggered indirectly via the manually operated 3/2-way valve 1S1 that forwards the control signal to the control element 1V1.

For the open position, ports 1 and 3 simply have to be connected inversely to the closed position. The head of the valve with pilot port 12 can be rotated 180°. The pilot port is then designated 10.



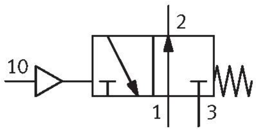




Figure 5.9: 3/2-way pneumatic valve, normally open, pneumatically actuated, with spring return, unactuated

### 5.4.4 3/2-way solenoid valve

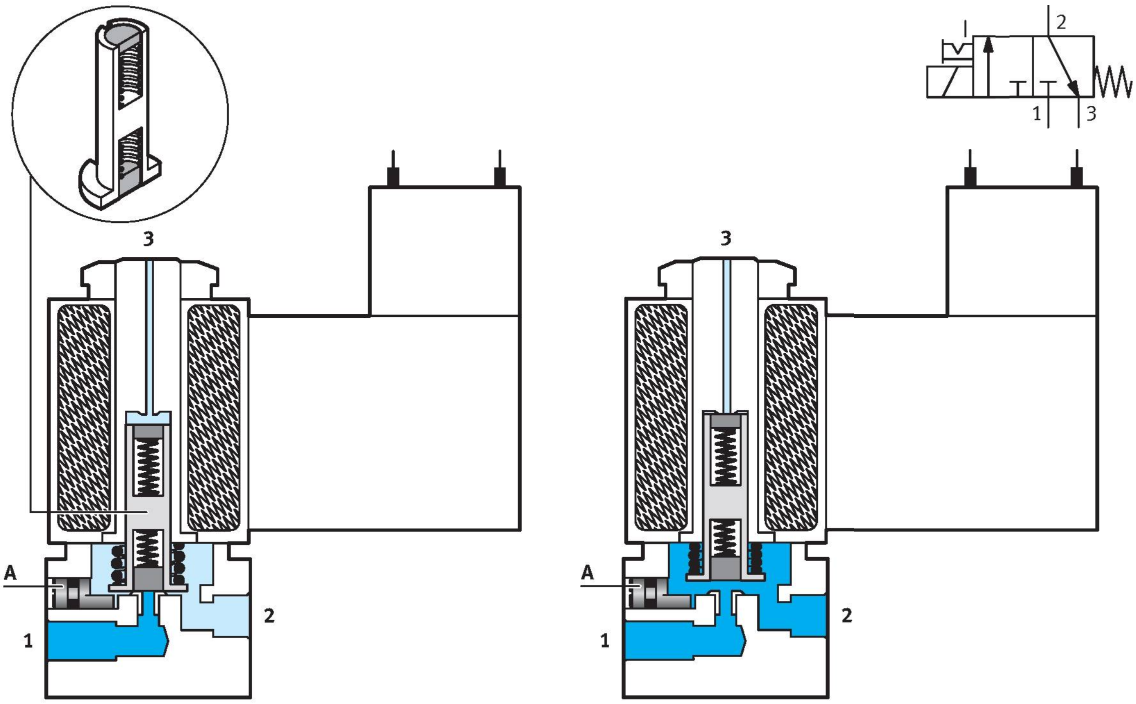
A: Manual override

Figure 5.10 shows two sectional views of a solenoid actuated 3/2-way valve.

- In the normal position, working port 2 is connected to exhaust port 3 by the groove in the armature (see close-up).
- When an electric current flows through the solenoid coil, the magnetic field exerts an upward force on the armature. The armature is lifted against the spring force. The lower sealing seat opens and the flow from pressure supply port 1 to working port 2 is opened. The upper sealing seat closes and shuts off the connection between port 1 and port 3.
- When the solenoid coil is de-energised, the spring force causes the armature to move back to its normal position. The connection between port 2 and port 3 is opened and the connection between port 1 and port 2 is closed. The compressed air escapes through the armature tube and port 3.

**Manual override**

Manual override A can be used to open the connection between port 1 and port 2 even if there is no current flowing through the coil of the solenoid. The screw is turned and the eccentric cam actuates the armature. The valve is returned to its normal position by turning the screw the other way.

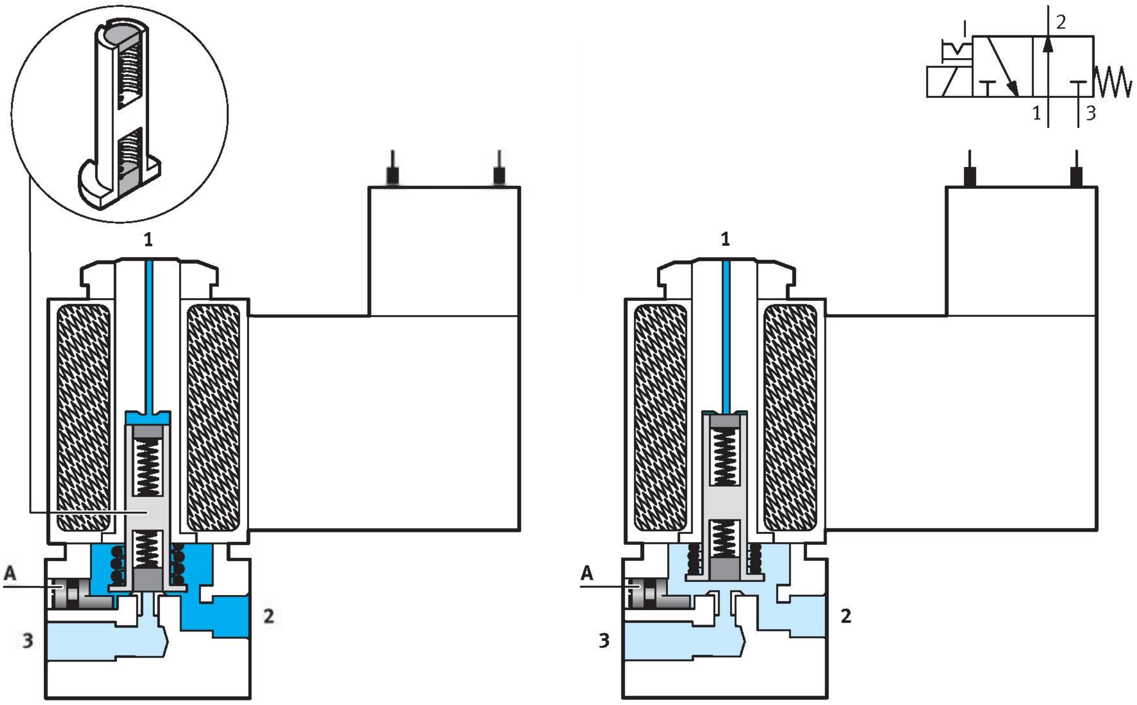



A: Manual override

Figure 5.10: 3/2-way solenoid valve with manual override, closed position

A: Manual override

Figure 5.11 shows a normally open, solenoid actuated 3/2-way valve. The picture on the left shows the valve in its normal position, while the picture on the right shows the valve in its actuated position. The pressure supply port and exhaust port are swapped compared with the normally closed valve (A: Manual override
Figure 5.10).




A: Manual override

Figure 5.11: 3/2-way solenoid valve with manual override, open position

## 5.5 Piloted directional control valves

### 5.5.1 How the pilot control stage works with manually and mechanically actuated directional control valves

With piloted directional control valves, the valve piston is indirectly actuated. Piloted valves require very little actuating force. A duct with a small diameter connects supply port 1 with the pilot valve. Once the pilot valve opens, the compressed air present flows to the diaphragm and moves the valve disc of the main valve downwards. When the pilot valve is closed, exhausting takes place along the guide bush of the stem. With directional control valves with spring return, the valve disc of the main valve is returned to its normal position by the return spring.

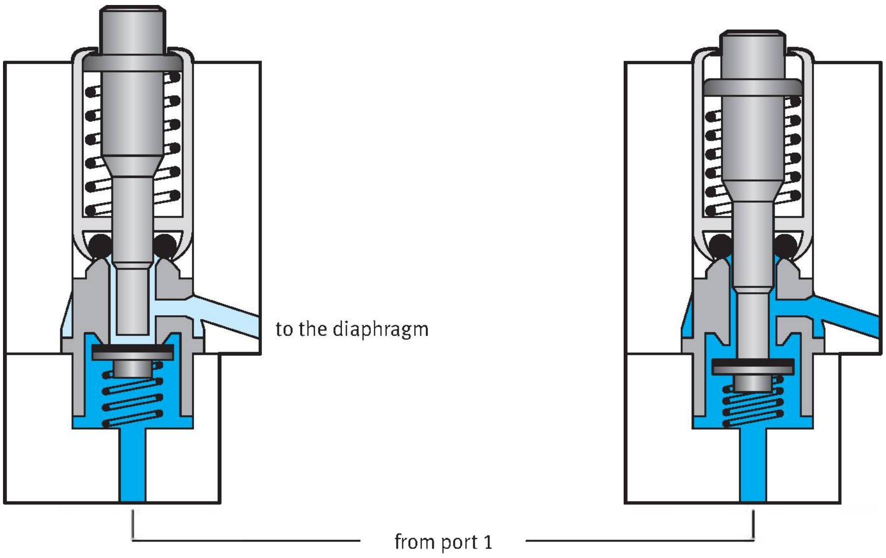



Figure 5.12: Pilot unit; left unactuated, right actuated

### 5.5.2 Piloted 3/2-way roller lever valve

When the roller lever is actuated, the pilot valve opens. The valve is switched in two phases: first port 2 to 3 is closed and then port 1 to 2 is opened. The valve is reset by releasing the roller lever.

This type of valve can either be used in closed or open position. You simply need to swap ports 1 and 3 and rotate the actuation setup by 180º.

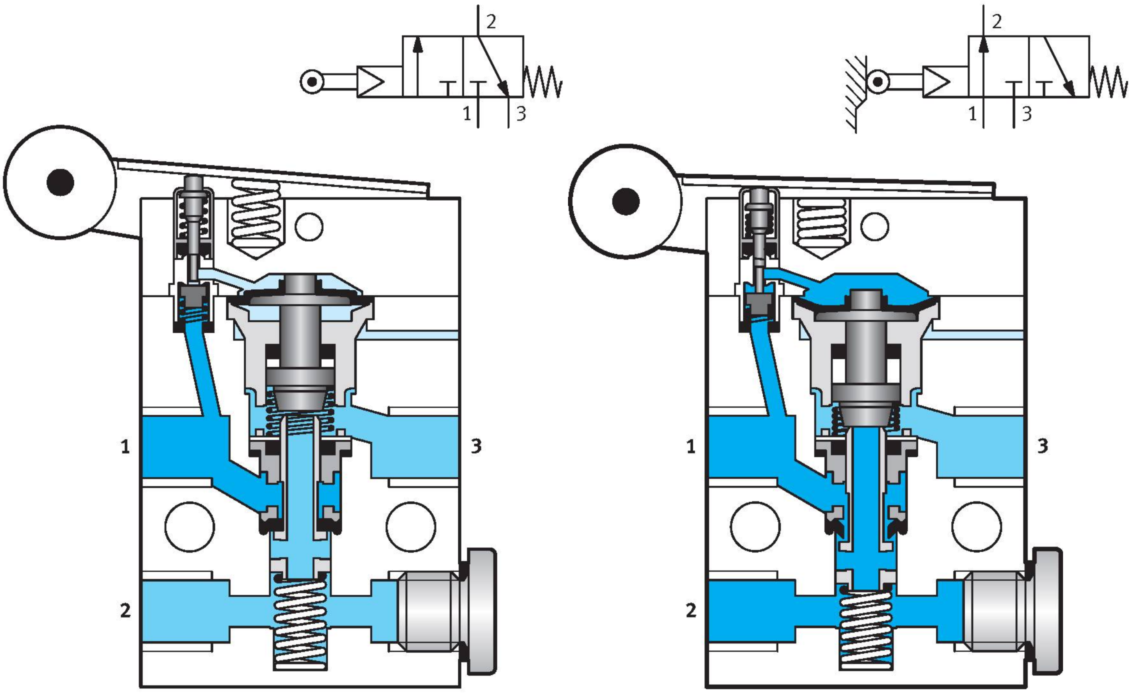



Figure 5.13: 3/2-way roller lever valve, piloted, closed position; left: unactuated; right: actuated

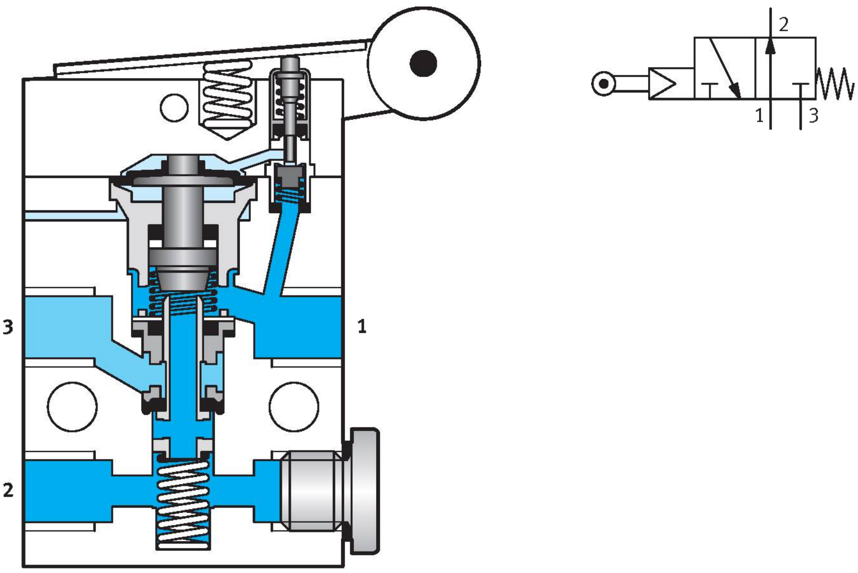
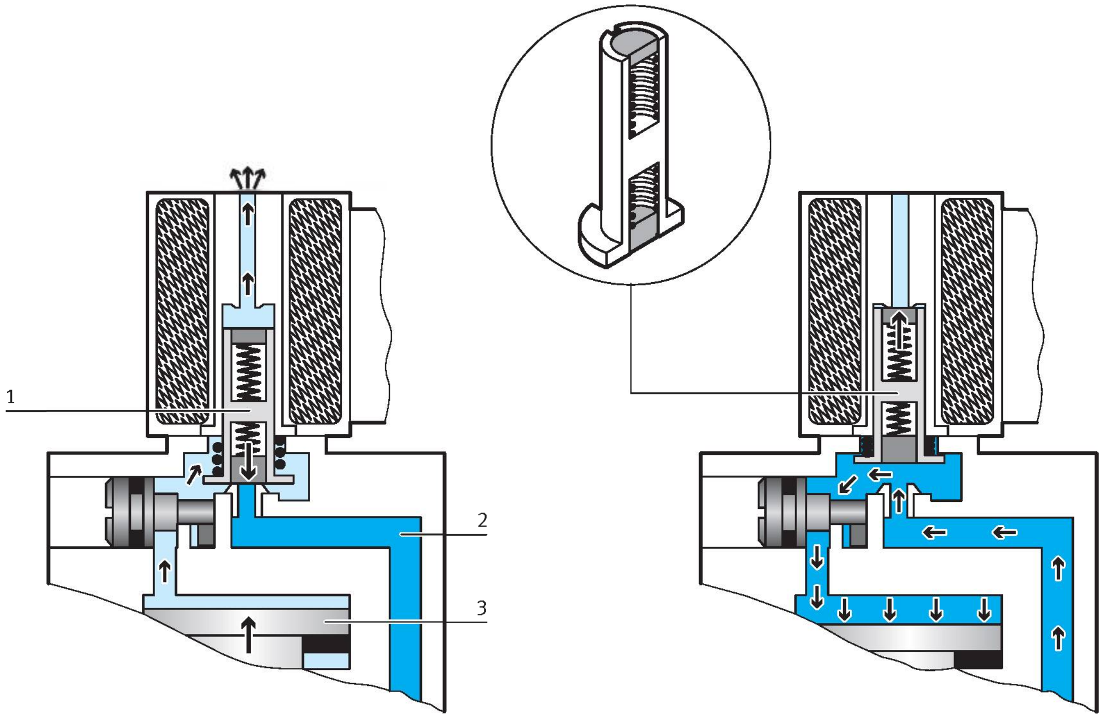



Figure 5.14: 3/2-way roller lever valve, piloted, open position, unactuated

### 5.5.3 How the pilot control stage works with solenoid actuated directional control valves

When the coil is de-energised, the armature is pressed into its lower sealing seat by the spring. The chamber on the top of the piston is exhausted.

When a current flows through the coil, the magnetic force exerted by the solenoid pulls the armature upwards. The chamber on the top of the piston is pressurised.




1: Armature; 2: Air duct; 3: Valve piston

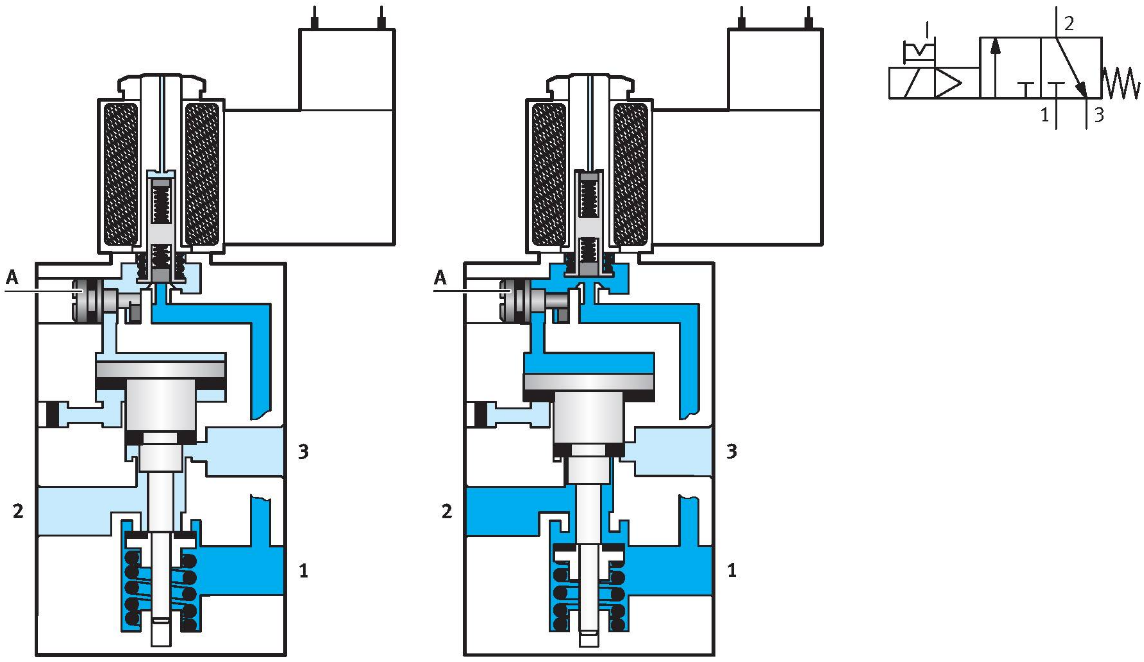
Figure 5.15: Pilot control of a solenoid actuated directional control valve

### 5.5.4 Piloted 3/2-way solenoid valve

Figure 5.16 shows two sectional views of a piloted 3/2-way solenoid valve.

- In the normal position, only the atmospheric pressure acts on the upper piston area which means that the spring force pushes the piston upwards (Figure 5.16, left). Ports 2 and 3 are connected.
- When a current flows through the solenoid coil, the chamber above the valve piston is connected to supply port 1 (Figure 5.16, right). The force above the valve piston increases and the valve piston is pushed downwards. The connection between ports 2 and 3 is closed and the connection between ports 1 and 2 is opened. This switching position is maintained for as long as current flows through the solenoid coil.
- When the solenoid coil is de-energised, the valve switches back to its normal position.

A minimum supply pressure (pilot pressure) is necessary to actuate the piston of a piloted valve against the spring force. This pressure is specified in the technical documentation for the valve and, depending on the valve type, is approx. 200 to 300 kPa (2 to 3 bar).




A: Manual override

Figure 5.16: Piloted 3/2-way solenoid valve, closed position, with manual override, with spring return;
left: unactuated; right: actuated

### 5.5.5 Comparison of piloted and directly actuated valves

The bigger the flow cross sections in a directional control valve, the higher the air flow.

With a directly actuated valve, the flow rate to the consuming device is opened by the armature
(A: Manual override
Figure 5.10). To achieve a sufficient opening cross section and therefore a sufficient flow rate, a comparatively large armature is needed. Accordingly a strong return spring is required and the solenoid must apply a large amount of force. It is therefore big in terms of size and has a high electric power consumption.

With a piloted valve, the flow rate to the consuming device is opened by the main stage (Figure 5.16). The valve piston is moved via the air duct. A low flow rate is sufficient for this, which means that a comparatively small armature with a low actuating force can be used. The solenoid can be smaller compared with a directly actuated valve. The electric power consumption and the thermal output are lower.

The advantages with respect to electric power consumption, size of the solenoid and thermal output mean that almost exclusively piloted directional control valves are used in electropneumatic control systems.

## 5.6 5/2-way valves

The 5/2-way valve has five working lines and two switching positions. It is mainly used as a control element for double-acting cylinders.

### 5.6.1 5/2-way pneumatic valve

An example of a 5/2-way valve is the longitudinal slide valve. As a control element it has a control piston that connects or disconnects the corresponding ports by means of longitudinal movements. Unlike with the ball or disc seat principle, the actuating force is low because there is no air pressure or spring pressure to overcome.

All methods of actuation – manual, mechanical, solenoid or pneumatic – are possible with longitudinal slide valves. These methods of actuation can also be used to return the valve to its initial position.

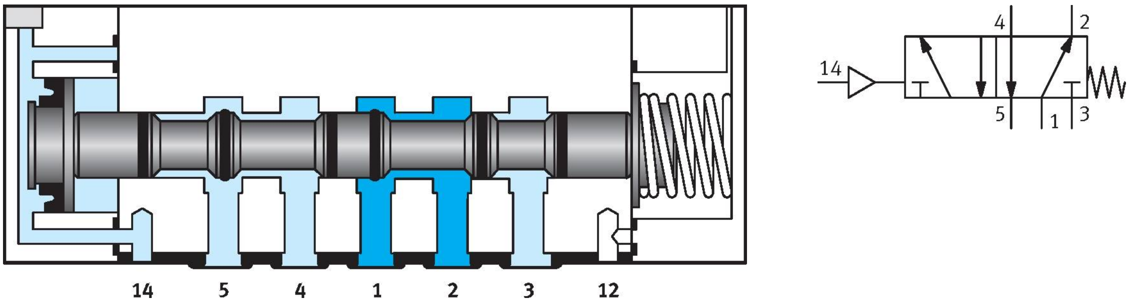



Figure 5.17: 5/2-way pneumatic valve – sectional view and symbol

### 5.6.2 5/2-way double pilot valve

The 5/2-way double pilot valve has a memory function. The valve is switched to port 14 or 12 by means of alternating pneumatic signals. After the signal is withdrawn, the switching position is maintained until a counter signal is received.

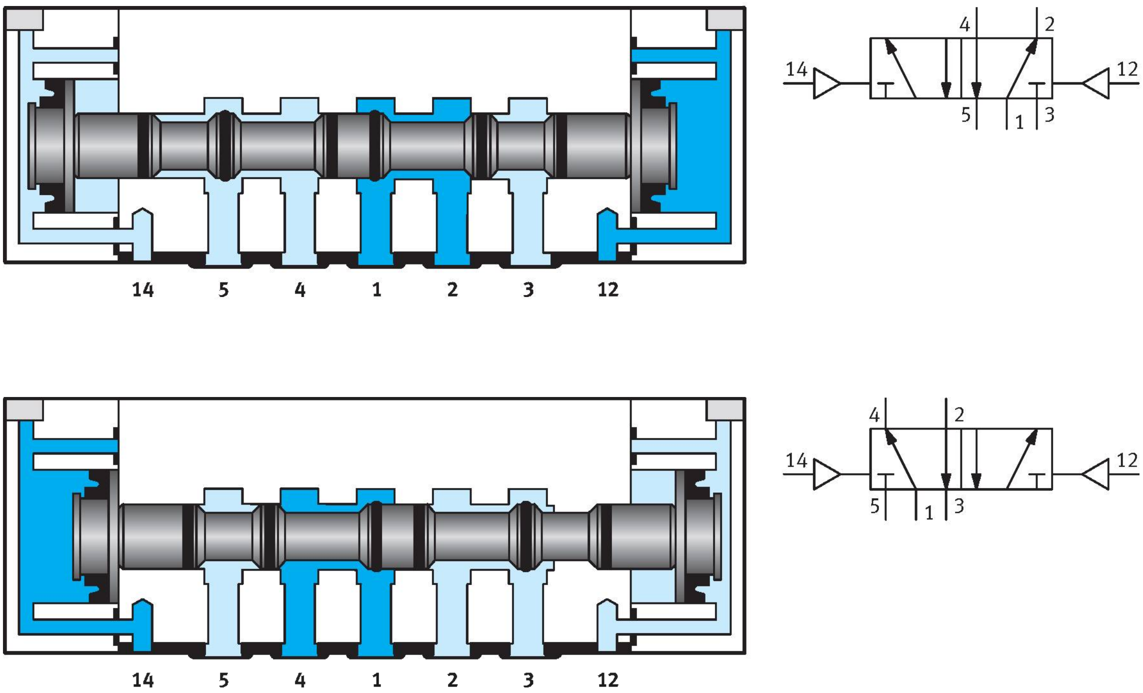



Figure 5.18: 5/2-way double pilot valve, longitudinal slide principle – sectional views and symbols

A further sealing method is the use of disc seat seals with a relatively small switching movement. The disc seat seal connects port 1 with 2 or 4. Secondary seals on the piston seal the exhaust port that is not required. The valve shown has a manual override for reversing the piston on both sides.

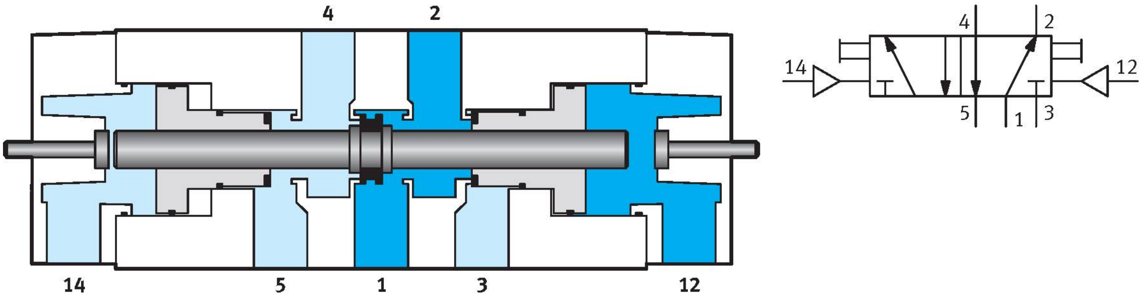



Figure 5.19: 5/2-way double pilot valve, flow from 1 to 2 and 4 to 5

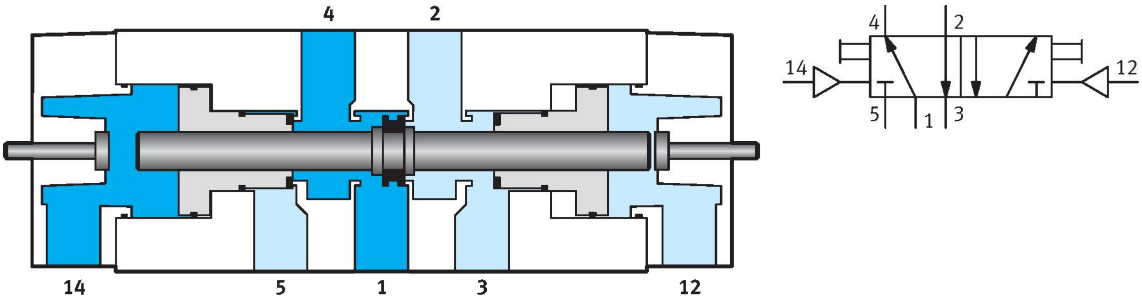



Figure 5.20: 5/2-way double pilot valve, flow from 1 to 4 and 2 to 3

### 5.6.3 Piloted 5/2-way solenoid valve

Figure 5.21 and Figure 5.22 shows the two switching positions of a piloted 5/2-way solenoid valve.

- In the normal position the piston is at the left stop (Figure 5.21). Ports 1 and 2 as well as ports 4 and 5 are connected.
- When a current flows through the solenoid coil, the valve piston moves to the right stop (Figure 5.22). Ports 1 and 4 as well as 2 and 3 are connected in this position.
- When the solenoid coil is de-energised, the spring force returns the valve piston to its normal position.
- The pilot air is vented through port 84.

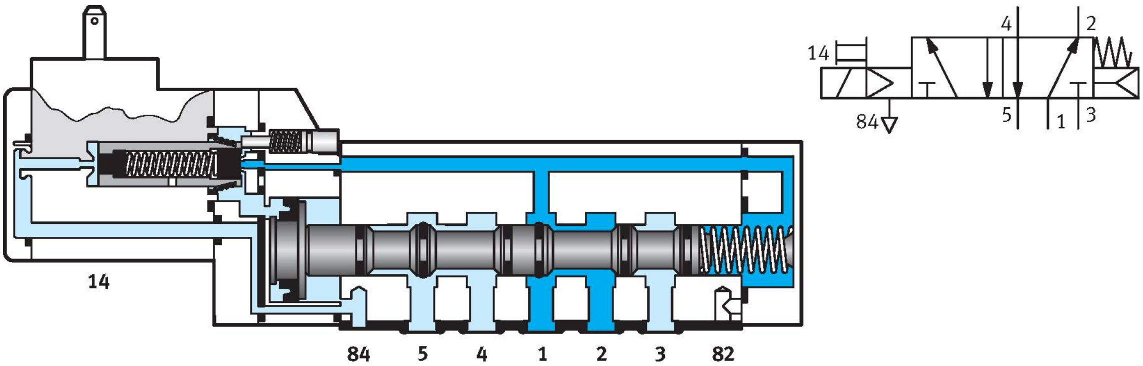



Figure 5.21: Piloted 5/2-way solenoid valve, unactuated

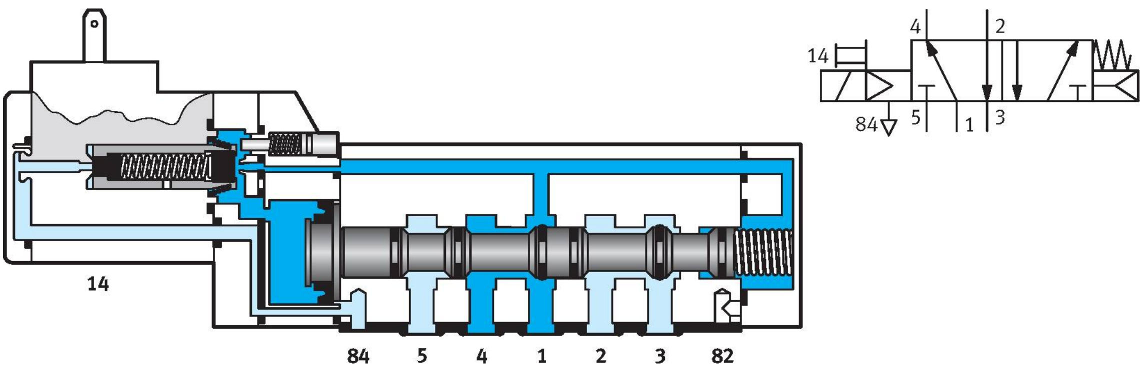



Figure 5.22: Piloted 5/2-way solenoid valve, actuated

### 5.6.4 Piloted 5/2-way double solenoid valve

Figure 5.23 and Figure 5.24 show two sectional views of a piloted 5/2-way double solenoid valve.

- Ports 1 and 2 as well as 4 and 5 are connected when the piston is at the left stop (Figure 5.23).
- When a current flows through the left solenoid coil, the piston moves to the right stop and ports 1 and 4 as well as 2 and 3 are connected (Figure 5.24).
- To return the valve to its initial position, it is not enough to interrupt the circuit to the left solenoid coil; the circuit of the right solenoid coil must also be closed.

If neither of the two solenoid coils is energised, friction causes the piston to remain in the last position assumed. The same applies if the circuits of both solenoid coils are closed at the same time as they then act against each other with equal force.

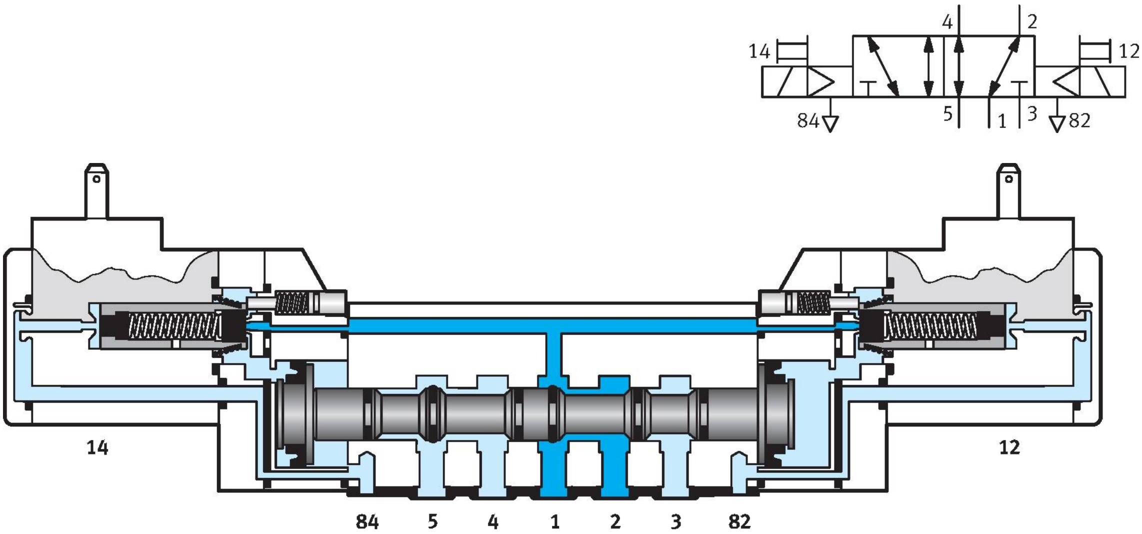



Figure 5.23: Piloted 5/2-way double solenoid valve, flow from 1 to 2 and 4 to 5

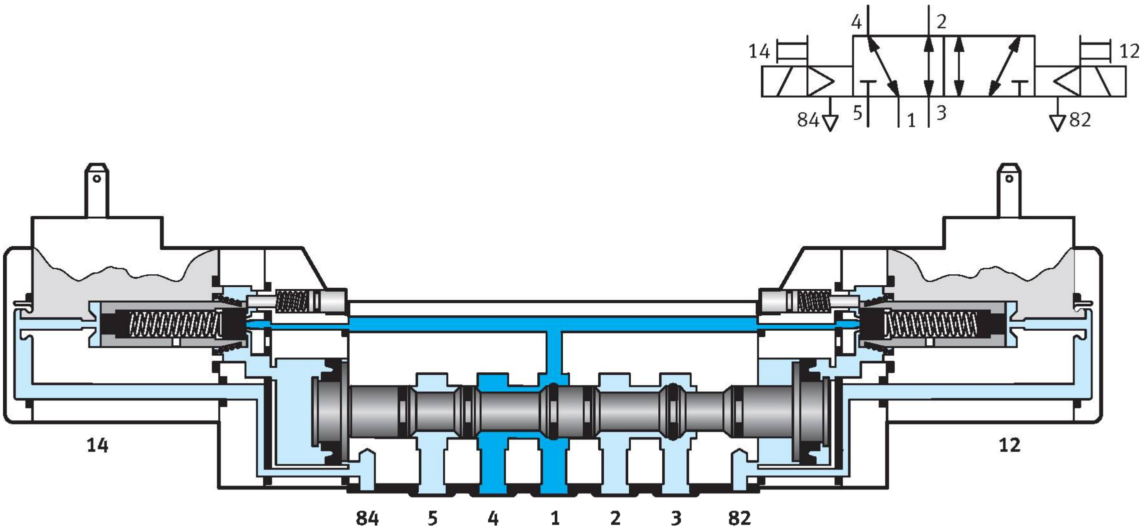



Figure 5.24: Piloted 5/2-way double solenoid valve, flow from 1 to 4 and 2 to 3

## 5.7 5/3-way valves

The 5/3-way valve has five working lines and three switching positions. These valves can be used to stop double-acting cylinders within the stroke range. If there is no signal at either pilot port, the valve is held spring-centred in the mid-position.

### 5.7.1 5/3-way pneumatic valves

Figure 5.25, Figure 5.26 and Figure 5.27 show the three switching positions of a 5/3-way pneumatic valve.

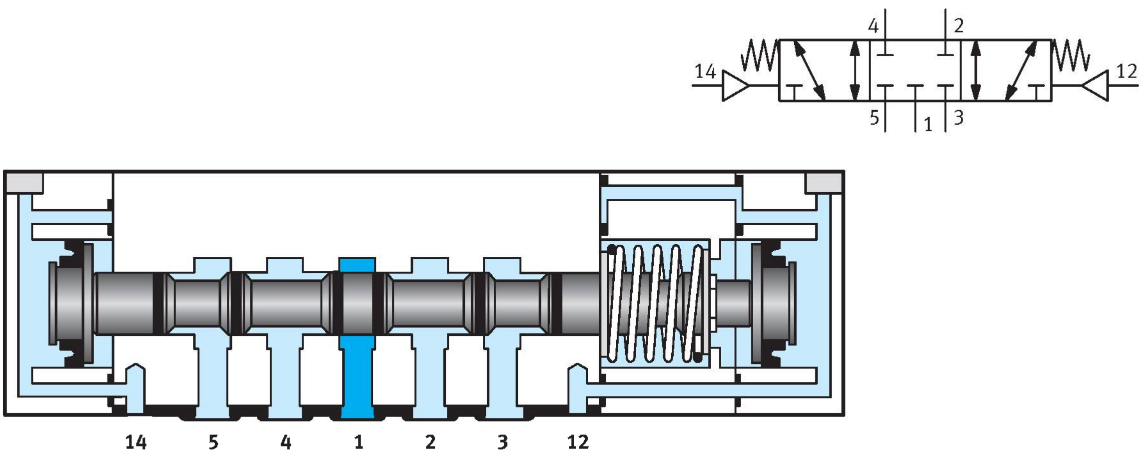



Figure 5.25: 5/3-way pneumatic valve, mid-position closed

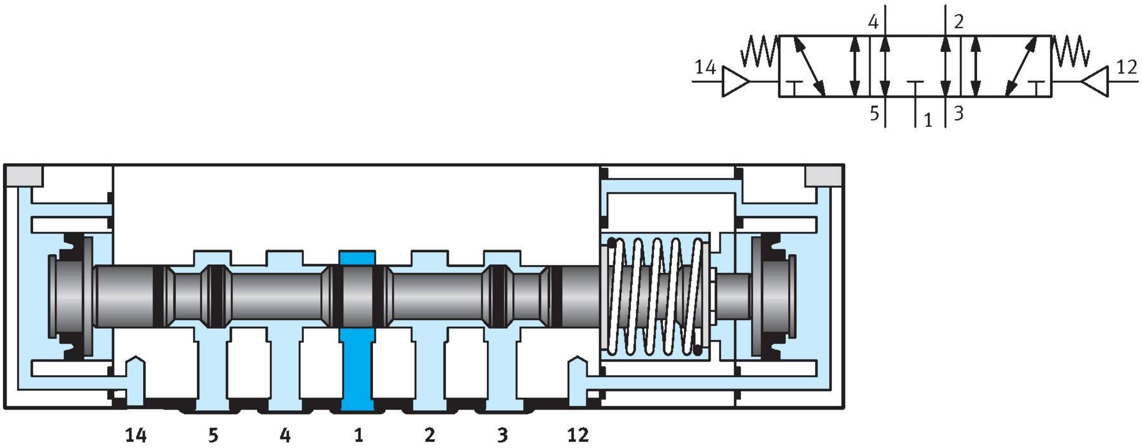



Figure 5.26: 5/3-way pneumatic valve, mid-position exhausted

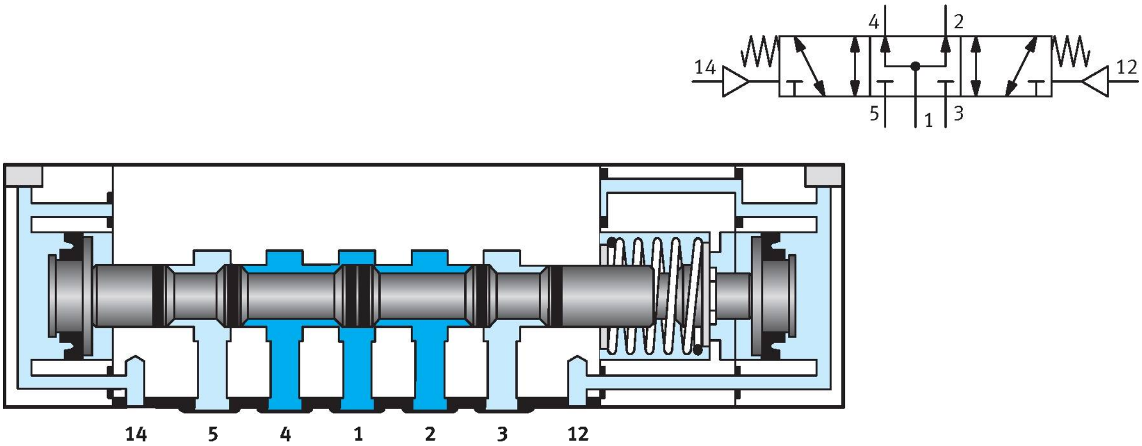



Figure 5.27: 5/3-way pneumatic valve, mid-position pressurised

### 5.7.2 Piloted 5/3-way solenoid valve with mid-position closed

Figure 5.28, Figure 5.29 and Figure 5.30 show the three switching positions of a solenoid actuated, piloted 5/3-way valve.

- The solenoid coils are de-energised and in the normal position and the piston is centred in its mid-position by the two springs (Figure 5.28). Ports 1, 2, 3, 4 and 5 are closed.
- When a current flows through the left solenoid coil, the piston moves to the right stop (Figure 5.29). Ports 1 and 4 and ports 2 and 3 are connected.
- When a current flows through the right solenoid coil, the piston moves to the left stop (Figure 5.30). Ports 1 and 2 as well as port 4 and 5 are connected in this position.
- Each of the two actuated switching positions is maintained for as long as there is current flowing through the associated solenoid coil. If the flow of current is interrupted, the piston switches to the mid-position.

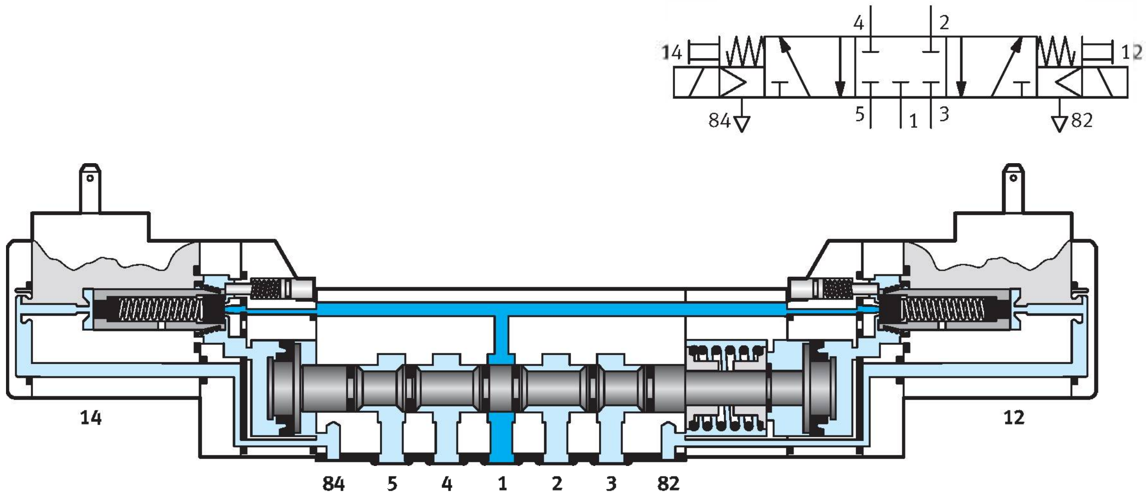



Figure 5.28: Piloted 5/3-way solenoid valve, mid-position closed

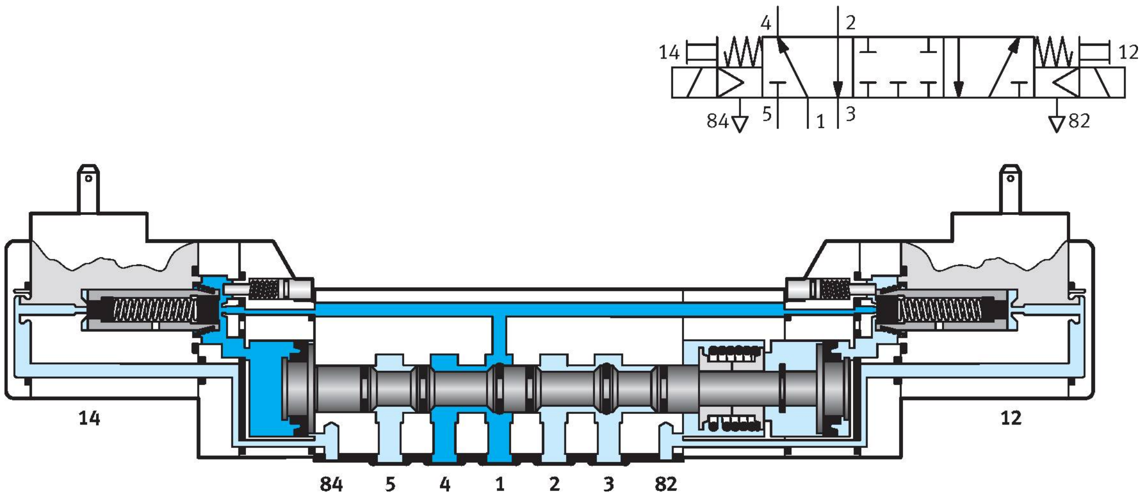



Figure 5.29: Piloted 5/3-way solenoid valve, flow from 1 to 4 and 2 to 3

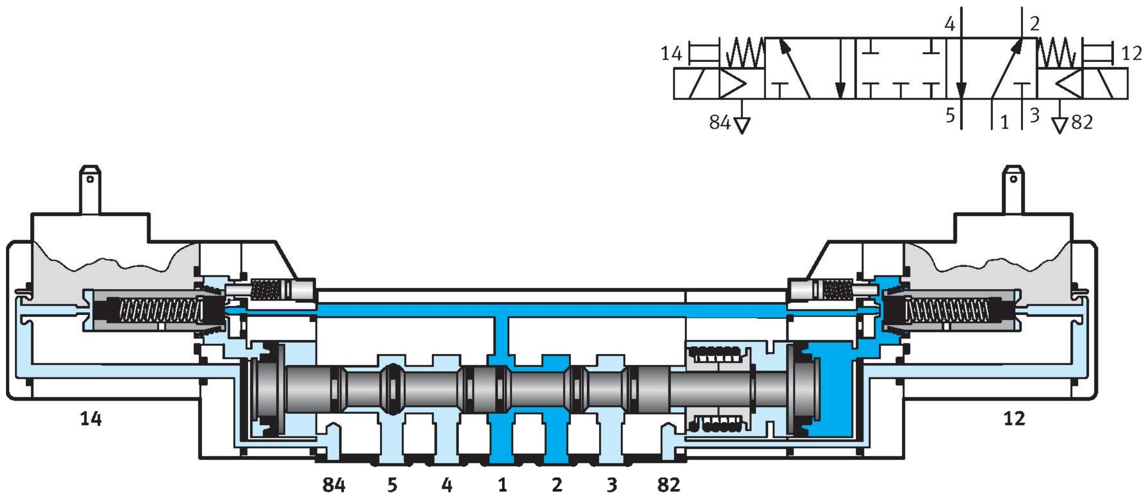



Figure 5.30: Piloted 5/3-way solenoid valve, flow from 1 to 2 and 4 to 5

### 5.7.3 Influence of the mid-position

Directional control valves with two switching positions (e.g. 3/2-way or 5/2-way valves) enable a cylinder to be advanced and retracted. Directional control valves with three switching positions (e.g. 5/3-way valves) offer more possibilities for cylinder actuation thanks to the additional mid-position. We will explain this using the example of three 5/3-way valves with different mid-positions. We will look at the behaviour of the cylinder when the directional control valve switches to the mid-position.

- If a 5/3-way valve with its working ports exhausted is used, the piston of the cylinder does not exert any force on the piston rod. The piston rod can move freely (Figure 5.31).

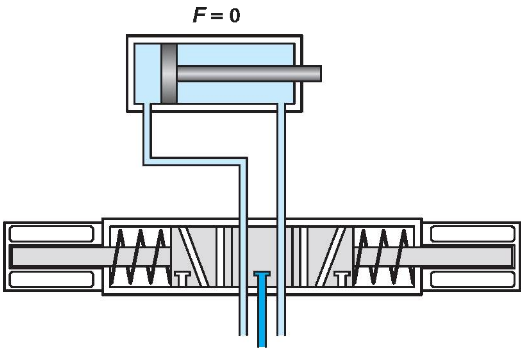



Figure 5.31: 5/3-way solenoid valve, mid-position exhausted: the piston rod can move freely

- With a 5/3-way valve with all ports closed, the piston rod remains stationary. The same applies if the piston rod is not at the stop (Figure 5.32).

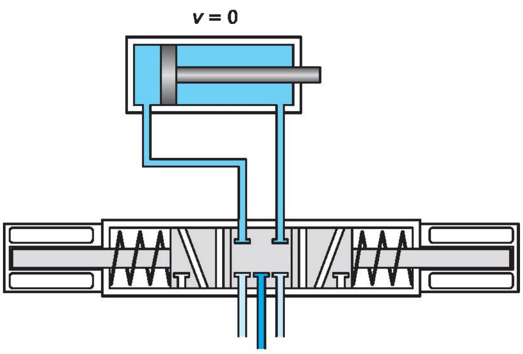



Figure 5.32: 5/3-way solenoid valve, mid-position closed: the piston rod is fixed between two air cushions

- When using a 5/3-way valve with pressurised ports, the piston advances with reduced force (Figure 5.33).

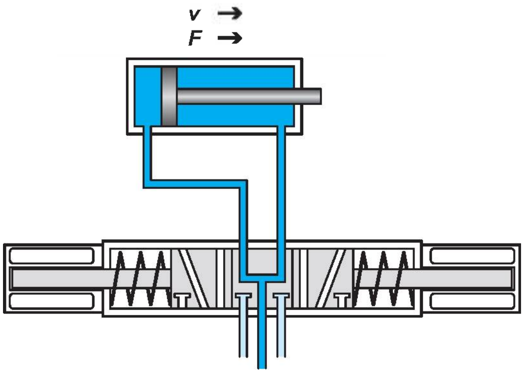



Figure 5.33: 5/3-way solenoid valve, mid-position pressurised: the piston rod advances with reduced force

### 5.8 Flow rates of valves

Pressure loss and air flow rate of pneumatic valves are important information for the user. The choice of valve depends on:

- Cylinder volume and speed
- Required switching frequency
- Permissible pressure drop

Pneumatic valves are identified using their nominal flow rate. Different factors must be taken into consideration when calculating flow rates. These are:

| | |
|---|---|
| $p_1$ | Pressure at the valve input side (kPa or bar) |
| $p_2$ | Pressure at the valve output side (kPa or bar) |
| $\Delta p$ | Differential pressure $(p_1 - p_2)$ (kPa or bar) |
| $T_1$ | Temperature (K) |
| $q_n$ | Nominal flow rate (l/min) |

Air flows through the valve in one direction during the measurement. The supply pressure and the output pressure are measured. The flow rate of the air is measured using a flow meter.

Information about the nominal flow rates can be found in the manufacturers' catalogues.

## 5.9 Reliable operation of valves

### 5.9.1 Assembling roller lever valves

The reliability of a control system depends to a large extent on the correct attachment of limit switches. The limit switches must be designed so that they can be easily set and adjusted at any time. This is important to guarantee precise coordination of the cylinder movements within a control system.

### 5.9.2 Installing the valves

As well as being careful when choosing the valves, correct installation is an important prerequisite for reliable switching properties, trouble-free operation and easy access for repair and maintenance work. This applies to both valves in the power section and in the control section.

Maintenance work and repairs are made easier by:

- Numbering the components
- Installing visual indicators
- Complete documentation

Manually operated valves for signal input are generally attached to the control panel or control desk. It is therefore practical and expedient to look for valves with actuating elements that are connected directly to the basic component. There is a host of different actuation methods for a wide range of input functions.

Valves as control elements control the sequence of pneumatic operating elements. They have to be designed to trigger the fastest possible response from the drives. The valve should therefore be installed as close as possible to the operating element in order to keep the tubing lengths and switching times as short as possible. Ideally, the valve should be mounted directly on the operating element. This also reduces the need for tubing materials and the assembly time.

# 6 Shut-off valves, flow control valves and pressure regulators, valve combinations

## 6.1 Shut-off valves

Shut-off valves close the flow in one direction and open it in the opposite direction. The pressure on the exhaust side acts on the closing part and boosts the sealing effect of the valve.

### 6.1.1 Non-return valves

Non-return valves can completely stop the flow in one direction while the air flows with the least possible pressure loss in the opposite direction. Blocking the one direction can be done using a cone, ball, flat slide or diaphragm.

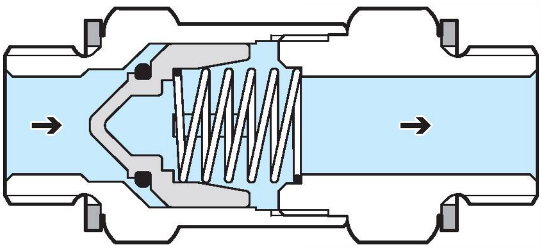


Figure 6.1: Non-return valve – sectional view and symbol

### 6.1.2 Processing elements

Elements with the characteristics of a non-return valve can be used as processing elements between two signal paths for controlling the signals. The two valves referred to as processing elements are used for logical processing of two input signals and forwarding the resulting signal. The dual-pressure valve then only generates one signal when there is a signal applied to both inputs (AND function), the shuttle valve forwards the signal when a signal is applied to at least one input (OR function).

### 6.1.3 Dual-pressure valve: logic AND function

The dual-pressure valve has two inputs 1 and one output 2. Flow is only possible if two input signals are present. An input signal at one of the two inputs closes the flow due to the differential forces at the piston spool.

With time differences in the input signals and with the same supply pressure, the last signal that arrived reaches the output. With pressure differences in the input signals, the greater pressure closes the valve and the lesser air pressure reaches the output 2. The dual-pressure valve is mainly used in locking controllers, check functions and logic AND operations.

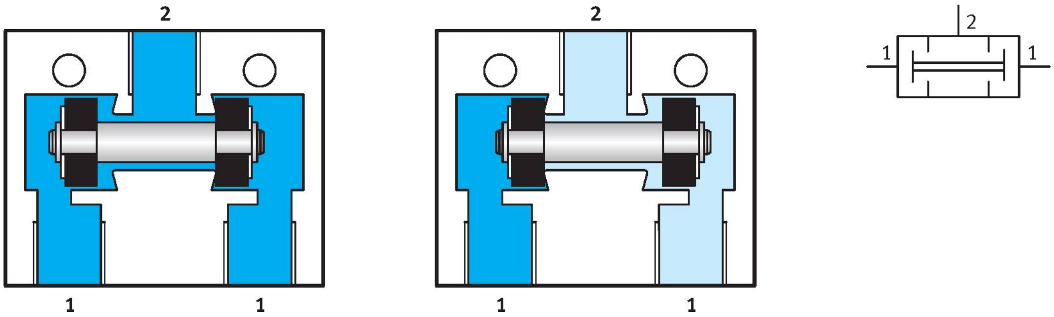



Figure 6.2: Dual-pressure valve: AND function – sectional views and symbol

### 6.1.4 Shuttle valve: logic OR function

This shut-off valve has two inputs 1 and one output 2. If the left input 1 is pressurised, the piston seals the right input 1 and the air flows from the left input 1 to 2. If the air goes from the right input 1 to 2, the left input is shut off. If the air flows back while the downstream valve is exhausted, the pressure conditions keep the piston in the previously assumed position. This valve is also called an OR gate. If a cylinder or a control element is to be actuated from one or more location, one or more shuttle valves must always be used.

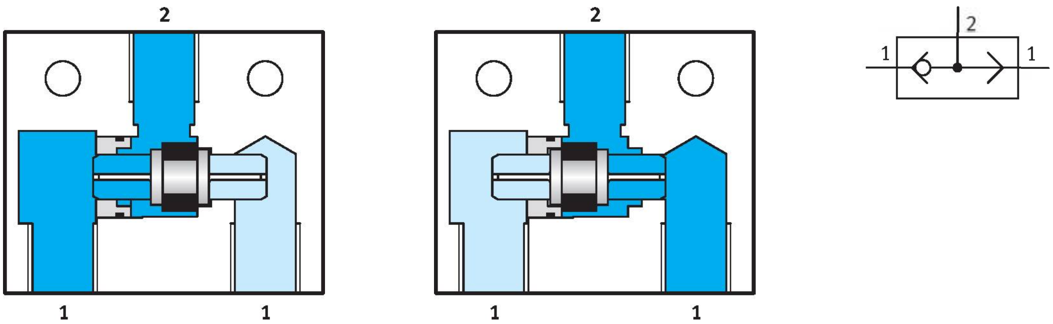
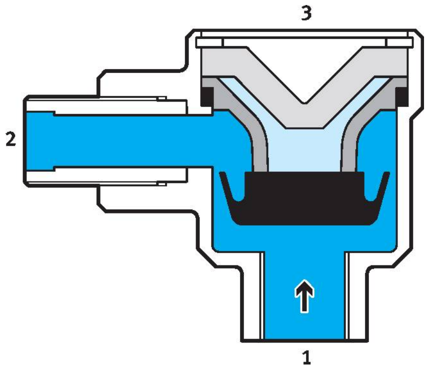



Figure 6.3: Shuttle valve: OR function – sectional views and symbol

### 6.1.5 Quick exhaust valve

Quick exhaust valves are used to increase cylinder piston speeds. This reduces long return times, particularly with single-acting cylinders. The piston rod can retract at almost full speed because the flow resistance of the exhaust air during the retraction movement is reduced via the quick exhaust valve. The air is discharged via a relatively large exhaust port. The valve has a pressure supply port 1 that can be shut off, an exhaust port 3 that can be shut off and an outlet port 2.



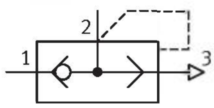




Figure 6.4: Quick exhaust valve, flow from 1 to 2

If port 1 is pressurised, the sealing disc will cover exhaust port 3. The compressed air then flows from 1 to 2. Once 1 is no longer pressurised, the air coming from 2 will move the sealing disc against port 1 and close it. The exhaust air can immediately flow into the open air. It does not have to travel a long way and in some cases narrow path via the connecting lines to the directional control valve. It makes most sense to install the quick exhaust valve directly at the cylinder or as close as possible to it.

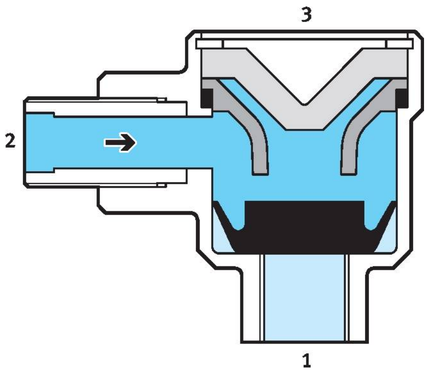



Figure 6.5: Quick exhaust valve, exhausting from 2 to 3

### 6.1.6 On-off valves

The term on-off valve is used for valves that infinitely open or close the flow in both directions. Typical examples are the stop cock and the ball valve.

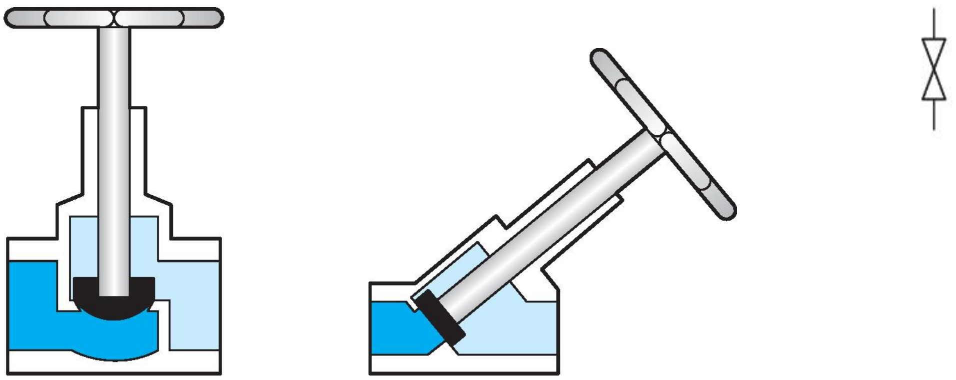


Figure 6.6: Stop cocks – sectional view and symbol

## 6.2 Flow valves

Flow valves influence the volumetric flow rate of the compressed air in both directions. The flow control valve is a flow valve.

### 6.2.1 Flow control valvess

Flow control valves are generally adjustable. The setting can be fixed. Flow control valves are used to regulate the speed of cylinders. Note that the flow control valve is never completely closed.

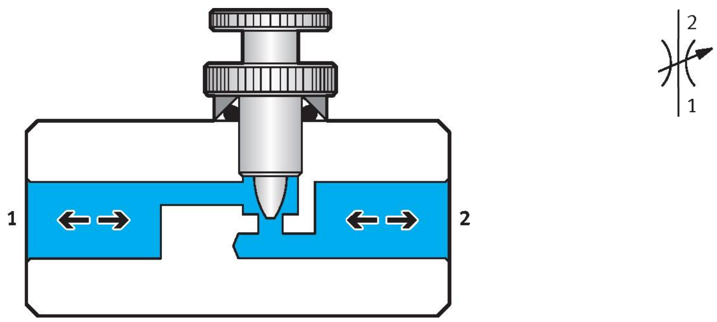



Figure 6.7: Flow control valve – sectional view and symbol

Design features of flow control valves:

- Flow control valve:
  The length of the restrictor is greater than its diameter.
- Orifice valve:
  The length of the restrictor is less than its diameter.

### 6.2.2 One-way flow control valves

With the one-way flow control valve, the air is restricted in one direction only. A non-return valve closes the air flow in one direction and the air can only flow via the set cross section. Air flows freely in the other direction through the open non-return valve. These valves can be used to regulate the speed of pneumatic cylinders. They should be mounted directly on the cylinder if possible.

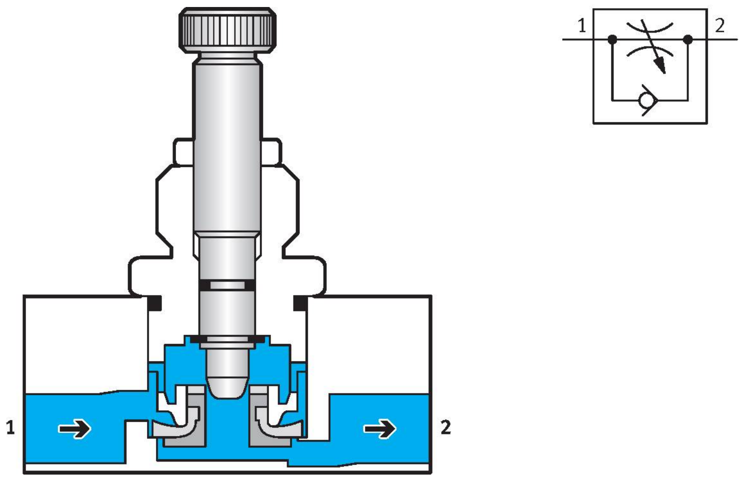



Figure 6.8: One-way flow control valve – sectional view and symbol

There are basically two types of flow control with double-acting cylinders:

- Supply air flow control
- Exhaust air flow control

### 6.2.3 Supply air flow control

With supply air flow control, the one-way flow control valves are installed so that the air flow to the cylinder is controlled. The exhaust air can escape freely via the non-return valve on the outlet side. The smallest fluctuations in load at the piston rod, for example as happens when passing a limit switch, result in very erratic feed speeds.

A load in the cylinder's direction of movement accelerates the cylinder above the set value. Therefore supply air flow control is frequently used with single-acting and low-volume cylinders.

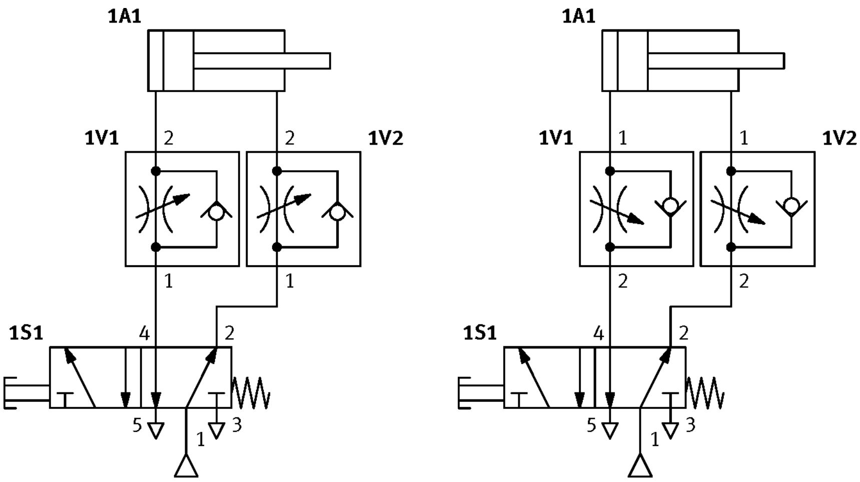



Figure 6.9: Left: supply air flow control; right: exhaust air flow control

### 6.2.4 Exhaust air flow control

With exhaust air flow control, the supply air flows freely to the cylinder and the flow control valve in the exhaust valve offers resistance to the outward flow. The piston is clamped between two air cushions which build up through the pressure of the supply air and the resistance of the flow control valve for the exhaust air. This layout for one-way flow control valves helps greatly to improve the feed behaviour. Exhaust air flow control is frequently used with double-acting cylinders. Combined supply air/exhaust air flow control must be chosen with miniature cylinders due to the low air flow rate.

### 6.2.5 Application of the flow control method

The question of when to use which method of flow control basically depends on the load conditions at the drive. Depending on the mounting position of the cylinder and the load to be moved, it may make sense to use a combination of both methods of flow control.

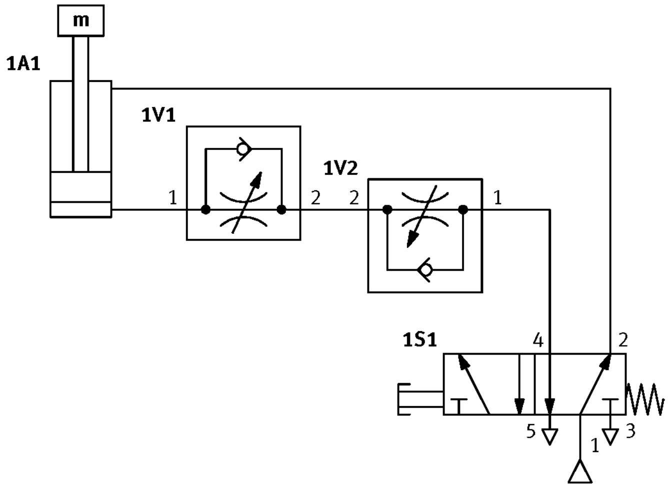



Figure 6.10: Pushing load; combination of supply air and exhaust air flow control

If the cylinder is working with the piston rod moving vertically upwards, then the load is a pushing load. Exhaust air flow control on the piston rod side delays the escape of the exhaust air. The cylinder piston only moves when the force on the piston side of the cylinder is greater than the force on the piston ring area plus the weight force of the load. Exhaust air flow control only acts as a time delay here.

To enable the piston to move out of its end position earlier in this case, no one-way flow control valve is installed on the piston rod side. However, exhaust air flow control is additionally used on the piston side so that the advancing speed can still be adjusted.

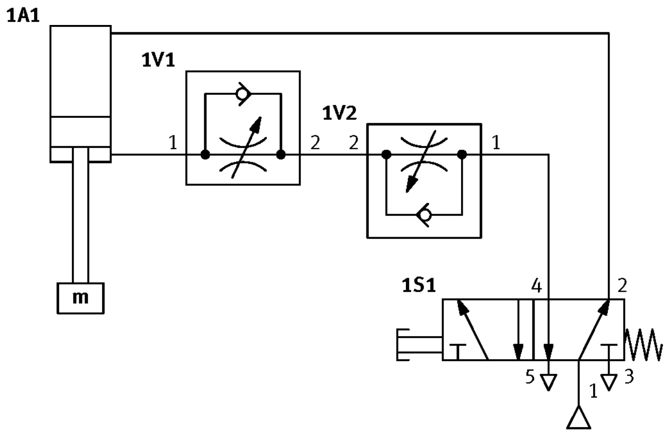



Figure 6.11: Pulling load; combination of supply air and exhaust air flow control

If the cylinder is working with the piston rod moving vertically downwards, then the load is a pulling load. A combination of supply air and exhaust air flow control is used in this case too.

## 6.3 Pressure regulators

Pressure regulators are components that mainly influence the pressure or are controlled by the pressure level. They are divided into three groups:

- Pressure regulators
- Pressure-relief valves
- Pressure sequence valves

### 6.3.1 Pressure regulator

The pressure regulator is used to maintain a constant pressure even in the event of fluctuations in the system pressure. The minimum supply pressure must be greater than the output pressure.

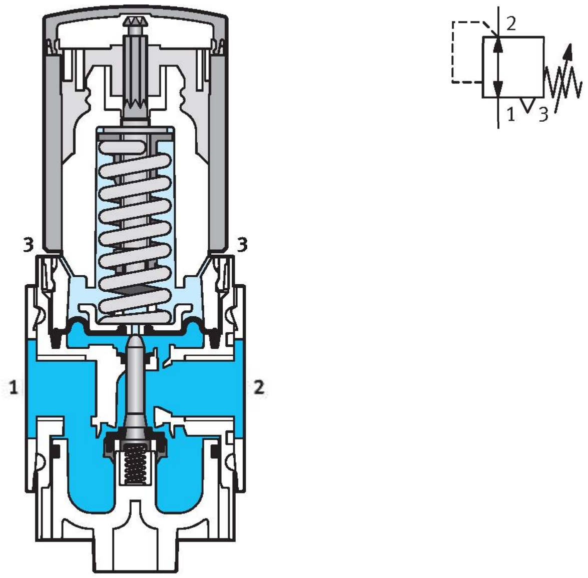



Figure 6.10: Pressure regulator – sectional view and symbol

### 6.3.2 Pressure-relief valve

These values are mainly used as safety valves. They prevent the maximum permissible pressure in a system being exceeded. If the maximum pressure value at the valve input has been reached, the valve output is opened and the air escapes. The valve remains open until it is closed by the integrated spring once the set pressure as appropriate to the spring characteristic curve has been reached.

### 6.3.3 Pressure sequence valve

This valve works on the same principle as the pressure-relief valve. The valve opens when the set pressure at the spring is exceeded.

The flow from 1 to 2 is closed. Output 2 is only opened when the preset pressure has built up at pilot line 12. A control piston opens the flow from 1 to 2.

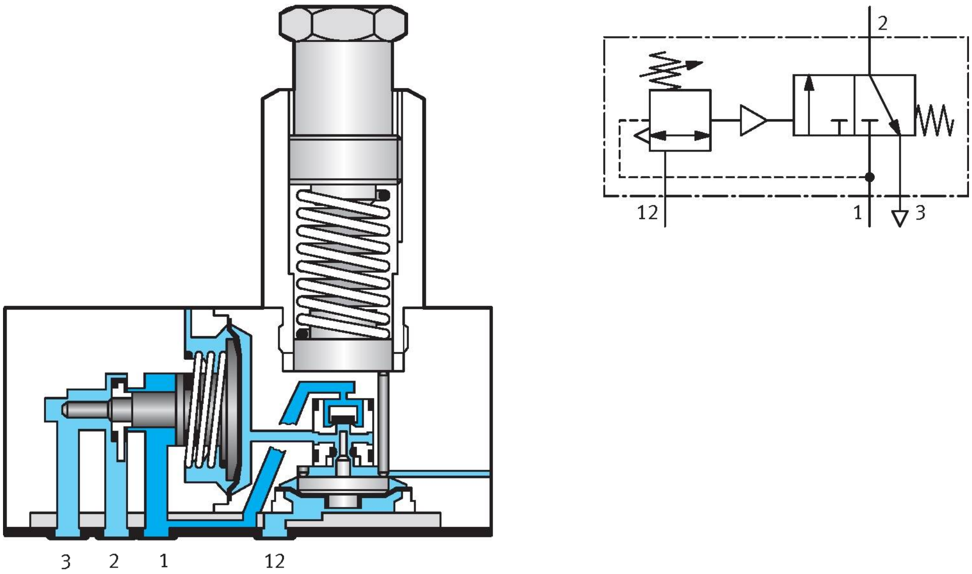



Figure 6.11: Pressure sequence valve, adjustable – sectional view and symbol

Pressure sequence valves are installed in pneumatic control systems if a specific pressure is required for a switching operation (pressure-dependent controllers).

## 6.4 Valve combinations

Valves from different valve groups can be combined into one unit. The properties and design features of these units are determined by the valves used. They are also called combination valves. The respective graphical symbols consist of the symbols for the individual components. The following units belong to the group of combination valves:

- Time delay valve: delays forwarding of signals
- Pneumatic control block: executes individual and oscillating movements with double-acting cylinders
- 5/4-way valve: pauses double-acting cylinders in any position
- Pneumatic 8-way valve: controls pneumatic feed units
- Pulse oscillator: executes high-speed cylinder movements
- Vacuum generator with ejector: grips and ejects parts
- Stepper modules: for sequence control tasks
- Command memory modules: for starts via signal input conditions

### 6.4.1 Time delay valves

The time delay valve consists of a pneumatically actuated 3/2-way valve, a one-way flow control valve and a small air reservoir. The 3/2-way valve can be normally closed or normally open. The delay time is normally 0 to 30 seconds with both types of valves.

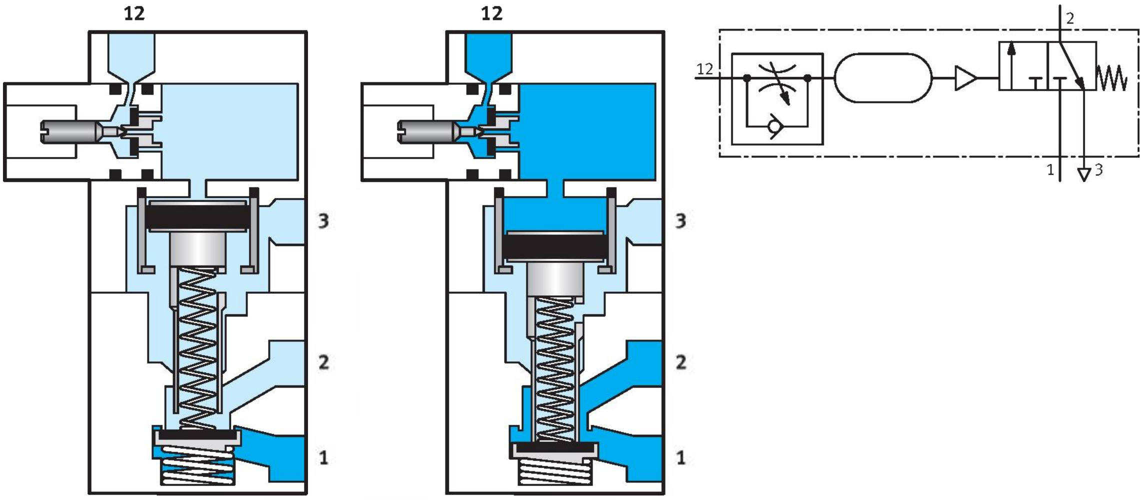



Figure 6.12: Time delay valve, normally closed; left: unactuated; right: actuated

The time can be extended by using additional air reservoirs. Clean air and constant pressure ensure a precise switching time.

**Operational principle**

The following operational principle is for a time delay valve with one normally closed 3/2-way valve:

The compressed air is supplied to the valve at port 1. The pilot air flows into the valve at input 12 and flows through the one-way flow control valve. Depending on the setting of the flow control screw, more or less air per unit of time flows into the attached air reservoir. Once the necessary pilot pressure has built up in the air reservoir, the control piston of the 3/2-way valve is moved downwards and closes the through flow from 2 to 3. The valve disc is lifted from its seat and the air can flow from 1 to 2. The time needed to build up the pressure in the air reservoir determines the switching time.

If the time delay valve is to return to its initial position, pilot line 12 must be exhausted. The air flows from the air reservoir and into the open via the one-way flow control valve and the exhaust line of the signal valve. The return spring in the valve returns the control piston and the valve disc to their initial position. Working line 2 exhausts to 3 and 1 is closed.

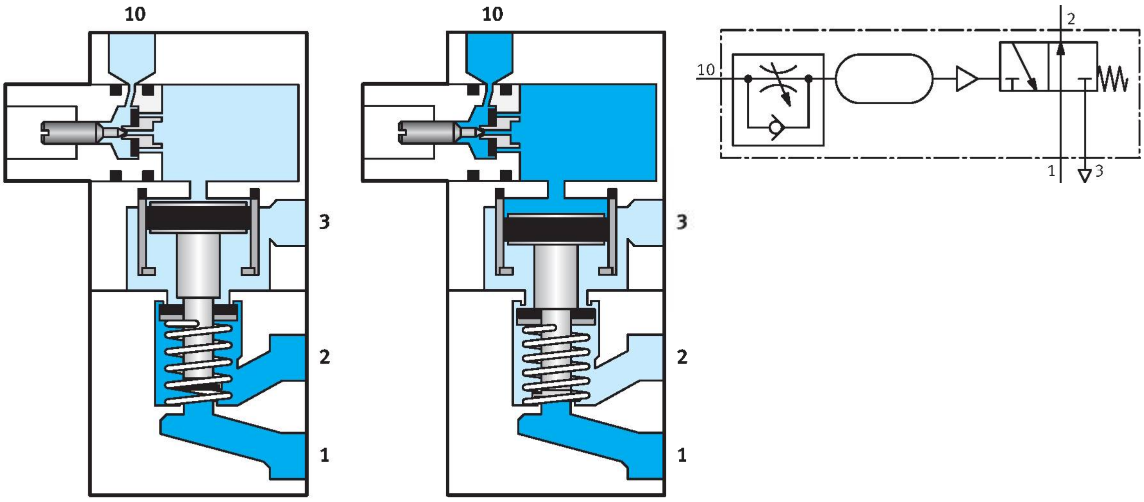



Figure 6.13: Time delay valve, normally open; left: unactuated; right: actuated

If a normally closed 3/2-way valve is installed, a signal is applied to output 2 in the initial position. If the valve is switched via the signal at input 10, the working line 2 exhausts to 3 and 1 is closed. This causes the output signal to be cleared after the set time.

The delay time once more corresponds to the pressure build-up time in the air reservoir. If the air at port 10 is taken away, the 3/2-way valve returns to its normal position.

# 7 Valve terminal technology

The further development of the solenoid actuated directional control valves affects separately assembled individual valves as well as valve combinations such as valve manifolds or valve terminals.

A valve manifold where the electrical cables are also combined (by means of multi-pin plug, fieldbus or AS-interface connection) is called a valve terminal.

## 7.1 Measures for optimising individual valves

The objective of further developing individual valves is to minimise the size and weight, shorten the switching times and reduce the electric power consumption. This is achieved through the following measures:

- The solenoid coils get a modified winding with reduced inductance. As a result the coil responds faster when it is energised and the force for switching the pre-stage is built up faster. After the valve switches, the current flowing through the solenoid coil is reduced electronically so that the pre-stage is held in the actuated position against the force of the return spring. This significantly reduces the electric consumption in this phase. Since the holding phase is much longer than the reversal phase, much less electrical energy is needed to operate the coil overall.
- The directional control valves are optimised with respect to dead volume, actuating force and moving load. This achieves fast switching of the valve.
- The inside of the housing is designed for favourable flow characteristics to achieve a high flow rate.
- The wall thickness of the housing is reduced as much as possible to minimise the weight and dimensions.

## 7.2 Advantages of optimised individual valves

An optimised solenoid actuated directional control valve has the following advantages:

- Increased dynamic response (thanks to short switching times and high flow rate)
- Reduced compressed air consumption (thanks to reduced air volume between the valve and the drive)
- Reduced costs for the power supply unit (due to lower energy consumption)
- Reduced installation space and minimised weight

### 7.3 Optimised valves for manifold assembly

The modular valve manifolds shown in the picture have an air duct with particularly low losses, very compact dimensions and a good price/performance ratio. A manifold consists of:

- Directional control valve modules
- Modules for pneumatic connection
- Modules for electrical connection

Figure 7.1 shows a directional control valve module optimised for manifold assembly. Several of these modules are assembled between two cover plates. The compressed air is either supplied via one of the two cover plates on the front (Figure 7.1) or via a connecting module underneath (Figure 7.2).

Figure 7.1: Modular structure of a valve manifold; left: valve module; right: air duct and silencer assembly on one side

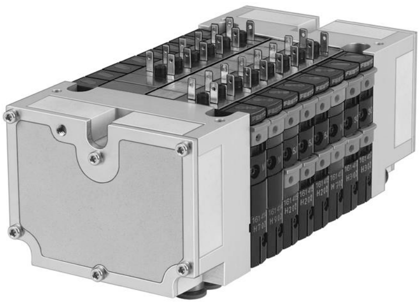


Figure 7.2: Modular structure of a valve manifold: air ducts underneath, flat plate silencers on the front sides

## 7.4 Electrical connection of valve manifolds

The valve manifolds' electrical contacts are on the top. This enables the solenoid coils to be wired differently by using the appropriate electrical connecting module:

1. Without an additional connecting module, each coil is connected via a separate cable socket.
2. Module for multi-pin plug connection: all solenoid coils are connected inside the valve terminal using a single multi-plug.
3. Module for fieldbus connection: all solenoid coils are connected inside the valve terminal using a fieldbus interface.
4. Module for connecting the AS-interface: all solenoid coils are connected inside the valve terminal with the two interfaces for connecting the actuator/sensor bus.

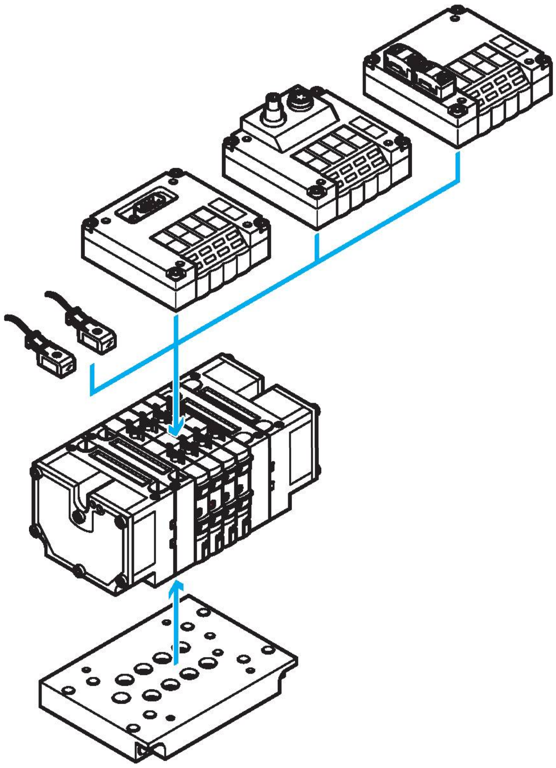


Figure 7.3: Electrical connection of valve manifolds or valve terminals;
from left to right: conventional connection using a separate plug for each solenoid coil, multi-pin plug connection, fieldbus connection, AS-interface

## 7.5 Modern installation concepts

With conventional wiring technology, all components in an electropneumatic control system are connected via terminal strips. A separate terminal box is needed to connect the solenoid coils and sensors. The electrical installation is correspondingly complex.

### 7.5.1 Advantages of modern installation concepts

Modern components in electropneumatics enable the valves to be combined on valve terminals. The solenoid coils' contacts engage directly in the corresponding plug sockets on the valve terminals. The sensors are connected using plugs to the input module, which is either separate or integrated in the valve terminal. This has the following advantages:

- No need for a terminal box and associated terminal strip.
- Defective directional control valves and sensors can be replaced without having to disconnect and reconnect them.
- Requires less wiring.

### 7.5.2 Control components for reduced installation complexity

The following pictures show two examples of modern control components.

- Figure 7.4 shows a valve terminal and an input module to which the sensors are connected using plugs. Both components are connected by means of a fieldbus line.
- Figure 7.5 shows a terminal that combines valves, sensor connections and PLC.

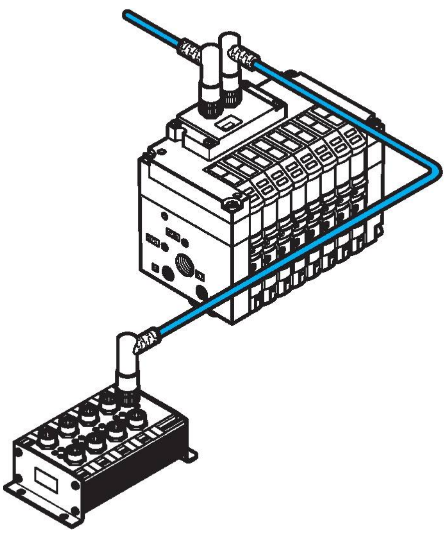
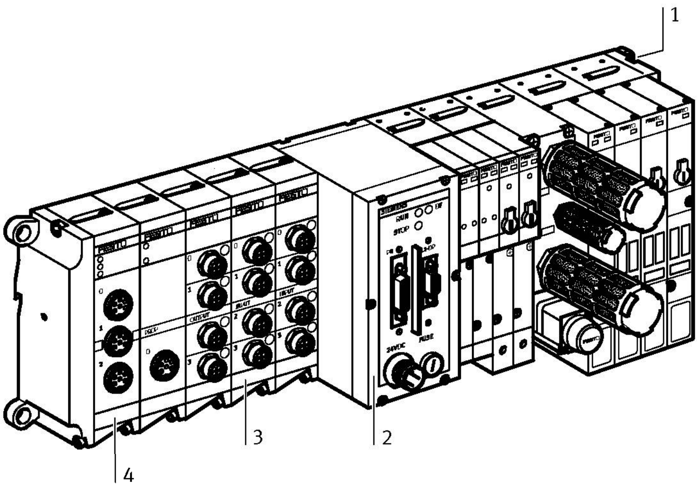


Figure 7.4: Control components for reduced installation complexity: valve terminal and separate sensor connection unit

### 7.5.3 Valve/sensor terminal

A valve terminal with additional functions (e.g. integrated PLC or integrated sensor connection module) is also called a valve/sensor terminal. The more common term valve terminal is used below.




1: Pneumatic output side; 2: PLC; 3: Sensor connection unit; 4: Electrical output section

Figure 7.5: Control components for reduced installation complexity: valve terminal with integrated sensor connection unit and integrated PLC

### 7.5.4 Wiring with multi-pin plug connection

On a valve terminal with multi-pin plug connection, all electrical connections in the valve terminal are bundled to a 4-pin plug connection (Figure 7.3). The cable that leads to the terminal strip in the control cabinet is connected via a mating connector. Several valve terminals with multi-pin plug connections can be connected to the terminal strip in the control cabinet.

### 7.5.5 Structure of a fieldbus system

Figure 7.6 shows the structure of a fieldbus system in electropneumatics.

- The programmable logic controller and the valve terminals each have an interface for connecting them to the fieldbus. Each interface consists of a transmitter circuit and receiver circuit.
- The fieldbus transmits the information between the PLC and the valve terminals.

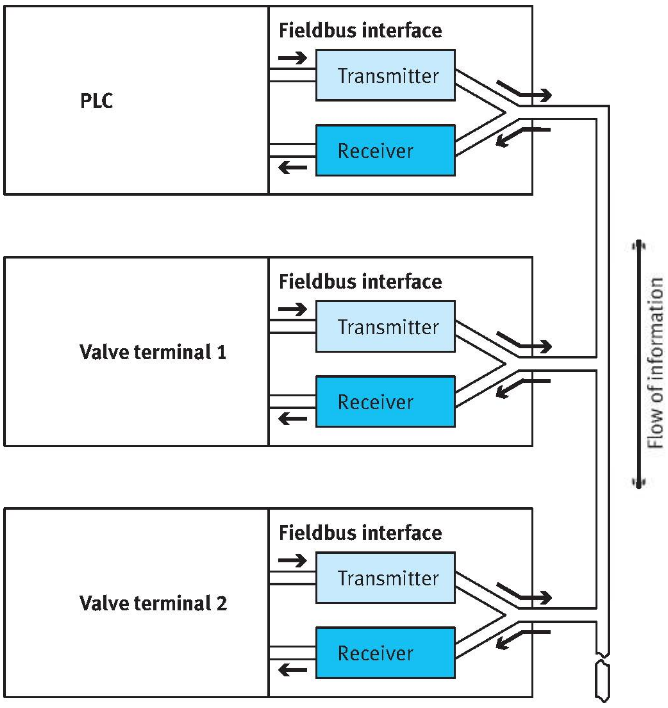



Figure 7.6: Structure of a fieldbus system in electropneumatics

The energy for operating the valves and sensors is transmitted via the same cable.

### 7.5.6 Mode of operation of a fieldbus system

The exchange of information between the PLC and valve terminal takes place as follows:

- If, for example, the solenoid coil of a valve is to be actuated, the PLC sends a sequence of binary signals via the fieldbus. The valve terminal identifies which solenoid coil is to be actuated from this signal sequence and executes the instruction.
- If a proximity sensor changes its signal status, the valve terminal or the sensor connection module sends a signal sequence to the programmable logic controller. This detects the change and takes it into consideration during program processing.

Besides the status of the inputs and outputs, further information is transmitted via the fieldbus that prevents, for example, the PLC and a valve terminal or two valve terminals transmitting at the same time.

It is also possible to network the PLCs for two electropneumatic control systems via a fieldbus system so that the two PLCs can exchange information between themselves.

### 7.5.7 Fieldbus types

There are numerous fieldbus types: They differ in

- the way in which the information is encrypted and decrypted,
- the electrical connection,
- the transmission speed.

Fieldbus systems can be broken down into company-specific bus systems and open bus systems that are used by different PLC manufacturers (e.g. Profibus). Valve terminals and sensor connection modules are available for a wide range of fieldbus systems. Only controllers and valve terminals that are designed for the same fieldbus can be combined.

# 8 Proportional pneumatics

Proportional pneumatics is primarily used for the following areas of application:

- Continuous adjustment of pressures and forces
- Continuous adjustment of flow rates and speeds
- Positioning using numerically controlled drives, for example in handling technology

## 8.1 Proportional pressure regulators

### 8.1.1 Function of a proportional pressure regulator

A proportional pressure regulator converts an electrical voltage as an input signal to a pressure as an output signal. The pressure at the working output can be continuously adjusted from 0 kPa up to the maximum pressure of, for example, 600 kPa.


Figure 8.1: Proportional pressure regulators with different nominal sizes

### 8.1.2 Application for a proportional pressure regulator

Figure 8.2 shows a device for checking office chairs. To test the durability of the backrest springs, the chair is subjected to a force that changes periodically. The maximum force and the force curve plotted as a function of time can be varied to enable different test cycles. Figure 8.2 also shows two possible force curves as a function of time.

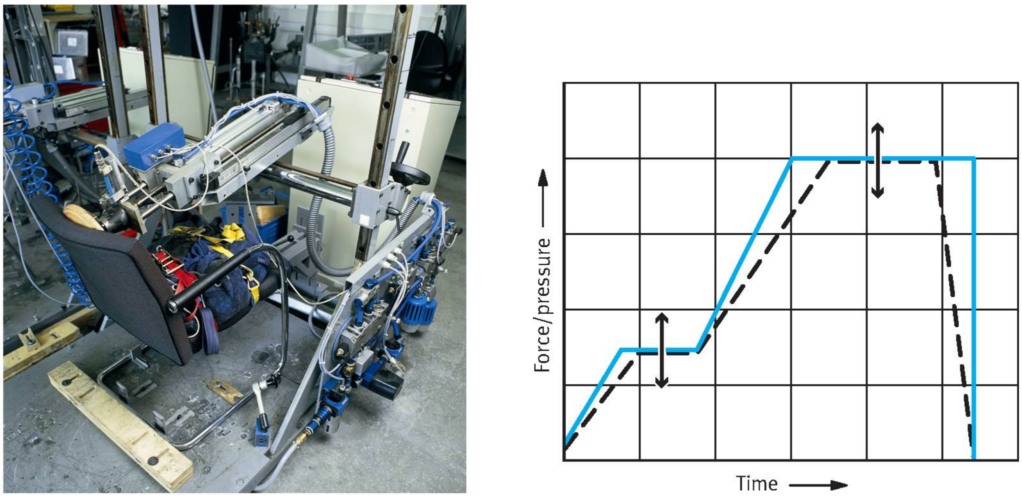



Figure 8.2: Test device for office chairs; left: test device setup; right: force curve plotted against time

### 8.1.3 Controlling the test device

The electropneumatic control system of the test device works according to the following principle:

- A programmable logic controller that can additionally process analogue signals outputs a setpoint pressure value in the form of an electric voltage.
- The proportional pressure regulator generates a pressure at its working output that is proportional to the electric voltage (low voltage = low pressure, high voltage = high pressure).
- The working output of the proportional pressure regulator is connected to the cylinder chamber. High pressure at the proportional valve output means high cylinder piston force; low pressure at the valve output means low piston force.

If the electric voltage at the output of the PLC increases, the proportional valve raises the pressure in the cylinder chamber. The piston force increases. If the electric voltage at the output of the PLC decreases, the proportional valve lowers the pressure in the cylinder chamber. The piston force drops.

### 8.1.4 Equivalent circuit diagram for a proportional pressure regulator

Figure 8.3 shows the equivalent circuit diagram for a proportional pressure regulator. The valve has a supply port, a working port and an exhaust port. The two electrical connections have the following functions:

- The valve's signal input is connected to the analogue output of the electric controller.
- The prevailing pressure at the working output can be tapped as an analogue electrical signal at the valve's signal output. This output does not have to be connected for the valve function.

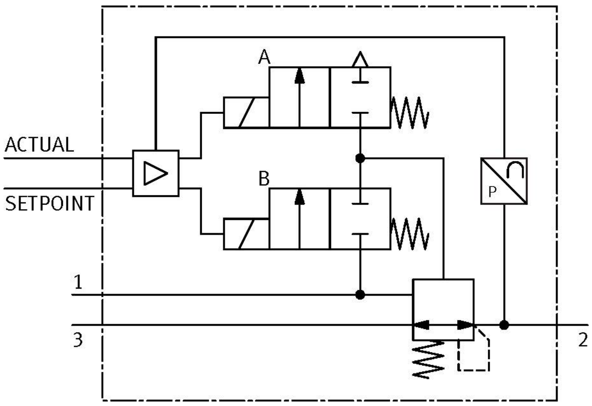



Figure 8.3: Proportional pressure regulators: equivalent circuit diagram

### 8.1.5 How a proportional pressure regulator works

The pressure at the working output is measured using a pressure sensor. The measured value is compared with the setpoint pressure value.

- If the setpoint pressure value is greater than the actual pressure value, switching valve A is opened (Figure 8.3). The pressure at the top of the pressure balance increases. As a result the working port is connected with the supply port. Compressed air flows to the working port and the pressure at the working port increases. The pressure on both sides of the pressure balance is equalised and the pressure balance returns to its initial position. The valve closes when the required pressure is reached.
- If the setpoint pressure value is less than the actual pressure value, switching valve B is opened. The pressure at the top of the pressure balance decreases. The working port is connected to the exhaust side. The pressure at the working port drops and the pressure balance returns to its initial position.

Figure 8.4 shows the pressure curve at the working port for three different, but constant input voltages. The valve keeps the pressure constant in a wide variety of pressure ranges, independent of the flow rate. The pressure only drops when the flow rate is very high.

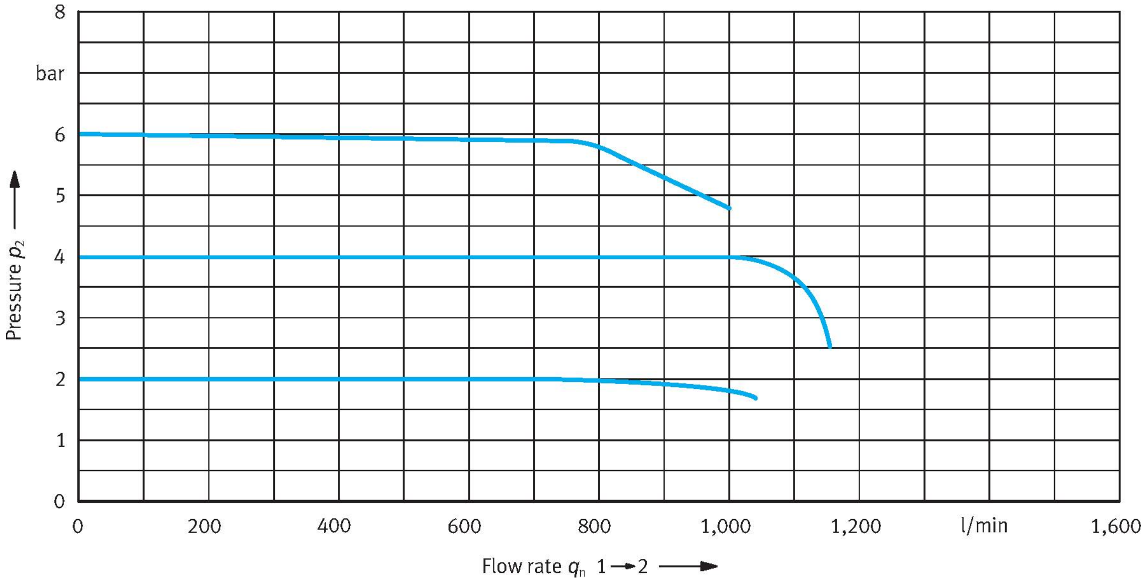



Figure 8.4: Proportional pressure regulators: pressure flow rate characteristic curve, $p_2$ = output pressure

## 8.2 Proportional directional control valves

### 8.2.1 Functions of a proportional directional control valve

A proportional directional control valve combines the characteristics of a solenoid actuated switching directional control valve and an electrically adjustable flow control valve. The connections between the valve ports can be opened and closed. The flow rate can be adjusted from zero to the maximum value.

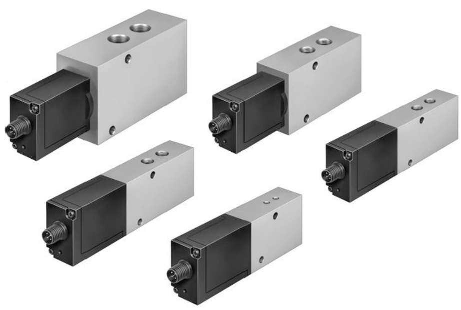


Figure 8.5: Proportional directional control valves with different nominal sizes

### 8.2.2 Application for a proportional directional control valve

A proportional directional control valve can be used to continuously change the valve flow rate and therefore the travel speed of a pneumatic cylinder's piston rod. This enables the speed curve to be optimised to enable high speeds with smooth acceleration and deceleration (Figure 8.6). Applications include transporting delicate goods (e.g. in the food industry).

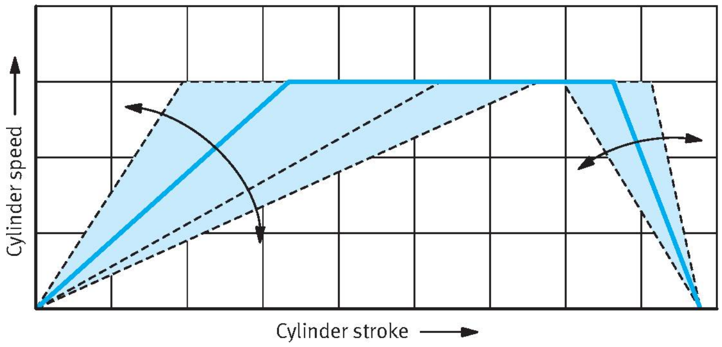



Figure 8.6: Proportional directional control valves: examples of speed curves

### 8.2.3 Equivalent circuit diagram for a proportional directional control valve

Figure 8.7 shows the equivalent circuit diagram for a 5/3-way proportional valve. The valve assumes different switching positions as appropriate to the analogue electrical input signal (= manipulated variable):

- Input signal less than 5 V:
  ports 1 and 2 as well as 4 and 5 connected
- Input signal 5 V:
  valve closed (mid-position)
- Input signal greater than 5 V:
  ports 1 and 4 as well as 2 and 3 connected

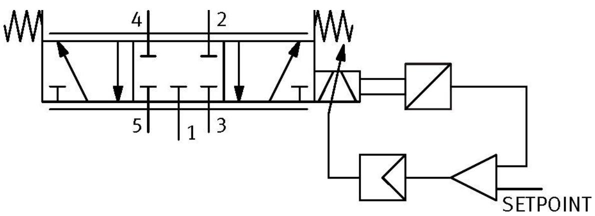



Figure 8.7: Proportional directional control valves: equivalent circuit diagram

### 8.2.4 Flow rate signal function of a proportional directional control valve

The valve opening is also changed as a function of the manipulated variable. The flow rate signal function describes the relationship between the manipulated variable and flow rate (Figure 8.8):

- Input signal 0 V:
  ports 1 and 2 are connected, maximum flow rate
- Input signal 2.5 V:
  ports 1 and 2 are connected, reduced flow rate
- Input signal 5 V:
  valve closed
- Input signal 7.5 V:
  ports 1 and 4 are connected, reduced flow rate
- Input signal 10 V:
  ports 1 and 4 are connected, maximum flow rate

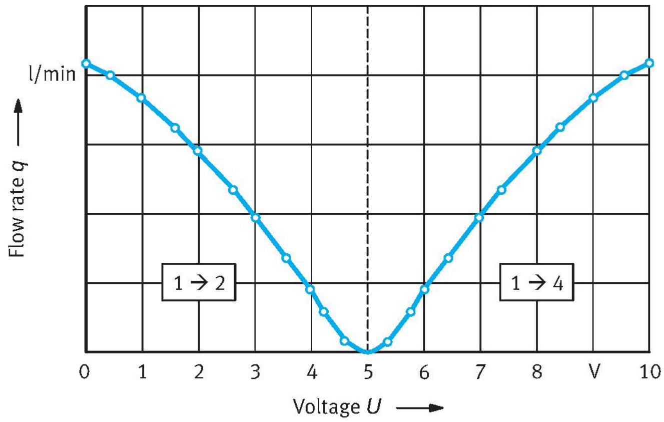



Figure 8.8: Proportional directional control valves: flow rate characteristic curve (flow rate signal function)

## 8.3 Pneumatic positioning drive

A pneumatic positioning drive is used to approach several pre-programmed positions with a pneumatic cylinder. The piston is held between the air pockets of the two cylinder chambers by means of position control. This means that the piston can be positioned not just at the stop, but at any point along the stroke range. Positioning accuracy of 0.1 mm is achieved depending on the drive. Thanks to the position control, a position is held even if there is a force acting on the piston.

### 8.3.1 Application for a pneumatic positioning drive

Pneumatic positioning drives are used, for example, for handling, palletising and assembly. Figure 8.9 shows a system for sorting drink cartons into packaging boxes using a pneumatic positioning drive.

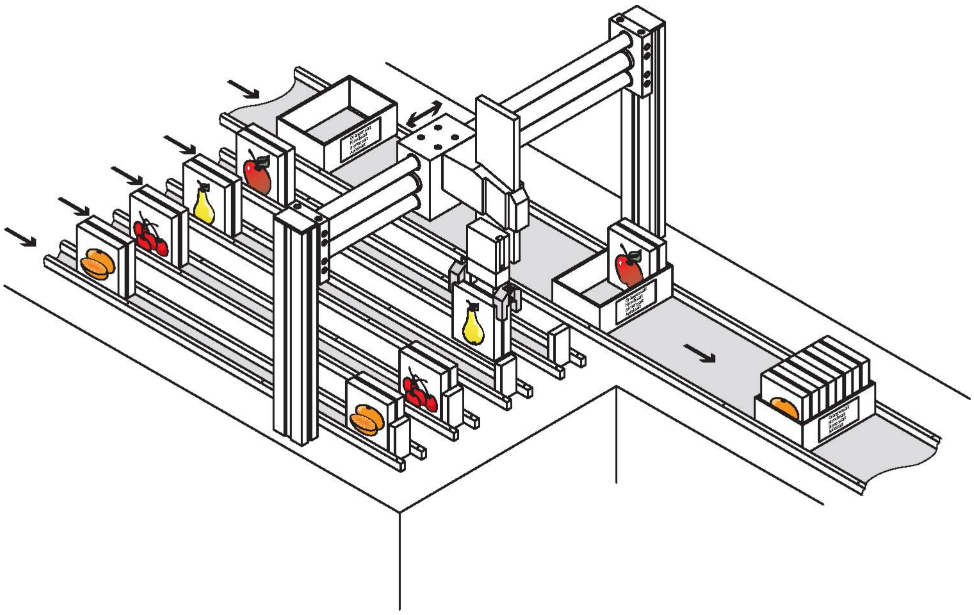


Figure 8.9: Application for a pneumatic positioning drive

### 8.3.2 Structure of a pneumatic positioning drive

A pneumatic positioning drive consists of the following components:

- Numerical controller
- Proportional directional control valve
- Double-acting pneumatic cylinder
- Displacement encoder

# 9 Basic principles of electrical engineering

## 9.1 Direct current and alternating current

A simple electric circuit consists of a voltage source, a consuming device and the connecting cables.

In physical terms, the negatively charged particles within the electric circuit, the electrons, move from the negative terminal of the voltage supply to the positive terminal via the electrical conductor. This movement of the charged particles is referred to as electric current. An electric current can only flow when the circuit is closed.

A distinction is made between direct and alternating currents:

- If voltage always flows in one direction in the circuit, this produces a current that also always flows in one direction. This is a direct current (DC) or a DC circuit.
- With alternating current (AC) or in an AC circuit, the voltage and current change direction and intensity at specific intervals.

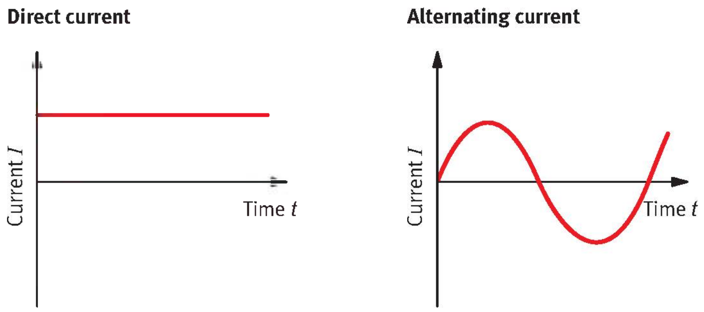



Figure 9.1: Direct current and alternating current plotted over time

Figure 9.2 shows a simple DC circuit consisting of a voltage supply, electrical cables, a control switch and a consuming device (a light in this example).

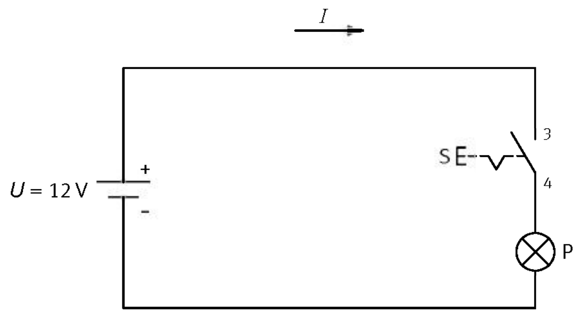



Figure 9.2: DC circuit

**Technical direction of current**

When the control switch is closed, a current I flows through the consuming device. The electrons move from the negative terminal to the positive terminal of the voltage supply. Before electrons were discovered, the direction of current was defined as going from "positive" to "negative". This definition is still valid in practice today; it is called the technical direction of current.

## 9.2 Ohm's law

Ohm's law describes the relationship between voltage, current intensity and resistance. It states that in a circuit with a given electrical resistance, the current intensity changes in direct proportion to the voltage, i.e.

- if the voltage rises, the current intensity rises too,
- if the voltage drops, the current intensity drops too.

$$U = R \cdot I$$

| | | |
|---|---|---|
| $U$ | Voltage | Unit: volt (V) |
| $R$ | Resistance | Unit: ohm (Ω) |
| $I$ | Current intensity | Unit: ampere (A) |

### 9.2.1 Electrical conductor

The term electric current refers to the directional movement of charged particles. For a current to flow in a material there must be enough free electrons present. Materials that meet this criterion are called electrical conductors. Copper, aluminium and silver are particularly good electrical conductors. Copper is the main conductive material used in control technology.

### 9.2.2 Electrical resistance

Every material offers resistance to an electric current. This is caused by the freely moving electrons colliding with the atoms in the conductive material, which results in their movement being impeded. Electrical conductors have a low resistance. Materials with a particularly high resistance to electric current are called electrical insulators. Rubber and plastic-based materials are used to insulate electrical lines and cables.

### 9.2.3 Source voltage

There is a surplus of electrons at the negative terminal of a voltage source and a shortage of electrons at the positive terminal. This effect produces the source voltage.

## 9.3 Electrical power

In mechanics, power can be defined in terms of work. The faster work is done, the greater the power required. Power therefore means: work per unit of time.

In the case of a consuming device in an electrical circuit, electrical energy is converted into kinetic energy (e.g. electric motor), light radiation (e.g. electric light) or thermal energy (e.g. electric heater, electric light). The faster the energy is converted, the higher the electrical power. Power therefore means: converted energy per unit time. It increases as the current and voltage grow.

The electrical power of a consuming device is also referred to as electrical consumption.

$$P = U \cdot I$$

| | | |
|---|---|---|
| $P$ | Power | Unit: watt (W) |
| $U$ | Voltage | Unit: volt (V) |
| $I$ | Current intensity | Unit: ampere (A) |

**Sample application – electrical power of a coil**

The solenoid coil of a 5/2-way valve is supplied with 24 V DC. The resistance of the coil is 60 Ω. What is the electrical consumption?

The current intensity is calculated using Ohm's law:

$$I = \frac{U}{R} = \frac{24\ \text{V}}{60\ \Omega} = 0.4\ \text{A}$$

The electrical consumption is the product of the current intensity and voltage:

$$P = U \cdot I = 24\ \text{V} \cdot 0.4\ \text{A} = 9.6\ \text{W}$$

## 9.4 How a solenoid works

When current flows through an electrical conductor, a magnetic field builds up around it. This magnetic field expands if the current intensity is increased. Magnetic fields exert an attractive force on workpieces made from iron, nickel or cobalt. This force increases as the magnetic field grows.

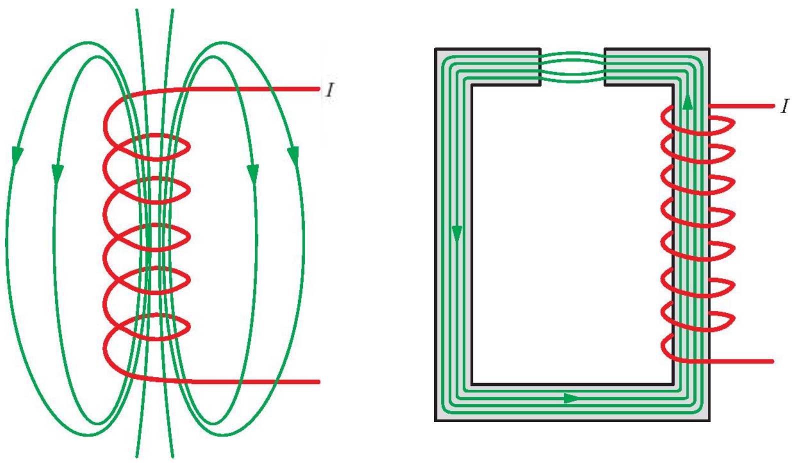



Figure 9.3: Electric coil and magnetic field lines; left: air-cored coil; right: coil with iron core and air gap

### 9.4.1 Structure of a solenoid

A solenoid has the following structure:

- The current-carrying conductor is wound in the shape of a coil. Superimposing the field lines of all coil windings increases the magnetic field and a primary field direction is formed.
- An iron core is placed in the coil. When an electric current flows, the iron is additionally magnetised. This enables a much stronger magnetic field to be generated at the same current intensity than with an air-cored coil.

Both of these measures ensure that a solenoid exerts a strong force on ferrous materials even when the current intensity is low.

### 9.4.2 Applications of solenoids

In electropneumatic control systems, solenoids are primarily used to influence the switching position of valves, relays or contactors. To explain how this happens, we will use the example of a directional control valve with spring return:

- When an electric current flows through the solenoid coil, the valve piston is actuated.
- When the current flow is interrupted, a spring pushes the valve piston back into its initial position.

### 9.4.3 Inductive resistance with AC voltage

An alternating current flows when an AC voltage is applied to a coil. This means that the current and magnetic field are constantly changing. A current is induced in the coil by changing the magnetic field. The induced current acts against the current generated by the magnetic field. The coil therefore offers resistance to the alternating current. This resistance is called inductive resistance. The greater the inductive resistance, the faster the electric voltage changes and the greater the inductance of the coil.

The unit for inductance is the "Henry" (H).

$$1\,\mathrm{H} = 1\,\frac{\mathrm{Vs}}{\mathrm{A}} = 1\,\Omega\mathrm{s}$$

### 9.4.4 Inductive resistance with DC voltage
With DC voltage, the current, voltage and magnetic field only change during switch-on. The inductive resistance is therefore only effective at the time of switch-on.

In addition to the inductive resistance, a coil also has an ohmic resistance. This resistance is effective both with DC voltage and with AC voltage.

## 9.5 How an electrical capacitor works
A capacitor consists of two conductive plates with an insulating layer (dielectric) between them. When a capacitor is connected to a DC voltage supply (closing the pushbutton S1 in Figure 9.4), there is a brief flow of charging current, which electrically charges the two plates. If the connection to the voltage supply is then interrupted, the charge remains stored in the capacitor. The greater the capacitance of a capacitor, the more electrically charged particles it stores at the same voltage.

The unit of capacitance is the "Farad" (F):

$$1\,\mathrm{F} = 1\,\frac{\mathrm{As}}{\mathrm{V}}$$

When the electrically charged capacitor is connected to a consuming device (closing the pushbutton S2 in Figure 9.4), charge balancing takes place. An electric current flows through the consuming device until such time as the capacitor is fully discharged.

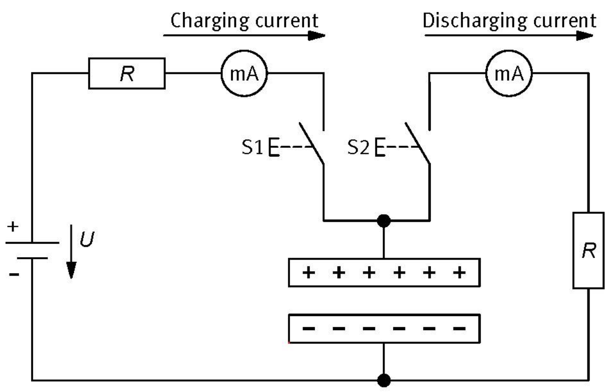



Figure 9.4: How a capacitor works

### 9.6 How a diode works

Diodes are electrical components whose resistance differs depending on the direction in which the electric current is flowing:

- The resistance is very low in the free-flow direction, which means the electric current can flow unimpeded.
- The resistance is extremely high in the blocked direction, which means no current can flow.

When a diode is integrated in an AC circuit, the current can only flow in one direction. The electric current is rectified.

A diode's effect on the electric current can be compared to the effect of a one-way flow control valve on the flow rate in a pneumatic circuit.

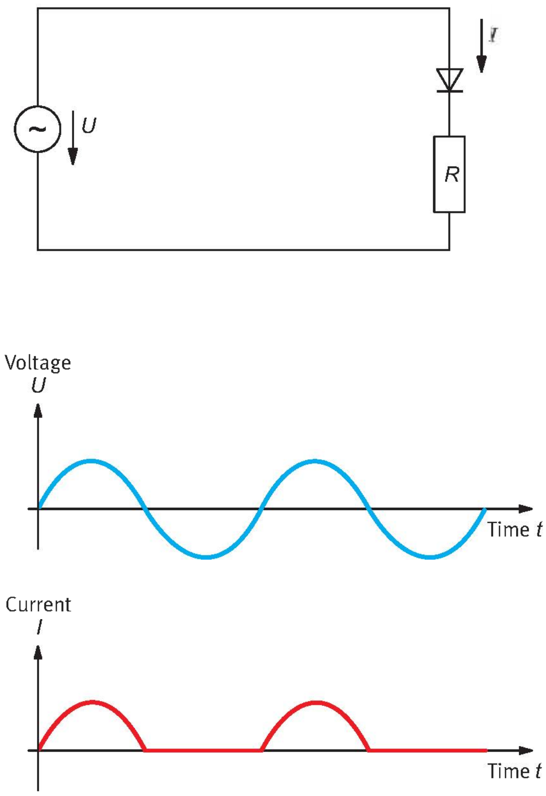



Figure 9.5: How a diode works

## 9.7 Measurements in an electrical circuit

### 9.7.1 Definition: Measuring

Measuring means comparing an unknown variable (e.g. the length of a pneumatic cylinder) with a known variable (e.g. the scale on a measuring tape). A measuring device (e.g. a tape measure) facilitates this comparison.

The result, the measured value, consists of a numerical value and a unit (e.g. 30.4 cm).

Electric currents, voltages and resistances are usually measured using multimeters. These measuring devices can be switched between different operation modes:

- AC voltage/alternating current and DC voltage/direct current
- Current measurement, voltage measurement and resistance measurement

Correct measurements are only possible if the correct operating mode is set.

A device for measuring voltage is also called a voltmeter, while a device for measuring current is also called an ammeter.

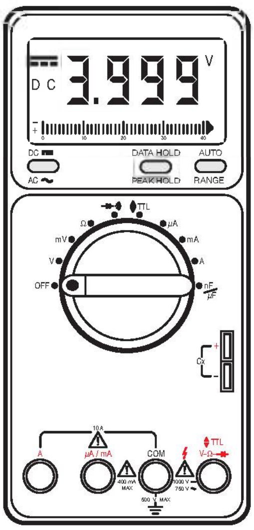



Figure 9.6: Multimeter

### 9.7.2 Safety measures

- Before taking a measurement, make sure that the electrical voltage of the part of the control system on which you want to perform the measurement is max. 24 V.
- Measurements on parts of a control system with a higher voltage (e.g. 230 V) can only be carried out by persons with the appropriate training or instruction.
- Failure to adhere to the correct procedure for measurements can be potentially fatal.

### 9.7.3 Procedure for measurements in an electrical circuit

Proceed in the following order when taking measurements in an electrical circuit:

- Switch off the supply voltage to the circuit.
- Set the required operating mode on the multimeter (current or voltage measurement, DC or AC voltage, resistance measurement).
- When using pointer measuring instruments, check and, if necessary, adjust the zero point.
- When measuring DC voltage/direct current, connect the measuring device to the correct terminal ("+" terminal of the measuring device to the positive terminal of the voltage supply).
- Choose the largest measuring range.
- Switch on the voltage supply to the circuit.
- Monitor the pointer or display and gradually switch over to a smaller measuring range.
- Read the display when the greatest pointer deflection occurs (smallest possible measuring range).
- When using pointer instruments, always read the display by looking down onto it to avoid reading errors.

### 9.7.4 Voltage measurement

For voltage measurements, the measuring device is connected parallel to the consuming device. The voltage drop across the consuming device corresponds to the voltage drop across the measuring device. Each voltage measurement device (voltmeter) has its own internal resistance. The current flowing through the meter should be minimal so as distort the measurement result as little as possible.

The internal resistance of the voltmeter must be as big as possible.

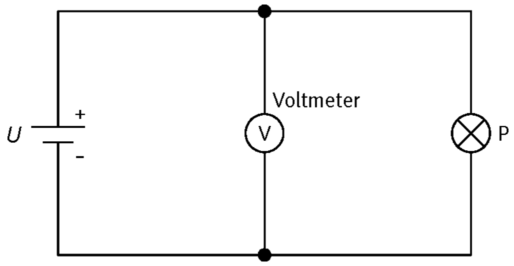



Figure 9.7: Voltage measurement

### 9.7.5 Current measurement

For current measurements, the measuring device is connected in series with the consuming device. The full consuming device current flows through the measuring device.

Each current measuring device (ammeter) has its own internal resistance. This additional resistance reduces the current flow. To keep measurement errors as low as possible, an ammeter may only exhibit a very small internal resistance.

The internal resistance of the ammeter must be as small as possible.

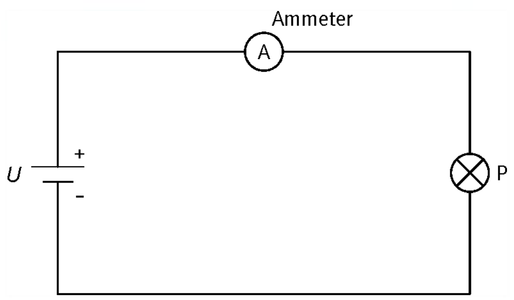



Figure 9.8: Current measurement

### 9.7.6 Resistance measurement

The resistance of a consuming device in a DC circuit can either be measured indirectly or directly.

- With indirect measurement, the current through the consuming device and the voltage drop across the consuming device are measured. Both measurements can either be performed one after the other or at the same time. The resistance is then calculated using Ohm's law.
- With direct measurement, the consuming device is separated from the circuit. The measuring device is switched to the "resistance measurement" operating mode and connected to the two terminals on the consuming device. The resistance value can then be read off.

If the consuming device is defective (e.g. the solenoid coil of a valve is burnt through), the resistance measurement will either give an infinitely high value or the value zero (short circuit).

**Important**
The ohmic resistance of a consuming device in an AC circuit must be measured using the direct method.

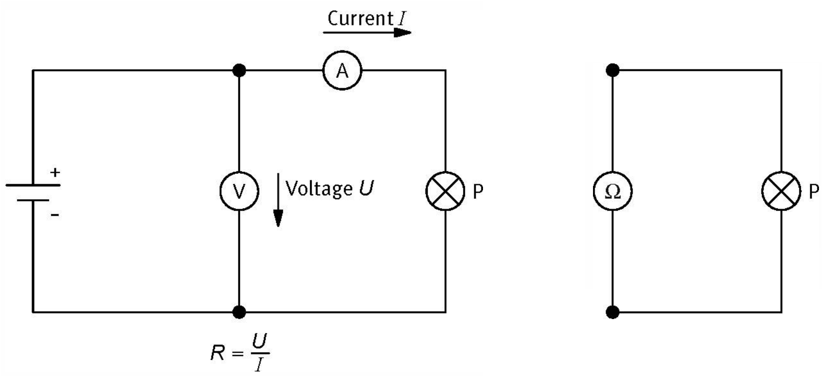



Figure 9.9: Resistance measurement; left: indirect measurement; right: direct measurement

### 9.7.7 Error sources when taking measurements in an electrical circuit

Measuring devices cannot measure electrical voltages, currents and resistances with arbitrary precision. On the one hand the measuring device itself influences the electrical circuit, on the other hand no measuring device indicates values exactly. The permissible indication error for a measuring device is specified as a percentage of the measuring range final value. If, for example, 0.5 is specified as an accuracy class for a measuring device, the indication error must not exceed 0.5% of the measuring range final value.

**Sample application: indication errors**

The voltage of a 9 V battery is measured using a measuring device from the 1.5 class. The measuring range is set once to 10 V and once to 100 V. What is the maximum permissible indication error for each of the two measuring ranges?

| Measuring range | Permissible indication error | Percentage error |
|---|---|---|
| 10 V | $10\ \text{V} \cdot \frac{1.5}{100} = 0.15\ \text{V}$ | $\frac{0.15\ \text{V}}{9\ \text{V}} \cdot 100 = 1.66\ \%$ |
| 100 V | $100\ \text{V} \cdot \frac{1.5}{100} = 1.5\ \text{V}$ | $\frac{1.5}{9\ \text{V}} \cdot 100 = 16.6\ \%$ |

Table 9.1: Calculating the indication error

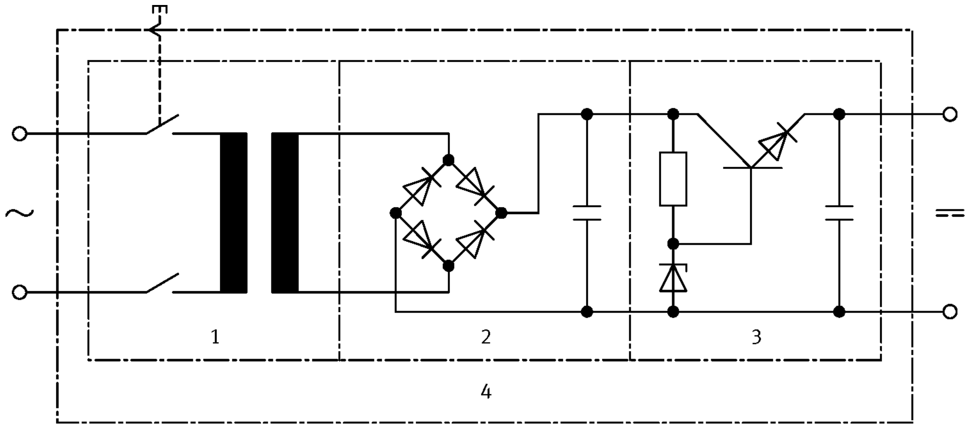
The sample calculation clearly shows that the permissible display error is smaller with the smaller measuring range. Furthermore, the measuring device can be read more effectively. For that reason the smallest possible measuring range should always be set.

# 10 Components and modules in the electrical signal control section

## 10.1 Power supply unit

The signal control section of an electropneumatic control system is supplied with energy via the electricity supply system. The control system has a power supply unit for this purpose (Figure 10.1). The individual modules of the power supply unit have the following purposes:

- The transformer reduces the operating voltage. The mains voltage is applied to the transformer inlet (e.g. 230 V AC), the voltage at the outlet is reduced (e.g. 24 V AC).
- The rectifier converts the AC voltage into DC voltage. The capacitor at the rectifier outlet smoothes the voltage.
- The voltage regulator at the power supply unit outlet is necessary to keep the electrical voltage constant irrespective of the flow of current.




1: Transformer; 2: Rectifier; 3: Stabiliser; 4: Power supply unit

Figure 10.1: Modules in a power supply unit

### Safety precautions

- Due to their high input voltage, power supply units are part of the high-voltage system (IEC 60346-1).
- The safety regulations for high-voltage systems must be observed.
- Work on the power supply unit must only be carried out by authorised persons.

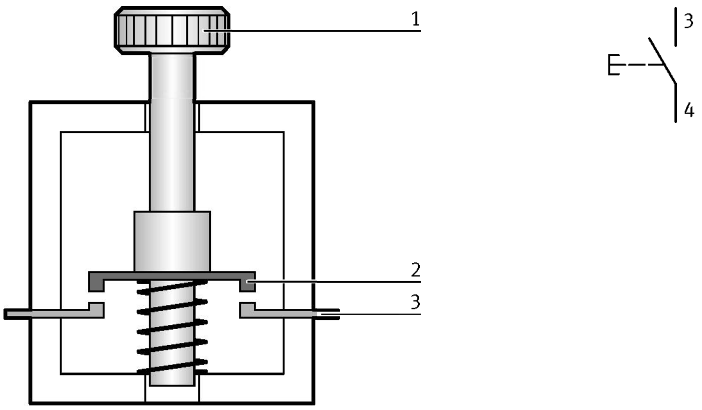
## 10.2 Pushbuttons and control switches

Switches are installed in a circuit to supply a consuming device in the electrical circuit with current or to interrupt the flow of current. These switches are divided into pushbuttons and control switches.

- With a pushbutton, the chosen switching position is only maintained for as long as the pushbutton is actuated. Pushbuttons are used, for example, to actuate bells.
- With a control switch, the two switching positions are mechanically locked. Each switching position is maintained until the switch is actuated again. Light switches in houses are an example of a control switch in use.

### 10.2.1 Normally open contacts

With a normally open contact, the electrical circuit is interrupted when the pushbutton is in its normal position, i.e. in unactuated condition. Actuating the control stem closes the electrical circuit and current flows to the consuming device. When the control stem is released, spring force returns the pushbutton to its normal position and the electrical circuit is interrupted.

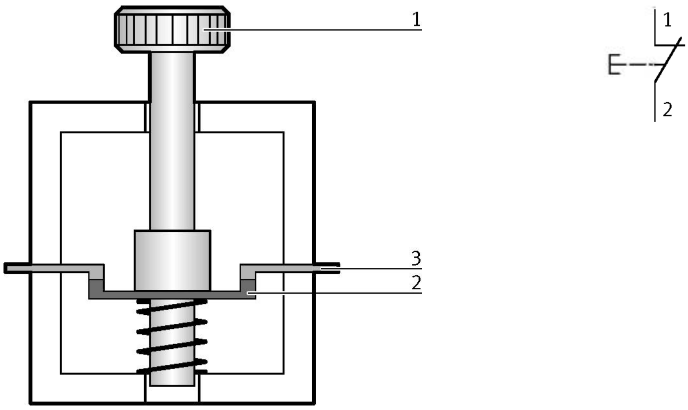



1: Button actuation method; 2: Switching element; 3: Connection

Figure 10.2: Normally open contact – sectional view and symbol

### 10.2.2 Normally closed contacts

With a normally closed contact, the circuit is closed by spring force when the pushbutton is in its normal position. Actuating the pushbutton interrupts the circuit.

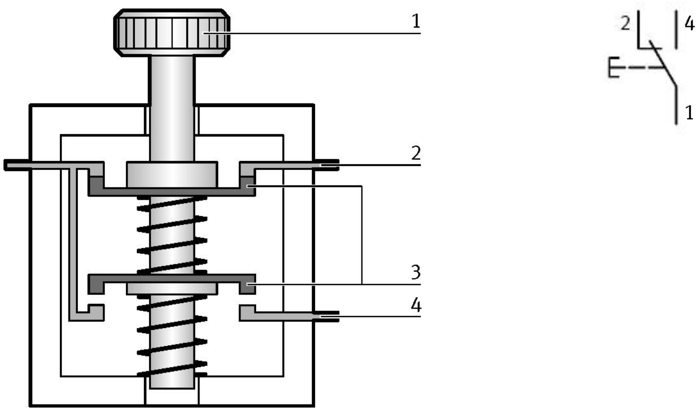



1: Button actuation method; 2: Switching element; 3: Connection

Figure 10.3: Normally closed contact – sectional view and symbol

### 10.2.3 Changeover switches

The changeover switch combines the functions of a normally closed contact and a normally open contact in one device. They are used to close one circuit and open another one with a single switching operation. Both circuits are briefly interrupted during the changeover.




1: Button actuation method; 2: Normally closed contact connection; 3: Switching element; 4: Normally open contact connection

Figure 10.4: Changeover switch – sectional view and symbol

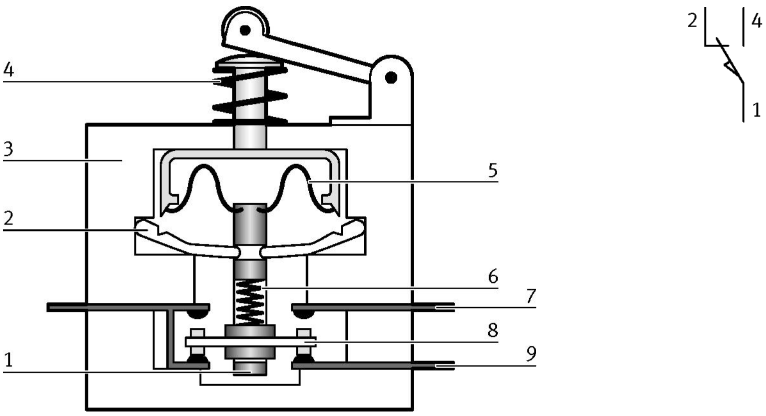
### 10.3 Sensors for position and pressure sensing

The purpose of sensors is to acquire information and to forward this information to the signal processing system in a format that is easy to evaluate. In electropneumatic control systems, sensors are primarily used to:

- Sense the advanced and retracted position of the piston rod in cylinder drives
- Determine the presence and position of workpieces
- Measure and monitor the pressure

#### 10.3.1 Limit switches

A limit switch is actuated when a machine part or a workpiece is in a specific position. This is generally done using a cam. Limit switches are usually designed as changeover switches. They can be connected as normally closed contacts, normally open contacts or changeover switches, depending on requirements.




1: Guide bolt; 2: Positive opening lever; 3: Housing; 4: Compression spring; 5: Bent leaf spring; 6: Contact compression spring; 7: Normally open contact connection; 8: Contact blade; 9: Normally closed contact connection

Figure 10.5: Mechanical limit switch – sectional view and symbol

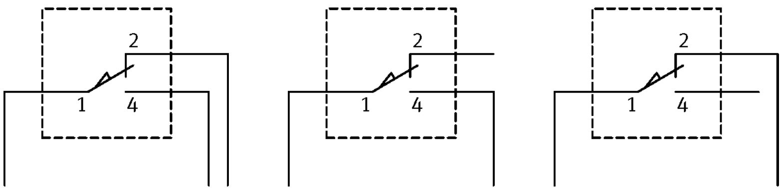



Figure 10.6: Mechanical limit switch – connection possibilities

### 10.3.2 Proximity sensors

In contrast to limit switches, proximity sensors operate without contact and without an external mechanical actuating force.

As a result, proximity sensors have a long service life and high switching reliability. There are the following types of proximity sensors:

- Reed switches
- Inductive proximity sensors
- Capacitive proximity sensors
- Optical proximity sensors

#### Reed switches

Reed switches are magnetically actuated proximity sensors. They consist of two contact reeds in a glass tube filled with inert gas. The field of a magnet causes the two reeds to close, allowing current to flow.

In reed switches that act as normally closed contacts, the contact reeds are closed by small magnets. This magnetic field is overcome by the considerably stronger magnetic field of the switching magnet.

Reed switches have a long service life and a short switching time (approx. 0.2 ms). They are maintenance-free, but must not be used in environments subject to strong magnetic fields (e.g. in the vicinity of resistance welders).

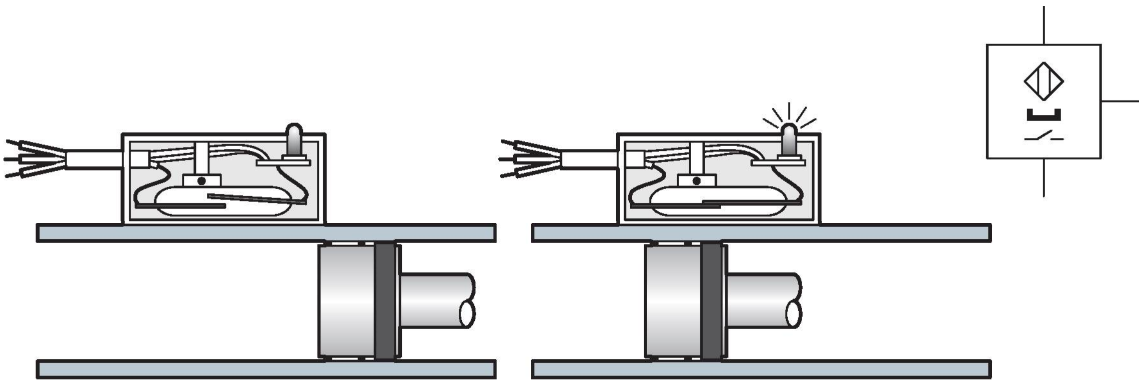


Figure 10.7: Reed switch (normally open contact) – sample application and symbol

**Electronic sensors**

Electronic sensors include inductive, optical and capacitive proximity sensors. They normally have three electrical connections:

- The connection for the supply voltage
- The connection for earth
- The connection for the output signal

With these sensors, no movable contact is switched over. Instead, the output is either electronically connected to the supply voltage or to ground (= output voltage 0 V).

**Positive-switching and negative-switching sensors**

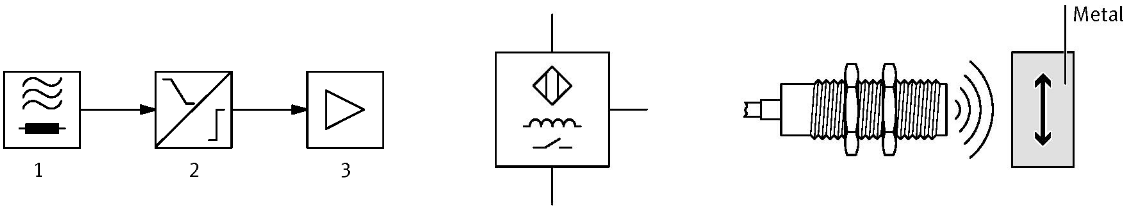
When it comes to the polarity of the output signal, there are two different designs of electronic proximity sensor:

- With positive-switching sensors, the output has a voltage of zero when there is no part within the sensor's response range. Approaching a workpiece or machine part results in the output being switched over so that supply voltage is applied.
- In the case of negative-switching sensors, supply voltage is applied to the output when there is no part within the sensor's response range. The approach of a workpiece results in the output being switched over to a voltage of 0 V.

**Inductive proximity sensors**

An inductive proximity sensor consists of an electrical resonant circuit (1), a flip-flop (2) and an amplifier (3). When voltage is applied to the terminals, the resonant circuit generates a high-frequency, alternating magnetic field that is emitted from the front of the sensor. If an electrical conductor is moved into this field, the resonant circuit is attenuated. The downstream electronic unit, consisting of a flip-flop and amplifier, evaluates the resonant circuit's behaviour and actuates the output.

Inductive proximity sensors can be used to detect all good electrical conductors, for example graphite as well as metals.




1: Resonant circuit; 2: Flip-flop; 3: Amplifier

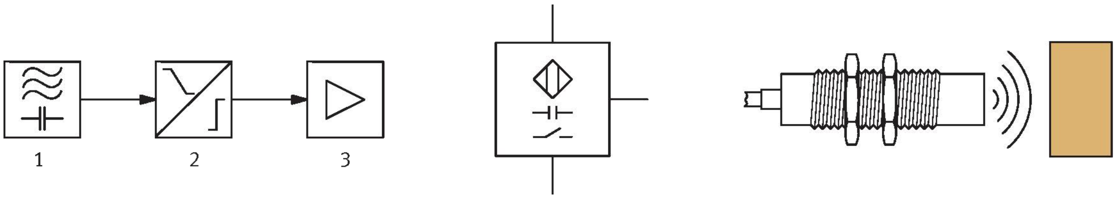
Figure 10.8: Inductive proximity sensor – operational circuit diagram, symbol, basic representation

### Capacitive proximity sensors

A capacitive proximity switch consists of a capacitor and a resistor that combine to form a RC oscillator circuit, as well as an electrical circuit for transmitting oscillation. An electrostatic field is generated between the capacitor's active and ground electrodes. A stray field is generated at the front of the sensor. If an object penetrates this stray field, the capacitance value of the capacitor is changed.

The oscillator circuit is attenuated. The downstream electronics activate the sensor's output.

Capacitive proximity sensors not only respond to materials with a high electrical conductivity (e.g. metals), but also to all insulators with a high dielectric constant (e.g. plastics, glass, ceramic, liquids and wood).




1: Oscillator circuit; 2: Flip-flop; 3: Amplifier

Figure 10.9: Capacitive proximity sensor – operational circuit diagram, symbol, basic representation

### Optical proximity sensors

Optical proximity sensors make use of optics and electronics in order to detect objects. Red or infrared light is utilised to this end. Particularly reliable sources for red and infrared light are semiconductor light emitting diodes (LEDs). They are small and sturdy, have a long service life and are easily modulated. Photodiodes or phototransistors are used as receiving elements. The advantage of red light is that it can be seen with the naked eye when adjusting the optical axes of the proximity switch used. Polymer optical fibres can also be used because of their low attenuation of light in this wavelength.

There are three types of optical proximity switches:

- Through-beam sensor
- Retro-reflective sensor
- Diffuse sensor

### Through-beam sensor

Through-beam sensors are equipped with physically separated transmitter and receiver units. The components are mounted so that the beam from the transmitter strikes the receiver directly. If the light beam is interrupted, the output is switched.

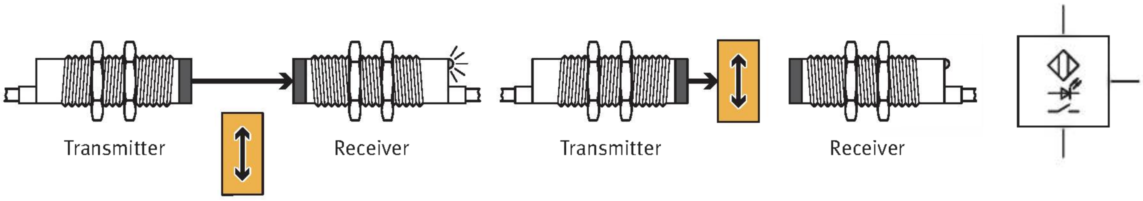



Figure 10.10: Through-beam sensor – basic representation, symbol

### Retro-reflective sensor

In the case of the retro-reflective sensor, the transmitter and the receiver are situated next to each other in a single housing. The reflector is mounted such that the light beam emitted by the transmitter is nearly fully reflected back to the receiver. If the light beam is interrupted, the output is switched.

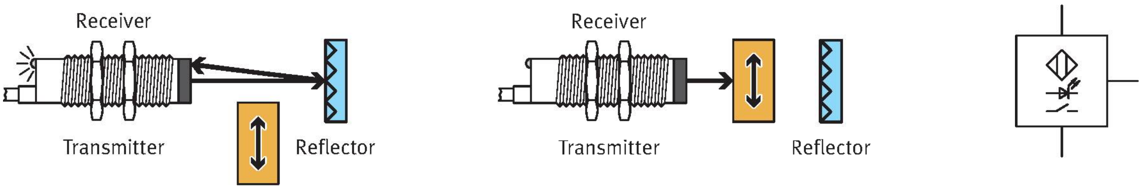



Figure 10.11: Retro-reflective sensor – basic representation, symbol

### Diffuse sensor

The transmitter and receiver in diffuse sensors are arranged side-by-side in a component. If the emitted light strikes a reflective surface, it is redirected to the receiver and the sensor's output is switched. This operational principle means diffuse sensors can only be used if the workpiece or machine part to be detected is highly reflective (e.g. metallic surfaces, light colours).

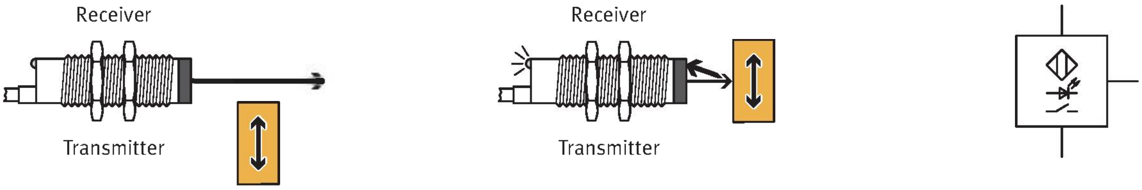



Figure 10.12: Diffuse sensor – basic representation, symbol

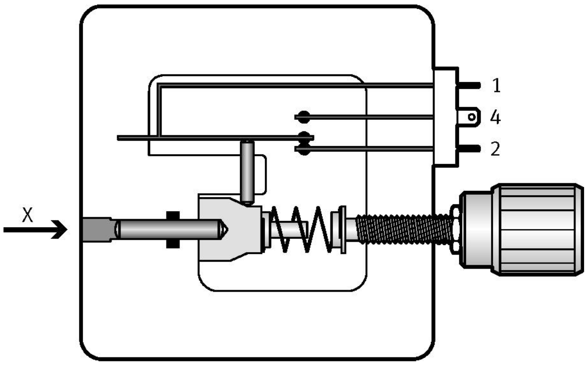
### Pressure sensors

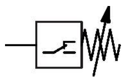
Pressure-sensitive sensors come in different designs:

- Pressure switches with mechanical contact (binary output signal)
- Pressure switches with electronic changeover (binary output signal)
- Electronic pressure sensors with analogue output signal

### Mechanical pressure switches

With mechanical pressure switches, the pressure acts on the surface of a piston. If the force generated by the prevailing pressure exceeds the force of the spring used, the piston is moved and actuates the contact points.



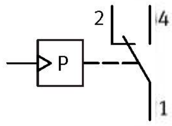



Figure 10.13: Piston pressure switch – sectional view, symbol to ISO 1219-1 and symbol to EN 60617-2

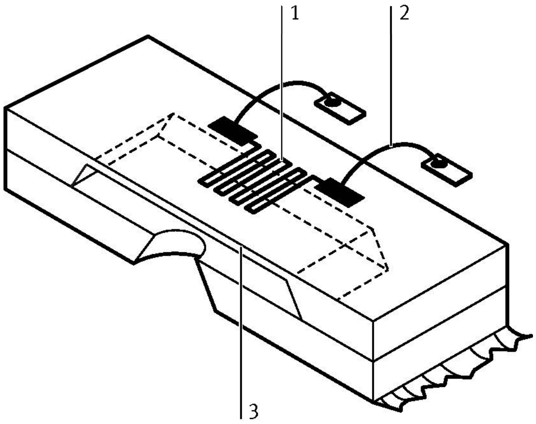
### Electronic pressure switches

Diaphragm pressure switches are gaining in significance. Instead of a contact being mechanically actuated, the output is electronically switched. Pressure or force-sensitive sensors are attached to the diaphragm for this purpose. The sensor signal is evaluated by an electronic circuit. As soon as the pressure exceeds a specific value, the output switches.

## Analogue pressure sensors

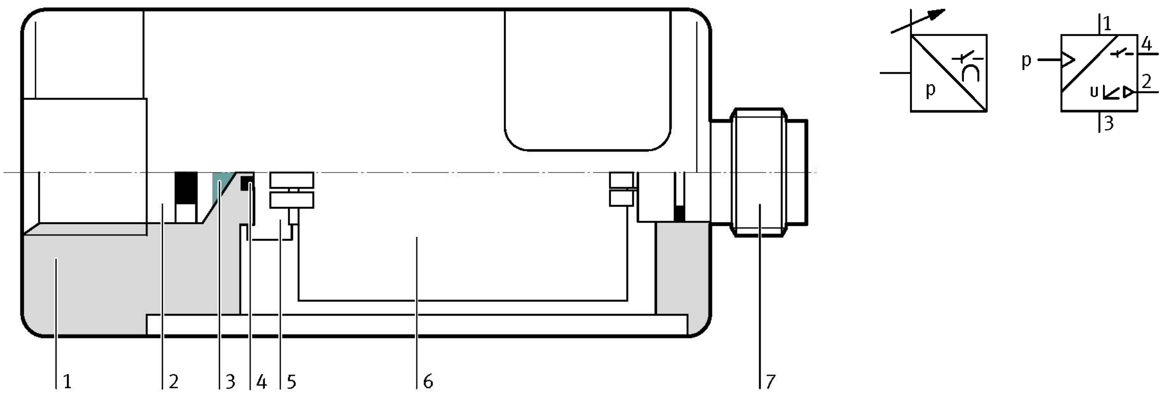
The structure and mode of operation of an analogue pressure sensor are explained below.

The electrical resistor (1) of the piezoresistive measuring cell changes its value as soon as a pressure acts on the diaphragm (3). The resistor is connected via the contacts (2) to the evaluation electronics that generate the output signal.




1: Diffused resistors; 2: Contacts; 3: Diaphragm

Figure 10.14: Measuring cell of a pressure sensor




1: Housing; 2: Cover; 3: Silica gel; 4: O-ring; 5: Measuring cell; 6: Amplifier; 7: Connector

Figure 10.15: Pressure sensor – sectional view, symbol to ISO 1219-1 and symbol to EN 60617-2

The sensor characteristic curve shows the relationship between the pressure and the electrical output signal. An increase in pressure results in an increase in the electrical voltage at the sensor output. A pressure of 1 bar generates an output voltage of 1 V, a pressure of 2 bar an output voltage of 2 V, etc.

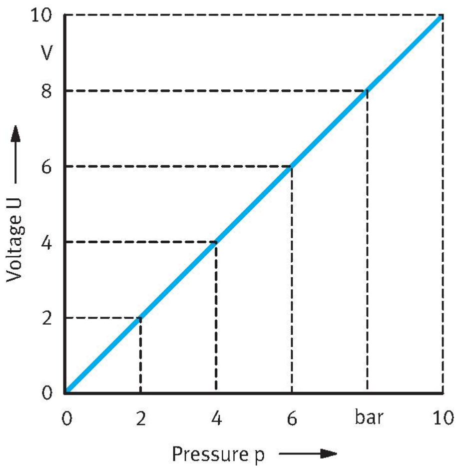
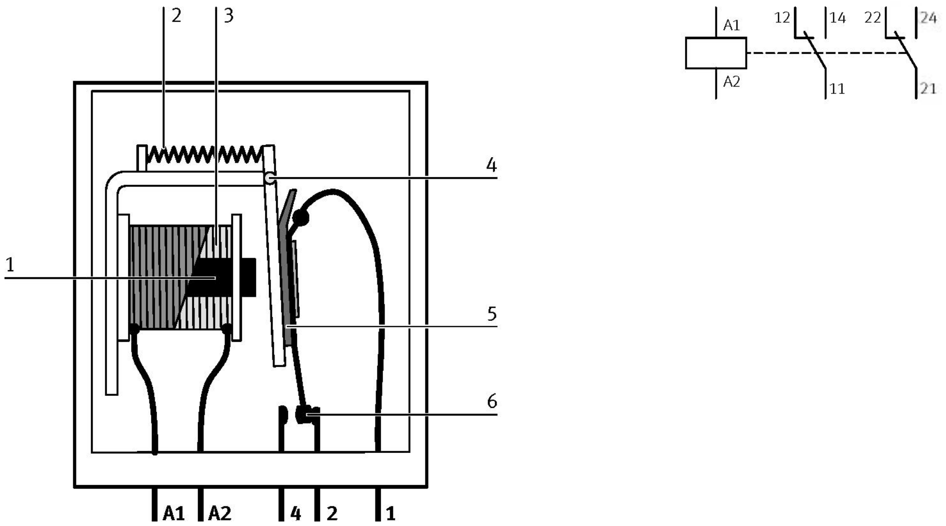



Figure 10.16: Characteristic curve for an analogue pressure sensor

## 10.4 Relays and contactors

### 10.4.1 Structure of a relay

A relay is an electromagnetically actuated switch. When a voltage is applied to the solenoid coil, an electromagnetic field is generated. This causes the movable armature to move towards the coil core. The armature acts upon the relay contacts that are either closed or opened, depending on the arrangement. If the flow of current through the coil is interrupted, a spring returns the armature to its initial position.




1: Coil core; 2: Return spring; 3: Relay coil; 4: Armature; 5: Insulation; 6: Contact

Figure 10.17: Relay – sectional view and symbol

A relay coil can be used to switch one or more contacts. In addition to the relay type described above, there are also other designs of electromagnetically actuated switches, for example the remanence relay, the time relay and the contactor.

### 10.4.2 Applications of relays

Relays are used in electropneumatic control systems for the following purposes:

- To multiply signals
- To delay and convert signals
- To link information
- To separate the control and main circuits

Relays are also used in purely electrical control systems to separate the DC and AC circuits.

### 10.4.3 Remanence relays

The remanence relay responds to current pulses.

- The armature is energised when a positive pulse is applied.
- The armature is de-energised when a negative pulse is applied.
- If no input signal is applied, the previously set switching position is retained.

The behaviour of a remenance relay is the same as that of a pneumatic double pilot valve that responds to pressure pulses.

### 10.4.4 Time delay relays

With time dealy relays, a distinction is made between relays with switch-on delay and relays with switch-off delay. With the relay with switch-on delay, the armature switches on with the delay; there is no switch-off delay. In a relay with switch-off delay, the reverse is true. The contacts switch accordingly. The delay time $t_d$ can be set.

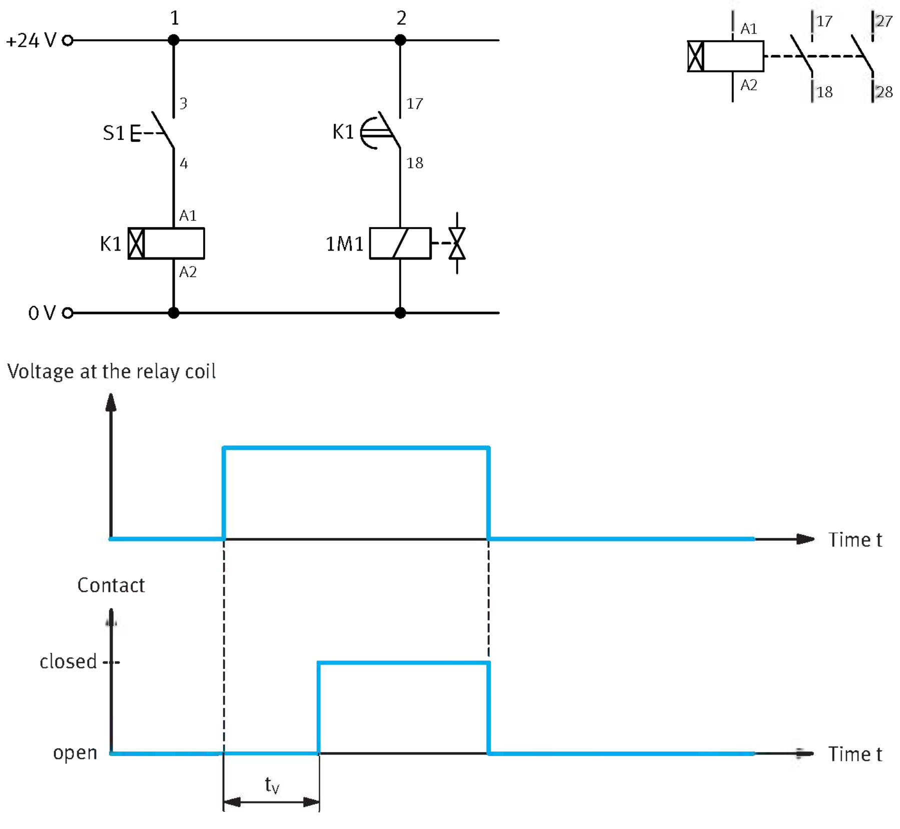



Figure 10.18: Relay with switch-on delay – representation in the circuit diagram, symbol and signal response

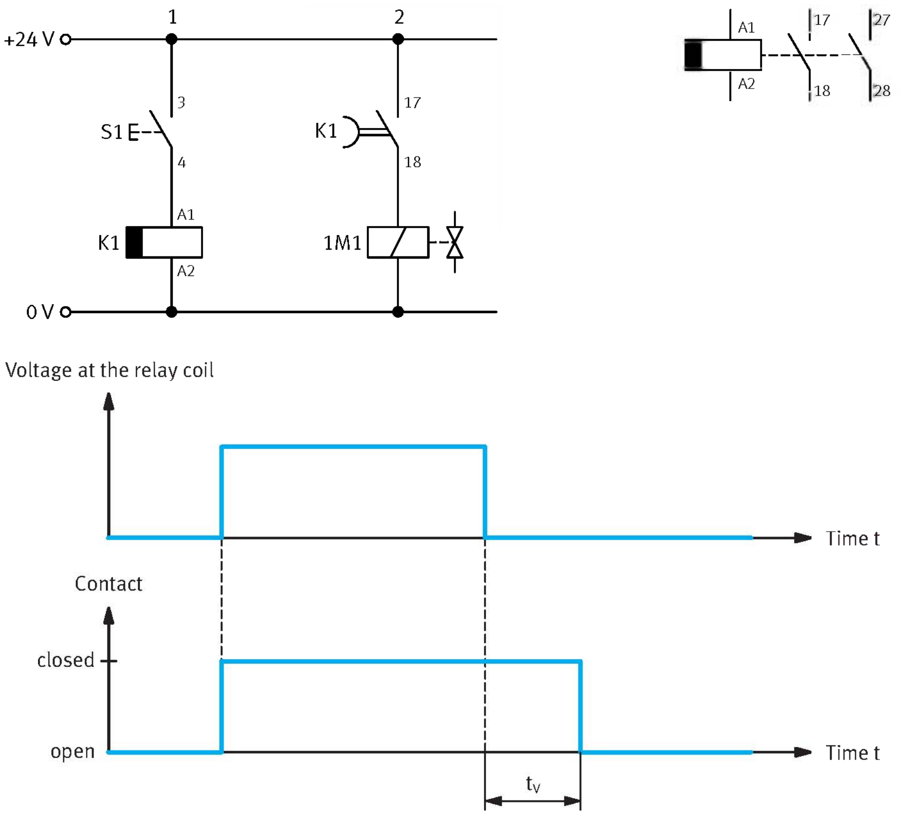


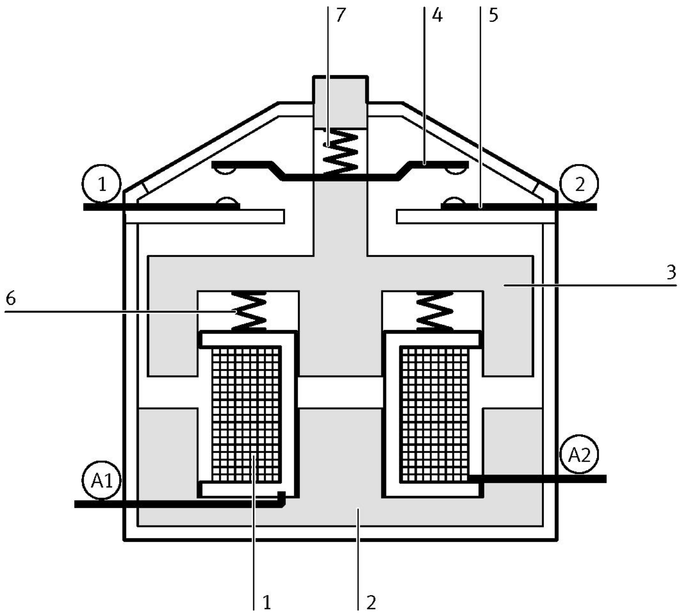

Figure 10.19: Relay with switch-off delay – representation in the circuit diagram, symbol and signal response

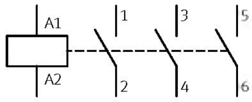
## 10.5 Structure of a contactor

Contactors work on the same principle as relays. Typical features of a contactor are:

- Double breaking (two breakpoints per contact)
- Forced contacts
- Enclosed chambers (arc-quenching chambers)

These design features enable contactors to switch higher currents than relays.




1: Coil; 2: Iron core (magnet); 3: Armature; 4: Moving switch element with contacts; 5: Static switch element with contacts; 6: Compression spring; 7: Contact compression spring

Figure 10.20: Contactor – sectional view and symbol

Each contactor has several logic elements; four to ten contacts are usual. Contactors, as relays, have different designs with combinations of normally closed contacts, normally open contacts, delayed normally closed contacts, etc. There are two types of contacts: main contacts and auxiliary contacts. Contactors that only switch auxiliary contacts (control contacts) are called auxiliary contactors. Contactors with main and auxiliary contacts are called main or power contactors.

**Applications of contactors**

Contactors are used for the following applications:

- Currents of 4 to 30 kW are switched via the main contacts of power contactors.
- Control functions and logic operations are switched by auxiliary contacts.

The electric currents and power in electropneumatic control systems are low. They can therefore be built using auxiliary contactors. Main or power contactors are not required.

## 10.6 Miniature controllers

The first programmable logic controller (PLC) was developed in 1968 by a group of engineers from General Motors when the company was looking for a replacement for complex relay controllers.

The new control system had to meet the following requirements:

- Simple programming
- Option to change the program without having to intervene in the system (no internal rewiring)
- Smaller, cheaper and more reliable than corresponding relay controllers
- Easy and cost-effective maintenance

Today, these requirements are also fully met by miniature controllers. These are suitable for simple switching and control tasks. Just a few inputs and outputs are often sufficient for quick and reliable automation of a process.

The main modules are

- the input module,
- the central unit and
- the output module.

The input module's role is to convert external signals into signals that can be processed by the PLC and to forward these signals to the control unit. The output module performs the reverse function. It converts the PLC signals into signals that the drives can use. The actual processing of the signals takes place in the central unit in accordance with the program stored in the memory.

The decisive advantage compared with relay controllers is that changes and extensions to controllers can be accomplished by simply changing or adding to the program in the miniature controller rather than having to change the wiring.

The following pictures show control systems that illustrate the transition from purely pneumatic controllers through relay controllers to miniature controllers.

**Sequence description for a continuous cycle**

1. If the limit switch 1B1 is actuated AND the control switch 1S1 is actuated, the 5/2-way valve switches and the piston rod of the cylinder 1A1 advances.
2. In the advanced end position, the piston rod of the cylinder 1A1 actuates the limit switch 1B2. The 5/2-way valve switches back and the piston rod of the cylinder 1A1 retracts.
3. The sequence repeats until the control switch 1S1 is switched back.

**Sequence description for an individual cycle**

1. If the limit switch 1B1 is actuated AND the pushbutton 1S2 is briefly actuated, the 5/2-way valve switches and the piston rod of the cylinder 1A1 advances.
2. In the advanced end position, the piston rod of the cylinder 1A1 actuates the limit switch 1B2. The 5/2-way valve switches back and the piston rod of the cylinder 1A1 retracts.

Figure 10.21 shows a purely pneumatic solution to the required sequence.

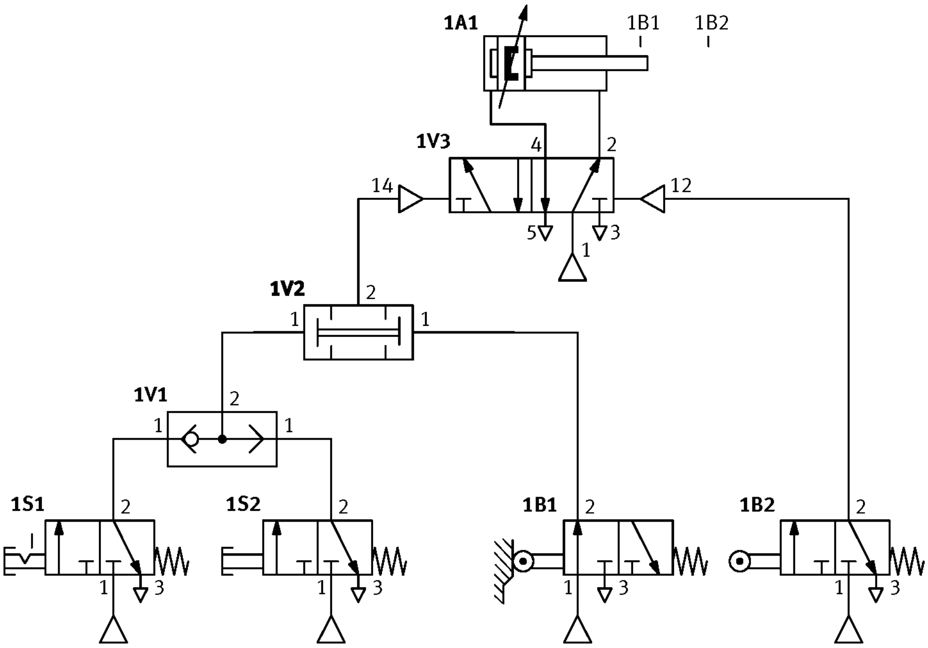



Figure 10.21: Pneumatic circuit diagram – pneumatic control system

In Figure 10.22, the specified sequence is realised using a 5/2-way double solenoid valve and a relay controller.

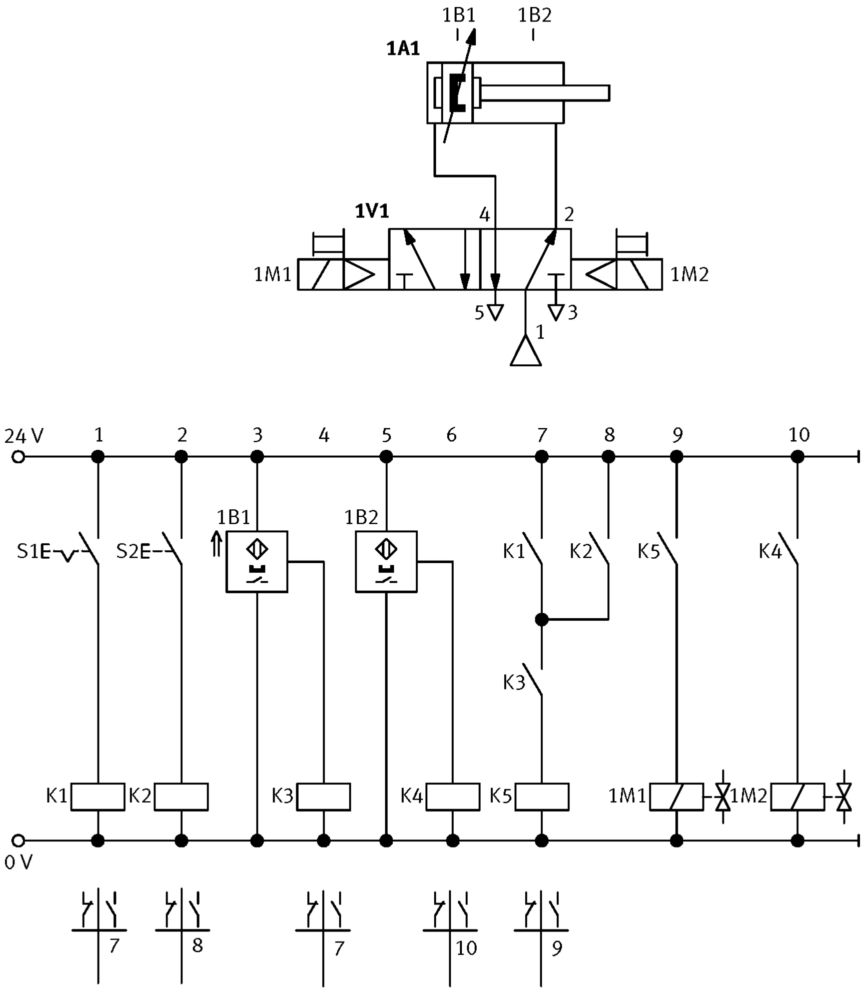



Figure 10.22: Pneumatic and electrical circuit diagram – control system with relay

In Figure 10.23, the sequence is controlled by a miniature controller. Figure 10.24 shows the associated logic program.

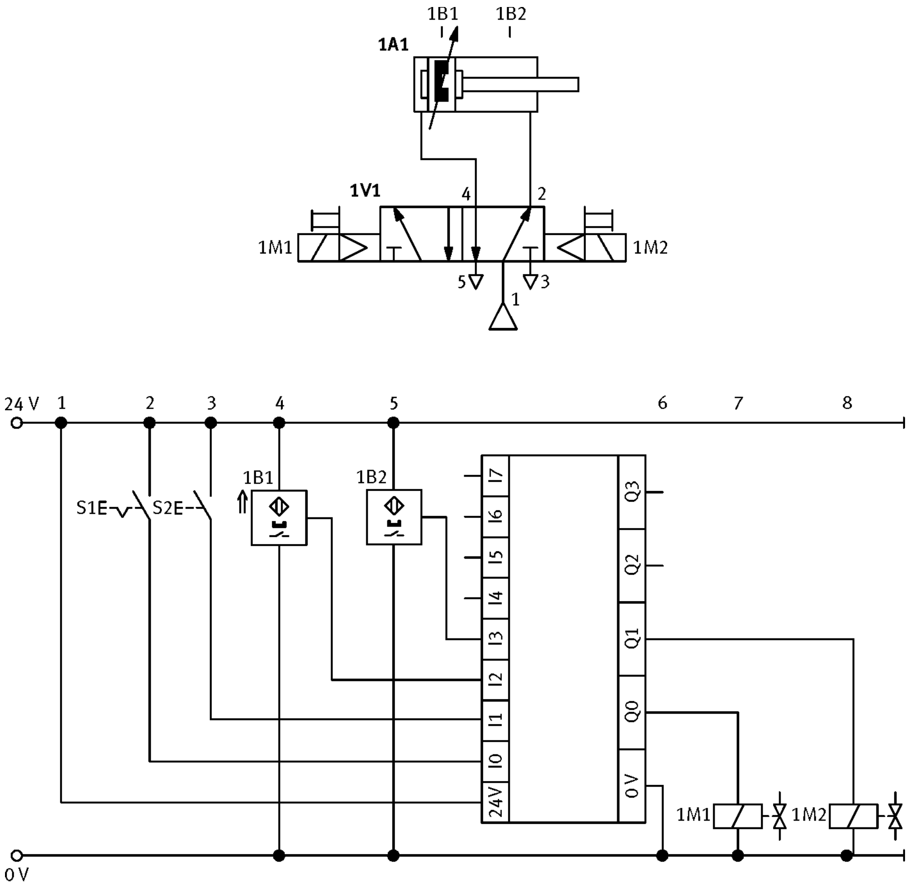



Figure 10.23: Pneumatic and electrical circuit diagram – control system with miniature controller

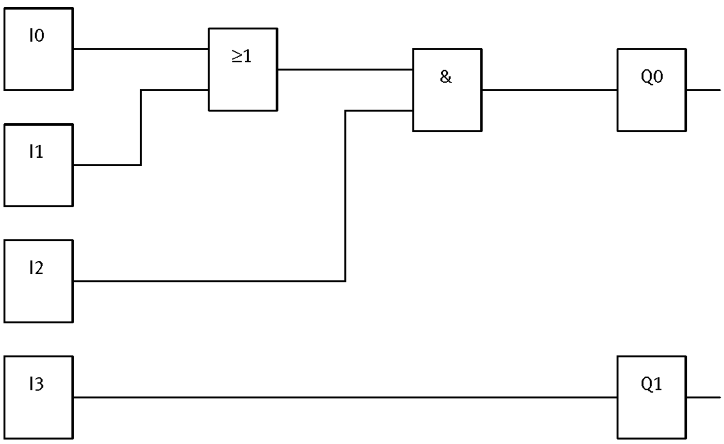



Figure 10.24: Logic program for the sequence described

# 11 Operating sequence descriptions

## 11.1 Function charts for processing machines and production systems

The purpose of the function chart is to simplify the planning, design and creation of the control system for processing machines and production systems. It is independent of the type of control system and the technology used.

The function chart can also be used as a fault-finding aid in the event of a malfunction. The representation principles and symbols should be the same in all cases so that representations of different origins (international) can be easily read and understood and there is no possibility of mix-ups. The simplest representation method is often sufficient to clearly describe the operating sequence.

**Note**

Function charts, logic symbols and action lines were recommended in the VDI guidelines 3226 and 3260. These VDI guidelines ceased to be valid in 1992 and 1994 respectively. They were replaced by DIN 40 719 Part 6 "Diagrams, charts, tables; rules for function charts".

This standard is also no longer valid; its last day of validity was 31 March 2005. The successor standard is called GRAFCET and is valid throughout Europe. Its designation is EN 60848.
Since function charts are widely used in industry for representing motion sequences, we will take a brief look at them.

### 11.1.1 Scope of validity of the function chart

Function charts are used to represent function sequences in mechanical, pneumatic, hydraulic, electric and electronic control systems as well as for combinations of these controller types, for example electropneumatic, electrohydraulic, etc.

Function charts consists of a motion diagram and a control chart. The motion diagram can be a displacement-step diagram or a displacement-time diagram. The following section deals exclusively with the displacement-step diagram.

### 11.1.2 Displacement-step diagram

The motion (travel, strokes) of the piston rods of cylinders 1A1 and 2A1 from sequence condition 1 to sequence condition 2 on the one hand and from sequence condition 2 to sequence condition 3 are represented graphically by means of function lines (motion lines) (Figure 11.1).

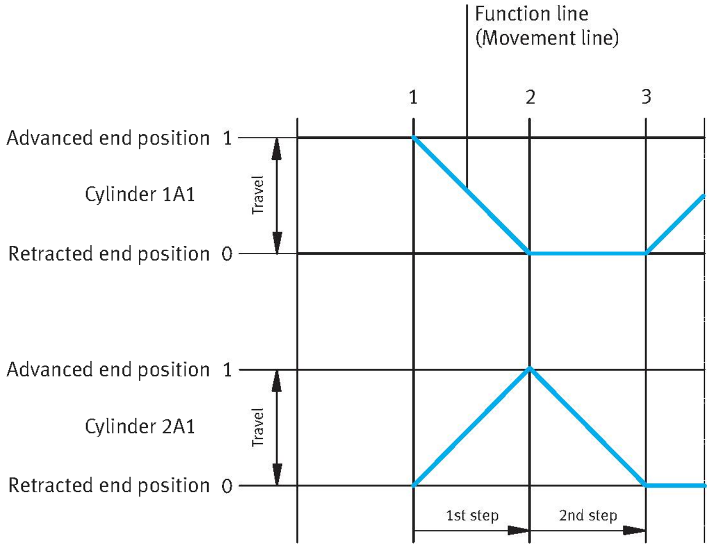
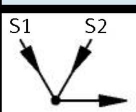
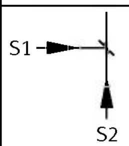
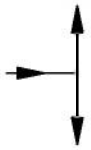



Figure 11.1: Displacement-step diagram for the movements of cylinder 1A1 and 2A1

In addition to the function lines, signal lines can also be plotted in the displacement-step diagram. The signal line starts at the signal element and ends wherever a change in status is initiated based on this signal. Arrows at the signal lines indicate the signal flow direction.

| Function | Symbol |
|---|---|
| OR operation |  |
| AND operation |  |
| Signal branch |  |

| Function | Symbol |
|---|---|
| Signalling element ON |  |
| Limit switch signalling element | ● |
| | |

Table 11.1: Representation of signal lines and input elements

The designations of the individual input elements are marked at the starting point of the respective signal line.

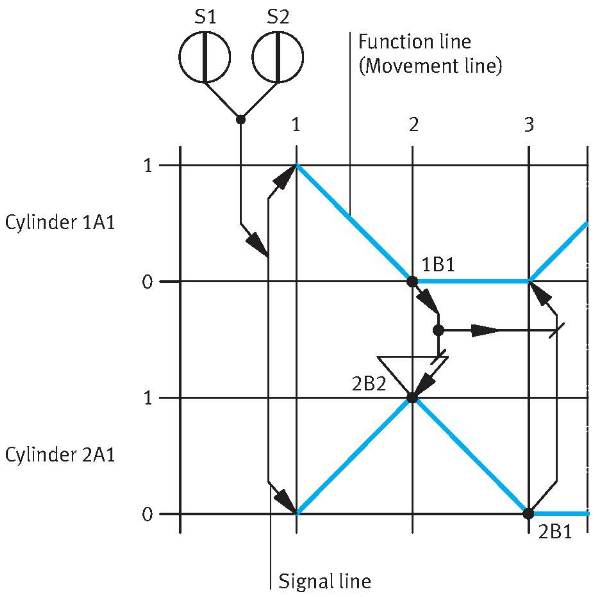



Figure 11.2: Displacement-step diagram with signal lines

## 11.2 Sequence description by means of GRAFCET to EN 60848

A GRAFCET essentially describes two aspects of a control process in accordance with defined rules:

- The actions to be executed (commands)
- The sequence in which they are executed

A GRAFCET – also called a GRAFCET plan – is therefore divided into two parts. The structure shows the timeline for the process, with the process broken down into consecutive steps.

The structure does not describe the individual actions to be executed. These are included in the action or working section. In the example shown, these are the blocks to the right of the steps as well as the transition conditions between the steps.

### 11.2.1 The basic principle of a GRAFCET

1. Sequences are broken down into alternating
   – steps and
   – transitions.
2. Only one step is active at any given time.
3. Any desired number of actions can be linked to the steps.
4. Sequences can be branched and merged as
   – alternative branchings or
   – parallel branchings.
   Step 1 must be observed in this case!

### 11.2.2 Steps

The sequences are broken down into steps. Each step is represented as a box (squares are preferable to rectangles). There must be an alphanumeric identification in the top centre of the step box.

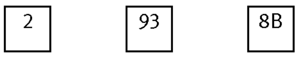



Figure 11.3: Examples of steps

### Initial step

Each sequence has an initial step. It is the initial position of the controller, the step where the controller (not the machine!) is located immediately after the controller is switched on. It is identified by the double frame.


Figure 11.4: Example of an initial step

### 11.2.3 Transition condition

A transition links one step to the next. It is represented by a line running at right angles to the connection between the two steps.

**Exception**

In the event of a return, the transition can also be on a horizontal action line to aid transparency.

**Most important rule**

For an error-free sequence, steps and transitions must always alternate.

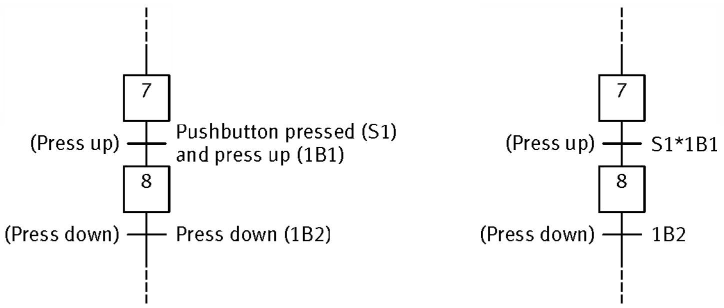



Figure 11.5: Examples of transition conditions

The step criterion is to the right of the transition. The transition can be assigned a transition name. To avoid mix-ups, it must be placed on the left and must be in brackets.

**Note:**

The dot or the asterisk used describes an AND operation, the plus sign describes an OR operation. Negations are represented by means of a line over the variable name.

To continue with the next step after a defined time, a time-dependent transition condition is used. The transition condition contains the time and status of the active step, separated by a slash.

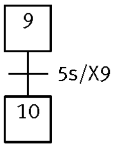



Figure 11.6: Example of time-limited execution of a step

In the example show, X9 is the step variable for step 9 and represents the Boolean status of step 9. After 5 seconds the sequence continues with step 10.

### 11.2.4 Actions

One or more actions can be added to a step. An action is represented as a rectangle with any aspect ratio. Different action behaviours are represented with different additions. The sequence shown in the representation is not a chronological sequence!

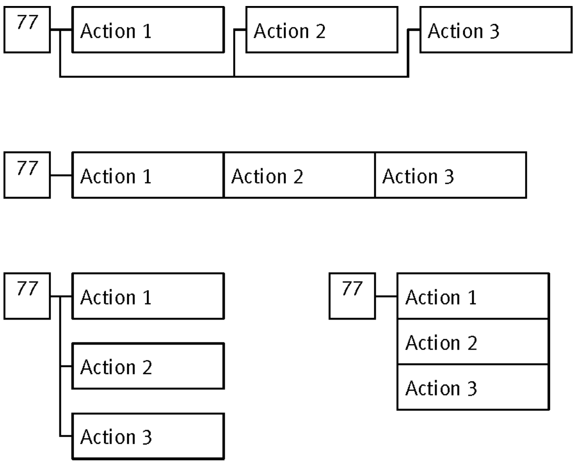



Figure 11.7: Examples for representing a step containing several actions

Actions differ according to how they are executed. Two action types can be distinguished:

1. **Continuous actions**
   These are executed over a specific period. Once the period ends, the action is automatically cancelled.
2. **Stored actions**
   These are executed once at a specific time. It is thus imperative that the time is specified precisely. To cancel the command, an additional command is needed.

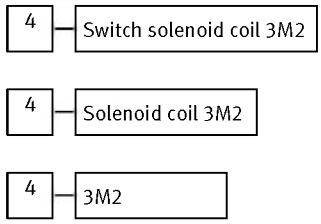
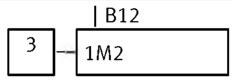
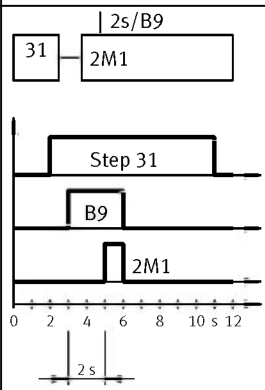
| **Type of action** | **Comment** | **Example** |
|---|---|---|
| Continuous action | Continuous action means: provided the associated step is active, the specified variable is assigned the value 1, i.e. TRUE. If the step is no longer active, the variable is assigned the value 0, i.e. FALSE. |   |
| Continuous action with assignment condition | The variable described in the action is only assigned the value 1 (TRUE) if the assignment condition (in the example B12) if satisfied (TRUE). Otherwise the variable is assigned the value 0 (FALSE) even if the step (step 3 in the example) is active. |   |
| Continuous action with time-dependent assignment condition | The time to the left of the variable is started by the rising edge of the variable. The action is executed after the time runs out. This behaviour corresponds to a switch-on delay. |   |

Table 11.2: Continuous actions

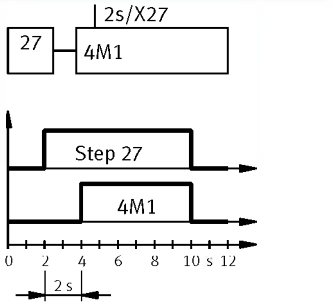
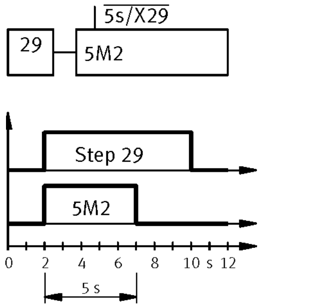
| Type of action | Comment | Example |
|---|---|---|
| Delayed continuous action | If an action is to be executed with a time delay, the continuous action with assignment condition can be extended to include a time. The time and the step variable of the active step are specified as the assignment condition. The assignment condition is only satisfied after the specified time runs out and the variable specified in the action is assigned the value 1. |  |
| Time-limited continuous action | The time-limited action is produced by negating the condition of the time-delayed action. |  |

Table 11.3: Continuous actions (continued)

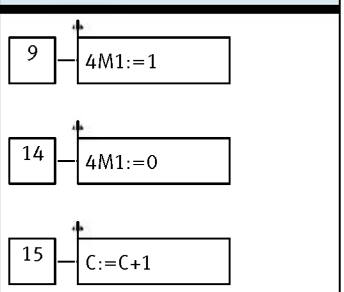
| Type of action | Comment | Example |
|---|---|---|
| Stored action on activation of the step | The variable is assigned the value specified in the action when the associated step becomes active. The value of the variable is stored until it is overwritten by another action.<br>Since the value is assigned when the step is activated, i.e. when the step variable has a rising signal edge, this action is identified by an arrow pointing upwards. |  |

Table 11.4: Stored actions

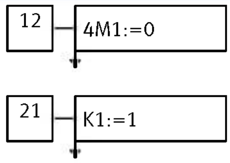
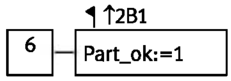
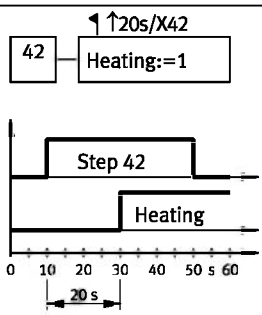
| Type of action | Comment | Example |
|---|---|---|
| Stored action on deactivation of the step | The variable is assigned the value specified in the action when the step is deactivated. The value for the variable is stored until it is overwritten by another action.<br>Since the value is assigned when the step is deactivated, i.e. when the step variable has a falling signal edge, this action is identified by an arrow pointing downwards. |  |
| Stored action on event | The variable described in the action is only assigned the specified value if the step is active and there is a rising edge for the expression that describes the events.<br>The symbol, which looks like a flag, is an arrow pointing to the side. It denotes that the action is only executed with memory function when an event occurs. The arrow pointing upwards indicates that the action is executed when the event has a rising edge. |  |
| Delayed stored action | If a time is defined as the event that triggers storage, the result is a delayed stored action. The arrow pointing upwards at the variable describes the rising edge, i.e. the specified time being reached. |  |

Table 11.5: Stored continuous actions (continued)

### 11.2.5 Sequence selection

**Alternative branching**

If a sequence offers a number of alternatives, this is represented by simple branches. A sequence can branch into any number of alternative sequences. For each alternative there is a separate step criterion. These must be clearly described so that several conditions cannot be satisfied at once (mutual locking).

Once the individual alternative branches, each with its own transition, have been completed, a simple merge leads directly to the next step.

**Parallel branch**

With parallel branching, several subsequences are activated simultaneously whenever a transition condition is fulfilled. The subsequences are started at the same time, but processed independently of each other.

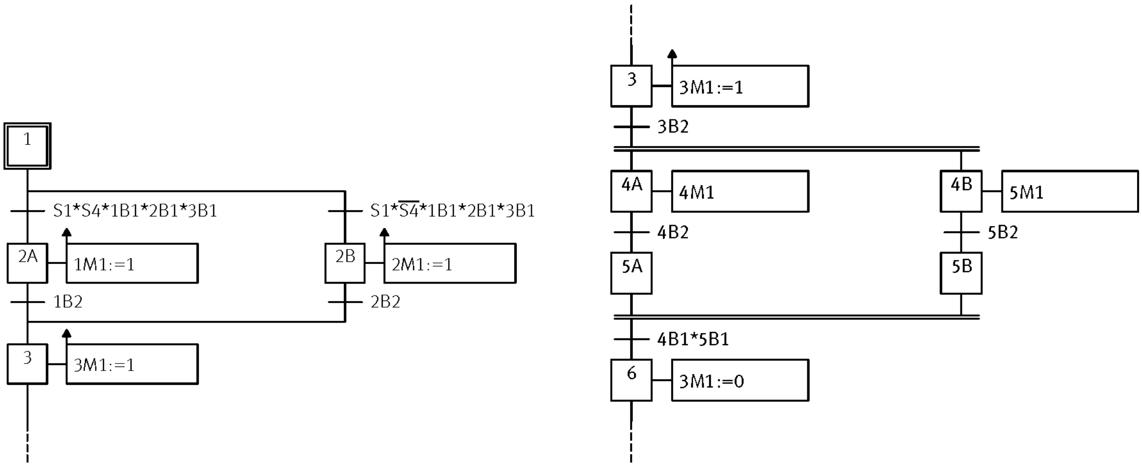



Figure 11.8: Branches; left: example of an alternative branch; right: example of a parallel branch

The merging of the subsequences is synchronised. A transition to the step under the double line – step 6 in the example – can only take place once all parallel subsequences have been processed in full. For this it is absolutely essential that a shared transition be fulfilled.

### 11.2.6 Returns and jumps

Sequences are normally run through cyclically, in other words they represent a loop. To represent the loop structure, a line must run from the bottom to the top. An arrow must be added since this direction is opposite to the normal sequence direction of top to bottom.

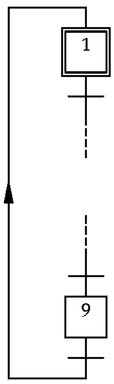



Figure 11.9: Example of a return in a sequence structure

### 11.2.7 Structuring of GRAFCETs

The elements described are sufficient to exactly and precisely describe sequences without hierarchical levels. However, the standard also includes the elements needed to structure the hierarchy.

Hierarchical levels are necessary for precisely defined general and detailed structures within the controller response, for operating modes and for the EMERGENCY STOP function of complex controllers.

A GRAFCET is divided into several parts when using different hierarchical levels. The parts are called sub-GRAFCETs. They are given a name, which is prefixed with a G.

The main structuring elements are:

- Forcing orders
- Enclosing steps
- Macro steps

This chapter does not describe the structuring elements.

### 11.2.8 Example of a slot cutting device

#### Functional description

U-shaped slots are cut into wooden boards. The double-acting cylinder 1A1 provides the feed for the longitudinal slots. The double-acting cylinder 2A1 provides the feed for the transverse slots. The end positions of the two cylinders are sensed by proximity sensors.

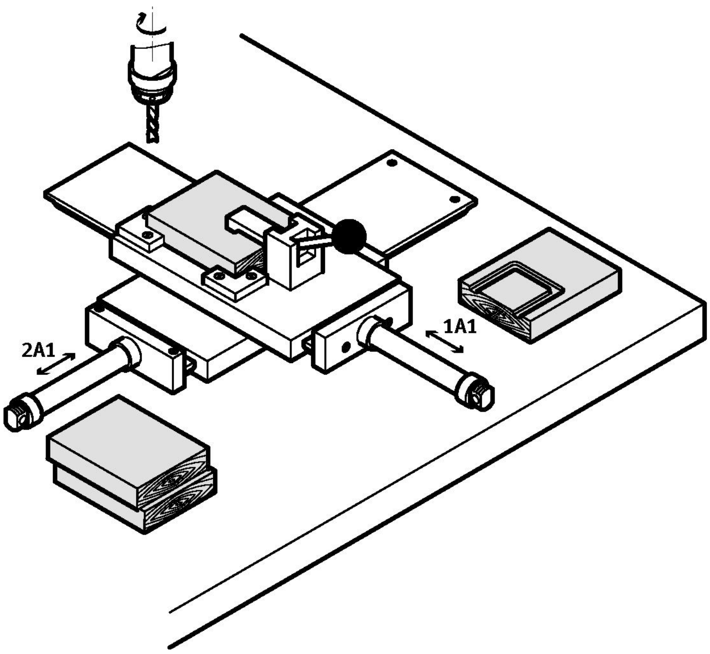



Figure 11.10: Positional sketch

#### Sequence description

1. The wooden board is manually clamped and the cutting device moved into the operating position.
2. In the initial step, the action with assignment condition controls the initial position display. The lamp P1 lights up when the device is in the initial position; otherwise the lamp P1 does not light up. The initial position with P1 and the START pushbutton S1 are sensed as the transition condition to step 2.
3. The coil 1M1 is actuated in step 2. The piston rod of the cylinder 1A1 advances and guides the cutting head through the first longitudinal slot. Reaching the advanced end position 1B2 is the transition condition to step 3.

4. The coil 2M1 is actuated in step 3. The piston rod of the cylinder 2A1 advances and guides the cutting head through the transverse slot. Reaching the advanced end position 2B2 is the transition condition to step 4.
5. The coil 1M1 is actuated in step 4. The piston rod of the cylinder 1A1 retracts and guides the cutting head through the second longitudinal slot. Reaching the retracted end position 1B1 is the transition condition to step 5.
6. The coil 2M1 is actuated in step 5. The piston rod of the cylinder 2A1 retracts and guides the cutting head back to its initial position. Reaching the retracted end position 2B1 is the transition condition to step 1.
7. The cutter is moved into the wait position and the machined wooden board is released.

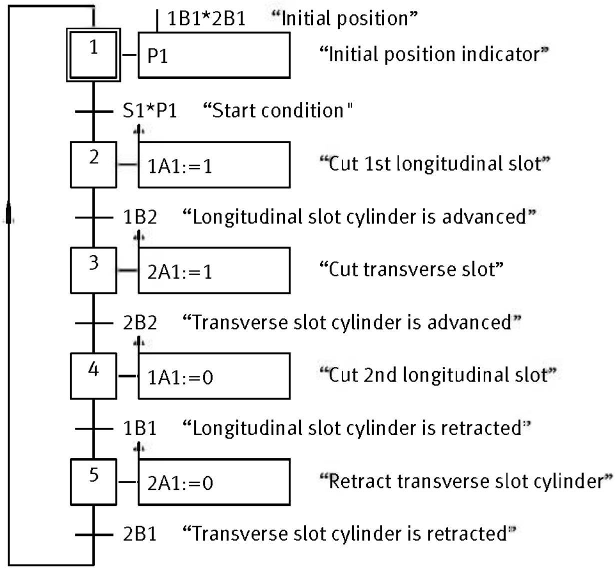



Figure 11.11: GRAFCET for the slot cutting device – technology-neutral solution

# 12 Structure of circuit diagrams

## 12.1 Pneumatic circuit diagram

### 12.1.1 Position of the symbols in the pneumatic circuit diagram

The structure of a pneumatic circuit diagram, the arrangement of the symbols and the identification and numbering of components are standardised to ISO 1219-2. The symbols for the pneumatic components are arranged as follows in the circuit diagram for an electropneumatic control system:

- At the top are the operating elements
- Next come the valves for influencing speed (e.g. flow control valves, one-way flow control valves, non-return valves)
- Next come the control elements (directional control valves)
- At the bottom left is the energy supply

Control systems that have more than one operating element, the symbols for the different drives are drawn next to each other. The symbols for the associated valves are arranged under the respective drive symbol.

### 12.1.2 Position of cylinders and directional control valves

All components are represented in the pneumatic circuit diagram with the operating pressure applied. With electropneumatic circuit diagrams, the electrical signal control section is de-energised.

**Normal position**

In the case of valves with return, for example springs, the normal position refers to the switching position assumed by the moving parts of the valve when the valve is not connected.

**Note**

The normal position cannot be clearly defined in the case of bistable valves because they have no return spring.

### Initial position

The initial position refers to the switching position assumed by the moving parts of a valve after the valve is installed in a system and the operating pressure as well as the electrical voltage, if applicable, are applied and the position where the specified control program starts.

If valves are actuated in the initial position, this must be indicated by showing a trip cam. In this case, the actuated switching position must be connected.

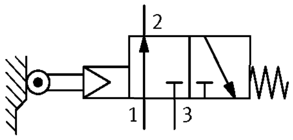



Figure 12.1: 3/2-way roller lever valve – actuated in initial position

### 12.1.3 Identification key for components

Each component (with the exception of connecting cables and tubing) is identified as per Figure 12.2. The identification key contains:

- The system number (digit, can be omitted if the entire circuit consists of one system)
- The circuit number (digit, mandatory)
- The component identifier (letter, mandatory)
- The component number (digit, mandatory)

The identification key should be enclosed in a frame.

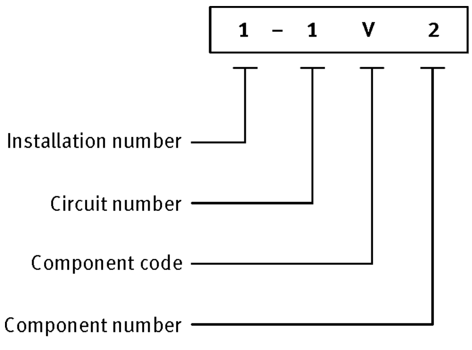



Figure 12.2: Identification key for components in pneumatic circuit diagrams

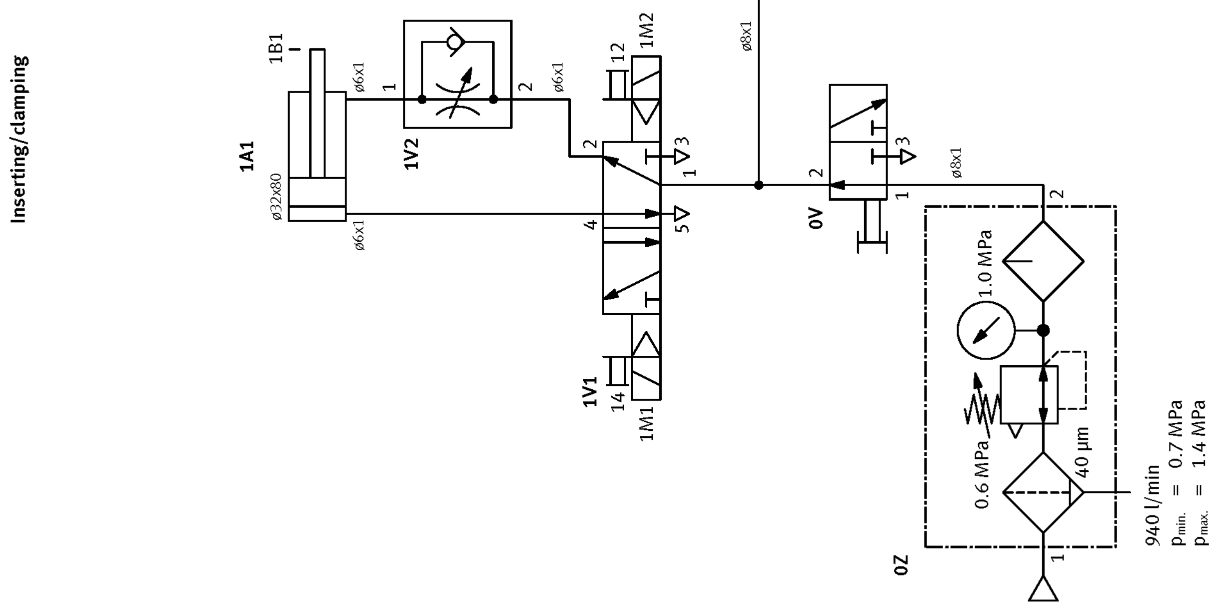
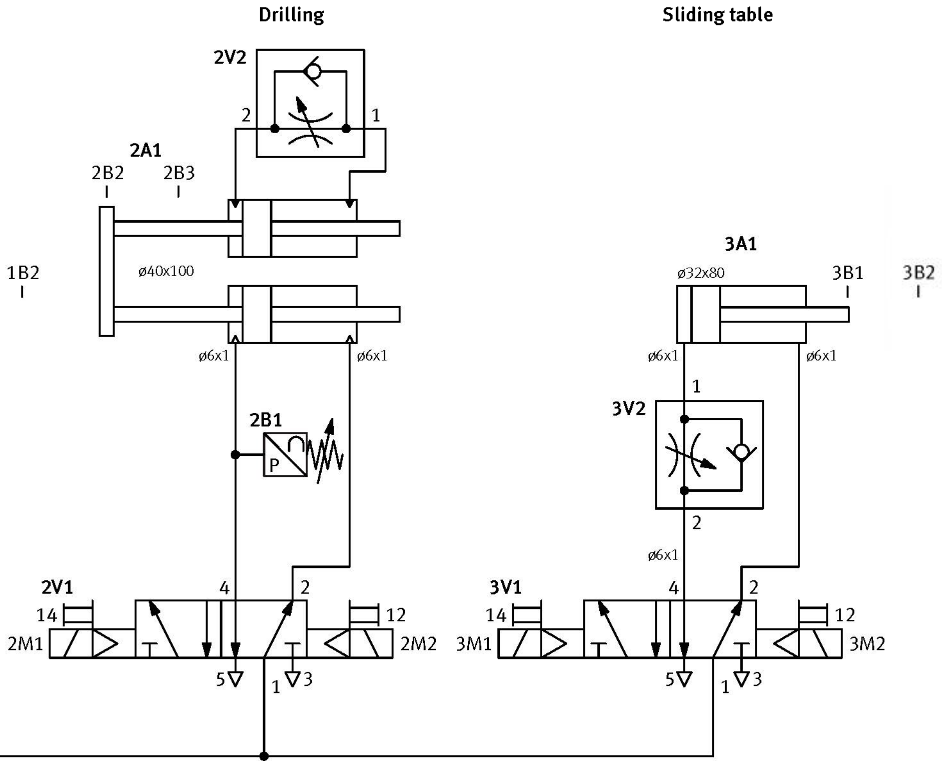



Figure 12.3: Pneumatic circuit diagram for an electropneumatic control system with three sequencers


Drilling
Sliding table
2V2
2
1
2A1
2B2
2B3
1B2
ø40x100
ø6x1
ø6x1
2B1
P
2V1
4
2
14
12
2M1
2M2
5
1
3
3A1
ø32x80
3B1
3B2
ø6x1
ø6x1
1
3V2
2
ø6x1
3V1
4
2
14
12
3M1
3M2
5
1
3

### System number
If there are numerous systems and electropneumatic control systems in a plant, the system numbers make it easier to assign the circuit diagrams to the system. All pneumatic components in a control system are identified by the same system number. The system number is not shown in the identification key in the sample circuit diagram (Figure 12.3).

### Circuit number
All components for supplying energy are preferably identified by the circuit number 0. The other circuit numbers are used for the different control systems (= circuits). The control system illustrated in Figure 12.3 has the following assignment:
- Energy supply and main switch: Number 0
- "Insert/clamp" sequencer: Circuit number 1
- "Drill" sequencer: Circuit number 2
- "Sliding table" sequencer: Circuit number 3

### Component identifier and component number
Each component in an electropneumatic control system is assigned a component identifier and a component number in the circuit diagram. Within a circuit, components with the same component identifier are numbered consecutively from bottom to top and from left to right. The valves in the "Insert/clamp" sequencer (circuit 1 in the circuit diagram Figure 12.3) must therefore be identified as follows:
- Directional control valve: 1V1 (circuit number 1, component identifier V, component number 1)
- One-way flow control valve: 1V2 (circuit number 1, component identifier V, component number 2)

| Components | Identifier |
|---|---|
| Compressors | P |
| Operating elements | A |
| Drive motors | M |
| Signal input | S |
| Sensors | B |
| Valves | V |
| Solenoid coils | M* |
| Other components | Z** |
| * National addition in German standard | |
| ** Or any other letter not in the list | |

Table 12.1: Identification key for components in a pneumatic circuit diagram

**Technical information**

Certain components in the pneumatic circuit diagram are identified with additional information to make assembling a control system and replacing components during maintenance work easier:

| | |
|---|---|
| • Cylinder | Piston diameter, stroke and function (e.g. "Insert/clamp") |
| • Compressed air supply | Supply pressure range in MPa or bar, nominal volumetric flow rate in l/min |
| • Filter | Nominal size in micrometres |
| • Tubing | Nominal internal diameter in mm |
| • Pressure gauge | Pressure range in MPa or bar |

## 12.2 Electrical circuit diagram

The electrical circuit diagram for a control system shows how the electrical control components are connected and how they interact. The following circuit diagram types are used in accordance with EN 61082 depending on the task:

- Block diagram
- Operational circuit diagram
- Schematic diagram

### 12.2.1 Block diagram

The block diagram provides an overview of the electrical devices in a larger system, for example a packaging machine or an assembly plant. It shows only the most important relationships. The various subsystems are shown in greater detail in other circuit diagrams.

### 12.2.2 Operational circuit diagram

The operational circuit diagram shows the individual functions of a system. It does not take into consideration how these functions are executed.

### 12.2.3 Schematic diagram

The schematic diagram shows the details of how systems, installations, equipment, etc. are implemented. It contains:

- The graphical symbols for the equipment
- The connections between these pieces of equipment
- The equipment identifiers
- The connection identifiers
- Further information needed to follow the paths (signal identifier, notes on the representation location)

**Coherent and resolved representation of a schematic diagram**
With the coherent representation of a schematic diagram, each device is drawn as a coherent symbol, even a relay, for example, that has several normally open and normally closed contacts.

With the resolved representation of a schematic diagram, the different components in a device can be drawn at different locations. They are arranged so as to produce a clear, linear representation with as few intersecting lines as possible. The normally closed and normally open contacts in a relay can, for example, be drawn across the entire circuit diagram.

**Electrical circuit diagram for an electropneumatic controller**
The resolved schematic circuit is used in electropneumatics to represent the signal control section. A block diagram or operational circuit diagram is only additionally created with very extensive controllers.

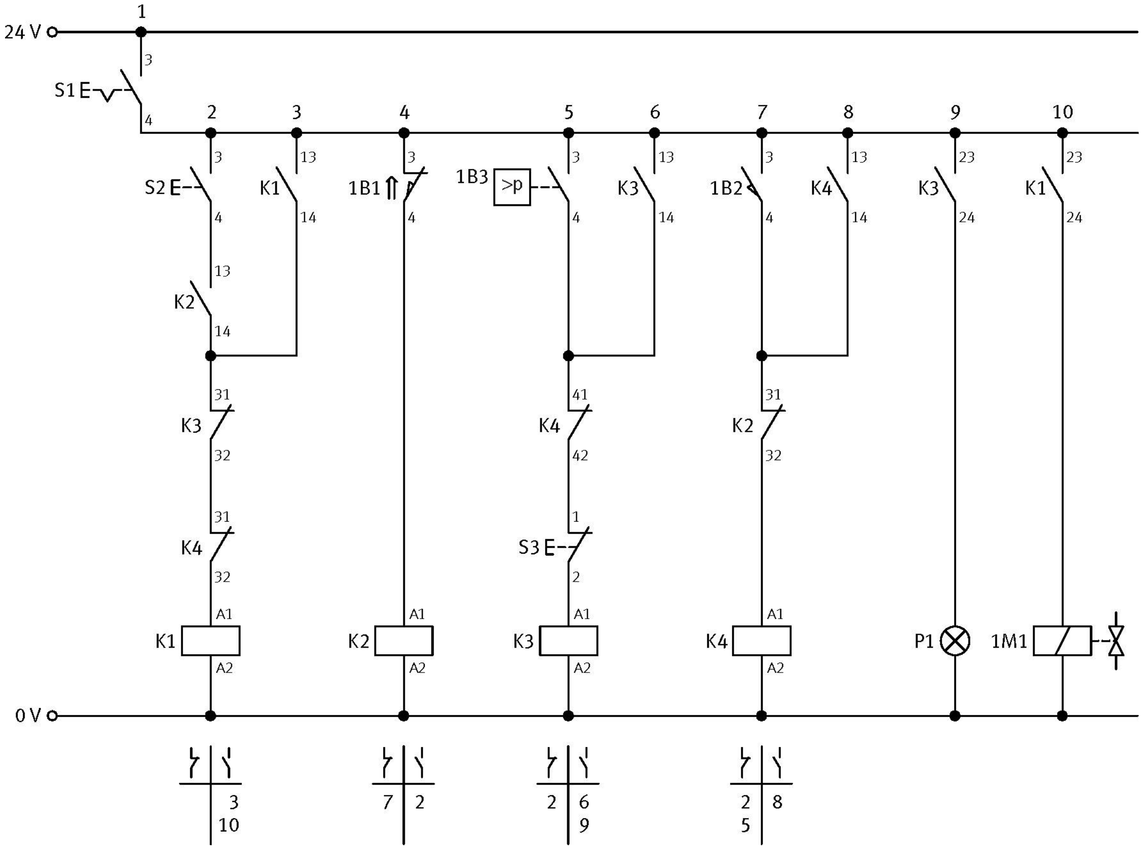
In practice, the term "electrical circuit diagram for an electropneumatic controller" always refers to the schematic diagram.

### 12.2.4 Schematic diagram for an electropneumatic control system
In the schematic diagram for an electropneumatic control system, the symbols for the components needed to realise operations and sequences are entered consecutively from top to bottom and from left to right. Relays and solenoid coils are always drawn underneath the contacts.

Further measures to ensure good legibility of a schematic diagram include:
- Classification into individual current paths
- Identification of the devices and contacts by means of letters and numbers
- Breakdown into control circuit and main circuit
- Preparation of logic element tables

## Current paths

The individual current paths in an electropneumatic controller are drawn next to each other in the schematic diagram and consecutively numbered. The schematic diagram for an electropneumatic controller shown in Figure 12.4 has ten current paths. Current paths 1 to 8 belong to the control circuit, current paths 9 and 10 to the main circuit.




S1 = Main switch; S2 = Start button; S3 = Acknowledgement button; 1B1/1B2 = Limit switch; 1B3 = Pressure switch

Figure 12.4: Electrical circuit diagram (schematic diagram) for an electropneumatic controller

## Identification of components

The components in the schematic diagram for a controller are identified by a letter. Components with the same identifier are consecutively numbered (e.g. with 1B1, 1B2, etc.).

Sensors and solenoid coils must be represented both in the pneumatic circuit diagram and in the schematic diagram. To ensure clarity and legibility, the symbols should be identified and numbered in the same way in both diagrams. If, for example, a specific limit switch in the pneumatic circuit diagram was identified with 1B1, the same identifier should also be used in the schematic diagram.

| Components | Identifier |
|---|---|
| Sensors (Limit switch, reed switch, electronic proximity sensor, pressure switch) | B |
| Relay | K |
| Valve solenoid coil | M |
| Indicators | P |
| Contactor | Q |
| Manually operated pushbutton | S |

Table 12.2: Identification of components in the schematic diagram (EN 81346-2)

### Example for identifying components

The components represented in the schematic diagram are identified as follows:

- The manually operated switches with S1, S2 and S3
- The limit switches with 1B1 and 1B2
- The pressure switch with 1B3
- The relays with K1, K2, K3 and K4
- The solenoid coil with 1M1
- The LED P1

### Terminal markings for contacts and relays

To avoid mistakes when wiring contacts, all ports on the component and in the schematic diagram are identified in the same way. Each port on a contact is given a function digit. The function digits for different contact types are summarised in Table 12.3. If a switch, relay or contactor has several contacts, they are numbered consecutively using sequence numbers that are placed in front of the function digit (see Figure 12.5).

The ports on a relay coil are called A1 and A2.

| Contact type | Function digit |
|---|---|
| Normally closed contact | 1, 2 |
| Normally open contact | 3, 4 |
| Normally closed contact, delayed | 5, 6 |
| Normally open contact, delayed | 7, 8 |
| Changeover switch | 1, 2, 4 |
| Changeover switch, delayed | 5, 6, 8 |

Table 12.3: Function digits for contacts

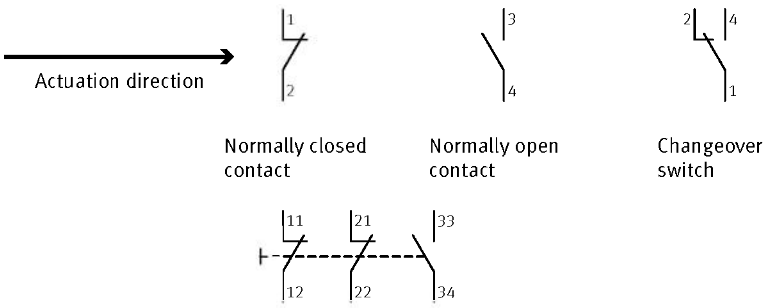



Figure 12.5: Contact identification by means of function and sequence digits

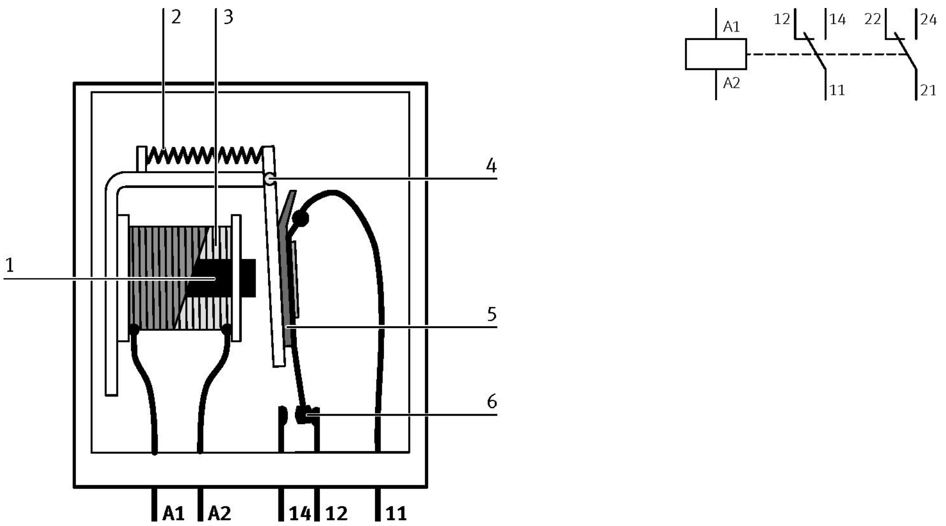



Figure 12.6: Relay – symbol, sectional view and terminal markings

### Example for the terminal markings for relays

In the schematic diagram Figure 12.4, the terminals on the relay K1 are identified as follows:

- Coil (current path 2): A1, A2
- Normally open contact (current path 3): 13, 14
- Normally open contact (current path 10): 23, 24

### Logic element table

All contacts actuated by a relay or contactor coil are listed in a logic element table. The logic element tables are arranged beneath the current path where the relay coil is located. Logic element tables can be simplified or detailed.

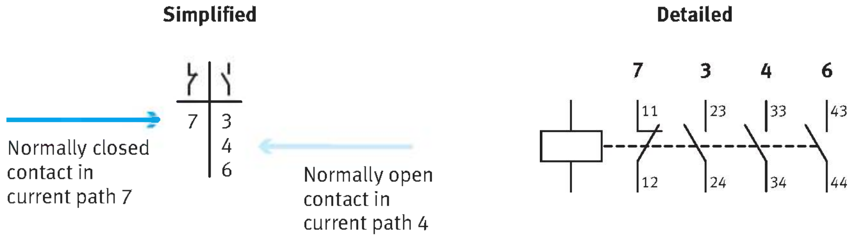



Figure 12.7: Simplified and detailed logic element table for a relay

### Examples of logic element tables

The schematic diagram in Figure 12.4 contains a total of four logic element tables:

- Current path 2: Logic element table for relay K1
- Current path 4: Logic element table for relay K2
- Current path 5: Logic element table for relay K3
- Current path 7: Logic element table for relay K4

### Actuated contacts and sensors

The electrical circuit diagram is represented in de-energised state (the electrical energy supply is switched off). If limit switches are actuated in this position, they are identified with an arrow. The associated contacts are also represented in actuated position.

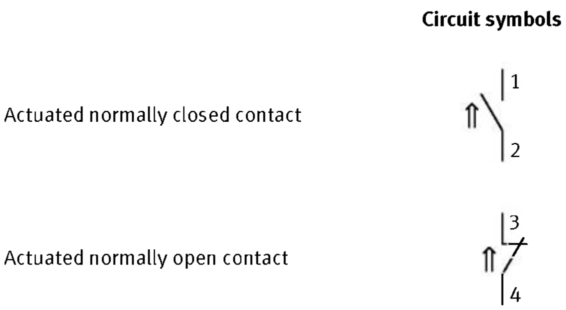



Figure 12.8: Representation of actuated contacts in the schematic diagram

### 12.3 Terminal connection diagram

With an electropneumatic control system, sensors, control elements, the signal processing components and solenoid coils have to be wired together. The layout of the control components must be taken into consideration here.

- Sensors are often mounted in locations that are difficult to access.
- The signal processing components (relay, programmable logic controller) are usually positioned in a control cabinet. However, programmable logic controllers are increasingly also being integrated in valve terminals.
- The control elements are either installed directly in the front of the control cabinet or the controller is operated via a separate console.
- The solenoid actuated directional control valves are mounted in blocks in the control cabinet or on valve terminals or individually near the drive.

The large number of components and the distances between them make the wiring a substantial cost factor in an electropneumatic controller.

#### 12.3.1 Requirements for the wiring

The wiring in an electropneumatic controller must satisfy the following requirements:

- Cost-effective setup (use of components that offer good optimisation of the schematic diagram with respect to wiring complexity, use of components with a reduced number of connections)
- Easy fault finding (clear, easy to understand and precisely documented wiring)
- Quick repair (easy replacement of components by means of clamped or plug connections, no soldered-on components)

#### 12.3.2 Wiring via terminal strips

Terminal strips are used in controllers with individual wiring to meet the requirements with respect to low wiring costs, easy fault finding and easy-to-repair structure. All lines that lead out of or into the control cabinet go via a terminal strip (Figure 12.9). Defective components can be easily disconnected from the strip and replaced.

If additional terminal strips are mounted directly at the system or machine, components mounted can be connected via much shorter supply lines outside the control cabinet (Figure 12.10). Installing and replacing the components are made even easier. Each additional terminal strip is installed in a terminal box to protect it against environmental influences.

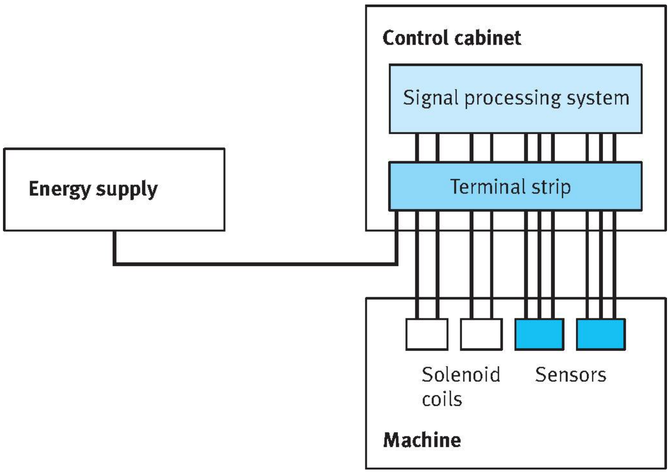



Figure 12.9: Structure of an electropneumatic controller using terminal strips – terminal strip in the control cabinet

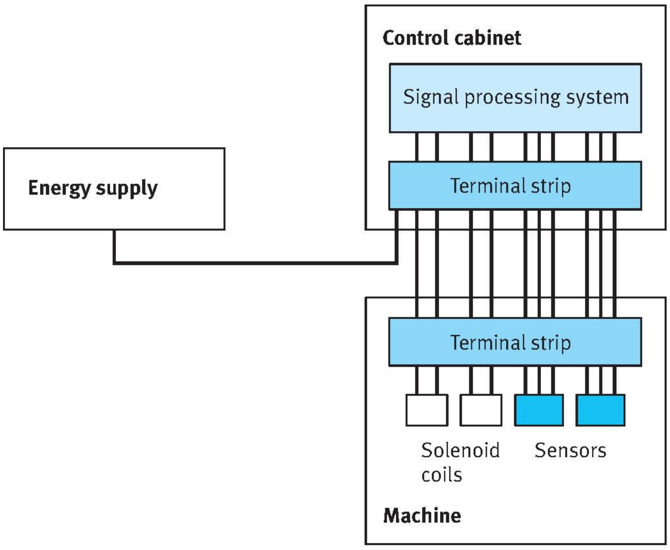
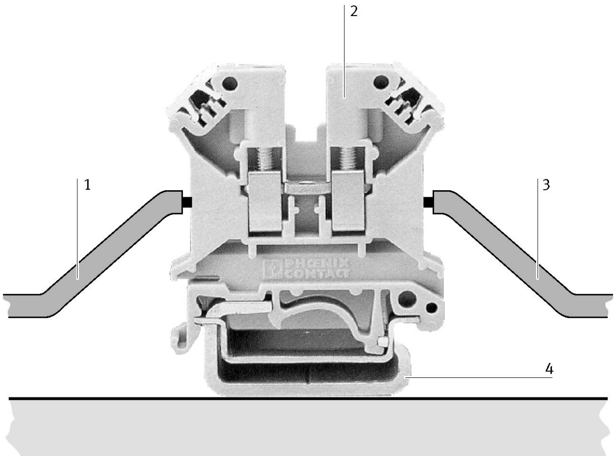



Figure 12.10: Structure of an electropneumatic controller using terminal strips – terminal strips in the control cabinet and at the machine

### 12.3.3 Structure of terminals and terminal strips

A terminal has two fixtures for electrical cables that conduct electricity between them. All terminals are secured on a strip one beside the other. Electrically conductive connections between adjacent terminals can be established by means of jumpers.




1: Cable 1; 2: Terminal; 3: Cable 2; 4: Assembly strip

Figure 12.11: Terminal

### 12.3.4 Terminal assignment

The two goals of wiring a controller as cost-effectively and clearly as possible are mutually exclusive. For maintenance of a controller, it makes sense if the terminals in a terminal strip are assigned so that the wiring structure is as clear as possible. In practice there are:

- Controllers with systematic, easy to maintain terminal assignments
- Controllers where the number of terminals has been minimised at the expense of clarity
- Hybrid forms

**Note**

Under no circumstances may other wires be connected to a terminal connection.

| | Clear terminal assignment | Reduced number of terminals |
|---|---|---|
| **Advantages** | – Fast fault finding<br>– Easy to understand<br>– Easy to repair | – Savings (space in the control cabinet, terminals)<br>– Less wiring required<br>– Few error sources in the wiring |
| **Disadvantages** | – Cost of materials<br>– Time-consuming wiring | – Unclear, time-intensive, particularly for people not familiar with the system |

Table 12.4: Approaches to terminal assignments

### 12.3.5 Structure of a terminal connection diagram

The terminal assignment is documented in the terminal connection diagram. It consists of two parts: the schematic diagram and the terminal allocation list.

In the schematic diagram, each terminal is represented as a circle (Figure 12.14). The terminals are identified with an 'X' and numbered consecutively within a terminal strip (terminal designation, e.g. X1, X2, etc.). If there are a number of terminal strips, each terminal strip is also given a sequence digit (terminal designation, e.g. X2.6 for the sixth terminal in terminal strip 2).

A terminal allocation list specifies the assignment of all terminals in a strip in sequence. If a controller has several terminal strips, a list is created for each strip. Terminal assignment lists are used as documentation when assembling the controller, when carrying out fault finding (measuring signals at the terminals) and when carrying out repairs.

### 12.3.6 Creating a terminal connection diagram

The starting point for the terminal connection diagram is the schematic diagram without any terminal assignments. The terminal connection diagram is created in two steps:

1. Terminal numbers are assigned and the terminals are drawn into the schematic diagram
2. The terminal allocation list(s) is (are) created

## Sample application

The following section describes an approach to assigning terminals that produces a clear, easily understood wiring setup. The starting point for creating the terminal connection diagram is:

- the schematic diagram for a controller without the terminals marked in (Figure 12.12),
- a blank terminal allocation list (Figure 12.13).

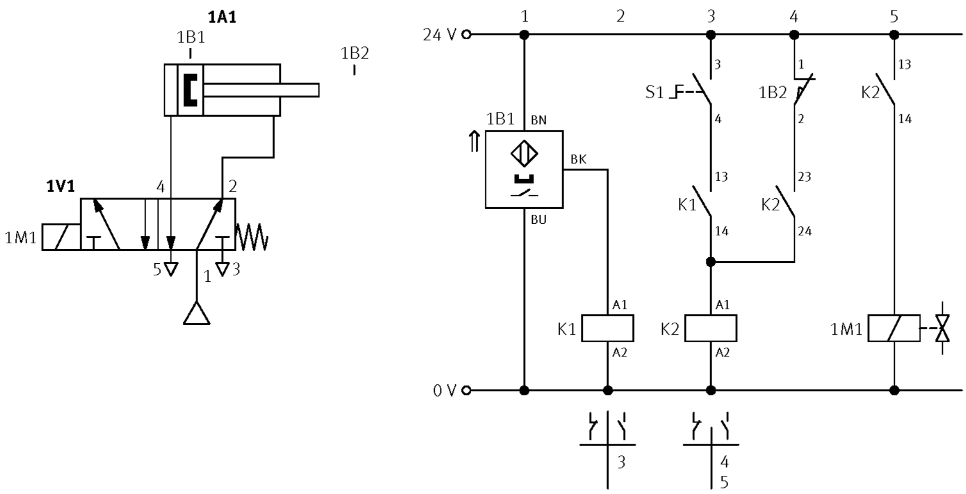



Figure 12.12: Pneumatic circuit diagram and schematic diagram for an electropneumatic control system

| Destination | | Jumper | Terminal no. X . . . | Destination | |
|---|---|---|---|---|---|
| Component designation | Terminal marking | | | Component designation | Terminal marking |
| | | ○ | 1 | | |
| | | ○ | 2 | | |
| | | ○ | 3 | | |
| | | ○ | 4 | | |
| | | ○ | 5 | | |
| | | ○ | 6 | | |
| | | ○ | 7 | | |
| | | ○ | 8 | | |
| | | ○ | 9 | | |
| | | ○ | 10 | | |
| | | ○ | 11 | | |
| | | ○ | 12 | | |
| | | ○ | 13 | | |
| | | ○ | 14 | | |
| | | ○ | 15 | | |
| | | ○ | 16 | | |
| | | ○ | 17 | | |
| | | ○ | 18 | | |
| | | ○ | 19 | | |
| | | ○ | 20 | | |

Figure 12.13: Blank terminal allocation list

**Assigning the terminal numbers**

The terminal numbers are assigned in ascending order and marked in the schematic diagram. The terminals in the schematic diagram are assigned in three steps:

1. Voltage supply for all current paths (terminals X1-1 to X1-4 in the schematic diagram Figure 12.14)
2. Earth connection for all current paths (terminals X1-5 to X1-8 in the schematic diagram Figure 12.14)
3. Connection of all components arranged outside the control cabinet in accordance with the following system:
   - in the order of the current paths,
   - within a current path from the top to the bottom,
   - with contacts in the order of the function digits,
   - with electronic components in the order: power supply connection, signal connection (if present), earth connection.

The components occupy terminals X1-9 to X1-17 in the circuit diagram below.

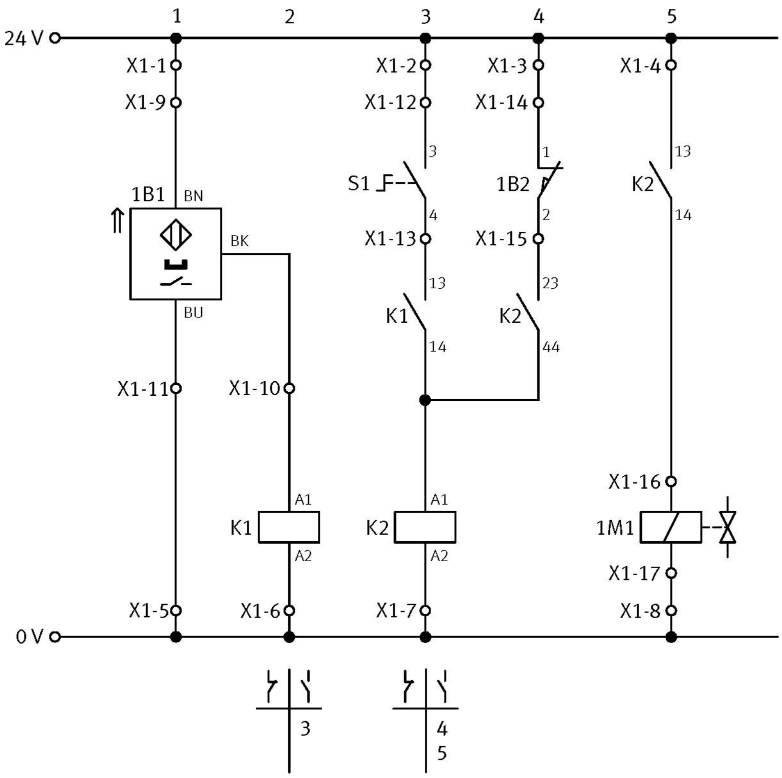



Figure 12.14: Schematic diagram with terminals

### Completing the terminal allocation list

Completing the terminal allocation list involves the following steps:

1. Entering the component and connection designations for the components outside of the control cabinet (on the left-hand side of the terminal allocation list)
2. Entering the component and connection designations for the components inside the control cabinet (on the right-hand side of the terminal allocation list)
3. Drawing in the necessary jumpers (in the example: terminals X1-1 to X1-4 for 24 V supply voltage, X1-5 to X1-8 for supply earth)
4. Entering the terminal/terminal connections that cannot be realised as jumpers

| Machine | | | | Control cabinet | |
|---|---|---|---|---|---|
| Destination | | | | Destination | |
| Component designation | Terminal marking | Jumper | Terminal no. X1 | Component designation | Terminal marking |
| | 24V | | 1 | X1 | 9 |
| | | | 2 | X1 | 12 |
| | | | 3 | X1 | 14 |
| | | | 4 | K2 | 13 |
| | 0V | | 5 | X1 | 11 |
| | | | 6 | K1 | A2 |
| | | | 7 | K2 | A2 |
| | | | 8 | X1 | 17 |
| 1B1 | BN | | 9 | X1 | 1 |
| 1B1 | BK | | 10 | K1 | A1 |
| 1B1 | BU | | 11 | X1 | 5 |
| S1 | 3 | | 12 | X1 | 2 |
| S1 | 4 | | 13 | K1 | 13 |
| 1B2 | 1 | | 14 | X1 | 3 |
| 1B2 | 2 | | 15 | K2 | 23 |
| 1M1 | | | 16 | K2 | 14 |
| 1M1 | | | 17 | X1 | 8 |
| | | | 18 | | |
| | | | 19 | | |
| | | | 20 | | |

Figure 12.15: Terminal assignment list for the sample controller

**Wiring an electropneumatic controller**

The layout of a terminal allocation list is tailored to the terminal strip structure. Accordingly an electropneumatic controller can, to a large extent, be wired on the basis of the terminal allocation list.

- All lines that lead to components outside of the control cabinet are connected to the left-hand side of the terminal strip in accordance with the list.
- All lines that lead to components inside the control cabinet are connected to the right-hand side of the terminal strip in accordance with the list.
- Adjacent terminals where a jumper is shown in the terminal allocation list are electrically conductively connected.

Lines that connect two components in the control cabinet are not wired via the terminal strip. They are therefore not included in the terminal allocation list and have to be wired according to the schematic diagram.

# 13 Safety measures with electropneumatic control systems

## 13.1 Hazards and protective measures

Numerous protective measures are necessary to ensure safe operation of electropneumatic controllers.

One potential source of hazards is moving machine and system parts. With a pneumatic press, for example, measures must be put in place to prevent the operator's fingers or hands getting caught. Figure 13.1 provides an overview of safety hazards and suitable protective measures.

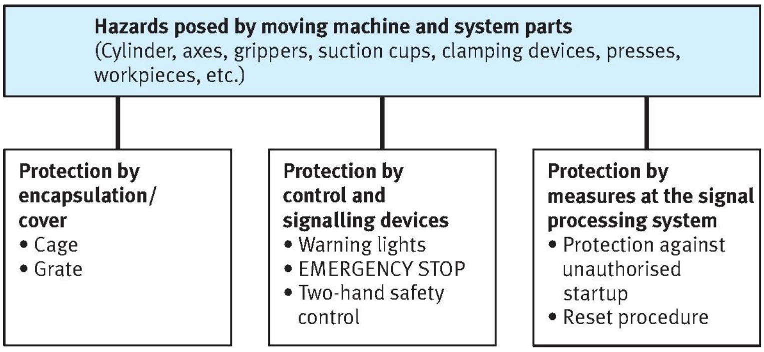



Figure 13.1: Moving machine and system parts: safety hazards and protective measures

Other hazards are posed by electricity. Figure 13.2 summarises hazards and protective measures related to electricity.

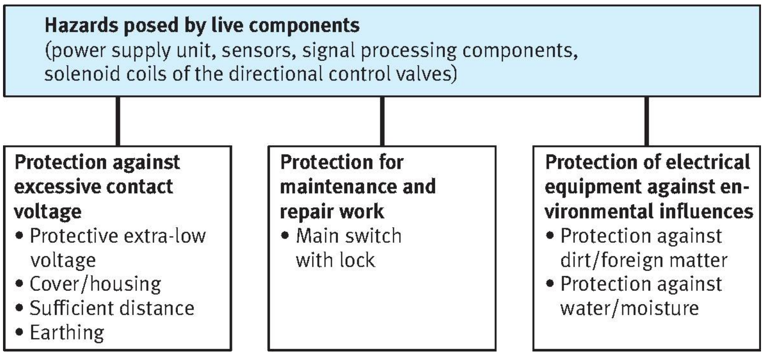



Figure 13.2: Electricity: safety hazards and protective measures

**Safety instructions**
Numerous safety regulations and standards must be adhered to when building electropneumatic controllers to rule out any risk to operating personnel insofar as possible. The main standards relating to protection against electrical hazards are listed below:

- Protective measures for high-voltage systems up to 1,000 V (IEC 60346-1)
- Provisions relating to electrical equipment and safety of machinery (EN 60204)
- Degree of protection of the electrical equipment used (EN 60529)

## 13.2 Effect of electric current on the human body

When a person touches a live part, an electrical circuit is completed. An electric current I flows through the person's body.

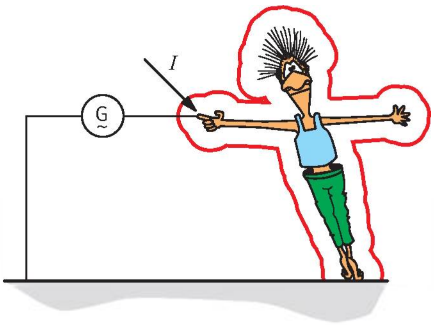



Figure 13.3: Touching live parts

### 13.2.1 Effect of electric current

The effect of electric current on the human body increases with the intensity of the current and the length of time in contact with the current. The effects are grouped according to the following threshold values:

- Below the threshold of perception, electric current has no effect on the human body or human health.
- Up to the release threshold, the electric current is felt but it poses no health risk.
- Above the release threshold, muscles cramp and cardiac function is impaired.
- Above the fibrillation threshold, the effects are cardiac arrest or ventricular fibrillation, respiratory arrest and unconsciousness. There is an acute risk to life.

The perception, release and fibrillation thresholds are plotted in Figure 13.4 for alternating current with a frequency of 50 Hz. This corresponds to the frequency of the electrical supply network. For direct current, the threshold values for endangering people are slightly higher.

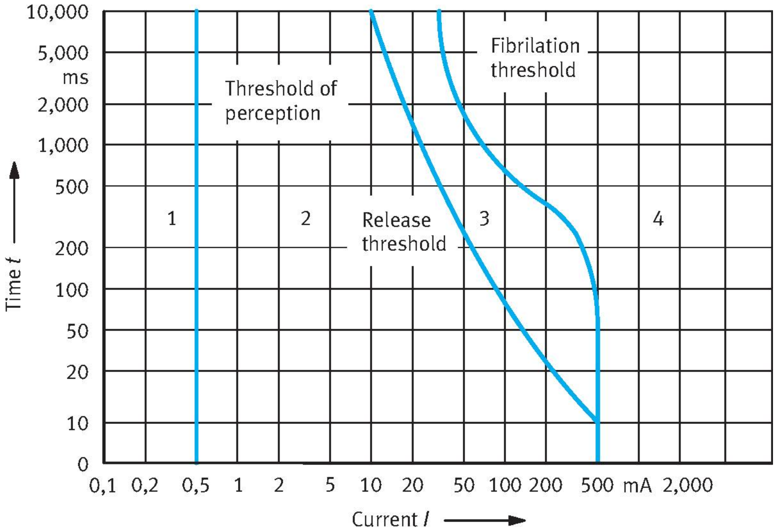



Figure 13.4: Danger zones with AC voltage (frequency 50 Hz/60 Hz)

### 13.2.2 Electrical resistance of the human body

The human body offers resistance to the flow of current. Electric current may enter the body through the hand, for example; it then flows through the body to re-emerge at another point (e.g. at the feet).

Accordingly, the electrical resistance $R_H$ of the human body is formed by a series circuit comprising the entry resistance $R_{E1}$, the internal resistance $R_I$ and the exit resistance $R_{E2}$. It is calculated using the following formula:

$$R_H = R_{E1} + R_I + R_{E2}$$

The contact resistances $R_{E1}$ and $R_{E2}$ vary greatly depending on the contact surface and the moistness and thickness of the skin. This affects the total resistance $R_H$. It may range between the following extremes:

- Less than 1,000 Ω (large contact surfaces; wet, sweaty skin)
- Several million Ω (point contact; very dry, thick skin)

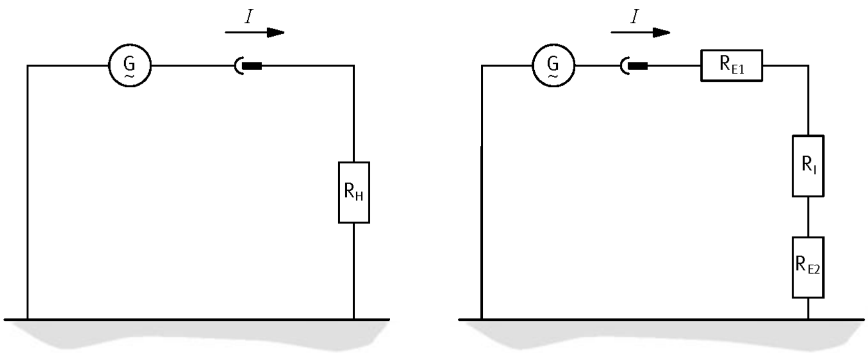



Figure 13.5: Electrical resistance of the human body

### 13.2.3 Variables influencing the risk of accident

The current I through the human body is dependent on the source voltage U, the resistance $R_L$ of the electric line, the resistant $R_H$ of the person and the resistance $R_E$ of the earth.

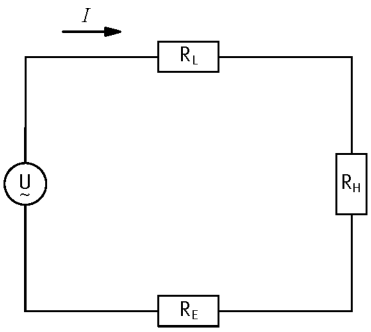



Figure 13.6: Current through the human body

It is calculated as follows:

$$I = \frac{U}{R_L + R_H + R_E}$$

According to this formula, a high current, i.e. a high level of danger is produced:

- When touching an electrical conductor carrying a high voltage $U$ (e.g. a conductor in the electrical supply network, 230 V AC)
- When touching a conductor at a low contact resistance $R_E$ and consequently low resistance $R_H$ (e.g. large contact surfaces, sweaty skin, wet clothing)

## 13.3 Protective measures against accidents with electric current

There are a wide variety of protective measures which prevent the operator of an electropneumatic controller from being put at risk from electric shock.

### 13.3.1 Protection against direct contact

Protection against touching live parts is prescribed for both high and low voltages. Such protection can be ensured by:

- Insulating
- Covering
- Maintaining sufficient distance

### 13.3.2 Earthing

Components that are liable to be touched by anyone must be earthed. If an earth housing becomes live, this results in a short circuit and the overcurrent protective devices are tripped, interrupting the voltage supply. Various devices are used for overcurrent protection:

- Fuses
- Power circuit breakers
- Fault-current-operated circuit breakers
- Fault-voltage-operated circuit breakers

### 13.3.3 Protective extra-low voltage

There is no risk to life when touching an electric conductor carrying a voltage of less than approx. 30 V because only a small current flows through the body.

For this reason, electropneumatic control systems are not normally operated at the voltage of the electrical supply network (e.g. 230 V AC) but at 24 V DC. The supply voltage is reduced by a power supply unit with an isolating transformer.

**Note**
Despite this precaution, the electrical wiring at the inputs to the power supply unit carries high voltage.

## 13.4 Control panel and indicators

Control elements and indicators must be designed so that they ensure safe and fast operation of the control system. The functions, arrangement and colour coding of the control elements and indicator lights are standardised. This allows the use of uniform operating procedures for different controllers and operating errors are prevented as far as possible.

### 13.4.1 Main switch

Every machine and system must have a main switch. This switch is used to switch off the electric power supply during cleaning, maintenance or repair work and for lengthy shutdown periods. The main switch must be manually operated and must have only two positions: "0" (OFF) and "1" (ON). The OFF position must be lockable in order to prevent manual starting or remote starting. If there is more than one incoming supply, the main switches must be interlocked so that no danger can arise for maintenance staff.

### 13.4.2 EMERGENCY STOP

The EMERGENCY STOP control switch is actuated by the operator in dangerous situations.

The EMERGENCY STOP operating device must have a mushroom button and is operated directly by hand. Indirect operation by pull-wire or foot pedal is permissible. If there is more than one workstation or operating panel, each one must have its own EMERGENCY STOP operating device. The colour of the EMERGENCY STOP actuation element is a conspicuous red. The area beneath the control switch must be marked in contrasting yellow.

Once the EMERGENCY STOP device has been actuated, the drives must be shut down as quickly as possible and the controller should be isolated from the electrical and pneumatic power supplies where possible. The following limitations have to be observed, however:

- If illumination is necessary, this must not be switched off.
- Auxiliary units and brake devices provided to aid rapid shutdown must not be rendered ineffective.
- Clamped workpieces must not be released.
- Retraction movements must be initiated by actuation of the EMERGENCY STOP device where necessary. Such movements should, however, only be initiated if this can be done without danger.

### 13.4.3 Control elements of an electropneumatic control system

An electropneumatic control system has other control elements in addition to the main switch and EMERGENCY STOP switch. An example of a control panel is shown below.

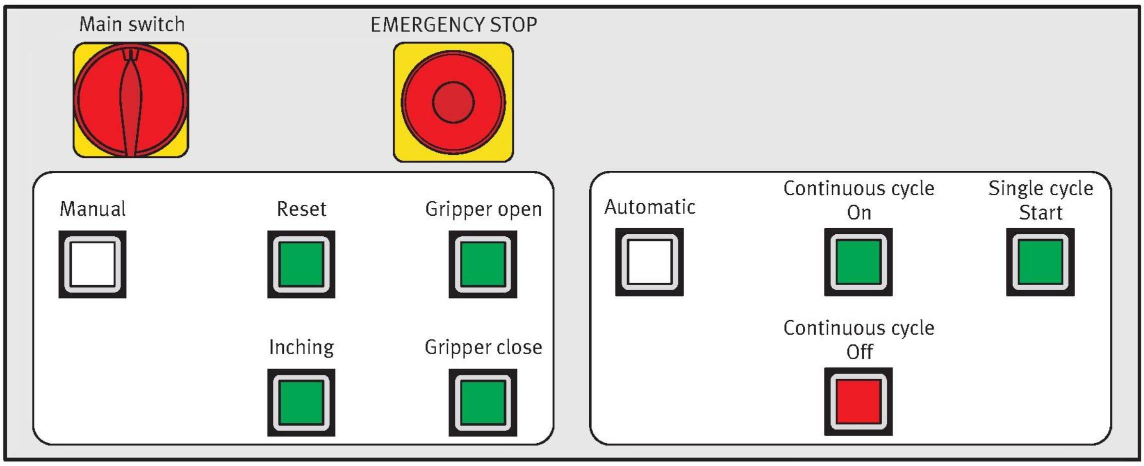



Figure 13.7: Control panel for an electropneumatic controller (example)

A distinction is made between two different operating modes for electropneumatic controllers:
- Manual operation
- Automatic, i.e. program-controlled operation

**Manual operation**
The following control elements have an effect during manual operation:
- "Reset": the system is moved to the initial position.
- "Inching": each time that this pushbutton is pressed, the sequence is extended by one step.
- Individual movements: a drive is actuated when the corresponding pushbutton or control switch is pressed (example: "Open gripper" or "Close gripper").

**Automatic operation**
The following operating modes are only possible only with automatic operation:
- Single cycle: he sequence is executed once.
- Continuous cycle: the sequence is executed continuously.

Pressing the "Continuous cycle OFF" pushbutton (or a "Stop" button) interrupts the sequence. The interruption occurs either after the next step or after completion of the entire sequence.

The main switch and EMERGENCY STOP switch are effective in all operating modes. They must be available on every electropneumatic controller together with control elements for "Manual" and "Automatic", "Start", "Stop" and "Reset". Which control elements are necessary in addition to these depends on each individual application.

### Colour coding of control elements

The following table provides an overview of the colours of control elements and their meaning in accordance with EN 60204.

| Colour | Command | Required operating status |
|---|---|---|
| Red | Stop, Off | Shut down one or more motors. Shut down units of a machine. Switch off magnetic clamping devices. |
| | | Stop the cycle (if the operator presses the pushbutton during a cycle, the machine stops once the current cycle has been completed). |
| | EMERGENCY STOP | Stop in the event of danger (e.g. shutdown because of dangerous overheating) |
| Green or black | Start, On, Inching | Energise control circuits (ready for operation). Start one or more motors for auxiliary functions. Start units of the machine. Switch on magnetic clamping devices. Inching operation (inching when switched on). |
| Yellow | Start a return movement outside the normal work sequence, or start a movement to counteract dangerous conditions. | Return machine units to the starting point of the cycle, if the cycle is not yet completed. Actuation of the yellow pushbutton may deactivate other, previously selected functions. |
| White or black | Any function for which none of the above colours is used. | Control auxiliary functions which are not directly linked to the operating cycle. |

13.1: Colour coding of control elements of machine controllers

### Colour coding of indicator lights

To enable operating staff to immediately identify the operating status of a system, especially malfunctions and dangerous situations, indicator lights are colour-coded in accordance with EN 60204. The following table shows the meaning of the various colours.

| Colour | Operating status | Sample applications |
|---|---|---|
| Red | Abnormal status | Indication that the machine has been stopped by a protective device (e.g. due to overload, overtravel or some other fault). Prompt to shut down the machine (e.g. because of overload). |
| Yellow | Attention or caution | A value (current, temperature) is approaching its permissible limit. Signal for automatic cycle. |
| Green | Machine ready to start | Machine ready to start: auxiliaries operational. The (various) units are in their initial positions and the pneumatic pressure or the voltage of a transformer have reached the prescribed values. The operation cycle is completed and the machine is ready for restarting. |
| White (colourless) | Electrical circuits energised. Normal operating status | Main switch in On position. Selection of speed or direction of rotation. Individual drives and auxiliary drives in operation. Machine running. |
| Blue | Any function for which none of the above colours is used. | |

13.2: Colour coding of indicator lights for machine controllers

## 13.5 Protecting electrical equipment against environment influences

Electrical equipment such as sensors or programmable logic controllers may be exposed to a variety of environmental influences. The factors which may impair operation of such equipment include dust, moisture and foreign matter.

Depending on the installation and environmental conditions, electrical equipment may be protected by housings and seals. Such measures also prevent danger to personnel handling the equipment.

### 13.5.1 Identification of the degree of protection

The identifier for the degree of protection in accordance with EN 60529 consists of the two letters IP (standing for "International Protection") and two digits. The first digit indicates the level of protection against the ingress of dust and foreign bodies, and the second digit the level of protection against the ingress of moisture and water. The following tables show the correlation between the class of protection and the scope of protection.

| First digit | Scope of protection Designation | Explanation |
|---|---|---|
| 0 | No protection | No particular protection of persons against accidental contact with live or moving parts. No protection of the equipment against the ingress of solid foreign matter. |
| 1 | Protection against large foreign matter | Protection against accidental contact of large areas of the body, e.g. the hand, with live and internal moving parts, but with no protection against intentional contact with these parts. Protection against the ingress of solid foreign matter with a diameter greater than 50 mm. |
| 2 | Protection against medium-sized foreign matter | Protection against finger contact with live or internal moving parts. Protection against the ingress of solid foreign matter with a diameter greater than 12 mm. |
| 3 | Protection against fine foreign matter | Protection against contact with live or internally moving parts with tools, wires, etc. with a thickness greater than 2.5 mm. Protection against the ingress of solid foreign matter with a diameter greater than 2.5 mm. |
| 4 | Protection against granular foreign matter | Protection against the ingress of solid foreign matter with a diameter greater than 1 mm. |
| 5 | Protection against dust deposits | Complete protection against contact with live or internal moving parts. Protection against harmful dust deposits. The ingress of dust is not totally prevented, but the dust is unable to enter in sufficient quantities to impair operation. |
| 6 | Protection against ingress of dust | Complete protection against contact with live or internal moving parts. Protection against ingress of dust. |

13.3: Protection against contact, dust and foreign matter

| Second digit | Scope of protection Designation | Explanation |
|---|---|---|
| 0 | No protection | No specific protection |
| 1 | Dripping water | Vertically falling droplets must not have any harmful effect. |
| 2 | Water drops at 15° angle | Vertically falling droplets must not have any harmful effect if the housing is tilted at an angle of up to 15° on either side of the vertical. |
| 3 | Spraying water | Water sprayed at any angle of up to 60° either side of the vertical must not have any harmful effect. |
| 4 | Splashing water | Water splashing against the enclosure from any direction must not have any harmful effect. |
| 5 | Jets of water | Water jets directed at the enclosure from any direction must not have any harmful effect. |
| 6 | Powerful water jets | Water projected in powerful jets against the enclosure from any direction must not have any harmful effect. |
| 7 | Periodic immersion | Water must not enter the equipment in amounts that can have a harmful effect if the enclosure is briefly submerged in water under standardised pressure and time conditions. |
| 8 | Prolonged immersion | Water must not penetrate in harmful amounts if the housing is continually submersed under water in conditions which must be agreed between the manufacturer and the user. However, the conditions must be more extreme than those for level. 7. |

13.4: Protection against moisture and water

# 14 Symbols and circuit symbols

## 14.1 Symbols for pneumatic components

The pneumatic circuit diagram for a controller shows how the individual pneumatic components are connected and how they interact. The symbols representing the components are arranged so as to obtain a clear circuit diagram in which there are as few intersecting lines as possible. A pneumatic circuit diagram therefore does not represent the actual spatial arrangement of the components.

In a pneumatic circuit diagram, the components are represented by symbols standardised according to ISO 1219-1. It must be possible to recognise the following characteristics from a symbol:

- Actuating method
- Number of ports and their designations
- Number of switching positions

The symbols shown on the following pages are only for those components that are used frequently in electropneumatic controllers.

### 14.1.1 Symbols for the power supply section

The power supply section can be represented by the symbols of the individual components, by a combined symbol or by a simplified symbol.

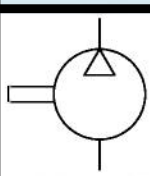
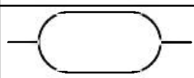
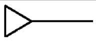
| Function | Symbol |
|---|---|
| Compressor with constant displacement volume |  |
| Accumulator, air reservoir |  |
| Pressure source |  |

Table 14.1: Symbols for the power supply section – supply

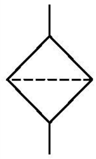
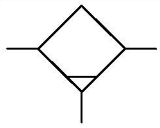
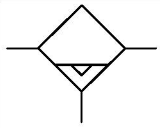
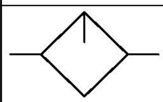
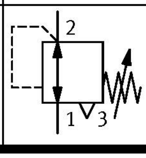
| Function | Comment | Symbol |
|---|---|---|
| Filter | Filtration of dirt particles |  |
| Water separator, manually actuated | |  |
| Water separator, automatic | |  |
| Lubricator | Metered quantities of oil are added to the air flow |  |
| Pressure regulator | Adjustable, with relief port |  |

Table 14.2: Symbols for the power supply section – maintenance unit

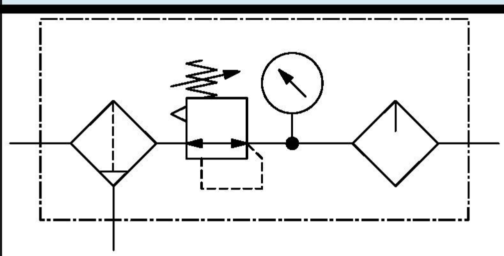
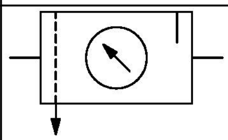
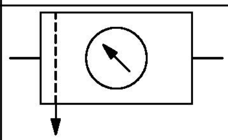
| Function | Comment | Symbol |
|---|---|---|
| Service unit | Consisting of water separator, compressed air filter, pressure regulator, pressure gauge and lubricator |  |
| | Simplified representation of a service unit |  |
| | Simplified representation of a service unit without lubricator |  |

Table 14.3: Symbols for the power supply section – combined symbols

### 14.1.2 Symbols for valves

The symbols for pneumatic valves consist of one or more squares.

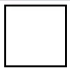
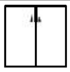
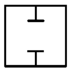
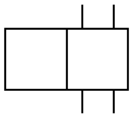
| Function | Symbol |
|---|---|
| Switching positions are represented by squares |  |
| The number of squares corresponds to the number of switching positions |  |
| Lines indicate flow paths, arrows indicate flow direction |  |
| Closed ports are represented by two lines drawn at right angles to each other |  |
| Connecting lines for supply air and exhaust air are drawn on the outside of a square |  |

Table 14.4: Building blocks for valve symbols

### 14.1.3 Symbols for directional control valves

The ports, switching positions and flow paths are represented in the symbol for a directional control valve. With a solenoid actuated directional control valve, the ports are drawn at the switching position assumed by the valve when the power supply is switched off.

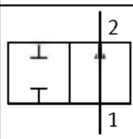
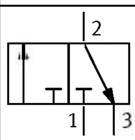
| Function | Symbol |
|---|---|
| 1st digit: number of ports<br>2nd digit: number of switching positions | |
| 2/2-way valve in flow position |  |
| 3/2-way valve in closed position |  |

Table 14.5: Directional control valves – ports and switching positions

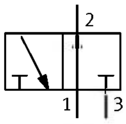
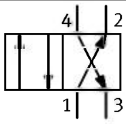
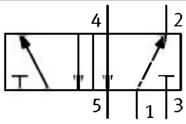
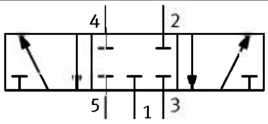
| Function | Symbol |
|---|---|
| 1st digit: number of ports<br>2nd digit: number of switching positions | |
| 3/2-way valve in flow position |  |
| 4/2-way valve, flow from 1 to 2 and 4 to 3 |  |
| 5/2-way valve, flow from 1 to 2 and 4 to 5 |  |
| 5/3-way valve blocked in mid-position |  |

Table 14.6: Directional control valves – ports and switching positions (continued)

### Identification of ports and actuation on directional control valves

In order to prevent incorrect connection of tubing on directional control valves, the valve ports are identified in accordance with ISO 5599-3 both on the valve itself and in the circuit diagram. Where actuation is by compressed air, the effect of actuation is represented in the circuit diagram either on the corresponding pilot line or, in the case of valves with internal pilot air supply, alongside the actuation symbol.

| | Function | Designation |
|---|---|---|
| Working lines (all valve types) | Supply port<br>Working ports<br>Exhaust ports | 1<br>2,4<br>3,5 |
| Pilot lines/actuation for pilot actuated or pneumatically actuated directional control valves | Close supply port<br>Connection between ports 1 and 2<br>Connection between ports 1 and 4<br>Exhaust ports for pilot air | 10<br>12<br>14<br>82,84 |

Table 14.7: Identification of working lines and pilot lines with directional control valves

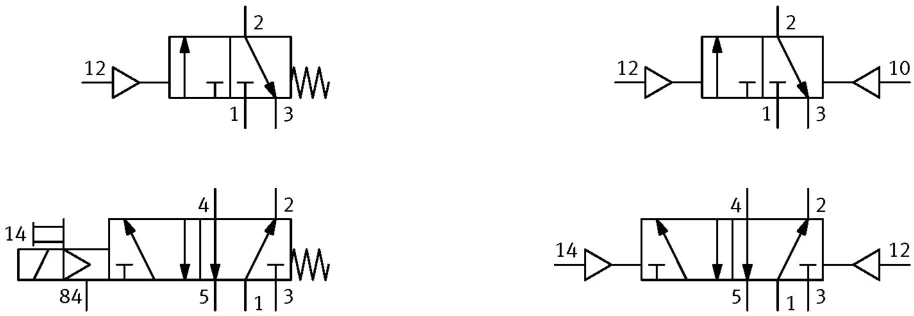



Figure 14.1: Examples of designations

### Actuation methods for directional control valves

A complete description of a directional control valve in the pneumatic circuit diagram includes

- Basic actuation method of the valve
- Reset method
- Pilot control (if present)
- Additional actuation options (e.g. manual override, if present)

Each actuation symbol is drawn on the side of the switching position that corresponds to its direction of action.

The actuation method of the directional control valves depends on the system requirements. They can include:

- Manually operated
- Mechanically actuated
- Pneumatically actuated
- Solenoid actuated
- Combinations of these

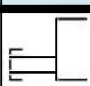
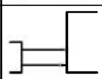
| Function | Symbol |
|---|---|
| By pressing |  |
| By pulling |  |

Table 14.8: Actuation methods for directional control valves – manual operation

| Function | Symbol |
|---|---|
| By spring |  |
| Spring-centred |  |

Table 14.9: Actuation methods for directional control valves – mechanical resetting

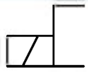
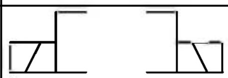
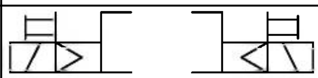
| Function | Symbol |
|---|---|
| By one solenoid |  |
| By two solenoids |  |
| Piloted valve, electromagnetically actuated at both sides, manual override |  |

Table 14.10: Actuation methods for directional control valves – solenoid actuation, combined actuation

### 14.1.4 Symbols for non-return valves, flow control valves and quick exhaust valves

Non-return valves determine the direction of flow, while flow control valves determine the flow rate in a pneumatic controller. With quick exhaust valves it is possible to achieve particularly high motion speeds with pneumatic drives because the compressed air can escape virtually unthrottled.

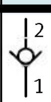
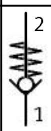
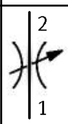
| Function | Symbol |
|---|---|
| Non-return valve |  |
| Non-return valve, spring-loaded |  |
| Flow control valve, adjustable |  |

Table 14.11: Symbols for non-return valves, flow control valves and quick exhaust valves

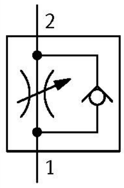
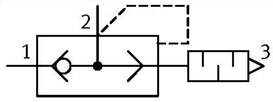
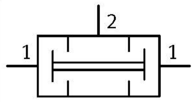
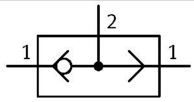
| Function | Symbol |
|---|---|
| One-way flow control valve, adjustable |   |
| Quick exhaust valve |   |
| Dual-pressure valve |   |
| Shuttle valve |   |

Table 14.12: Symbols for quick exhaust valve, dual-pressure valve and shuttle valve

### 14.1.5 Symbols for pressure regulators

Pressure regulators are used for:

- Maintaining a constant pressure (pressure regulator)
- Pressure-dependent changeover (pressure sequence valve)

As an alternative to a pressure sequence valve in an electropneumatic control system it is also possible to use a directional control valve that is actuated by a signal from a pressure switch or pressure sensor.

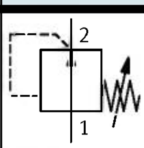
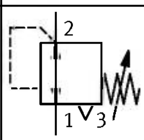
| Function | Symbol |
|---|---|
| Adjustable pressure regulator without relief port |   |
| Adjustable pressure regulator with relief port |   |

Table 14.13: Symbols for pressure regulators

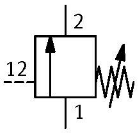
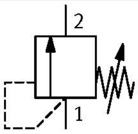
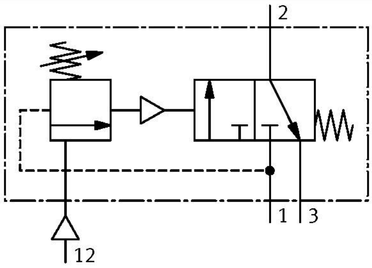
| Function | Symbol |
|---|---|
| Pressure sequence valve with external supply line |  |
| Pressure-relief valve |  |
| Pressure sequence valve (combination) |  |

Table 14.14: Symbols for pressure regulators (continued)

### 14.1.6 Symbols for operating elements

The following operating elements are used in electropneumatic controllers:

- Pneumatic cylinders for linear movements (single-acting cylinders, double-acting cylinders, rodless cylinders, etc.)
- Swivel cylinders
- Motors for continuous rotary movements (e.g. vane motor for pneumatic screwdrivers)
- Suction cups

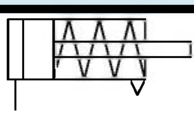
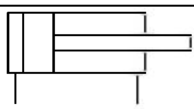
| Function | Comment | Symbol |
|---|---|---|
| Single-acting cylinder | Advance by pneumatic power.<br>Retract by return spring. |  |
| Double-acting cylinder | Advance and retract by pneumatic power. |  |

Table 14.15: Symbols for pneumatic operating elements

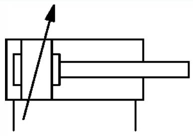
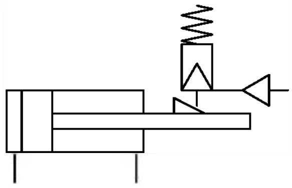
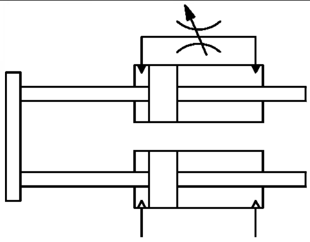
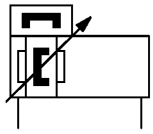
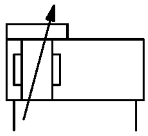
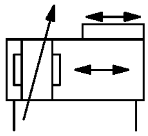
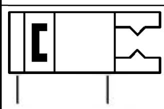
| Function | Comment | Symbol |
|---|---|---|
| Double-acting cylinder | Adjustable end-position cushioning for forward and return stroke. |  |
| Double-acting cylinder with clamping unit | Mechanical clamping unit with pneumatic unlocking. |  |
| Double-acting cylinder with hydraulic slave cylinder | Cylinder is pneumatically controlled. The hydraulic slave cylinder provides for even movement. |  |
| Rodless cylinder with adjustable end-position cushioning | Usually cylinder with long stroke lengths. Power transmission by permanent magnet. |  |
| Rodless cylinder with adjustable end-position cushioning | Power transmission by mechanical means, for example sealing band cylinder. |  |
| Rodless cylinder with adjustable end-position cushioning | Power transmission by mechanical means,<br>cable/band design. |  |
| Double-acting pneumatic gripper | |  |

Table 14.16: Symbols for pneumatic operating elements (continued)

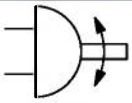
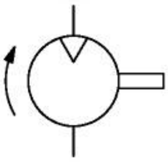
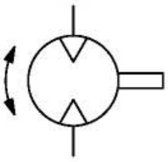
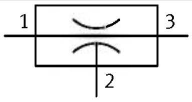
| Function | Comment | Symbol |
|---|---|---|
| Semi-rotary drive, pneumatic | Rotary drive with limited swivelling range. |  |
| Compressed air motor | Compressed air motor with constant capacity and one direction of rotation. |  |
| Compressed air motor | Pneumatic motor with two directions of rotation. |  |
| Vacuum generator | Vacuum input via ejector. |   |

Table 14.17: Symbols for pneumatic operating elements (continued)

### 14.1.7 Symbols for other components

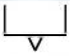
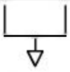
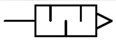
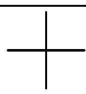
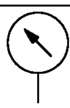
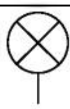
| Function | Symbol |
|---|---|
| Exhaust port with no facility for connection |  |
| Exhaust port with facility for connection |  |
| Silencer |  |
| Line connection |  |
| Crossing lines |  |
| Pressure gauge |  |
| Visual indicator |  |

Table 14.18: Symbols for other pneumatic and electropneumatic components

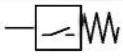
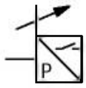
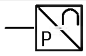
| Function | Symbol |
| --- | --- |
| Electromechanical pressure switch (P/E converter) |  |
| Electronically adjustable pressure switch, output signal switching |  |
| Pressure sensor, analogue electrical output signal |  |

Table 14.19: Symbols for other pneumatic and electropneumatic components

## 14.2 Circuit symbols for electrical components

In the schematic diagram, the components are represented by circuit symbols that are standardised in accordance with EN 60617. Circuit symbols for representing electrical components that are frequently used in electropneumatic controllers are summarised in Table 14.20 to Table 14.28.

### 14.2.1 Circuit symbols for basic functions

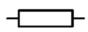
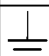
| Function | Circuit symbol |
| --- | --- |
| DC voltage, direct current |  |
| AC voltage, alternating current |  |
| Rectifier (power supply unit) |  |
| Indicator light |  |
| Permanent magnet |  |
| Resistor, general |  |
| Coil (inductance) |  |
| Capacitor |  |
| Earthing, general |  |

Table 14.20: Electrical circuit symbols – basic functions

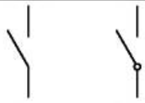
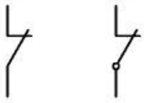
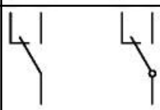
| | Circuit symbol for basic function | Circuit symbol for function with automatic drop | Circuit symbol for function without automatic drop |
|---|---|---|---|
| Normally open contact |  |  |  |
| Normally closed contact |  |  |  |
| Changeover switch |  | | |

Table 14.21: Circuit symbols for logic elements – basic functions

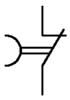
| Function | Circuit symbol for delayed actuation | Circuit symbol for delayed recoil | Circuit symbol for delayed actuation and delayed recoil |
|---|---|---|---|
| Normally open contact |  |  |  |
| Normally closed contact |  |  |  |

Table 14.22: Circuit symbols for logic elements – delayed actuation

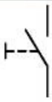
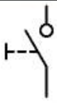
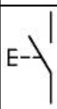
| Function | Circuit symbol for pushbutton | Circuit symbol for control switch |
|---|---|---|
| Normally open contact, manually operated |  |  |
| Normally open contact, manually operated by pressing |  |  |

Table 14.23: Circuit symbol for manually operated logic elements

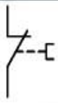
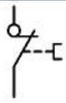
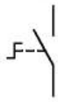
| Function | Circuit symbol for pushbutton | Circuit symbol for control switch |
| --- | --- | --- |
| Normally closed contact, manually operated by pulling |  |  |
| Normally open contact, manually operated by turning |  |  |

Table 14.24: Circuit symbol for manually operated logic elements (continued)

### 14.2.2 Circuit symbols for electromechanical drives

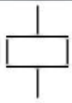
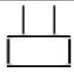
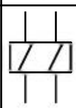
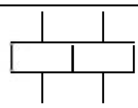
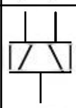
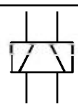
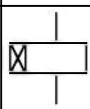
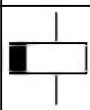
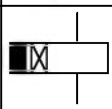
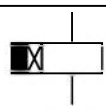
| Function | Circuit symbol |
| --- | --- |
| Electromechanical drive, general |   |
| Electromechanical drive with two windings working in the same direction |   |
| Electromechanical drive with two windings working in the opposite direction |   |
| Electromechanical drive with switch-on delay |  |
| Electromechanical drive with switch-off delay |  |
| Electromechanical drive with switch-on and switch-off delay |   |

Table 14.25: Circuit symbols for electromechanical drives

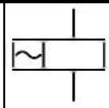
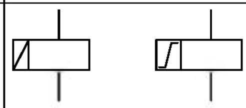
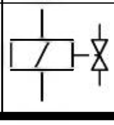
| Function | Circuit symbol |
|---|---|
| Electromechanical drive for an AC relay |  |
| Electromechanical drive for a remanence relay |  |
| Electromechanical drive for a directional control valve |  |

Table 14.26: Circuit symbols for electromechanical drives (continued)

### 14.2.3 Circuit symbols for relays and contactors

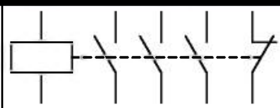
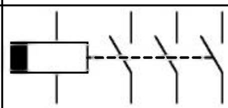
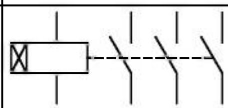
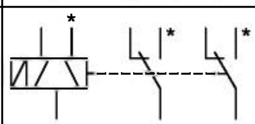
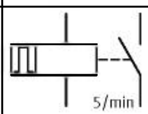
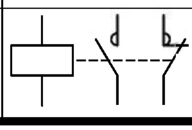
| Function | Circuit symbol |
|---|---|
| Relay with three normally open contacts and one normally closed contact |  |
| Relay with switch-off delay |  |
| Relay with switch-on delay |  |
| Remanence relay<br>If voltage is applied at the winding connection marked with an *, the contact is specified at the points in the logic elements marked with * |  |
| Flasher relay |  |
| Contactor with one normally closed contact and one normally open contact |  |

Table 14.27: Circuit symbols for relays and contactors (coherent representation)

### 14.2.4 Circuit symbols for sensors

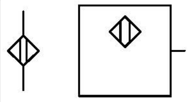
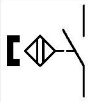
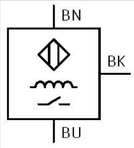
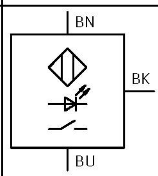
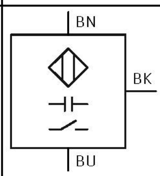
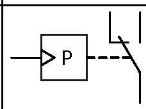
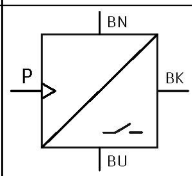
| Function | Circuit symbol |
|---|---|
| Limit switch, normally open contact |  |
| Limit switch, normally closed contact |  |
| Proximity sensor, proximity-sensitive device |  |
| Proximity sensor (normally open contact), solenoid actuated |  |
| Proximity sensor, inductive |  |
| Proximity sensor, optical |  |
| Proximity sensor, capacitive |  |
| Pressure switch, electromechanical |  |
| Pressure switch, electronic |  |

Table 14.28: Circuit symbols for sensors

## Standards

DIN 1343
Reference conditions, normal conditions, normal volume – concepts and values; January 1990
(q.v. IUPAC Compendium of Chemical Terminology 2nd Edition (1997))

EN 60073
Basic and safety principles for man-machine interface, marking and identification – Coding principles for indicators and actuators; May 2003

EN 60204, Part 1
Safety of machinery – Electrical equipment of machines: General requirements; June 2007

EN 60529
Degrees of protection provided by enclosures (IP code); September 2000

EN 60617
Graphical symbols for diagrams, Part 2 to Part 8; August 1997

EN 60848
GRAFCET – Specification language for sequential function charts; December 2002

EN 61082, Part 1
Preparation of documents used in electrotechnology – Rules; March 2007

EN 81346-2
Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Classification of objects and coding of classes; May 2010

IEC 60364-1
Low-voltage electrical installations – Fundamental principles, assessment of general characteristics, definitions Scope, purpose and basic principles; November 2005

ISO 1219, Part 1
Fluid power systems and components – Graphic symbols and circuit diagrams, graphic symbols; December 2007

ISO 1219, Part 2
Fluid power systems and components – Graphic symbols and circuit diagrams, circuit diagrams; November 1996

# Index