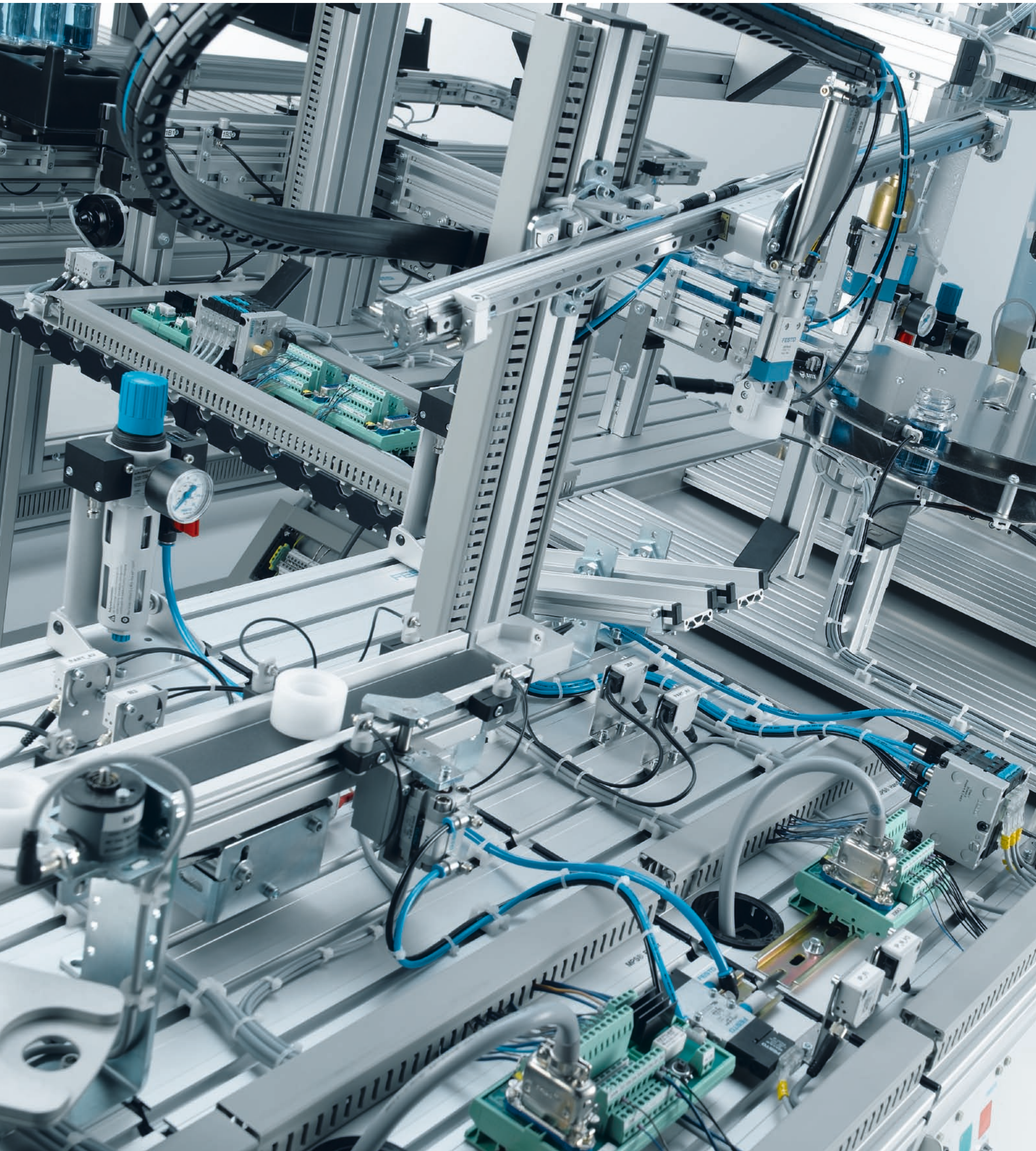
# Fundamentals of automation technology

Technical book



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**Note**
The use of just one gender form (e.g. he, him) in this manual should not be considered gender discrimination; it is intended solely to make the manual easier to read and the formulations easier to understand.

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# 1 How do engineers work?

Engineering sciences, like the arts, social sciences and natural sciences, are a discrete discipline with their own language, practices and tools. Of course they also draw on and use principles from other sciences, in particular mathematics and physics but also social sciences. In turn, many of the findings in these latter disciplines are based on the results of research carried out in the field of engineering sciences.

Unlike natural sciences, engineering sciences are not primarily concerned with acquiring information and discovering the laws of nature but rather with creating technical solutions to satisfy human needs.

The engineer therefore is always asking "How can I solve this problem?". This leads to a typical technical approach such as "black-box thinking". Black box thinking means that engineers use technical systems without needing to know precisely how the individual components and modules work in detail. All engineers need to know is that the device will deliver a specific output from a specific input.

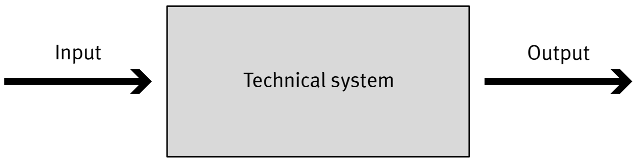



Figure 1.1: Black box representation of a technical system

For example, automated machines use electric motors of different sizes and outputs. The machine designer doesn't need to know exactly how the electric motor works. All he needs to do is select the right motor using characteristics such as dimensions, torque, speed, current consumption, output, etc.

In contrast, a situation in which engineers design electric motors themselves is completely different. In this case they need an in-depth knowledge of the mode of operation and physical fundamentals of the electric motor and its components.

Another distinctive feature of engineering sciences is the manner in which technical solutions are represented. Engineers use standardised and therefore internationally understood description tools, most of which are graphical. The main ones are:

- technical drawings and parts lists,
- circuit diagrams,
- flow charts and programs,
- technical plans and schematic diagrams.

## 1.1 Technical drawings and parts lists

Technical drawings are used to illustrate the design of products. They show in detail the dimensions, tolerances, surface finish and materials of the workpieces (dimensional drawings) or the assembly of modules (assembly drawings).

The views of a workpiece are arranged on paper using a standard protocol whereby each view shows the workpiece rotated by 90° to the plane of projection. A maximum of six views are possible with this approach. However, normally only those views are reproduced that are needed to show all the dimensions required for production. Figure 1.2 shows an example of a dimensional drawing.

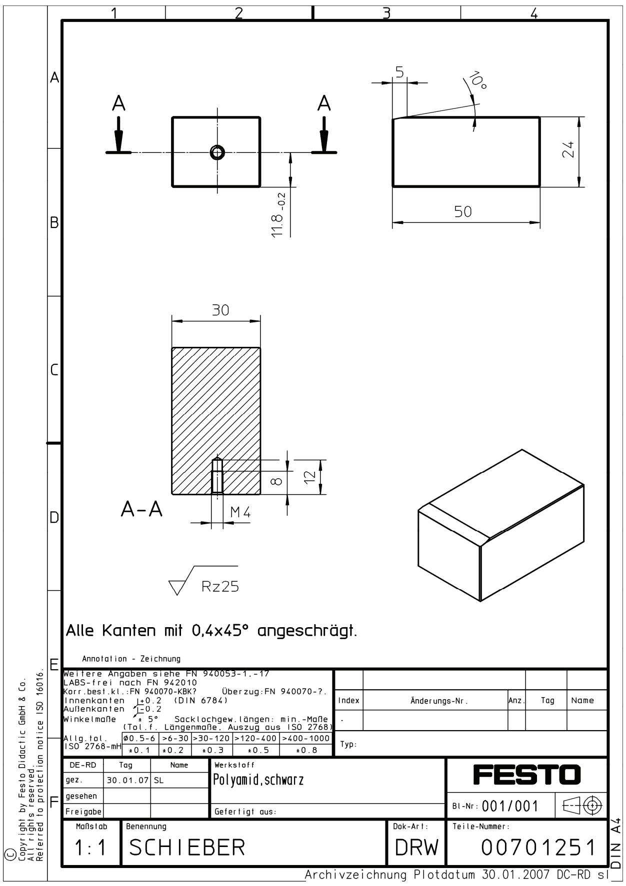



Figure 1.2: Dimensional drawing of the slide from the stacking magazine (original size A4)

Assembly drawings show how the component parts make up the finished product or module. These drawings contain few dimensions, but do show the exact designations of the component parts (cf. Figure 1.3).

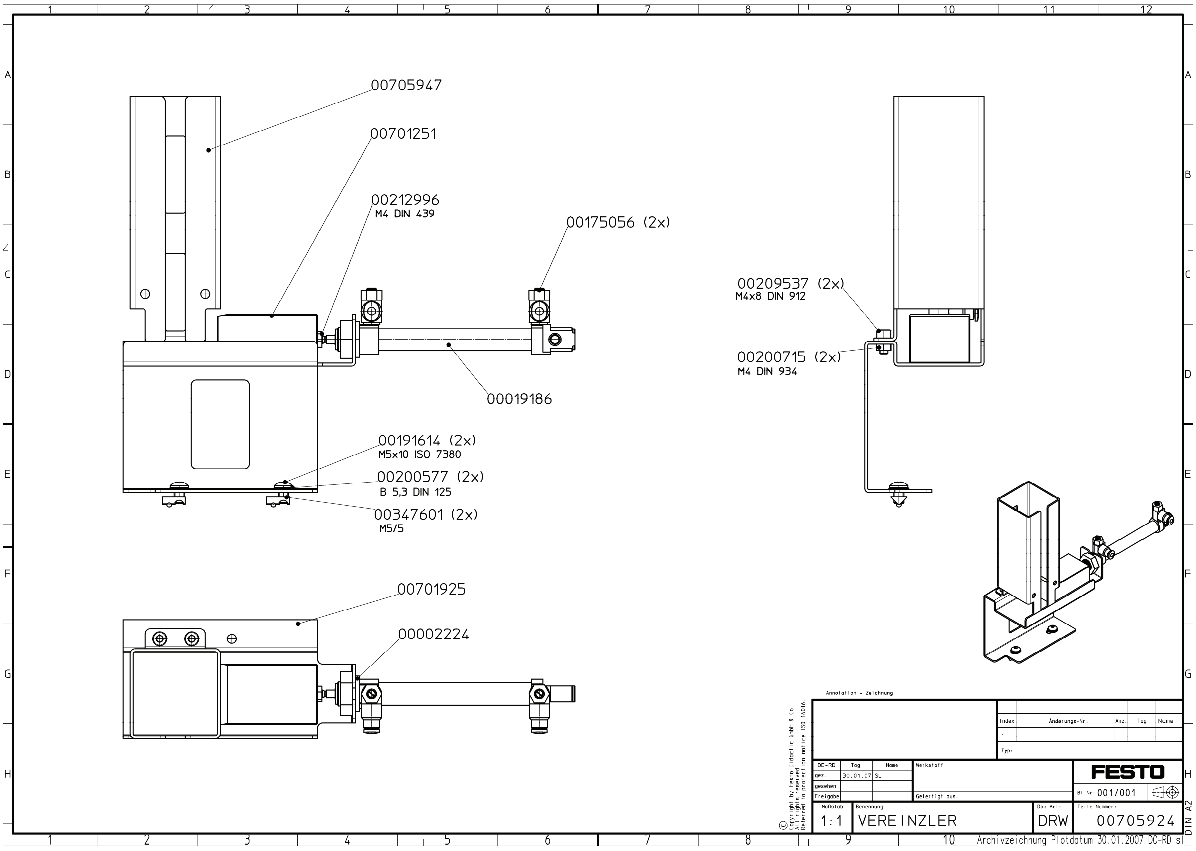



Figure 1.3: Assembly drawing of the stacking magazine (original size A3)

These component parts are compiled in a parts list that provides information on how many of the respective parts are needed to manufacture a product (cf. Table 1.1).

| Number | Material number | Description |
|---|---|---|
| 1 | 00705947 | Gravity feed chute |
| 1 | 00701251 | Slide |
| 1 | 00701925 | Body |
| 1 | 00019186 | Pneumatic cylinder DSNU 10-50-PA |
| 2 | 00175056 | One-way flow control valve GRLA-M5-QS-4-LF-C |
| 2 | 00191614 | Tallow-drop screw M5 x1 0 ISO 7380 |
| 2 | 00200577 | Washer B 5.3 DIN 125 |
| 2 | 00347601 | T-head nut M5 |
| 2 | 00209537 | Socket head screw M4 x 8 DIN 912 |
| 2 | 00200715 | Nut M4 DIN 934 |
| 1 | 00002224 | Sealing ring |

Table 1.1: Example of a parts list (for Figure 1.3)

Each component has its own dimensional drawing that can be used as a basis for its manufacture. The only parts for which individual drawings are not produced are standard parts such as screws and ball bearings or other bought-in parts. You can identify bought-in standard parts in the parts list from their designations, which include a reference to the standard (e.g. DIN 125 or ISO 7380).

Engineers use standard parts whenever possible as they are inexpensive; they can be bought in the exact quantities required and in the stipulated quality from other specialist manufacturers, which usually works out cheaper than producing them in-house. This not only makes it easier for engineers to design the product, but also to repair it in the event of a defect.

## 1.2 Circuit diagrams

While technical drawings show the outer design of a product, circuit diagrams show how the electric, pneumatic or hydraulic components of a technical system or installation are interconnected. Standardised symbols are used to refer to the function of the component, regardless of their design or what they actually look like. Circuit diagrams are therefore much more abstract than technical drawings.

Figure 1.4 shows the circuit diagram for an actual pneumatic circuit.

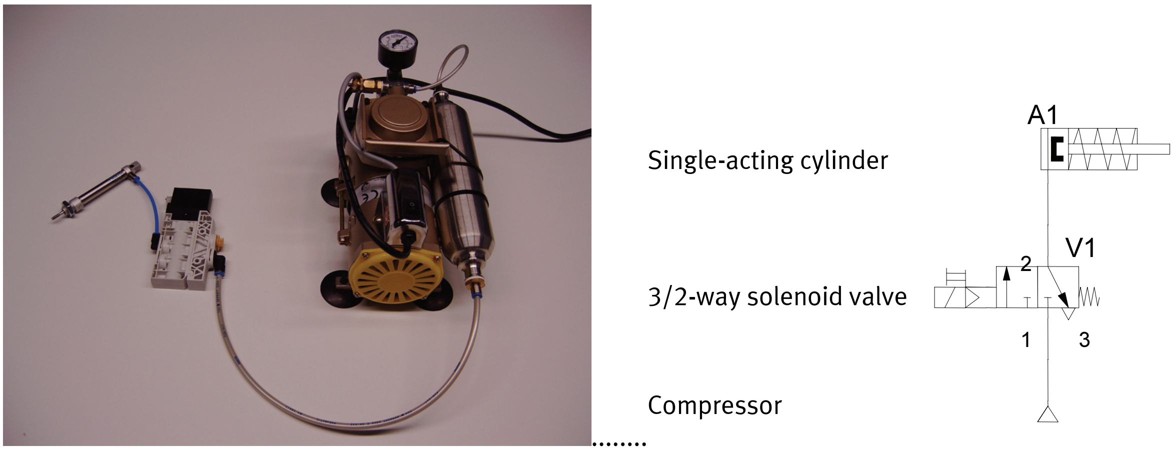



Figure 1.4: Actual components and how they are represented in a (pneumatic) circuit diagram

The components, connections, etc. are numbered so that the overview is retained when building the circuit. The components are labelled in the same way in the machine so that their function can be reproduced later in the circuit diagram.

## 1.3 Flow charts and programs

Most modern controllers are program controllers. This means that a computer program coordinates and directs the individual control phases. Special programming languages have been developed for the most varied of problems in engineering, for example Fortran (Formula Translation) for predominantly mathematical tasks, Cobol (Common Business Oriented Language) for business programs, ladder diagram for logic control systems or Basic (Beginner's All-purpose Symbolic Instruction Code) as an easy-to-learn, all-purpose programming language for beginners.

Here is a simple example of how a rudimentary program is developed.
Before the actual programming can be started, the algorithm is developed in the form of a flow diagram. Figure 1.5 shows a flow diagram for the following control sequence:

- the switching status of pushbuttons 1 and 2 is checked,
- if both switches have the status 1 (on), then the cylinder is advanced,
- in all other cases the interrogation is repeated.

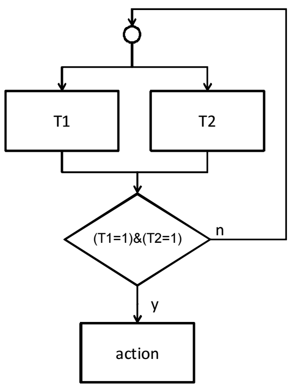



Figure 1.5: Flow diagram

A Basic program for the sequence shown in Figure 1.5 could go something like:

```
10    P1 = Pushbutton 1
20    P2 = Pushbutton 2
30    If (P1 = 1) and (P2 = 1) then advance cylinder, otherwise go to 10
```

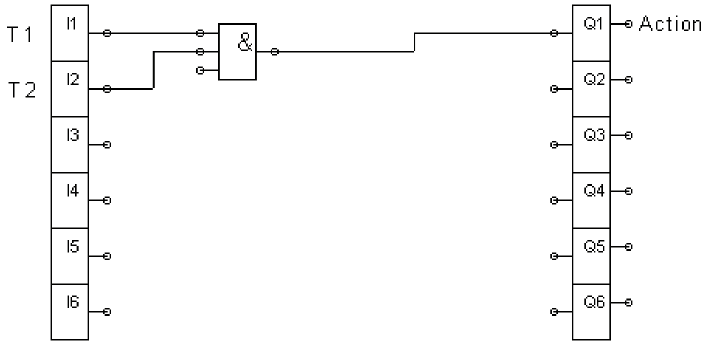
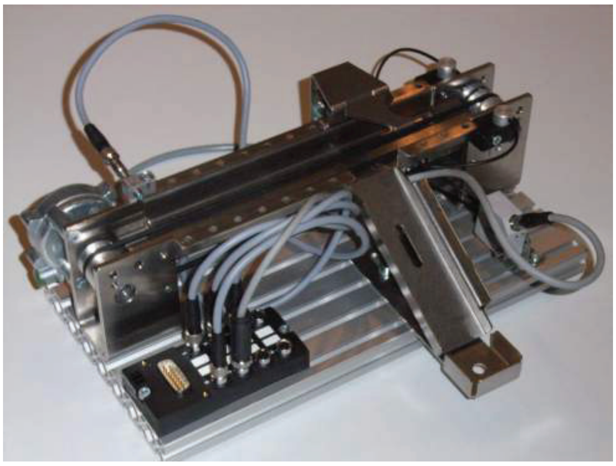



Figure 1.6: Logic program

## 1.4 Technical plans and schematic diagrams

A technical plan or schematic diagram is used to illustrate the function of a machine. The representation may be more or less abstract, depending on the purpose; the most important aspect is to realistically portray the interaction and basic arrangement of the components and modules. To illustrate key relationships, control components such as sensors or actuators can be labelled in the technology pattern with the same abbreviated designations as in the program or the circuit diagram. Figure 1.7 shows an example.



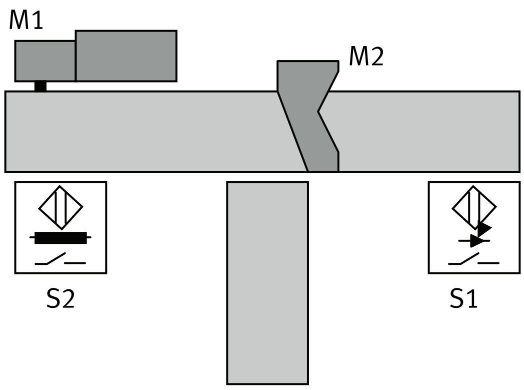



Figure 1.7: Picture and schematic diagram of the conveyor module

## 1.5 Calculations and simulation

Calculations for sizing components are one of the most important steps in the entire development process. In many cases, detailed proofs of strength are formally required by law (e.g. when building houses or airplanes) to avert the dangers caused by undersized machines. Generally, calculations are frequently required to ensure the operability of the machines under all circumstances. Examples of this are the calculation of forces and torques for sizing drives or the calculation of current intensities for sizing power lines.

Closely related to the topic of calculation is the use of simulation. Engineers try, wherever possible, to test and optimise their solutions via simulation before a (costly) prototype is built.

A good example of this is the FluidSIM® program that enables students to test and simulate their pneumatic, logic or electrical circuits before building them. If the circuit works, then it can also be used to control the actual model. In this case, the use of simulation enables several students to work simultaneously on one problem with less (expensive) training hardware required.

# 2 Automation technology as a part of engineering sciences

Examples of engineering-related sciences include:
- mechanical engineering,
- electrical engineering,
- production engineering,
- structural engineering,
- and so on.

One point these sciences all have in common is the researching, definition and application of engineering principles. What differentiates them is the subject matter and the orientation of the respective discipline.

Automation technology is a crossover discipline that uses knowledge and scientific methods from numerous other technical sciences. According to DIN 19223, an automatic machine is an artificial system that makes decisions based on the linking of inputs with the respective states of the system; these decisions then produce very specific desired outputs.

Three components are needed to realise modern automatic processes:
- sensors to detect the system states,
- actuators to output the control commands,
- controllers for the program flow and to make decisions.

## 2.1 Key development milestones in the history of automation technology

These days when we hear "automation technology" we immediately think of industrial robots and computer controllers. In fact, automation technology in craft and industry began much earlier with the utilisation of the steam engine by James Watt in 1769. For the first time, a machine could replace manpower or horsepower.

The first steam engines were used to drain water from mines and to drive machine tools. These applications involved a single steam engine driving a number of machines via a complicated system of transmission shafts and leather belts (so-called transmission belts) mounted on the ceiling of the machine hall.

In 1820 the Danish physicist Oersted discovered electromagnetism, in 1834 Thomas Davenport developed the first direct current motor with commutator (reverser) and received the patent for it one year later. Nevertheless, it was not until 1866 that the electric motor became widely used. This was after Werner von Siemens invented the dynamo that provided a simple way of generating electrical current in large quantities. The electric motor replaced the steam engine as a driving component.

In 1913 Henry Ford introduced the first assembly line production system for the famous Model T (Figure 2.1). This resulted in much higher productivity, as production time for a car fell from 750 to just 93 hours. That was the foundation for the series production of cars. This higher productivity enabled the Ford company to pay its workers a daily wage of 5 dollars for 8 hours of work in 1913. The price for a Model T fell to around 600 dollars. The automobile became a consumer item for wider sections of the population and no longer the few well-to-do.

The science behind assembly line production was based on the work of the American Frederick Winslow Taylor on the division of labour, where production is divided into lots of simple work steps that even unskilled workers can perform.

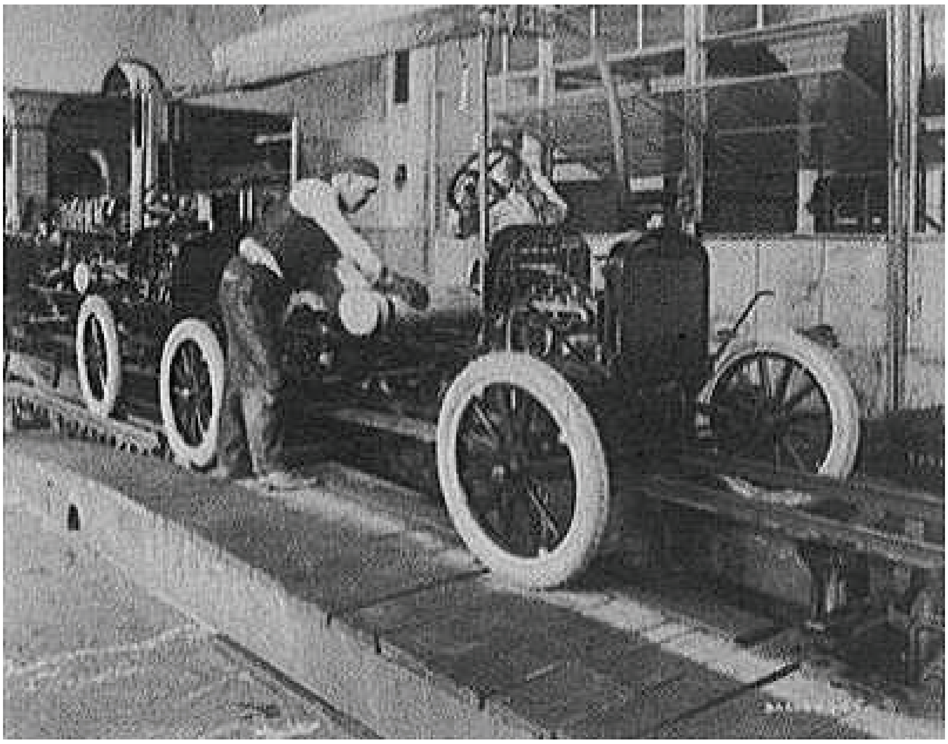


Figure 2.1: Assembly line production at Ford (1921)

In 1873 a patent was granted for a fully automatic machine for manufacturing screws that used cam disks to store the individual program sequences.

In 1837 Joseph Henry invented an electromagnetic switch that was called a relay after the relay stations where post riders could swap their tired horses for fresh ones.

They were initially used for signal amplification in Morse stations. Later they were used for building electrical controllers. This type of controller, where the relays are hard wired together, were called hard-wired programmed controllers, a name still used today. Relays could now be used to master complex control tasks, however the hard wiring meant that programming still took quite a long time and troubleshooting was time-consuming.

In 1959 Joseph Engelberger presented the prototype for an industrial robot that was used by General Motors in automobile production from 1961. This robot still had hydraulic drives; it was not until later that industrial robots were fitted exclusively with electric motors.

In 1968 a team from the American company Allen Bradley under the leadership of Odo Struger developed the first programmable logic controller (PLC). Now it was possible to simply change a program without having to rewire lots of relays.

Industrial robots became mainstream in modern industrial production in 1970 and remain so to this day. Modern production cannot manage without them for the moment at least. Quite the opposite in fact, their importance is continuously growing. In Germany alone there are well over 100,000 robots, mostly in the automotive industry and its suppliers.

## 2.2 Effects of automation on people

One of the main reasons for the introduction of automated systems was and remains the desire to be able to produce goods less expensively than the competition. Automation technology can do this in several ways:

- Fewer staff are needed for automated production.
- Production can run round the clock, except for a few maintenance interval periods.
- Machines generally make fewer mistakes, which means the quality of the produced products is consistently high.
- The processing times are shortened, which means that larger quantities can be shipped faster.
- Automation relieves people of boring, physically heavy or hazardous work (humanisation of the world of employment).

On the other hand, there are also less positive effects associated with automation technology, such as:

- The loss of jobs, in particular those with a low skill level (one highly qualified service technician takes the place of 10 unskilled assembly workers).
- The automation of production demands that employees occasionally make decisions, however the complexity of the system structure is such that they cannot fully decipher their consequences.
- The expenditure for an automated system of this type increases each individual's responsibility for the success of the company as a whole.

# 3 Fundamentals of electrical engineering

## 3.1 Direct current and alternating current

One of the most important foundations for automation technology is electrical engineering, since most technical systems need electrical energy both to drive them and to process incoming signals. For that reason an overview of the most important fundamentals of electrical engineering is provided below.

A simple electrical circuit consists of a voltage supply, a consuming device and the connecting cables for transferring the electrical energy. Every electrical circuit is subject to the following simple rule: "from the generator to the consuming device and back". In physical terms, within the electrical circuit are negatively charged particles, the electrons that 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 electrical current. An electrical 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.

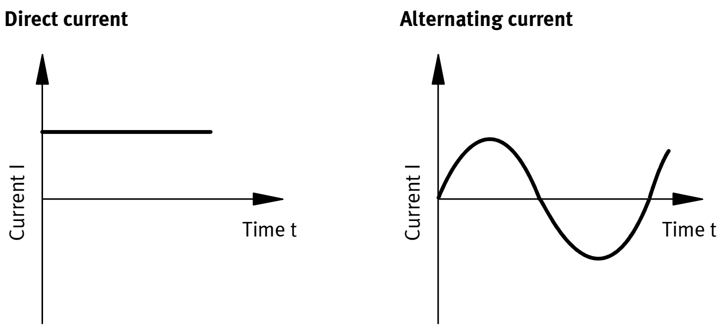



Figure 3.1: Direct current and alternating current plotted over time

Figure 3.2 shows a simple DC circuit consisting of a voltage supply, electrical cables, a control switch and a consuming device (a bulb in the example).

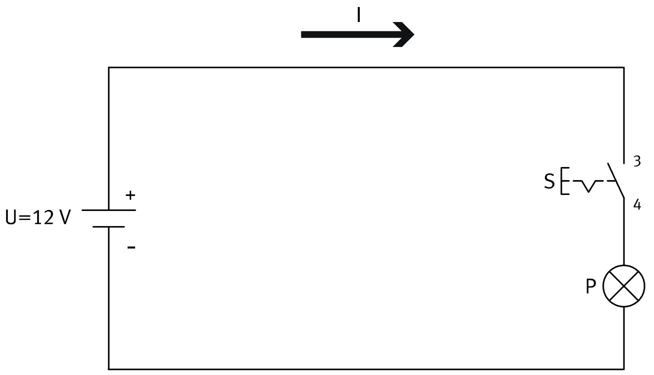



Figure 3.2: DC circuit

**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 the existence of electrons was discovered, the direction of current was defined as flowing from "positive" to "negative". This definition is still valid in practice today and is called the technical direction of current.

## 3.2 Electrical resistance and electrical power

### 3.2.1 Electrical conductor
The term electrical current refers to the directional movement of charged particles. For a current to flow in a material, there must be sufficient 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.

### 3.2.2 Electrical resistance
All materials, including good electrical conductors, offer resistance to the electrical 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 the electrical current are called electrical insulators. Rubber and plastic-based materials are used to insulate electrical cables.

### 3.2.3 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 with the voltage, i.e.

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

$$V = R \cdot I$$

| | | |
|---|---|---|
| V | = voltage | Unit: volt (V) |
| R | = resistance | Unit: ohm (Ω) |
| I | = current intensity | Unit: ampere (A) |

### 3.2.4 Electrical power

In mechanics, power can be defined in terms of work. The faster work is done, the greater the power required. Power is therefore 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. rotation in an electric motor), light radiation (e.g. electric lamp) or thermal energy (e.g. electric heater, electric lamp). The faster the energy is converted, the higher the electrical power. Power in this case is therefore converted into energy per time. It increases as the current and voltage grow.

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

$$P = V \cdot I$$

| | | |
|---|---|---|
| P | = power | Unit: watt (W) |
| V | = voltage | Unit: volt (V) |
| I | = current intensity | Unit: ampere (A) |

**Application example: Electrical power of a coil**
The solenoid coil of a pneumatic valve (e.g. the 4/2-way solenoid valve in the handling station) is supplied with 24 V DC. The resistance of the coil is 60 Ω.

– Calculate the solenoid coil's electrical consumption.

The current intensity is calculated using Ohm's law:

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

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

$$P = V \cdot I = 24\,V \cdot 0.4\,A = 9.6\,W$$

The electrical consumption of the solenoid coil is 9.6 W.

## 3.3 How a solenoid works

When current flows through an electrical conductor, a magnetic field builds up around it. This magnetic field grows in size 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.

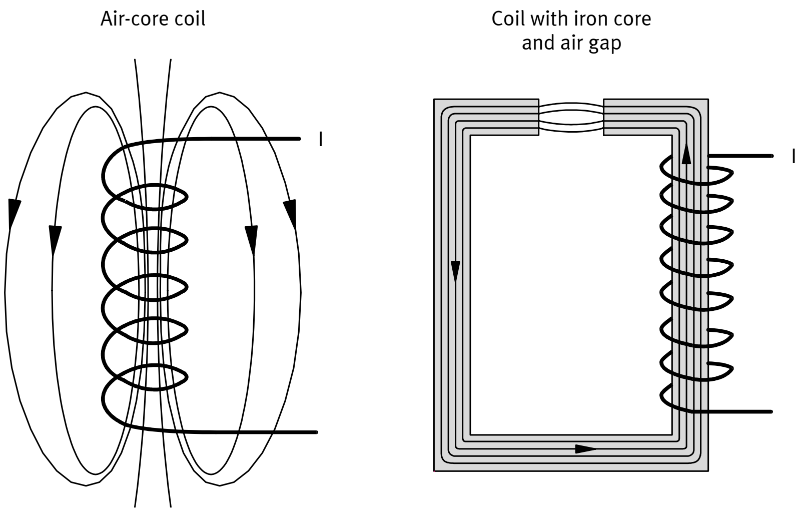



Figure 3.3: Electric coils with and without an iron core and their magnetic field lines

### 3.3.1 Structure of a solenoid

A solenoid has the following structure:

- The current-carrying conductor is wound in the shape of a coil (air-cored coil). The overlaying of the magnetic field lines of all the coil windings (see Figure 3.3) amplifies the magnetic field.
- 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 features ensure that a solenoid exerts a strong force on ferrous materials even when the current intensity is low.

### 3.3.2 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 spring-return directional control valve:

- 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.

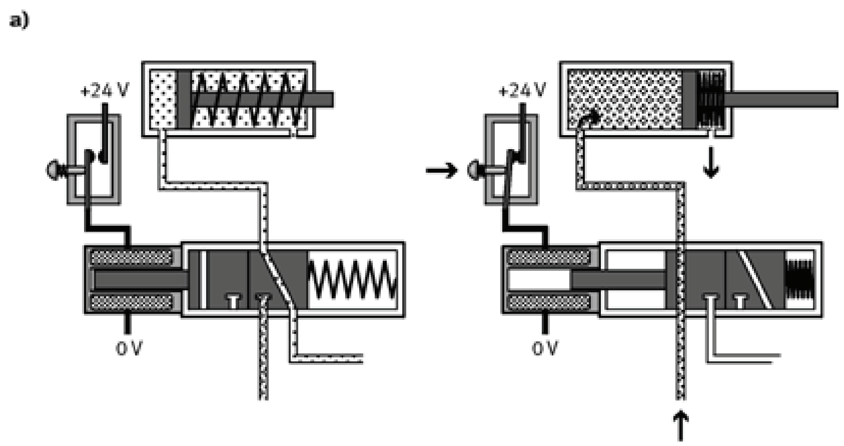



Figure 3.4: How a solenoid valve works

### 3.4 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 3.5), there is a brief flow of charging current, which electrically charges the two plates.

If the connection to the voltage supply is then interrupted (opening the pushbutton S1), 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 actual size specification for a capacitor is the capacitance C. It is defined as the relationship between the magnitude of charge Q stored in the capacitor and the voltage V applied to the capacitor:

$$C = \frac{Q}{V}$$

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

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

When the electrically charged capacitor is connected to a consuming device (closing the pushbutton S2 in Figure 3.5), charge balancing takes place. An electrical current flows through the consuming device until such time as the capacitor is fully discharged.

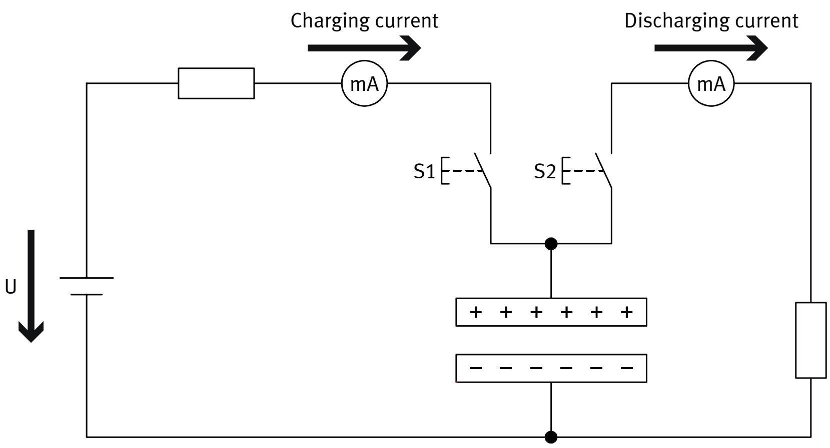



Figure 3.5: How a capacitor works

### 3.5 How a diode works

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

- When the diode is switched in the free-flow direction its resistance is very low, which means the electrical current can flow almost unimpeded.
- When it is switched in the blocked direction its resistance is extremely high, which means no current can flow.

When a diode is integrated in an AC circuit, the current can only flow in one direction. The electrical current is rectified (see Figure 3.6).
A diode's effect on the electrical current can be compared to the effect of a bicycle valve that allows air to enter a tyre but prevents it from escaping again.

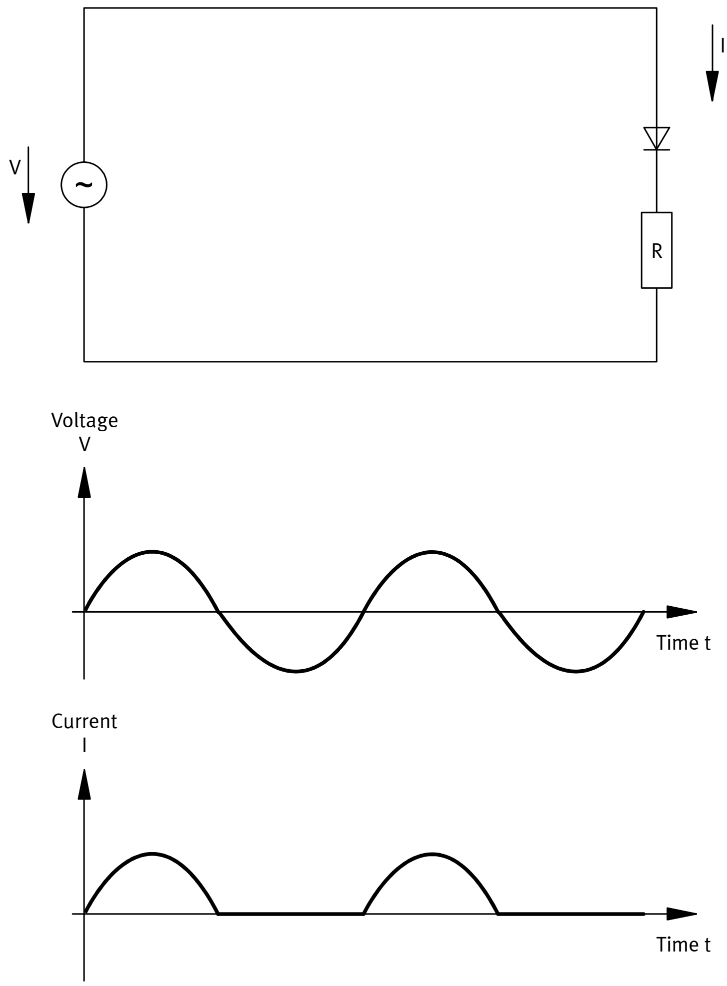



Figure 3.6: How a diode works

### 3.6 How switches work and their structure

Switches are used to facilitate or to interrupt a current flow in an electrical circuit. Depending on their design, these switches can either be pushbuttons or detenting switches.

- In the case of a pushbutton, the chosen switching position is only maintained for as long as the pushbutton is actuated. Pushbuttons are used in doorbells, for example.
- In the case of a detenting switch, both switching positions (ON/OFF) are mechanically latched. Each switching position is maintained until the switch is actuated again. Light switches in houses are an example of a latching switch in use.

A further classification and selection criterion for switches is their switching status in normal position (i.e. unactuated).

#### 3.6.1 Normally open contacts

In the case of a normally open contact (or N/O contact), the circuit is interrupted when the pushbutton is in its normal position. Actuating the pushbutton closes the circuit and supplies the consuming device with current. When the pushbutton is released, spring force returns it to its normal position and the circuit is interrupted once more.

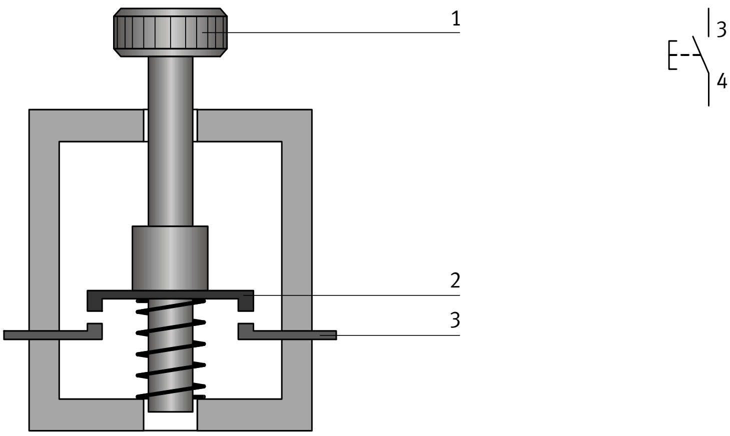
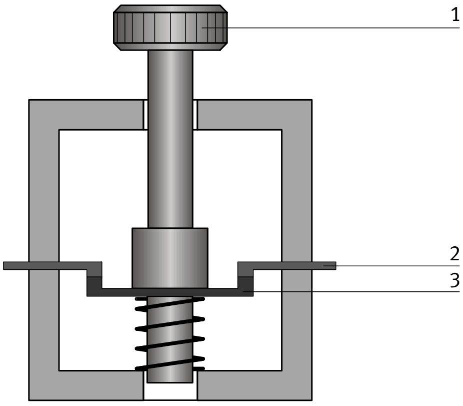



Figure 3.7: Sectional view and circuit symbol for an N/O contact

### 3.6.2 Normally closed contacts
In the case of a normally closed contact (or N/C contact), the circuit is closed by spring force when the pushbutton is in its normal position. Actuating the pushbutton interrupts the circuit.



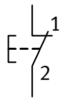
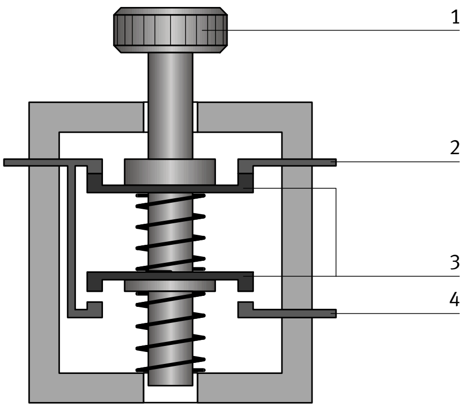




Figure 3.8: Sectional view and circuit symbol for an N/C contact

### 3.6.3 Changeover switches
The changeover switch combines the functions of an N/C contact and an N/O 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.



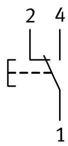




Figure 3.9: Sectional view and circuit symbol for a changeover switch

## 3.7 Relays and contactors

### 3.7.1 Applications of relays

Relays are used in electropneumatic control systems to:

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

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

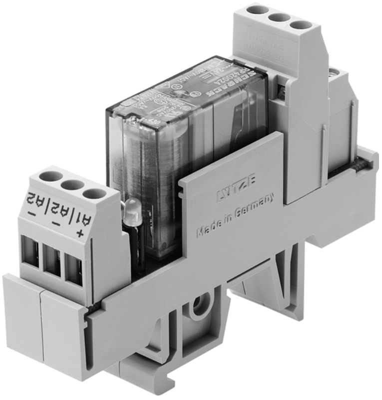


Figure 3.10: Relay

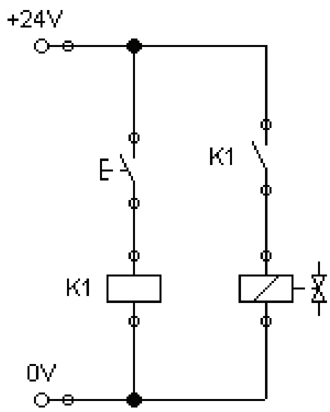
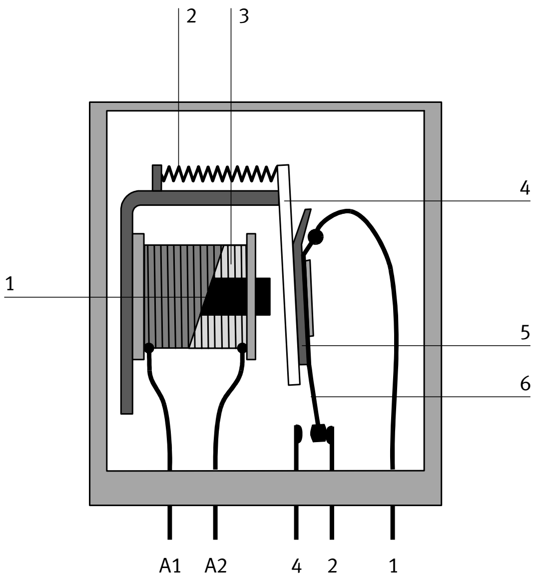
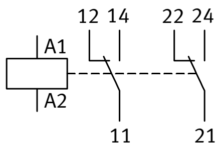



Figure 3.11: Circuit diagram for a basic relay circuit

### 3.7.2 Structure of a relay

A relay is an electromagnetically-actuated switch where the control circuit and the controlled circuit are electrically separated from each other. It essentially consists of a coil with an iron core (see (3)(1) in Figure 3.12), an armature as a mechanical actuating element (4), a return spring (2) and switch contacts (6). 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.




Coil core (1) Relay coil (3) Insulation (5)
Return spring (2) Armature (4) Contact (6)

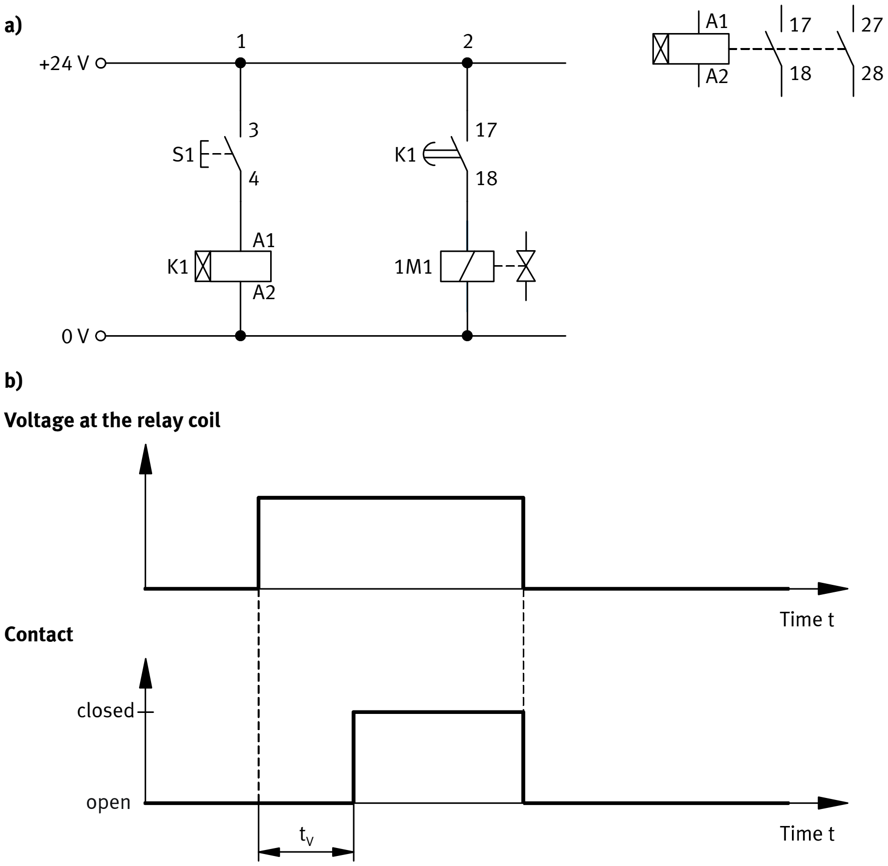
Figure 3.12: Sectional view and circuit symbol for a relay

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.

### 3.7.3 Time relays

In the case of time relays, a distinction is made between relays with switch-on delay and relays with switch-off delay.

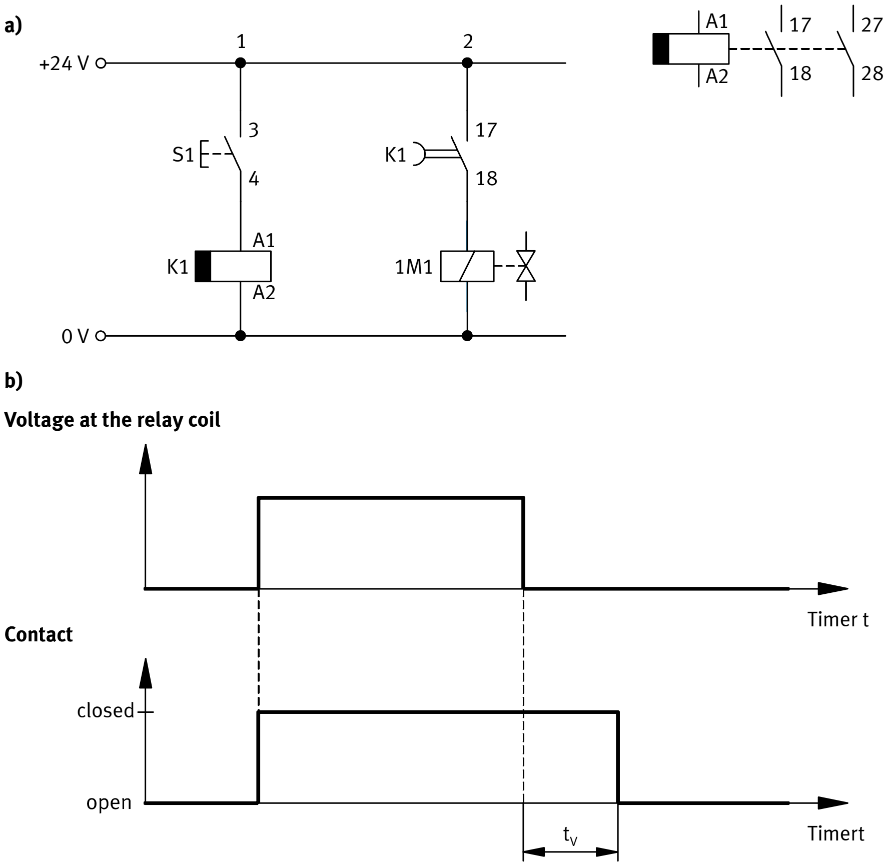
In a relay with switch-on delay, the armature switches on with a preset delay $t_d$; there is no switch-off delay. In a relay with switch-off delay, the reverse happens. The contacts switch accordingly (see Figures 3.13/3.14). The delay time $t_d$ can be set as required.




a) Representation in the circuit diagram b) Signal behaviour

Figure 3.13: Relay with switch-on delay




a) Representation in the circuit diagram    b) Signal behaviour

Figure 3.14: Relay with switch-off delay

### 3.8 Function and structure of the power supply unit

Control systems are supplied with power via the electrical network. The MecLab® controller has a power supply unit for this purpose (see Figure 3.15). The individual modules of the power supply unit have the following purposes:

- The transformer serves to reduce 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 serves to smooth 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.

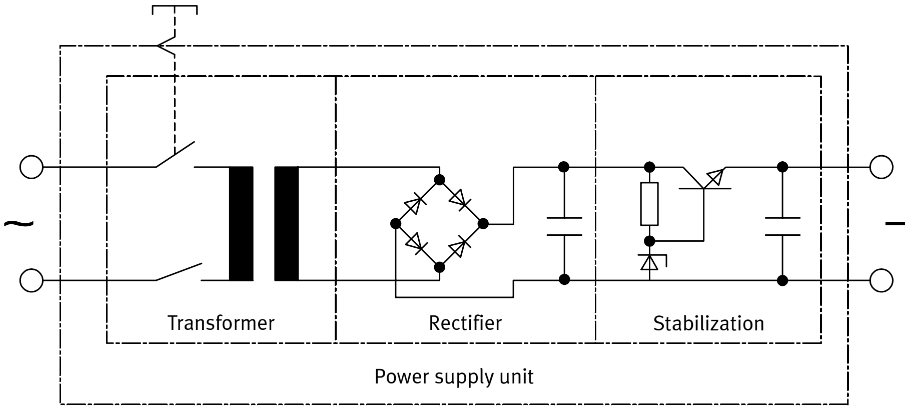



Figure 3.15: Modules in the power supply unit of an electropneumatic control system

**Safety information**

- Due to their high input voltage, power supply units are part of the high-voltage system (DIN/VDE 100).
- The safety regulations for high-voltage systems must be observed.

Work on the power supply unit must only be carried out by authorised persons.

## 3.9 Measurements in an electrical circuit

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 steel ruler) facilitates this comparison. The result, the measured value, consists of a numerical value and a unit (e.g. 30.4 cm).

Electrical currents, voltages and resistances are usually measured using multimeters. These measuring devices can be switched between different operating 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 and the measuring device has been correctly switched into the circuit.

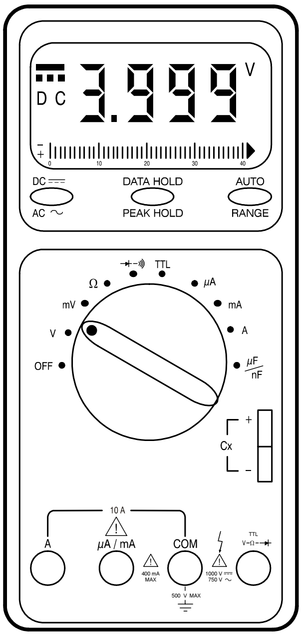



Figure 3.16: Multimeter

**Safety information**

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

### 3.9.1 Procedure for measurements in an electrical circuit

Proceed in the following order when performing 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.

### Voltage measurement

For voltage measurements, the measuring device is connected parallel to the consuming device. The voltage drop across it corresponds to the voltage drop across the measuring device. Each voltage measurement device (voltmeter) has its own internal resistance. To get the truest possible measurement result, only a very small current may flow through the measuring device, i.e. the voltmeter's internal resistance must be as great as possible.

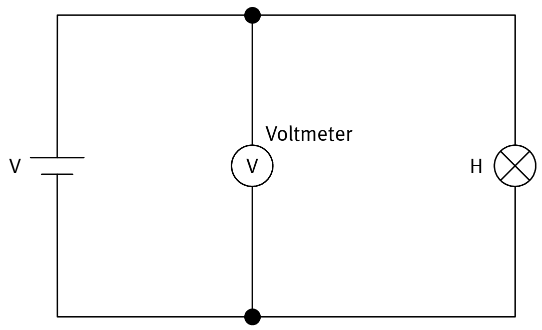



Figure 3.17: Voltage measurement

### 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.

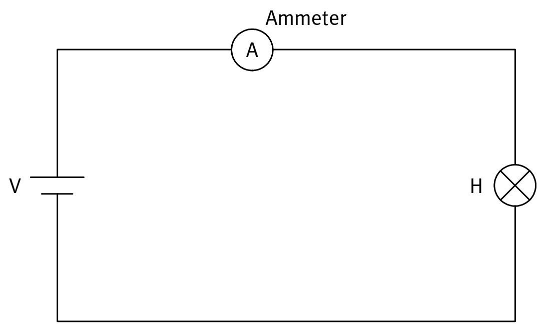



Figure 3.18: Current measurement

**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 (Figure 3.19a). 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 (Figure 3.19b). The measuring device is switched to the "resistance measurement" operating mode and connected to the two terminals on the consuming device. The resistance value is read directly on the measuring device.

If the consuming device is defective (e.g. the solenoid coil of a valve is burnt out), 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.

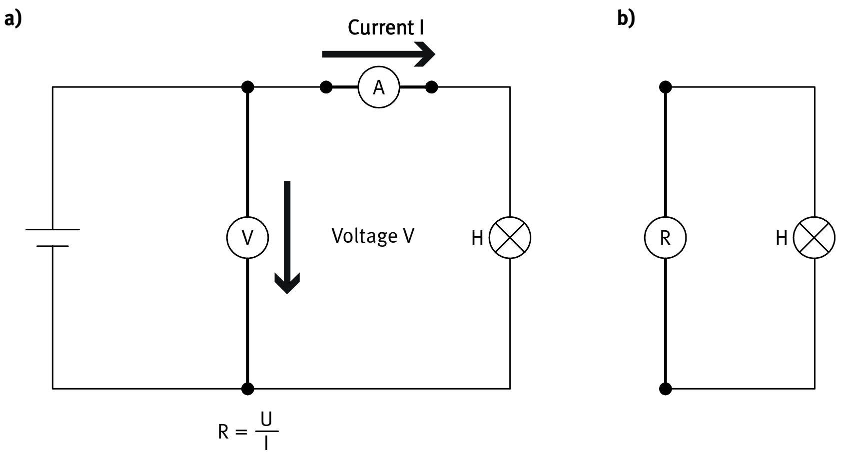



Figure 3.19: Resistance measurement

# 4 Sensors

The purpose of sensors is to acquire information and to forward it in an evaluable format to the signal processing system. They are found in diverse tasks in technology, with different designs and operating principles. That is why it is important to categorise them. Sensors can be classified according to

- operating principle (optical, inductive, mechanical, fluid, etc.),
- measured variable (displacement, pressure, distance, temperature, ph value, luminous intensity, presence of objects, etc.) or
- output signal (analogue, digital, binary, etc.), to name just a few methods.

The sensors used most frequently in automation technology are those with digital outputs as they are much more immune to interference than those with analogue outputs. Digital controllers can also use the signals from these sensors directly without first having to convert them into digital signals by means of so-called analogue-digital converters as is the case with analogue signals.

The sensors used most frequently in industrial automation are the so-called proximity sensors that determine the presence (or approach) of a workpiece.

## 4.1 Proximity sensors

Proximity sensors are non-contacting and therefore have no external mechanical actuating force. As a result they have a long service life and are very reliable. A distinction is made between the following types of proximity sensor:

- Sensors with mechanical switch contact
  - Reed switches
- Sensors with electronic switch output
  - Inductive proximity sensors
  - Capacitive proximity sensors
  - Optical proximity sensors

### 4.1.1 Magnetic sensors

Reed switches are magnetically-actuated proximity sensors. They consist of two contact blades in a small glass tube filled with protective gas. The action of a magnet causes the contact between the two blades to close so that an electrical current can flow (cf. Figure 4.1). In the case of reed switches that work as N/C contacts, the contact blades are preloaded using small magnets. This preload is overcome by the then much stronger 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 areas with strong magnetic fields (e.g. in the vicinity of resistance welders or CAT scanners).

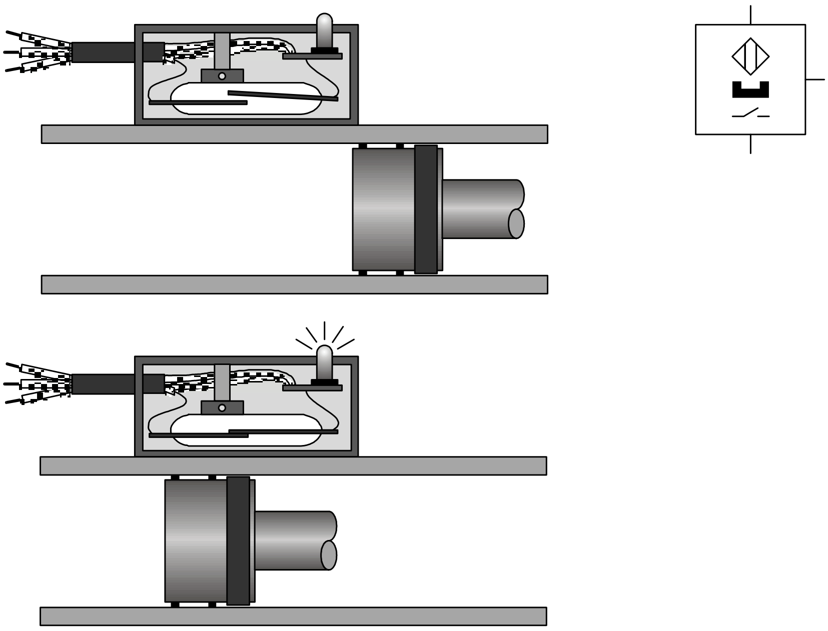


Figure 4.1: Schematic diagram and circuit symbol for a reed switch (N/O contact)


Figure 4.2: Actual picture of a reed switch

### 4.1.2 Electronic sensors

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

- supply voltage,
- earth,
- output signal.

In the case of electronic sensors, no movable contact is switched over. Instead the output is either electrically connected with the supply voltage or to earth (= output voltage 0 V).

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

- In the case of positive-switching electronic sensors, the output has a voltage of zero (OFF) when there is no part within the sensor's response range. The approach of a workpiece results in the output being switched over (ON) 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.

### 4.1.3 Inductive proximity sensors

Inductive proximity sensors consist of an electrical resonant circuit (1), a flip-flop (2) and an amplifier (3) (cf. Figure 4.3). When voltage is applied to the connections, the resonant circuit generates a (high-frequency) magnetic alternating field that escapes from the front side of the sensor.

Bringing an electrical conductor into this alternating field "attenuates" the resonant circuit. 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 materials with good electrical conductivity, for example graphite as well as metals.

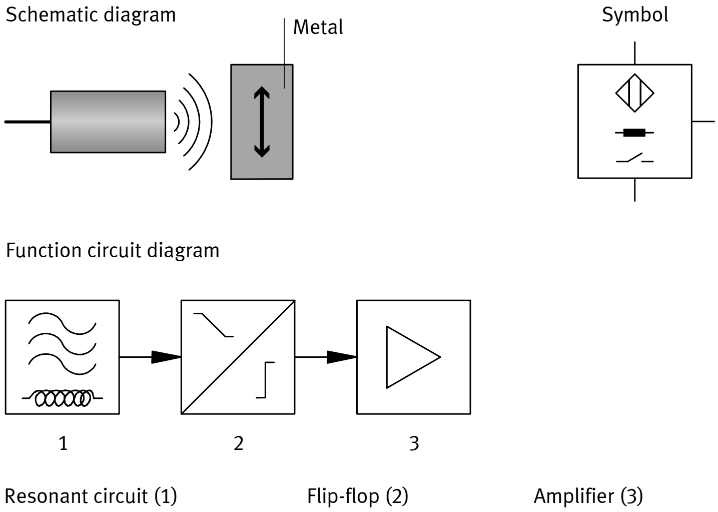



Figure 4.3: Basic representation, function and symbol for an inductive proximity sensor

Figure 4.4: Illustration of an inductive sensor

### 4.1.4 Capacitive proximity sensors

Capacitive proximity sensors consist of an electrical resistor (R) and a capacitor (C) that together form an RC resonant circuit as well as an electronic circuit for evaluating the oscillation.

An electrostatic field is generated between the active electrode and the ground electrode of the capacitor. A stray field forms on the front side of the sensor. When an object is brought into this stray field, the capacitance of the capacitor changes (cf. Figure 4.5).

The resonant circuit is attenuated and the downstream electronic unit actuates the 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).

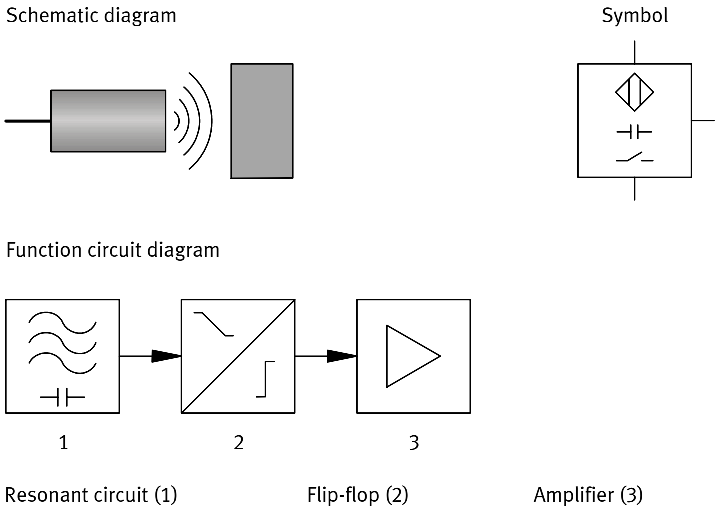



Figure 4.5: Basic representation, function and symbol for a capacitive proximity sensor

### 4.1.5 Optical proximity sensors
Optical proximity sensors always have a transmitter and a receiver. They use optical (red or infrared light) and electronic components and modules to detect an object located between the transmitter and receiver.

Particularly reliable transmitters of red and infrared light are semiconductor light emitting diodes (LEDs). They are small, robust, inexpensive, reliable, durable and easy to install. Red light has the advantage that it can be seen with the naked eye when aligning (adjusting) the optical axes of the proximity sensors.

Photodiodes or phototransistors are used as the receiver component in optical proximity sensors.

A distinction is made between three types of optical proximity sensor:
- through-beam sensors,
- retro-reflective sensors,
- diffuse sensors.

**Through-beam sensors**
Through-beam sensors have transmitter and receiver units that are set apart. The components are mounted in such a way that the beam of light emitted by the transmitter hits the receiver (e.g. phototransistor) directly (cf. Figure 4.6). If an object, workpiece or even a person enters the path between the transmitter and receiver, the light beam is interrupted and a signal is triggered that initiates a switching operation at the output (ON/OFF).

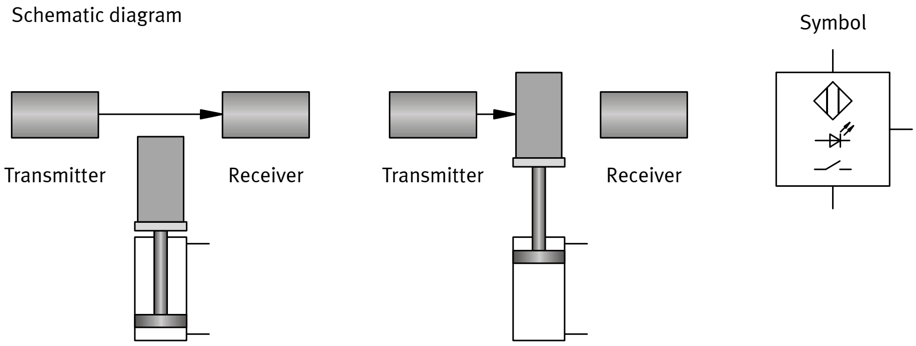



Figure 4.6: Schematic diagram and circuit symbol for a through-beam sensor

Figure 4.7: Fork light barrier

**Retro-reflective sensors**

In retro-reflective sensors the transmitter and receiver are arranged side-by-side in a housing. The reflector reflects the light beam from the transmitter to the receiver. It is mounted in such a way that the light beam emitted by the transmitter impinges almost entirely on the receiver. If an object, workpiece or even a person enters the path between the transmitter and reflector, the light beam is interrupted and a signal triggered that initiates a switching operation at the output (ON/OFF).

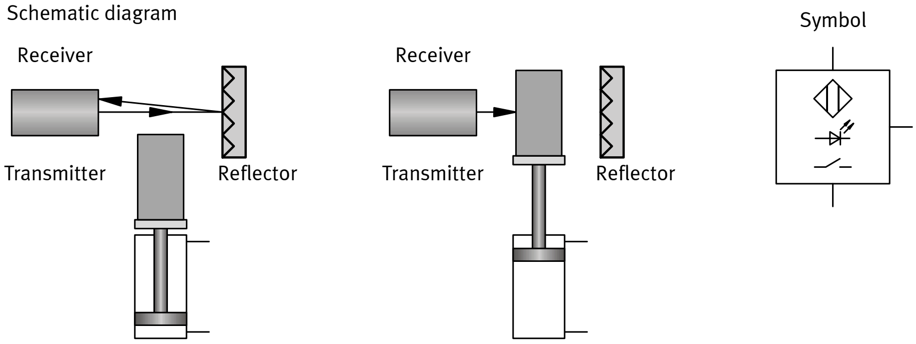



Figure 4.8: Schematic diagram and circuit symbol for a retro-reflective sensor

**Diffuse sensors**

The transmitter and receiver in diffuse sensors are arranged side-by-side in a component. In contrast to the retro-reflective sensor, a diffuse sensor does not have its own reflector. Instead it uses the reflective property of the object or workpiece that enters its transmission range. If the light hits a reflective body, it is redirected to the receiver and the sensor 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).

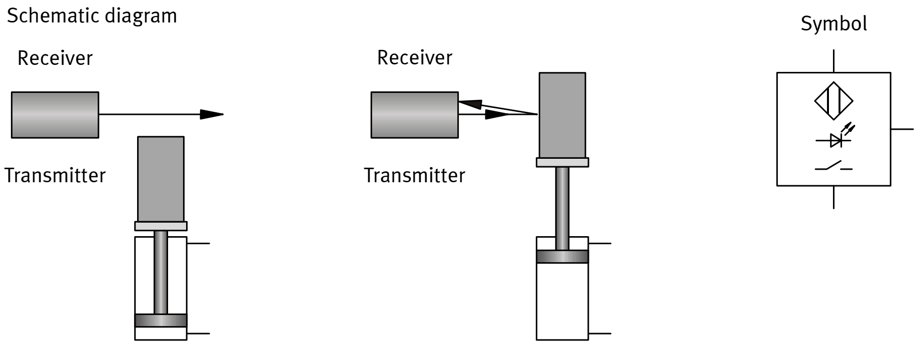



Figure 4.9: Schematic diagram and circuit symbol for a diffuse sensor

## 4.2 Pressure sensors

Pressure-sensitive sensors come in different designs:

- mechanical pressure switches with binary output signal,
- electronic pressure switches with binary output signal,
- electronic pressure sensors with analogue output signal.

### 4.2.1 Mechanical pressure switches with binary output signal

In a mechanical pressure switch, the pressure acts on a piston area. If the force exerted by the pressure exceeds the spring force, the piston moves and actuates the contacts of the switching elements.

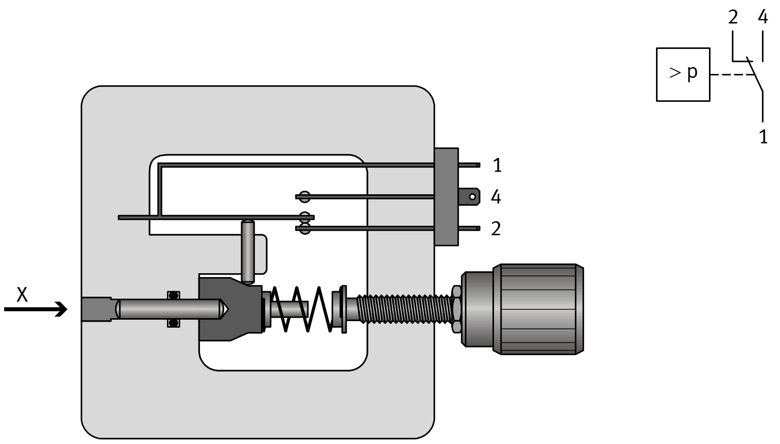



Figure 4.10: Schematic diagram and circuit symbol for a piston pressure switch

### 4.2.2 Electronic pressure switches with binary output signal

Typical examples of electronic pressure switches with binary output signal are diaphragm pressure switches that switch the output electronically instead of actuating a contact mechanically. Pressure or force-sensitive sensors are attached to a diaphragm for this purpose. The sensor signal is evaluated by an electronic circuit. As soon as the pressure exceeds a previously defined value, the output switches.


Figure 4.11: Electronic pressure switch and circuit symbol

# 5 Fundamentals of pneumatics

The term pneumatics comes from the Greek work "pneuma", meaning wind or breath. It refers to the use of compressed air or systems driven by compressed air in an engineering application. A modern pneumatic system in automation technology consists of subsystems for:

- generating and providing the compressed air (compressors, radiators, filters),
- distributing the compressed air (ducts, pneumatic tubing, coupling pieces),
- controlling the compressed air (pressure regulators, directional control valves, stop valves),
- performing work using the compressed air (cylinders, rotary drives).

Compressed air is most often used to perform mechanical work, i.e. to carry out movements and to generate high forces.

Pneumatic drives serve to convert the energy stored in the compressed air into kinetic energy.

For the most part, cylinders are used as pneumatic drives. They have a sturdy design, are easily installed, offer a favourable price/performance ratio and come in a wide choice of variants. These advantages have opened up a wide range of applications for pneumatics in modern engineering. The following table outlines further advantages.

| **Characteristics** | **Advantages of pneumatics** |
|---|---|
| Quantity | Air is available virtually everywhere in unlimited quantities. |
| Transport | Air can be very easily transported over large distances in ducts. |
| Storage ability | Compressed air can be stored in a reservoir and supplied from there. The reservoir (bottle) can also be transportable. |
| 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. |
| Setup | The operating elements have a simple setup, therefore they are 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 finally become inoperative and are therefore overload-proof. |

## 5.1 Physical fundamentals

Air is a gaseous mixture with the following composition:

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

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

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

### 5.1.1 Basic units

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

### 5.1.2 Derived units

| Variable | Symbol | Units |
|---|---|---|
| Force | F | Newton (N), 1 N = 1 kg • $m/s^2$ |
| Surface | A | Square metre ($m^2$) |
| Volume | V | Cubic metre ($m^3$) |
| Volumetric flow rate | $q_V$ | ($m^3/s$) |
| Pressure | p | Pascal (Pa)<br>1 Pa = 1 $N/m^2$<br>1 bar = $10^5$ Pa |

### 5.1.3 Newton's law

Force = mass • acceleration

F = m • a

(in the case of free fall, a is replaced by gravitational acceleration g = 9.81 $m/s^2$)

### 5.1.4 Pressure

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

The pressure 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:

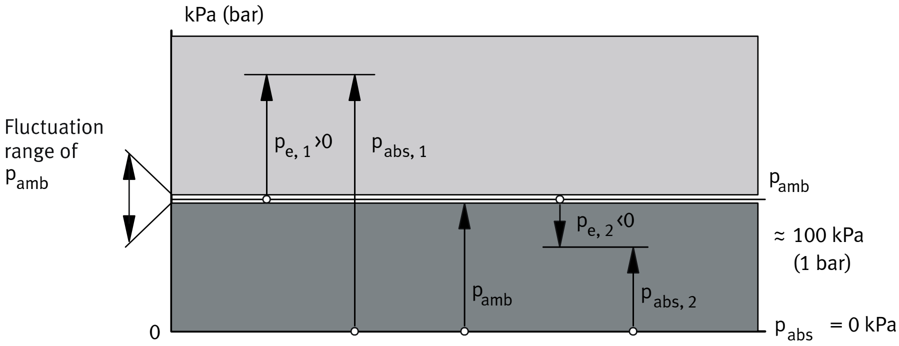



Figure 5.1: Air pressure

Atmospheric pressure is not constant; its value changes depending on the geographical location and the weather.

Absolute pressure $p_{abs}$ is the value referred to as zero pressure (vacuum). It is equal to the sum of the atmospheric pressure and excess pressure or vacuum. The pressure gauges used most frequently 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.

It is usual in pneumatics to refer all specifications relating to air quantities to the so-called normal condition. The normal condition 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 pressure $p_n$ = 101325 Pa = 1.01325 bar

## 5.2 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.

### 5.2.1 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.

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

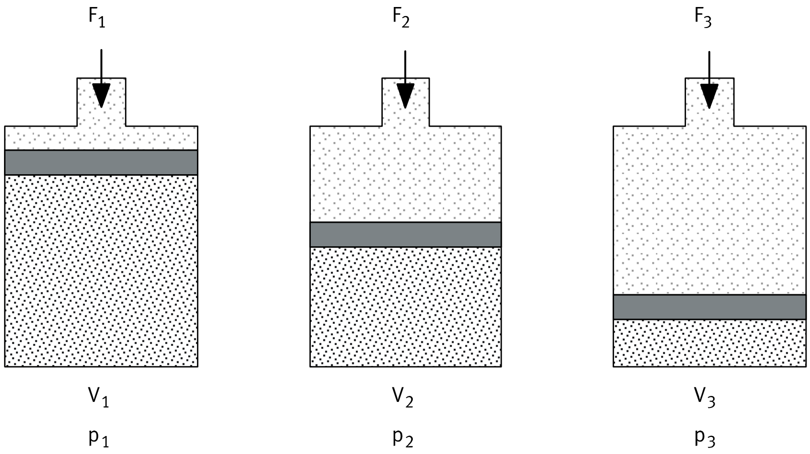



Figure 5.2: Boyle's law

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

Solution

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

$$p_2 = p_1 \cdot \frac{V_1}{V_2} \qquad \text{Note: } \frac{V_1}{V_2} = \frac{1}{7}$$

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

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

From this it follows that: $p_e = p_{abs} - p_{amb} = (700 - 100)$ kPa = 600 kPa = 6 bar

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

### 5.2.2 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 its absolute temperature when pressure is constant.

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

or

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

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 applies to $V_2$: $V_2 = V_1 + \Delta V = V_1 + \frac{V_1}{T_1}(T_2 - T_1)$

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

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

**Calculation example**
0.8 $m^3$ of air with a temperature of $T_1$ = 293 K (20 °C) is heated to $T_2$ = 344 K (71 °C). By how much does the air expand?

$$V_2 = 0.8\,m^3 + \frac{0.8\,m^3}{293\,K}(344\,K - 293\,K)$$
$$V_2 = 0.8\,m^3 + 0.14\,m^3 = 0.94\,m^3$$

The air expands by 0.14 $m^3$ to 0.94 $m^3$.

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

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

### 5.2.3 General gas equation
Fulfilling the basic laws is the general gas equation that states:
with a fixed amount of gas, the product of pressure and volume divided by the absolute temperature is constant.

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

From this general gas law can be derived the above mentioned laws, when one of the three factors p, V or T remains constant.

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

## 5.3 Individual components in a pneumatic control system and their functions

**Compressor**
The energy for compressed air networks is supplied by screw or piston compressors. They supply an output pressure of 700 – 800 kPa (7 – 8 bar). This ensures that a working pressure of at least 600 kPa (6 bar) is available at the cylinder, notwithstanding leakages (defective points at which air can unintentionally escape) and line losses.

**Compressed air filters**
Compressed air filters are placed centrally or decentrally upstream of the compressed air system. They remove condensate and any particles of dirt taken in. Properly filtered compressed air plays a major role in prolonging the service life of downstream components.

**Pressure regulator**
The pressure regulator is where the necessary pressure level for individual sub-systems is set. It compensates fluctuations in the compressed air network. The set pressure remains constant as long as the pressure at the regulator input is at least 50 kPa (0.5 bar) above the required setpoint pressure.

**On-off valves**
Separate individual compressed air networks.

**Control valves**
Shut off the compressed air and route it to the operating elements at the required time. The safety and reliability of the system depend on the elements being correctly interconnected.

**Power valves**
Are adapted to the cylinder diameter and supply the cylinders with the necessary quantity of compressed air.

**Cylinders**
Pneumatic cylinders are sturdy operating elements with a low susceptibility to failure and a long service life. The right cylinder dimensions can produce high speeds. For fault-free operation, the cylinders must be correctly sized and assembled.

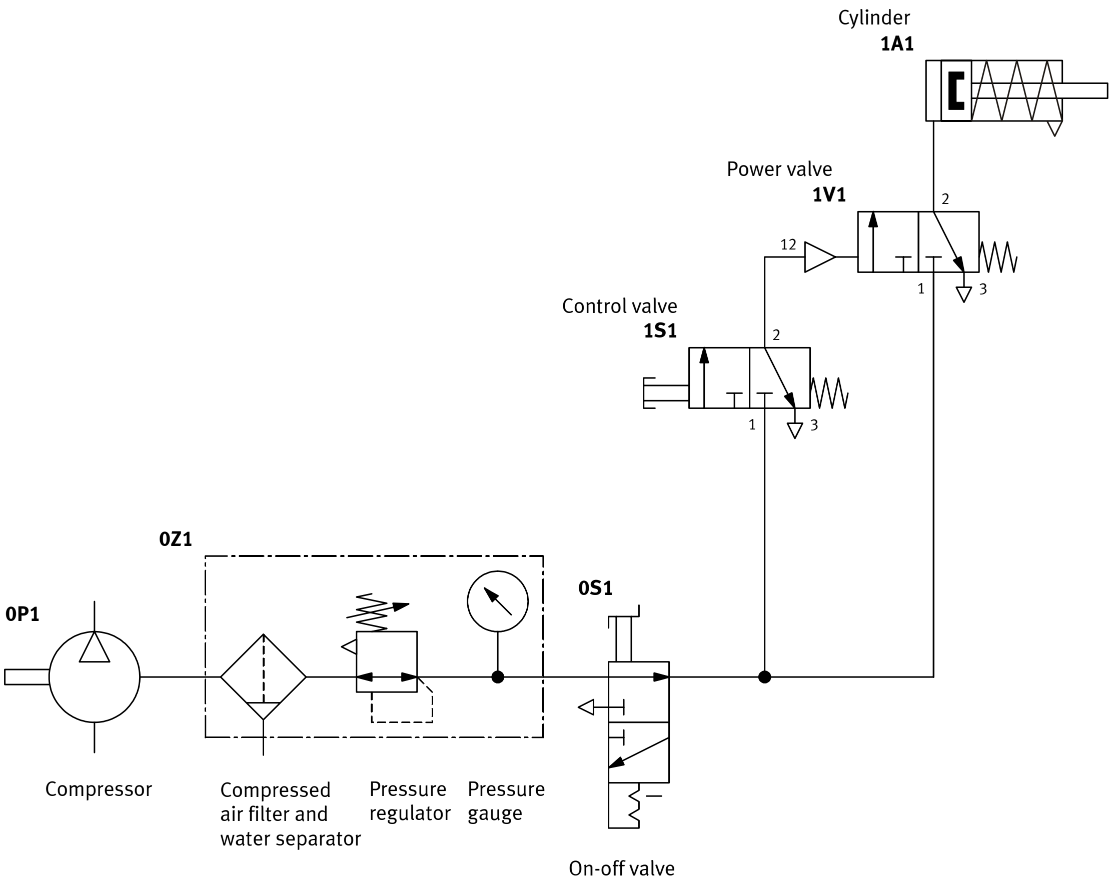



Figure 5.3: Key components and modules in a pneumatic control system

## 5.4 Functions and features of actuators (pneumatic cylinders)

### 5.4.1 Single-acting cylinders

Single-acting cylinders are supplied with compressed air at one end only, where they have a port for the compressed air supply. This means they can only work in one direction. The cylinder chamber must be exhausted before the return stroke, after which retraction of the piston rod can be initiated by a built-in spring or through the application of external force (see Figure 5.4). Exhausting takes place through a hole in the cylinder end cap.

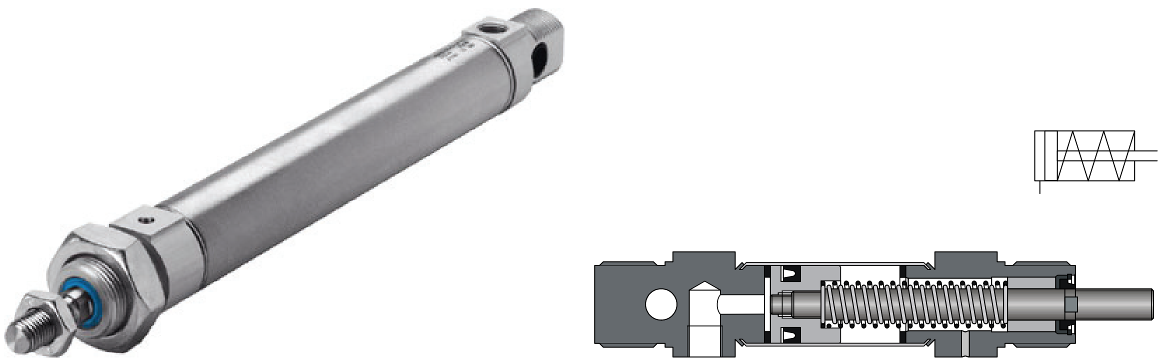


Figure 5.4: Actual picture, sectional view and circuit diagram of a single-acting cylinder

### 5.4.2 Double-acting cylinders

Double-acting cylinders are supplied with compressed air at both ends. This means these cylinders can also work in both directions. The force transferred to the piston rod is slightly greater for the forward stroke than for the return stroke, since the area supplied with compressed air is greater on the piston side than on the piston rod side (see Figure 5.5).

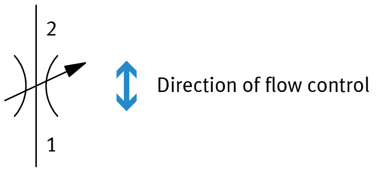
The double-acting cylinder has a port for each pressurised chamber. Before switching to the reverse direction, the appropriate chamber (piston side or piston rod side) must first be exhausted.


Figure 5.5: Actual picture, sectional view and circuit diagram of a double-acting cylinder

### 5.4.3 Speed regulation with single-acting cylinders

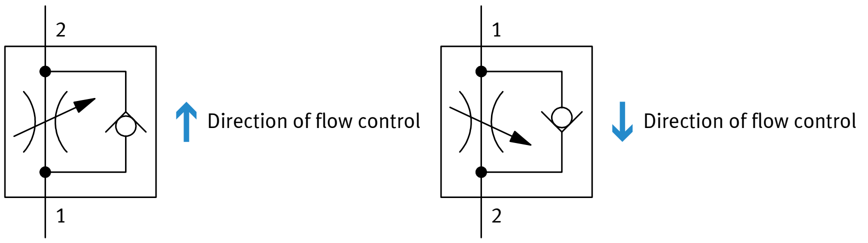
**Flow control valve**

The tubing cross section is infinitely adjusted at a flow control valve. The effect of the reduced volumetric flow is the same in both directions.




**One-way flow control valve**

The setting at the one-way flow control valve is only effective in one direction; the valve has no effect in the opposite direction (the volumetric flow is routed through the non-return valve). The direction of flow control is indicated on the components by an arrow.



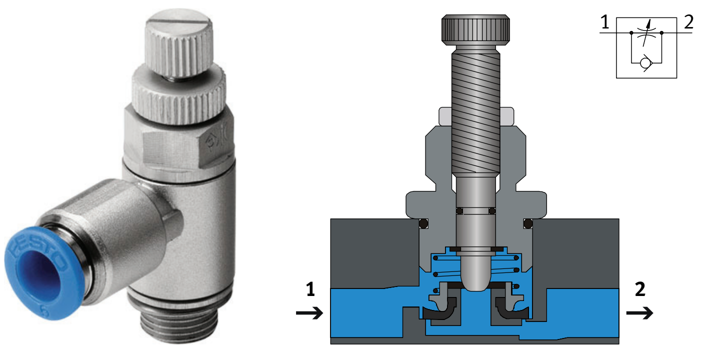
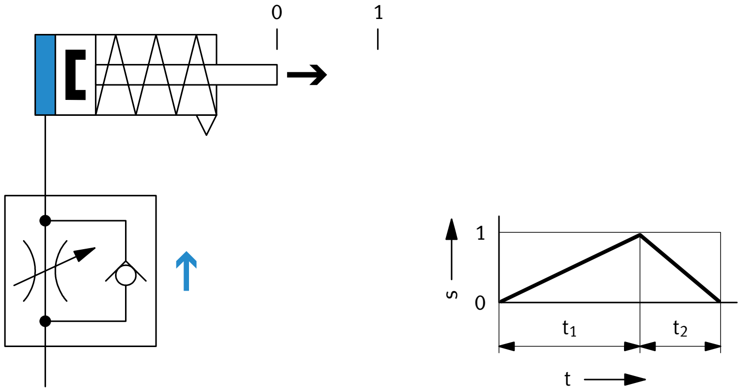




Figure 5.6: Actual picture, sectional view and circuit diagram of a one-way flow control valve

**In the forward stroke**

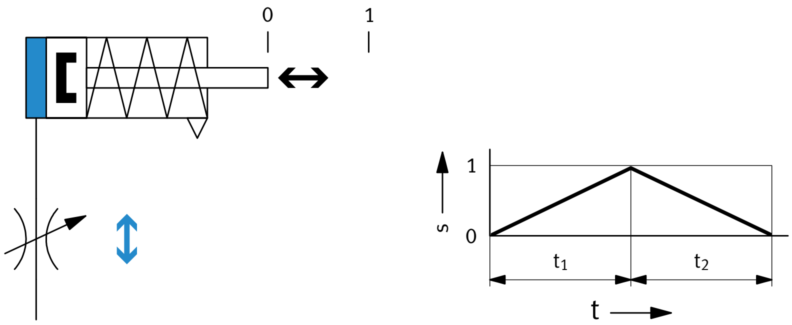
The air supply is reduced by means of a one-way flow control valve. The set speed is only effective in the forward stroke. For the return stroke, the volumetric flow is routed through the non-return valve.




$t_1$ = adjustable, $t_2$ = constant (non-adjustable)

**In the forward and return strokes**

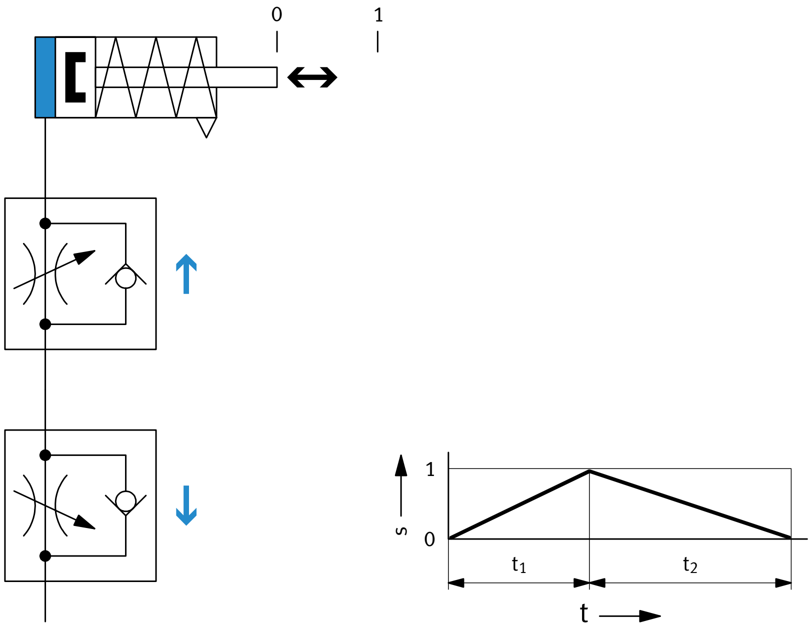
The flow control valve is at the port that supplies and exhausts the compressed air. The set speed is effective in the forward and return strokes.




$t_1$ = $t_2$ = adjustable

### Using two one-way flow control valves

The speed can be set separately for the forward and return strokes.

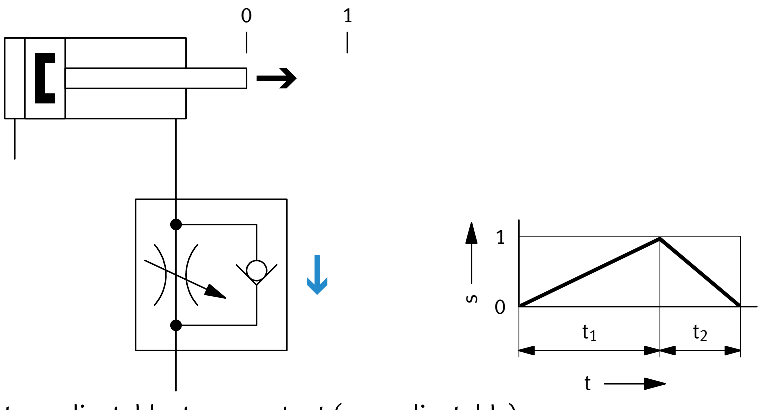



$t_1$ = adjustable, $t_2$ = adjustable

### 5.4.4 Speed regulation with double-acting cylinders

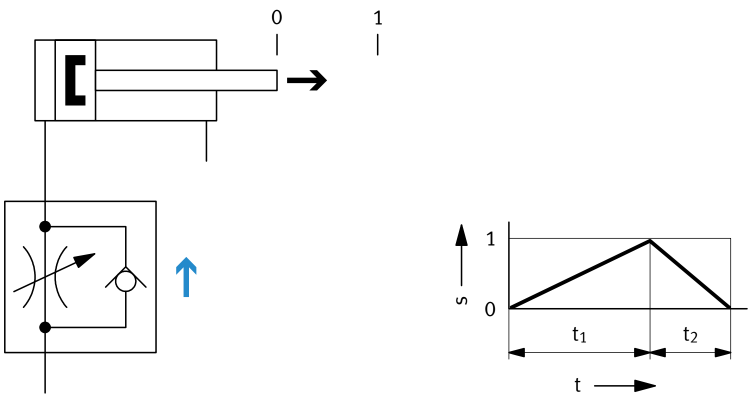
#### In the forward stroke (exhaust air flow control)

The one-way flow control valve is at the port that exhausts the compressed air (exhaust air flow control). The escaping air is routed through the flow control valve. Exhaust air flow control is the method used most frequently with double-acting cylinders. Speed regulation is unaffected by load.



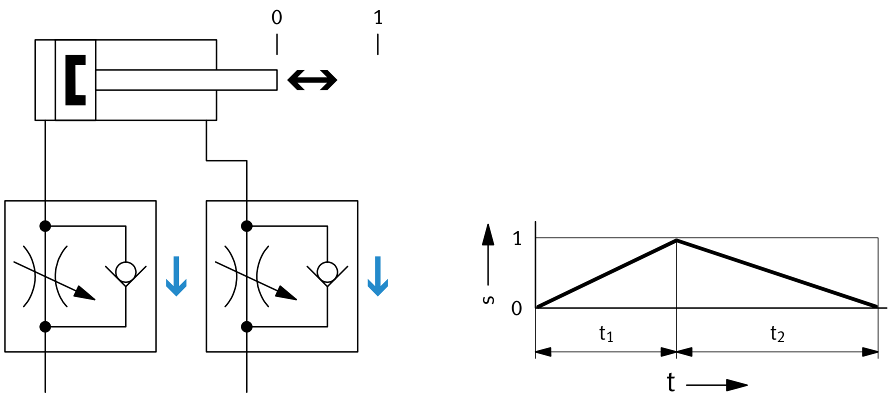

$t_1$ = adjustable, $t_2$ = constant (non-adjustable)

**In the forward stroke (supply air flow control)** (not suitable for vertical cylinder arrangements)
The one-way flow control valve is at the port that supplies the compressed air (supply air flow control). The set speed is only effective in the forward stroke. Minimal load fluctuations at the piston rod result in huge irregularities in the feed speed. A load in the cylinder's direction of movement accelerates the cylinder above the set value.




$t_1$ = adjustable, $t_2$ = constant (non-adjustable)

**In the forward and return strokes**
Exhaust air flow control using two one-way flow control valves. The speed can be set separately for the forward and return strokes.




$t_1$ = adjustable, $t_2$ = adjustable

## 5.5 Functions and features of pneumatic valves

Pneumatic valves control the path of the compressed air. The direction of flow is indicated by an arrow. Actuation can take place manually, mechanically, pneumatically or electrically. Automated systems generally use solenoid-actuated valves that form the interface between pneumatic and electrical control. 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. The main functions of electrically-actuated directional control valves include:

- connecting or shutting off the compressed air supply,
- retracting and advancing cylinder drives.

Figure 5.7 and Figure 5.8 show two actual valve designs.

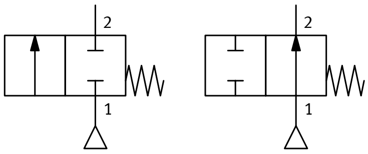
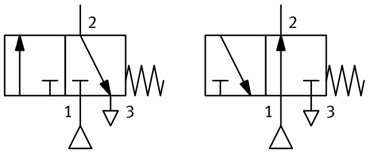
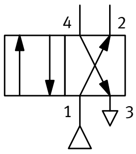
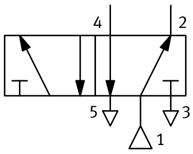
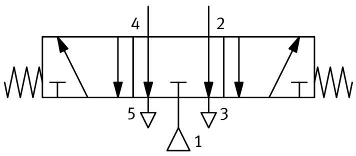
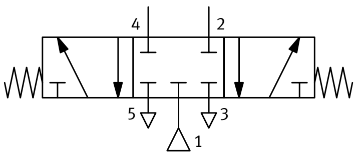
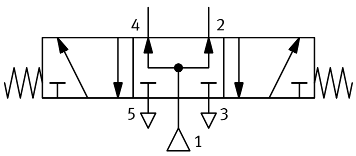
Figure 5.7: Manually-actuated 3/2-way valve with locking function

Figure 5.8: Actual picture of a 4/2-way single solenoid valve with manual override

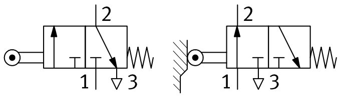
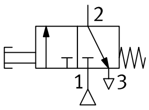
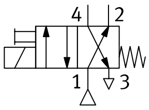
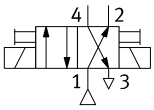
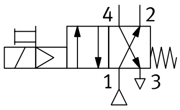
### 5.5.1 Pneumatic valve designations and symbols

The following table shows the main designs of directional control valve.

| Symbol | Designation | Function |
|---|---|---|
|  | 2/2-way valve<br>– normally closed<br>– normally open | Valve with two switching positions and two ports |
|  | 3/2-way valve<br>– normally closed<br>– normally open | Valve with two switching positions and three ports |
|  | 4/2-way valve | Valve with two switching positions and four ports |
|  | 5/2-way valve | Valve with two switching positions and five ports |
|  | 5/3-way valve,<br>mid-position exhausted | The piston of the cylinder drive exerts no force on the piston rod. The piston rod can move freely. |
|  | 5/3-way valve,<br>mid-position closed | The piston rod comes to a stop, even if it is not at the defined stop. |
|  | 5/3-way valve, mid-<br>position pressurised | The piston rod of cylinders with single-ended piston rod advances with reduced force. |

### 5.5.2 Pneumatic valve actuation types

The following table provides an overview of the main actuation types of directional control valves.

| Symbol | Designation | Function |
|---|---|---|
|   | Roller lever valve, spring return, single solenoid | This valve is actuated by means of cylinder cams or similar. It is mainly used for sensing end positions. |
|   | Manually actuated, spring return, single solenoid | This valve is manually actuated and is returned by a spring when released. |
|   | Single solenoid valve with manual override, spring return | This valve is actuated by a solenoid and is returned by a spring as soon as the control current is switched off. |
|   | Double solenoid valve with manual override | This valve is actuated by solenoids and remains in its current position until the other solenoid is actuated. |
|   | Solenoid valve with pneumatic pilot control | This valve is actuated by a solenoid. The solenoid controls a pneumatic auxiliary circuit that actuates the valve spool. |

### 5.5.3 Controlling a single-acting cylinder

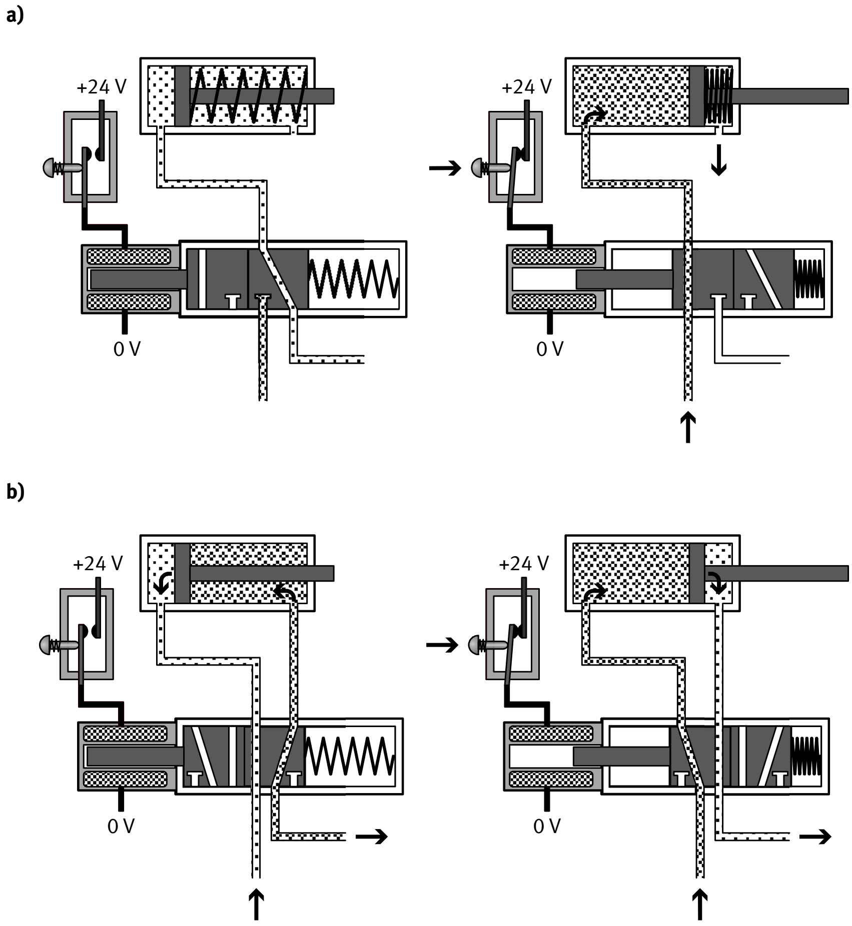
Figure 5.9a shows a solenoid-actuated valve that controls the movement of a single-acting cylinder drive. It has three ports and two switching positions.

- When the solenoid coil of the directional control valve is de-energised, the cylinder chamber is exhausted via the directional control valve. The piston rod is retracted.
- When current is applied to the solenoid coil, the directional control valve switches and the cylinder chamber is pressurised. The piston rod advances.
- When current is no longer applied to the solenoid coil, the valve switches back. The cylinder chamber is exhausted and the piston rod retracts.

### 5.5.4 Controlling a double-acting cylinder

The double-acting cylinder in Figure 5.9b is actuated by a directional control valve with five ports and two switching positions.

- When the solenoid coil is de-energised, the left-hand cylinder chamber is exhausted and the right-hand cylinder chamber is pressurised. The piston rod is retracted.
- When electrical current is applied to the solenoid coil, the valve switches. The left-hand cylinder chamber is pressurised and the right-hand cylinder chamber is exhausted. The piston rod advances.
- When current is no longer applied to the solenoid coil, the valve switches back and the piston rod retracts.




a) Single-acting
b) Double-acting

Figure 5.9: Controlling cylinders using solenoid valves

## 5.6 Functions and features of pneumatic drives

### 5.6.1 Guided cylinders, rodless linear drives and rotary drives

Guided pneumatic cylinders are frequently used for special applications, particularly in handling technology (see Figure 5.11). Unlike conventional cylinders, in this case the piston rod cannot be turned and subjected to additional forces. Depending on the design, they can either be plain-bearing guides for simple applications with low loading by external forces and limited accuracy or high-precision ball bearing guides that can absorb considerable forces and torques and are slightly more expensive.

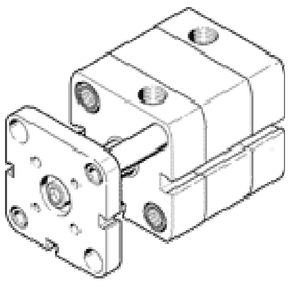


Figure 5.11: Guided pneumatic cylinder

Another class of drives are the rodless cylinders (see Figure 5.12). These have no piston rod and are therefore suitable for long stroke lengths.

The rodless cylinder is only slightly longer than the cylinder stroke, while a piston rod cylinder is at least twice as long as the cylinder stroke when advanced. These drives are also mostly fitted with high-quality guides.

Figure 5.12: Rodless pneumatic drive

Pneumatic semi-rotary drives are used wherever a rotational or swivel motion is required.

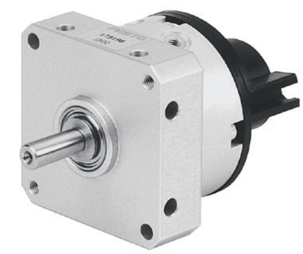
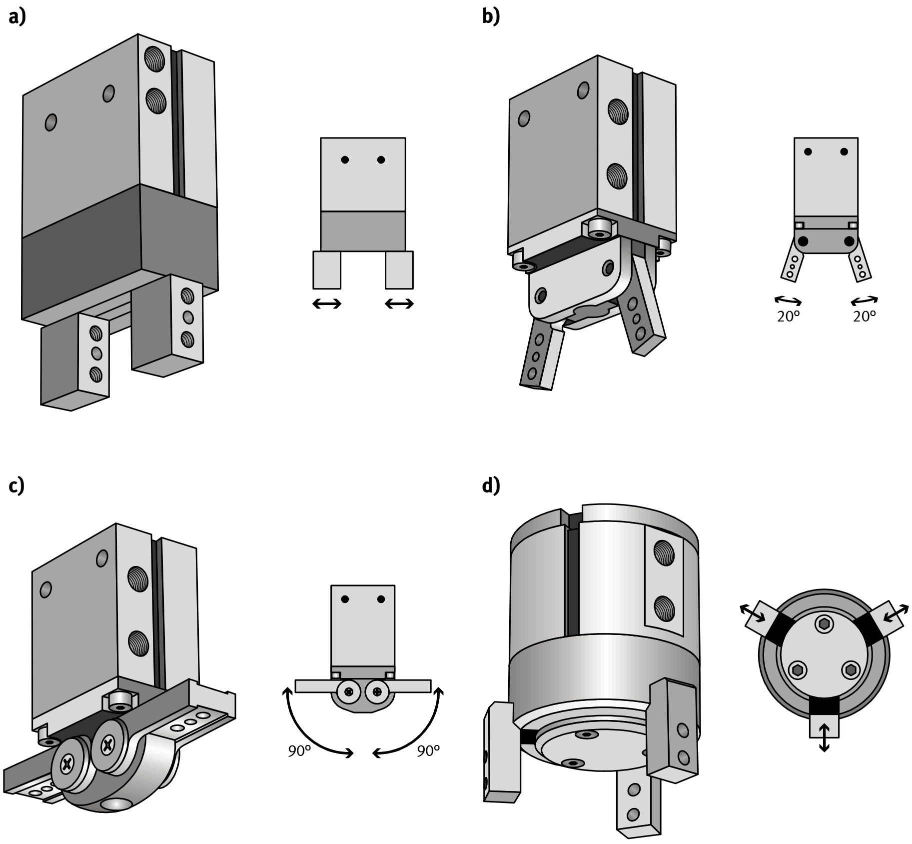


Figure 5.13: Pneumatic rotary drive

### 5.6.2 Pneumatic grippers

Pneumatic grippers are used for handling workpieces. The following illustrations show various gripper types.




a) Parallel gripper
b) Angle gripper
c) Radial gripper
d) Three-point gripper

Figure 5.14: Pneumatic grippers

The following illustration (see Figure 5.15) shows a sectional view of an angle gripper driven by a double-acting cylinder. It shows how gripper fingers (for cylindrical workpieces in this case) and proximity sensors are mounted on the gripper.

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

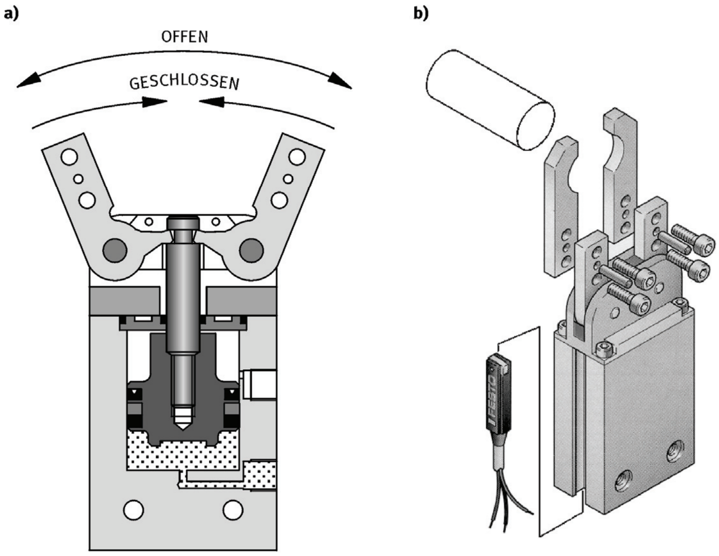



Figure 5.15: Drive principle, gripper jaw and proximity sensors for an angle gripper

## 5.7 Pneumatic control system represented in a circuit diagram

The simplest way to control single and double-acting cylinders is by means of direct cylinder control. In this case the cylinder is controlled directly via a manually or mechanically-actuated valve without the interposition of any other directional control valves.

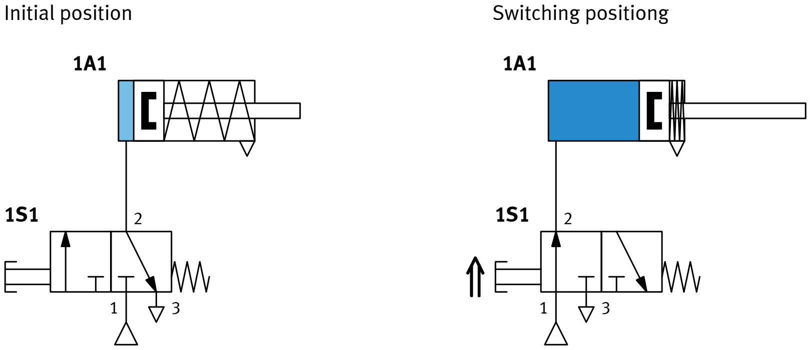



Figure 5.16: Circuit diagram for direct control via a manually-actuated 3/2-way valve

The symbols for the individual components must be drawn in the circuit diagram in an unactuated condition. Experience has shown that this representation confuses beginners. For that reason and departing from the standards, the respective switched-through function (switching position) is also shown in the first examples to make them easier to understand. The arrow beside the actuating element of the 3/2-way valve with pushbutton actuator indicates that this valve is actuated (Figure 5.16 on the right).

### 5.7.1 Symbol designations in circuit diagrams

The structure of pneumatic circuit diagrams and the arrangement of the circuit symbols as well as the designation and numbering of components are defined in DIN/ISO 1219-2. The switching status of the valves is the initial position (normal position). The operating section (cylinders with power valve) is shown at the top. The control section with the signal input components is underneath.

The elements are designated from bottom to top and from left to right (see Figure 5.17).

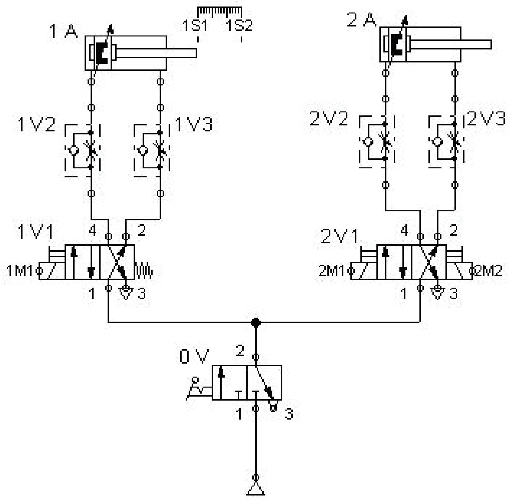



Figure 5.17: Designations in a pneumatic circuit diagram

**Sample representation of an electropneumatic circuit and its function**

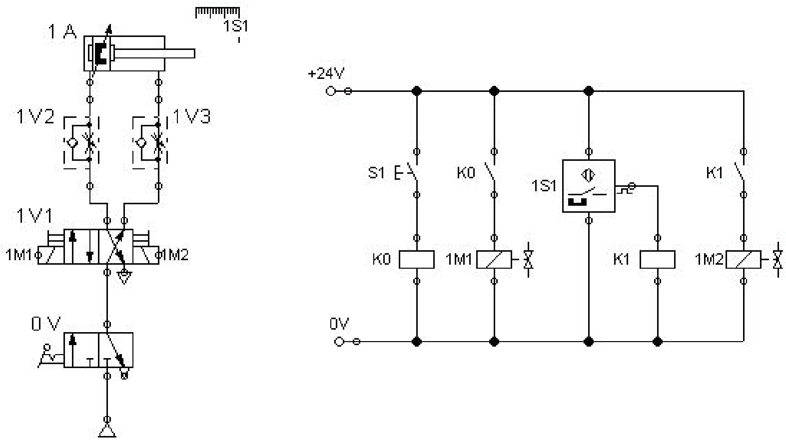



Figure 5.18: Representation of an electropneumatic circuit

Function of the electropneumatic circuit shown above:

- When the pushbutton S1 is actuated, the valve solenoid 1M1 is switched via a N/O contact of the relay K0 and the cylinder 1A advances.
- When the advanced end position is reached, the magnetic proximity sensor 1S1 switches the relay K1, thereby actuating the valve solenoid 1M2. The cylinder then returns to the retracted end position.

# 6 Electric drives

It's impossible to imagine the modern world without electric motors. Unlike pneumatics, which are primarily used in the production environment as a simple and reliable drive technology, electric motors we use in our private lives. Examples of domestic electric motors include washing machines, telephones, CD players, many toys, food processors and fans, to name just a few. These days electric motors are even used in cars as the actuator in the technical system for functions such as seat adjustment and opening/closing windows.

There are various types of electric motor specially designed for specific applications:

- simple and cost-effective DC drives with relatively low power for portable applications with battery operation,
- sturdy three-phase motors with relatively high power for stationary use in industry,
- highly dynamic servo drives for machine tools or robots with high requirements for speed and precision,
- stepper motors for simple movement processes, e.g. feed movements in machine tools.

Electric motors can perform both turning (rotational) and linear (translational) movements. For the various requirements there are designs rated from just a few milliwatts to several megawatts or weighing from just a few grammes to several tonnes. They are the most frequently used actuator in engineering today.

Almost all electric drives are based on the principle of electromagnetic force or Lorentz force. The following sections describe the operational principle of a permanently excited DC motor since this motor type is relatively easy to understand and is very widely used.

## 6.1 Physical/technical fundamentals of the DC motor

If a wire conductor through which a current I is flowing is in a magnetic field B, there is a force F acting on this wire. The direction of this force can be determined using the so-called "three-finger rule". We will assume that the magnetic field lines run from the magnet's north pole to its south pole and that the current in the wire flows from the power source's positive terminal to its negative terminal. The three fingers (thumb, index finger and middle finger) are aligned at right angles to each other so they form a Cartesian coordinate system.

When the thumb points in the direction of the flow of current (i.e. from the positive terminal to the negative terminal) and the index finger points in the direction of the magnetic field (north/south), the middle finger points in the direction of the active force. In Figure 6.1, the wire would therefore move forwards out of the magnetic field plane.

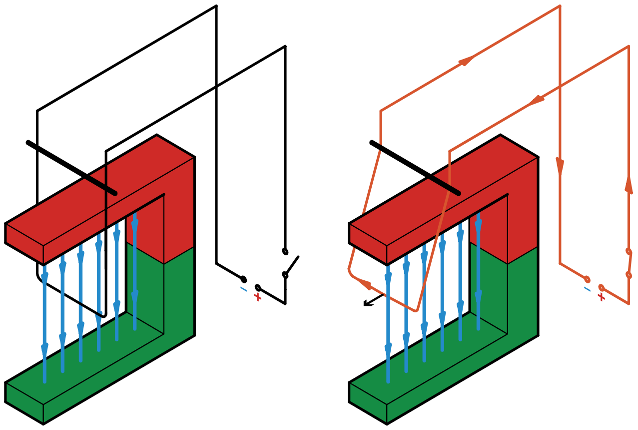


Figure 6.1: Lorentz force

The magnitude of the force depends on the strength of the magnetic field, the intensity of the current and the length of the wire in the magnetic field. The DC motor uses this force action to generate a rotation. To this end, a conduction loop is configured between the two magnetic poles (north/sound) so it can rotate (Figure 6.2).

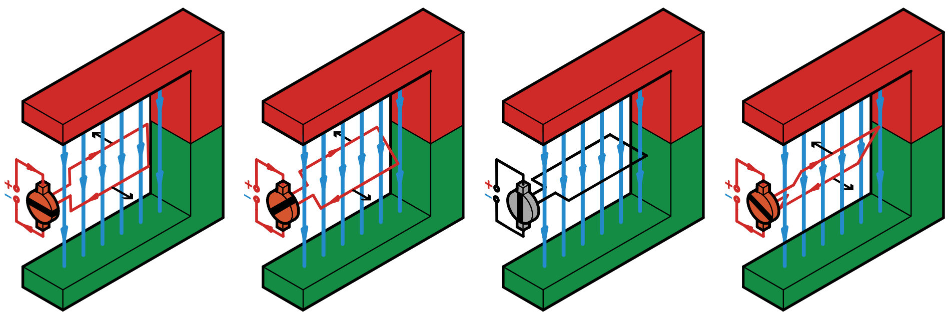


Figure 6.2: How a DC motor works

The current flows through the two halves of the conduction loop in opposite directions. This means that the force action on the two halves of the conduction loop is also opposed. A north and south pole are also established, that are attracted (north/south or south/north) or repelled (south/south or north/north) by the poles of the permanent magnet. Both forces generate a torque that keeps the conduction loop turning. The mechanical commutator (current converter) reverses the polarity of the current after a maximum of one half-revolution of the conduction loop and the process repeats itself.

The commutator is the important component since it generates rotation from each individual one-off event of the action of force on the conductor with current flowing through it. It consists of two metal half shells that are insulated from each other to which the current is transferred by means of carbon brushes.

Since DC motors normally generate low torques (Md) at high speeds (n), gear units are frequently placed upstream as a transmission component to reduce the output speed ($n_2$) by the transmission ratio i and increase the output torque ($Md_2$) by the same factor. The following rule applies:

$$i = \frac{n_1}{n_2} = \frac{Md_2}{Md_1}$$

Gear units come in a wide range of designs. Figure 6.3 shows a DC motor with worm gear unit where the drive shaft is turned 90° to the motor shaft.

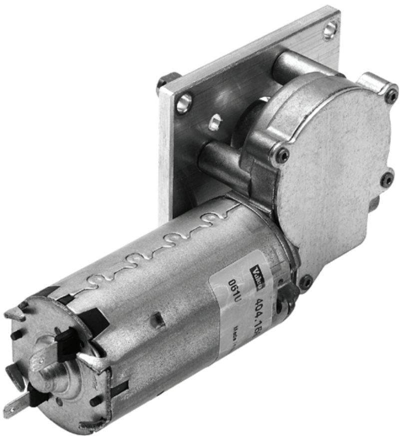


Figure 6.3: DC motor with gear unit

### 6.1.1 Activating DC motors

The DC motor begins to turn when it is connected to a power source. The direction of rotation depends on the polarity. Figure 6.4 shows the simplest method of activation, with the switch open (motor off) and with the switch closed (motor on).

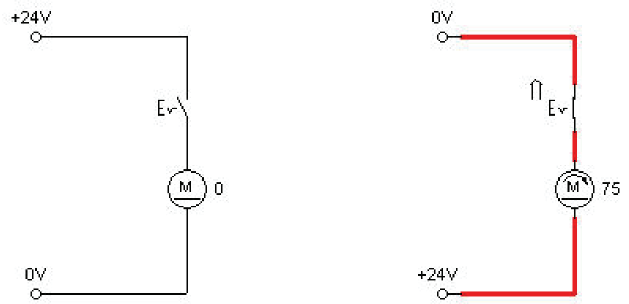



Figure 6.4: Activating a DC motor

Since electric motors need comparatively high currents, activation takes place via relays so as not to overload the switches. Figure 6.5 shows the corresponding circuit diagram.

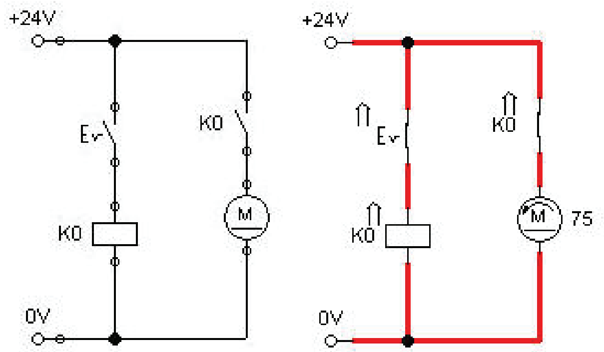



Figure 6.5: Activating a DC motor using relays

To reverse the direction of rotation of the motor, the direction of the current must be reversed by the motor (Figure 6.6).

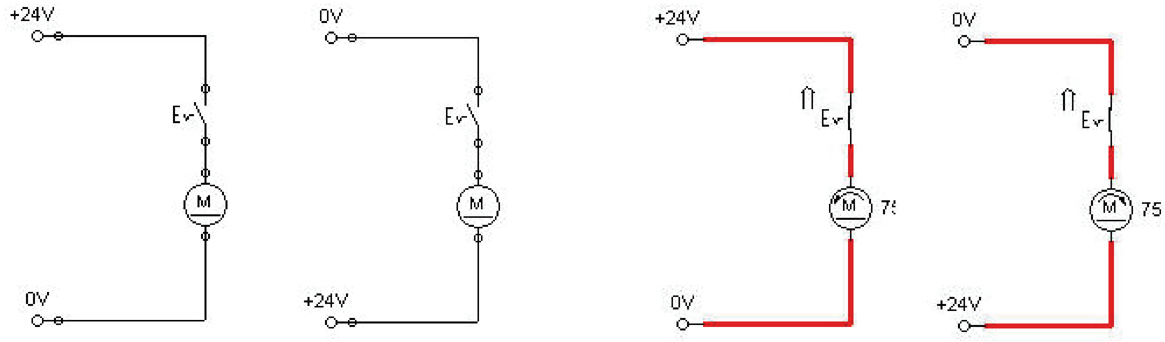



Figure 6.6: Reversal of the direction of rotation in a DC motor

Since it is not possible or practical to keep changing the motor wiring, a so-called pole reversal circuit is used in DC motors to reverse the direction of rotation (Figure 6.7).

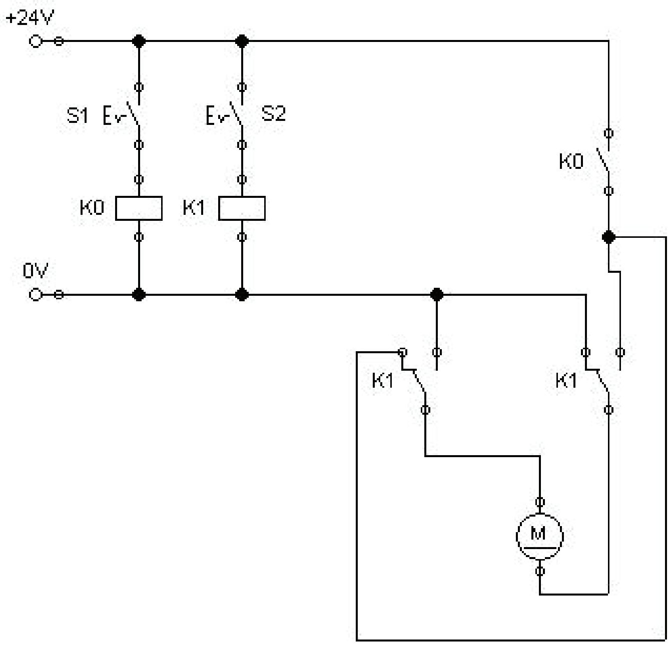



Figure 6.7: Pole reversal circuit

Here the motor is activated using two relays; the relay K0 switches the motor current on or off while the changeover relay K1 reverses the polarity of the motor current so that the motor runs forwards and backwards.

### 6.1.2 Solenoids as simple actuators

Another electric drive that is suitable for simple positioning tasks is the solenoid. Solenoids actuate the piston spools of solenoid valves, for example, and can be used in principle wherever small linear strokes are sufficient.

Figure 6.8 shows the operational principle. The solenoid essentially consists of a coil and an iron core. The coil generates a magnetic field when current flows through it and then exerts an attractive force on the iron core. This causes the iron core to be pulled into the coil. When the current is switched off, a spring pushes the iron core back out of the coil. A change in the direction of current does cause a change in the direction of the magnetic field, however this does not affect the attraction exerted on the iron core by the magnetic field.

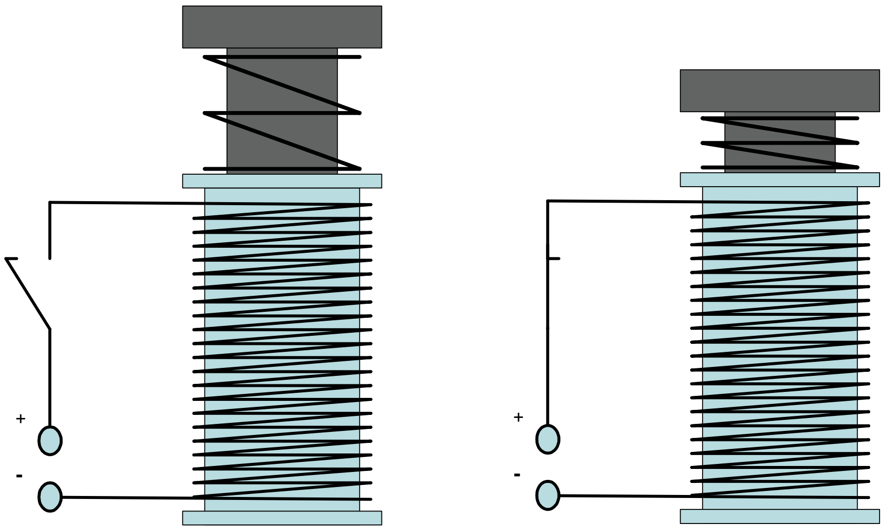



Figure 6.8: How a solenoid works

# 7 Fundamentals of control technology

Control systems are a central element in automation technology along with actuators and sensors. The term control system is frequently used in the broad sense to describe devices used for:

- open-loop control,
- closed-loop control,
- monitoring,
- (process) data collection,
- communication,
- diagnostics.

In the narrower sense, control within automation technology refers to influencing an energy or material flow by means of one or more signals in an open control loop (DIN 19226). Control systems are frequently used for processes that are performed in steps. Examples of these include:

- opening a door when there is someone standing in front of it,
- switching a traffic light to red after a specific time,
- switching on a corridor light after the light switch is pressed and automatically switching it off again after a specific time.

Control systems such as these are characterised by an open-loop process, i.e. the input variable (x) is not influenced by the controlled output variable (y). The control system cannot react to possible disturbance variables. In bullet-point three (above), this means that the open-loop time control system for the corridor lighting switches the light off after the specified time whether or not the person who pressed the light switch and thereby initiated the process has reached the apartment door. Figure 7.1 shows an open control loop.

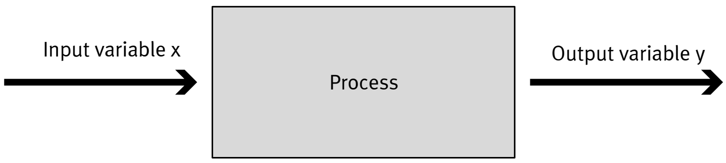



Figure 7.1: Open control loop

A closed-loop control system, on the other hand, continuously records the output variables (y) of the process, compares them with the input variables (x) and then automatically readjusts the process in the sense of an alignment of the output and input variables. It has a closed control loop and can react to disturbance variables. Closed-loop control processes are, for the most part, continuous processes where the output variable is to be maintained at a specific value. Examples of these include:

- controlling the water temperature in an aquarium,
- controlling the speed in a vehicle (cruise control),
- controlling the rotational speed in an electric motor.

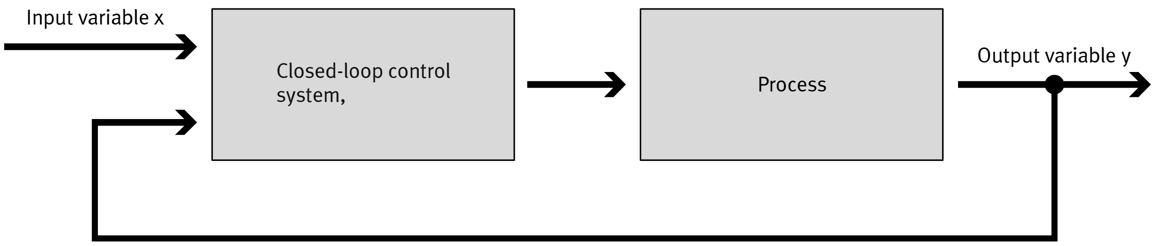



Figure 7.2: Closed control loop

Many terms are coined within automation technology for controller types with specific functions. Some examples of these include:

- Hard-wired programmed control systems
  Hard-wired programmed control systems function whereby the control logic or the "program" is realised by connecting relays. Contact control systems are an example of this. They are usually constructed from relays and are used for simple control tasks. A typical area of application of this type of control is the activation of electric motors.
- PLCs – Programmable logic controllers (see Figure 7.3)
  PLCs were developed to replace the less flexible contact control systems. They consist of a computer with special input and output modules. The program is not defined by linking individual relays but rather is stored in the controller memory, where it can be easily changed. PLCs mainly process binary signals.
  In the MecLab® learning media system, the actual PLC is replaced by a simulated PLC in the FluidSIM® software. In addition to programmable logic controllers, contact control systems can also be simulated in FluidSIM®.
- CNC – Computer numeric controllers
  These controllers are used to control machine tools such as drilling, cutting and turning machines, for example. The first automated machine tools used wooden patterns that were gauged to transfer their shape to the workpiece. The wooden pattern was then replaced by a numeric model where the workpiece coordinates are stored in the form of mostly binary numeric codes. The main purpose of the CNC controller is to translate the computer model of the workpiece created using software into a motion sequence for the tool.
- RC – Robot controllers
  Robot controllers have been specifically designed for controlling industrial robots and are similar in structure to the CNC controllers.

## 7.1 How programmable logic controllers (PLCs) work and their structure

Since the PLC is the most frequently used and also the simplest controller, it is considered in more detail below.

Figure 7.3: Programmable logic controller (Festo)

The main component in a PLC is the microprocessor system. The programming of the microprocessor defines:

- which controller inputs (I1, I2, etc.) are read in and in what order,
- how these input signals are linked,
- the outputs (O1, O2, etc.) to which the results of the signal processing are output.

In the case of a PLC, the controller's behaviour is not determined by the interconnection of electrical components (hardware), but rather by a program (software).

Figure 7.4 shows the basic structure of a PLC.

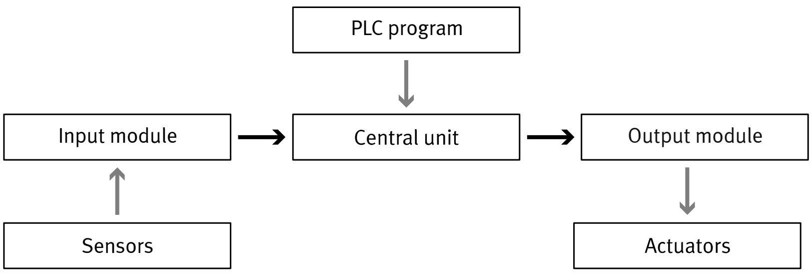



Figure 7.4: System components of a PLC

## 7.2 Mathematical fundamentals – basic logic functions

### 7.2.1 General information

Basic logic functions form the basis of most controllers. Therefore an overview of the most important basic logic functions is provided below. Logic functions can be represented in tabular form, in the form of equations, using relay circuits (operations) or using logic symbols (see Section 7.2.6). Logic symbols are used in a PLC to create the program.

### 7.2.2 Identity (YES function)

The pushbutton shown is an N/O contact. When it is unactuated, the lamp P1 does not light up. When, on the other hand, it is actuated, the lamp P1 lights up.

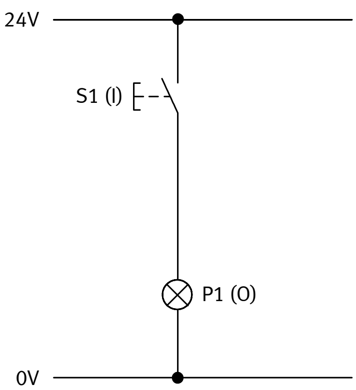



Figure 7.5: Circuit diagram (identity)

The pushbutton S1 acts as the signal input, the lamp is the output. The known facts can be recorded in a truth table:

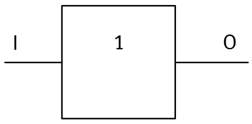
| I | O |
|---|---|
| 0 | 0 |
| 1 | 1 |

Truth table (identity)

The Boolean equation is therefore:

I = O

The logic symbol for identity is:




### 7.2.3 Negation (NOT function)

The pushbutton shown is an N/C contact. When it is unactuated, the lamp P1 lights up. When, on the other hand, it is actuated, the lamp P1 switches off.

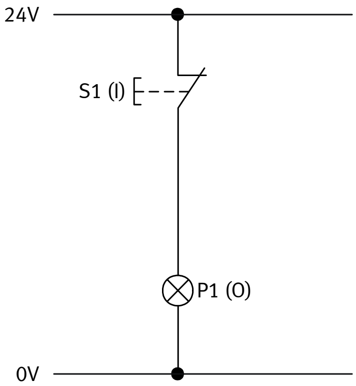



Figure 7.6: Circuit diagram (negation)

The pushbutton S1 acts as the signal input, the lamp is the output. The known facts can be recorded in a truth table:

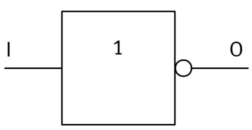
| I | O |
|---|---|
| 0 | 1 |
| 1 | 0 |

Truth table (negation)

The Boolean equation is therefore:

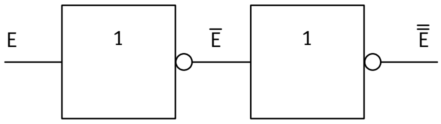
$\overline{I} = O$ (reads: not I equal to O)

The logic symbol is:



If two negations are used in a series (negation of the negation), they cancel each other out.

$\overline{\overline{E}} = E$




Two linked NOT functions

### 7.2.4 Conjunction (AND function)

If two N/O contacts are connected in series, the activated lamp only lights up if both pushbuttons are actuated.

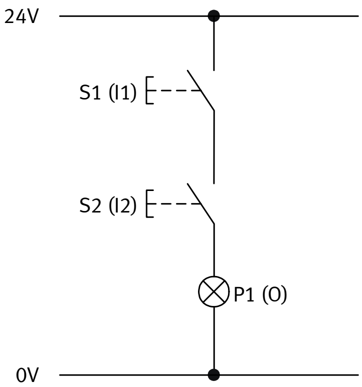



Figure 7.7: Circuit diagram (conjunction)

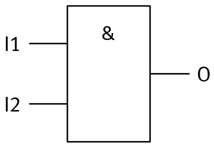
| I1 | I2 | O |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

Truth table (conjunction)

The truth table describes the relationship. The output only becomes 1 if both input 1 and input 2 exhibit a "1" signal. This is described as an AND operation. It is expressed as follows as an equation:

$I1 \wedge I2 = O$

The logic symbol is:




The following arithmetic rules also apply to the AND operation:

$$a \wedge 0 = 0$$
$$a \wedge 1 = a$$
$$a \wedge \bar{a} = 0$$
$$a \wedge a = a$$

### 7.2.5 Disjunction (OR function)

Another basic logic function is the OR function. If two N/O contacts are switched in parallel, the lamp will always light up if at least one pushbutton is actuated.

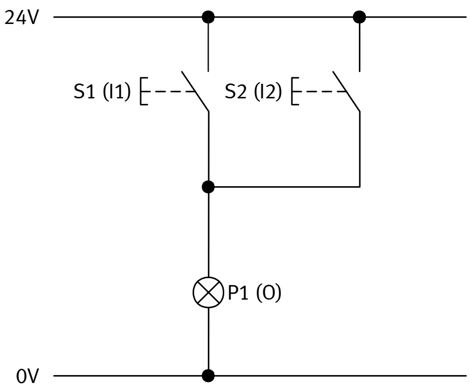



Figure 7.8: Circuit diagram (disjunction)

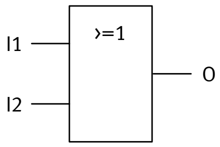
| I1 | I2 | O |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

Truth table (disjunction)

The OR operation is expressed as follows as an equation:

$$I1 \vee I2 = O$$

The logic symbol is:




The following arithmetic rules also apply to the OR operation:

$$a \vee 0 = a$$
$$a \vee 1 = 1$$
$$a \vee a = a$$
$$a \vee \overline{a} = 1$$

### 7.2.6 Further logic operations

The realisation of the NOT/AND/OR function using electrotechnical circuits has already been described. Each of the functions can naturally also be realised pneumatically or electronically. Boolean algebra also recognises further logic functions, an overview of which is given in the following table.

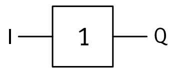
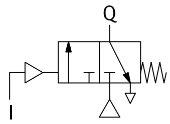
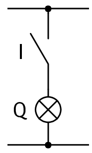
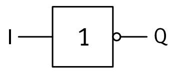
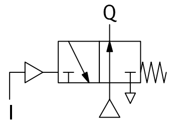
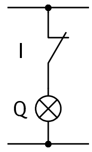
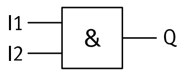
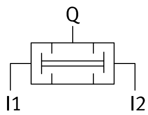
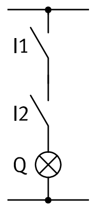
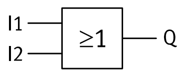
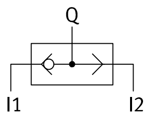
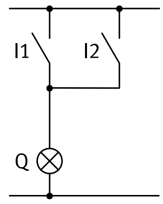
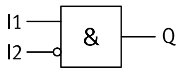
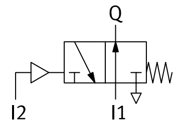
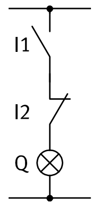
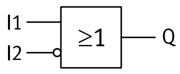
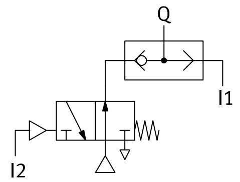
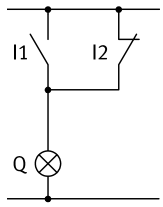
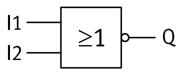
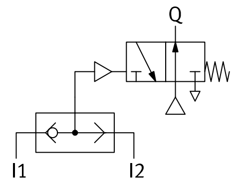
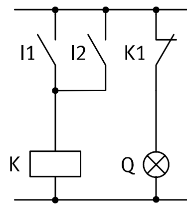
| Designation | Truth table | Equation | Symbol to EN 60617-12 | Representation to ISO 1219-1 (pneumatic) | Representation to EN 60617-7 (electric) |
|---|---|---|---|---|---|
| Identity | I \| Q<br>0 \| 0<br>1 \| 1 | Q=IQ=I |  |  |  |
| Negation | I \| Q<br>0 \| 1<br>1 \| 0 | $Q = \bar{I}$ |  |  |  |
| Conjunction (AND) | I1 \| I2 \| Q<br>0 \| 0 \| 0<br>0 \| 1 \| 0<br>1 \| 0 \| 0<br>1 \| 1 \| 1 | $Q = I1 \wedge I2$ |  |  |  |
| Disjunction (OR) | I1 \| I2 \| Q<br>0 \| 0 \| 0<br>0 \| 1 \| 1<br>1 \| 0 \| 1<br>1 \| 1 \| 1 | $Q = I1 \vee I2$ |  |  |  |

Table 7.1: Logic operations

<table>
<tr><th>Designation</th><th>Truth table</th><th>Equation</th><th>Symbol to EN 60617-12</th><th>Representation to ISO 1219-1 (pneumatic)</th><th>Representation to EN 60617-7 (electric)</th></tr>
<tr><td>Inhibition</td><td>I1 | I2 | Q<br>0 | 0 | 0<br>0 | 1 | 0<br>1 | 0 | 1<br>1 | 1 | 0</td><td>$Q = I1 \wedge \overline{I2}$</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Implication</td><td>I1 | I2 | Q<br>0 | 0 | 1<br>0 | 1 | 0<br>1 | 0 | 1<br>1 | 1 | 1</td><td>$Q = I1 \vee \overline{I2}$</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>NOR</td><td>I1 | I2 | Q<br>0 | 0 | 1<br>0 | 1 | 0<br>1 | 0 | 0<br>1 | 1 | 0</td><td>$Q = \overline{I1 \vee I2}$</td><td>
</td><td>
</td><td>
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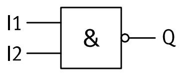
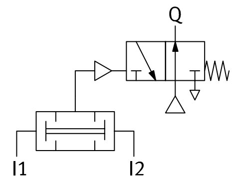
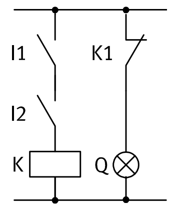
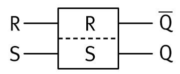
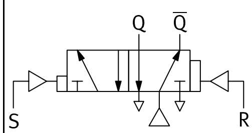
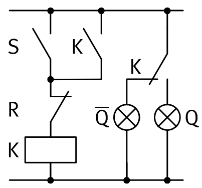
<tr><td>NAND</td><td>I1 | I2 | Q<br>0 | 0 | 1<br>0 | 1 | 1<br>1 | 0 | 1<br>1 | 1 | 0</td><td>$Q = \overline{I1 \wedge I2}$</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Memory</td><td>S | R | Q | $\overline{Q}$<br>0 | 0 | $q^{n-1}$ | $\overline{q}^{n-1}$<br>0 | 1 | 0 | 1<br>1 | 0 | 1 | 0<br>1 | 1 | 0 | 1</td><td></td><td>
</td><td>
</td><td>
</td></tr>
</table>

Table 7.1: Logic operations (continued)

## 7.3 Examples of controller structure

The section of an electropneumatic controller that processes signals encompasses three functional modules. An example of its structure is shown in Figure 7.9.

- Signal input takes place by means of sensors or by means of pushbuttons or control switches. In Figure 7.9, two proximity sensors (1B1/1B2) are used for signal input.
- Signal processing usually takes place using a relay controller or programmable logic controller. There are other forms of signal processing, however these are of much less importance in automation practice. In Figure 7.9, signal processing is carried out by a relay controller (K1/K2).
- Signal output takes place using electromagnetically-actuated directional control valves (1M1/1M2).

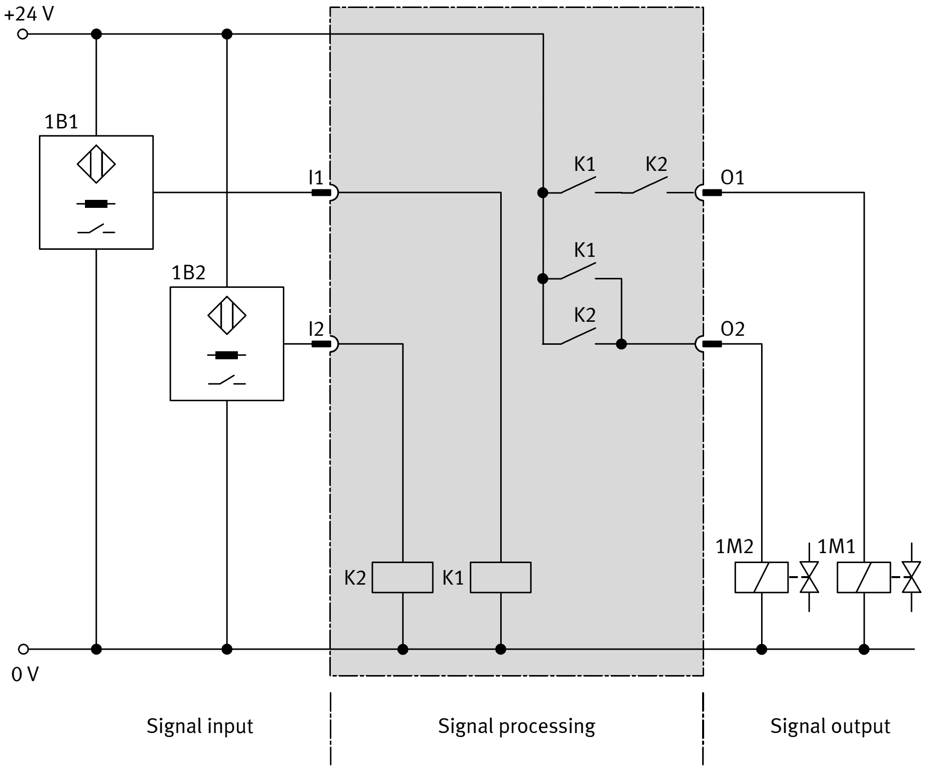



Figure 7.9: Signal control section with relay controller (schematic, circuit diagram not to standards)

Functional description of the relay controller in Figure 7.9:

- The components for signal input, the inductive proximity sensors 1B1 and 1B2, are connected with the relay coils (K1, K2, etc.) via the controller inputs (I1, I2, etc.).
- Signal processing is realised through respective interconnection of a number of relay coils and relay contacts. In this case, the relay contacts to the output O1 are ANDed and the contacts to the output O2 are ORed.
- The components for signal output, directional control valve solenoid coils 1M1 und 1M2, are connected to the controller outputs (O1, O2, etc.). They are actuated via the contacts of the relays K1 and K2.

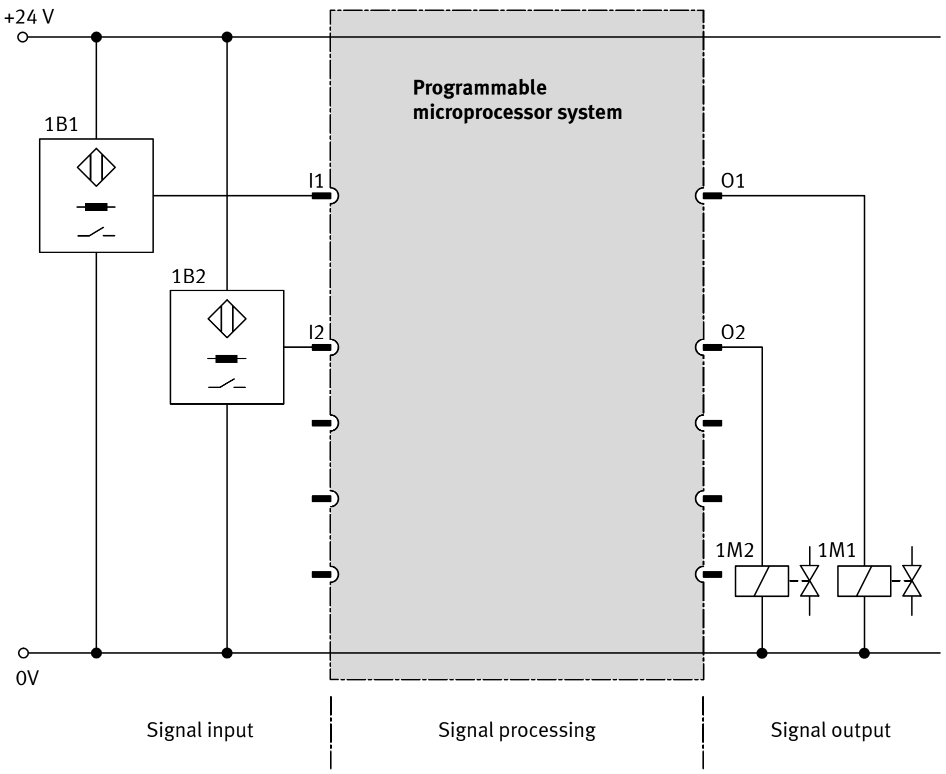



Figure 7.10: Signal control section of a programmable logic controller (PLC)

Figure 7.10 shows the signal control section of an electropneumatic controller that uses a programmable logic controller for signal processing.

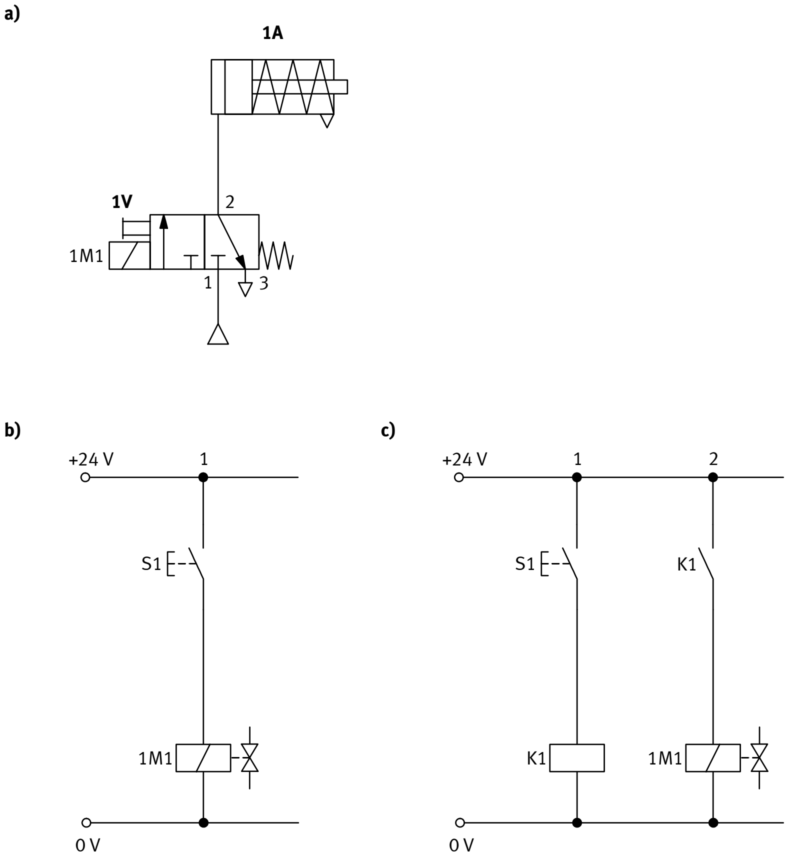
- The components for signal input (in Figure 7.10: the inductive proximity sensors 1B1 and 1B2) are connected with the inputs of the PLC (I1, I2).
- The programmable microprocessor system of the PLC handles all the signal processing tasks.
- The components for signal output (in Figure 7.10: directional control valve solenoid coils 1M1 and 1M2) are connected with the outputs of the PLC (O1, O2). Actuation takes place via an electronic circuit that is part of the microprocessor system.

# 8 Applications of relays in electropneumatics

Relays can be used for all the signal processing requirements of an electropneumatic controller. In the past, relay controllers were manufactured in large numbers. Their main advantages are their clear structure and easy to understand mode of operation. Since they are relatively reliable, relay controllers are still used today in industrial applications such as emergency-stop switchgears, for example. Increasingly, however, they are being replaced in signal processing by programmable logic controllers.

## 8.1 Direct and indirect control using relays

The piston rod of a single-acting cylinder is to advance when the pushbutton S1 is actuated and retract again when the pushbutton is released. Figure 8.1a shows the accompanying pneumatic circuit diagram.




a) Pneumatic circuit diagram
b) Electrical circuit diagram for direct control
c) Electrical circuit diagram for indirect control

Figure 8.1: Circuit diagrams for the control model for a single-acting cylinder

### 8.1.1 Direct control of a single-acting cylinder

Figure 8.1b shows the electrical circuit diagram for direct control of a single-acting cylinder. When the pushbutton is actuated, current flows through the solenoid coil 1M1 of the 3/2-way valve. The solenoid exerts a pulling force, the valve switches to the actuated position and the piston rod advances. Releasing the pushbutton interrupts the flow of current. The solenoid is de-energised, the directional control valve switches to its normal position and the piston rod retracts again.

### 8.1.2 Indirect control of a single-acting cylinder

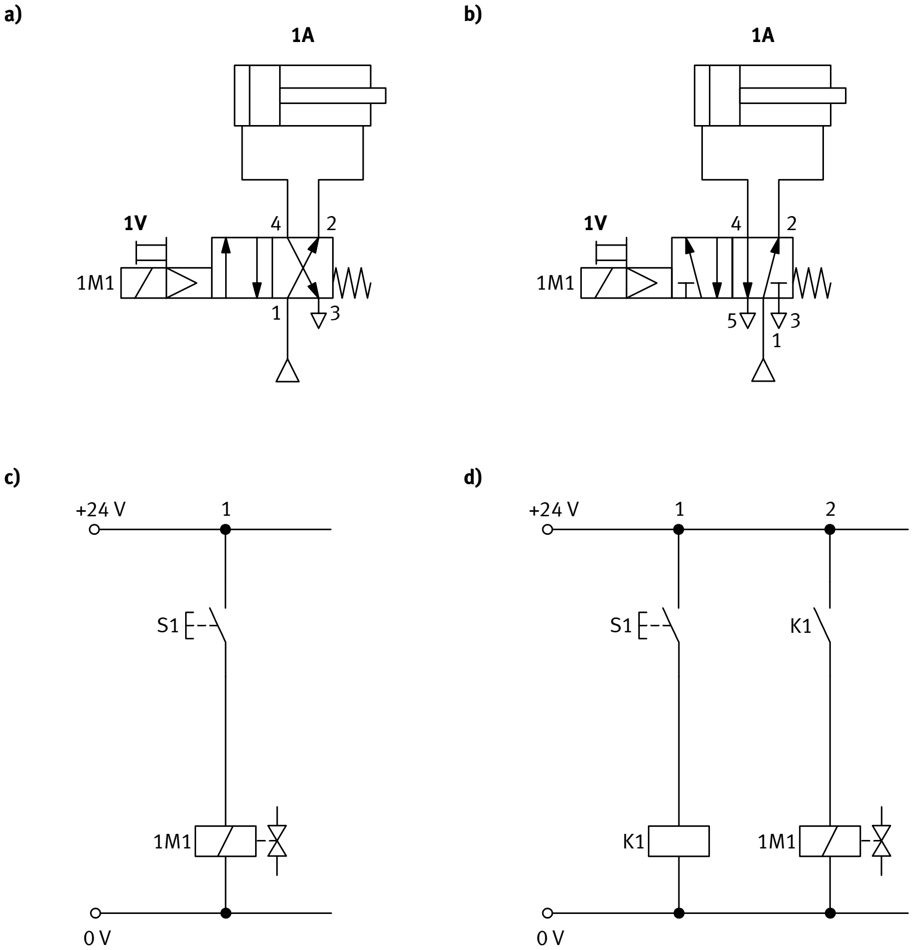
With indirect control, when the pushbutton is actuated (Figure 8.1c), current flows through the relay coil. The contact K1 of the relay closes and the directional control valve switches. The piston rod advances.

Releasing the pushbutton interrupts the flow of current through the relay coil. The relay is de-energised and the directional control valve switches to its normal position. The piston rod retracts. The result is initially the same as with direct control. The more complex indirect control is used if:

- the control circuit and main circuit are working with different voltages (e.g. 24 V and 230 V),
- the current through the coil of the directional control valve exceeds the permissible current for the pushbutton (e.g. current through the coil: 0.5 A; permissible current through the pushbutton: 0.1 A),
- one pushbutton or control switch is used to switch a number of valves,
- extensive logic operations are required between the signals of the various pushbuttons.

### 8.1.3 Controlling a double-acting cylinder

The piston rod of a double-acting cylinder is to advance when the pushbutton S1 is actuated and retract when the pushbutton is released.




a) Pneumatic circuit diagram with 4/2-way valve
b) Pneumatic circuit diagram with 5/2-way valve
c) Electrical circuit diagram with direct control
d) Electrical circuit diagram with indirect control

Figure 8.2: Circuit diagrams for the control model of a double-acting cylinder

The electrical signal control section remains unchanged in comparison with the control model for the single-acting cylinder. Since two cylinder chambers have to be exhausted or pressurised, either a 4/2-way valve or a 5/2-way valve is used (Figures 8.2a and 8.2b respectively).

The designation 4/2-way or 5/2-way indicates the number of ports (4 or 5) and switching positions (2) offered by the valve.

## 8.2 Logic operations using relays

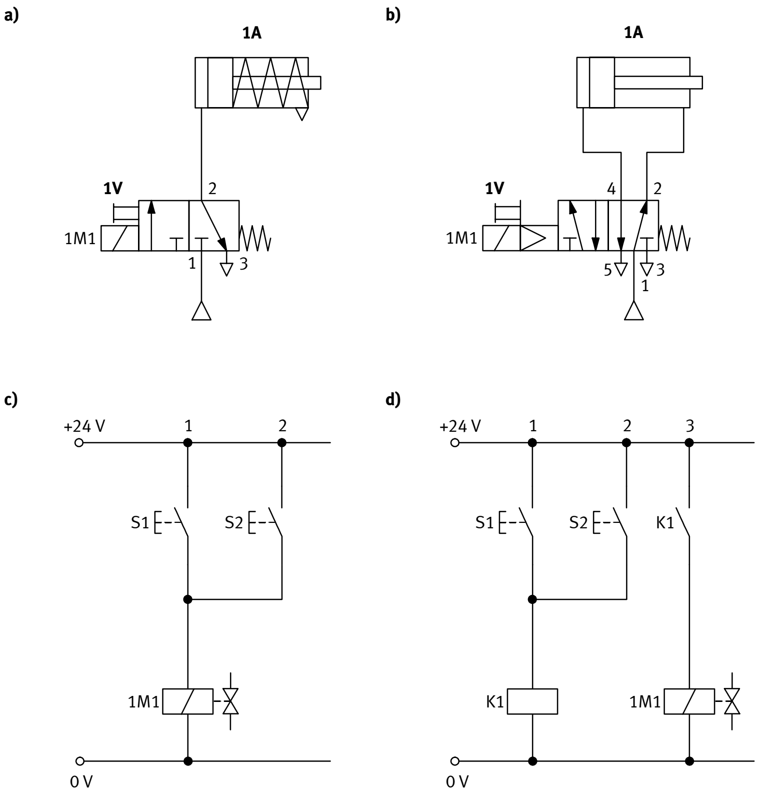
Signals from several control components frequently have to be combined to realise the pneumatic cylinder movements required for an application.

### 8.2.1 Parallel connection (OR operation)

The advancing of a cylinder piston rod is to be triggered using one of two independent input components, the pushbuttons S1 and S2.

To this end, the contacts of the two pushbuttons are arranged in parallel in the circuit diagram (Figures 8.3c and 8.3d).

- As long as neither pushbutton is actuated ($S1 \wedge S2 = 0$), the directional control valve remains in its normal position. The piston rod is retracted.
- If at least one of the two pushbuttons is actuated ($S1 \vee S2 = 1$), the directional control valve switches to the actuated position. The piston rod advances.
- If both pushbuttons are released and thus opened ($S1 \wedge S2 = 0$), the valve switches to its normal position. The piston rod retracts.



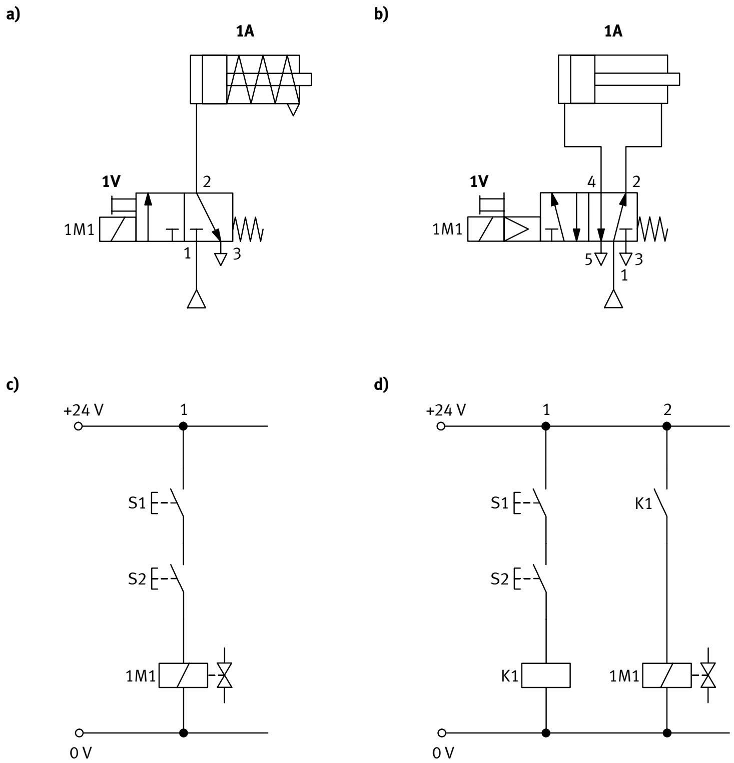

a) Pneumatic circuit diagram with single-acting cylinder
b) Pneumatic circuit diagram with double-acting cylinder
c) Electrical circuit diagram with direct control
d) Electrical circuit diagram with indirect control

Figure 8.3: Parallel connection of two contacts (OR operation)

### 8.2.2 Series connection (AND operation)

The piston rod of a cylinder is only to advance if the two pushbuttons S1 and S2 are actuated. To this end, the contacts of the two pushbuttons are arranged in series in the circuit diagram (Figures 8.4c and 8.4d).

- As long as neither pushbutton or just one of the two pushbuttons is actuated ($S1 \vee S2 = 0$), the valve remains in its normal position. The piston rod is retracted.
- If both pushbuttons are actuated simultaneously ($S1 \wedge S2 = 1$), the directional control valve switches. The piston rod advances.
- If at least one of the two pushbuttons is released ($S1 \vee S2 = 0$), the valve switches to its normal position. The piston rod retracts.




a) Pneumatic circuit diagram with single-acting cylinder
b) Pneumatic circuit diagram with double-acting cylinder
c) Electrical circuit diagram with direct control
d) Electrical circuit diagram with indirect control

Figure 8.4: Series connection of two contacts (AND operation)

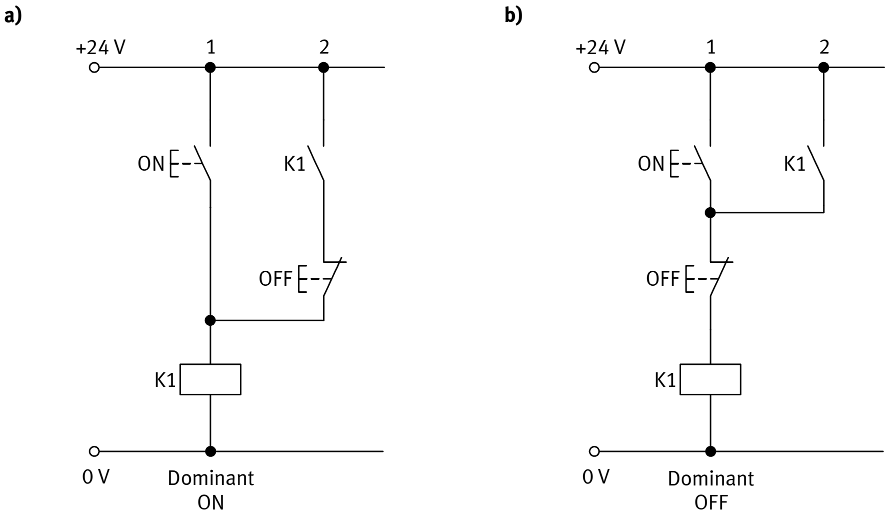
## 8.3 Signal storage using relays and double solenoid valves

In the case of the circuits discussed so far, the piston rod only advances as long as the input pushbutton is actuated. If the pushbutton is released during the advancing operation, the piston rod retracts without having reached the advanced end position.

### 8.3.1 Signal storage by means of a relay circuit with self-latching loop

For reasons of effectiveness, it is general practice that the piston rod has to be fully advanced even if the operator only actuates the pushbutton briefly. To this end, the directional control valve must remain in the intended position even after the pushbutton is released, i.e. the actuation of the pushbutton must be stored.

When the "ON" pushbutton in the circuit in Figure 8.5a is actuated, the relay coil is energised. The relay pulls in and the contact K1 closes. After the "ON" pushbutton is released, current continues to flow through the coil via the contact K1 and the relay remains in the actuated position. The "ON" signal is stored. The circuit is a relay circuit with self-latching loop.




a) Dominant setting
b) Dominant resetting

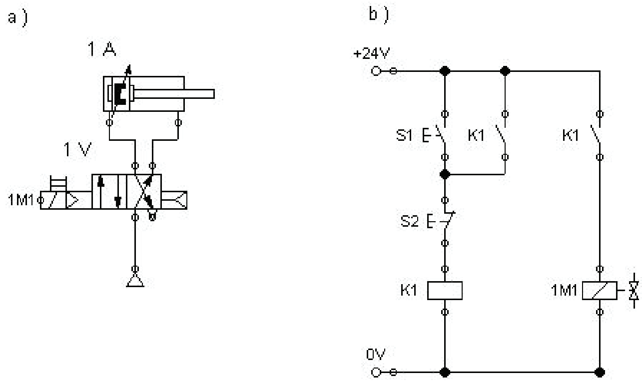
Figure 8.5: Latching circuit using relays

Only actuating the "OFF" pushbutton causes the flow of current to be interrupted and the relay to drop out. If the "ON" and "OFF" pushbuttons are actuated at the same time, the relay coil is energised. This circuit is referred to as a dominant (ON) setting self-latching loop.

The circuit in Figure 8.5b demonstrates the same behaviour as the circuit in Figure 8.5a, provided only the "ON" pushbutton or only the "OFF" button is actuated. The behaviour differs if both pushbuttons are actuated: the relay coil is not energised. This circuit is referred to as a dominant resetting self-latching loop.

### 8.3.2 Manual forward and return stroke control using relays with self-latching loop

The piston rod of a cylinder is to advance when the pushbutton S1 is actuated and retract when the pushbutton S2 is actuated. A relay with self-latching loop is to be used to store the signal.




a) Pneumatic circuit diagram with double-acting cylinder
b) Electrical circuit diagram

Figure 8.6: Manual forward and return stroke control with signal storage by means of a latching relay

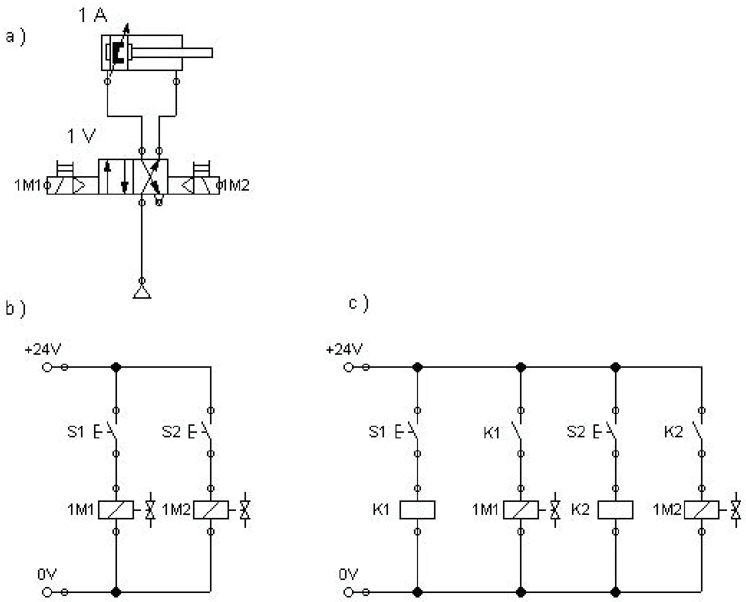
When the pushbutton S1 is actuated, the relay goes into the self-latching loop (Figure 8.6b). The directional control valve is actuated via a further relay contact. The piston rod advances. If the self-latching loop is interrupted by the pushbutton S2 being actuated, the piston rod retracts.

Since the circuit is a dominant resetting relay circuit, actuating the two pushbuttons results in the piston rod retracting or remaining in the retracted end position.

### 8.3.3 Signal storage by means of a double solenoid valve

A double solenoid valve is a component that retains its switching position even if the associated solenoid coil is no longer energised. This means it can fulfil the function of a memory.

The piston rod of a cylinder is to be controlled by briefly actuating two pushbuttons (S1: advance, S2: retract).




a) Pneumatic circuit diagram with double-acting cylinder
b) Electrical circuit diagram with direct control
c) Electrical circuit diagram with indirect control

Figure 8.7: Manual forward and return stroke control with signal storage by means of a double solenoid valve

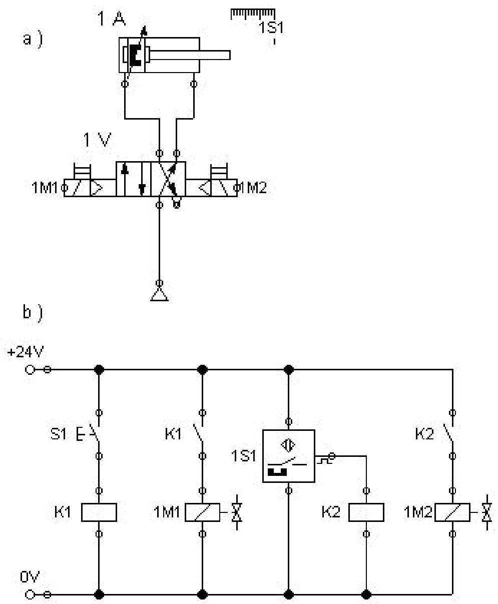
The two pushbuttons act directly or indirectly on the coils of a double solenoid valve (Figures 8.7b and 8.7c respectively).

Actuating the pushbutton S1 causes an attractive force to be exerted on the solenoid coil 1M1. The double solenoid valve switches and the piston rod advances. If the pushbutton is released during the advancing operation, the piston rod still keeps moving to the advanced end position since the valve retains its switching position.

Actuating the pushbutton S2 causes an attractive force to be exerted on the solenoid coil 1M2. The double solenoid valve switches again and the piston rod retracts. Releasing the pushbutton S2 has no effect on the movement.

### 8.3.4 Automatic return stroke control using double solenoid valves

The piston rod of a double-acting cylinder is to advance when the pushbutton S1 is actuated. After it reaches the advanced end position, the piston rod must automatically retract. To this end, a magnetic proximity sensor S1 that controls (reverses) the solenoid valve via the relay K2 is mounted at the advanced end position. Figure 8.6b shows the circuit diagram for the return stroke control model. The piston rod advances when the pushbutton S1 is actuated. When the piston rod reaches the advanced end position, the solenoid coil 1M2 can receive (draw) current via the limit switch 1S2 and the piston rod retracts.




a) Pneumatic circuit diagram
b) Electrical circuit diagram with indirect control

Figure 8.8: Automatic return stroke control with signal storage by means of a double solenoid valve

### 8.3.5 Comparison of signal storage by means of latching relays and double solenoid valves

Signal storage can take place in the power section of the controller by means of a double solenoid valve or in the signal control section by means of a relay with self-latching loop. The different circuits behave differently in the event of simultaneous set and reset signals as well as in the event of a power failure or defect such as a wire break, for example (Table 8.1).

| **Situation** | **Signal storage by means of a double solenoid valve** | **Signal storage by means of an electrical latching circuit combined with valve with spring return** | |
|---|---|---|---|
| | | **Dominant setting** | **Dominant resetting** |
| Set and reset signals together | Valve position unchanged | Valve is actuated | Valve switches to normal position |
| Failure of the electrical power supply | Valve position unchanged | Valve goes to normal position | Valve switches to normal position |

Table 8.1: Comparison of signal storage by means of latching circuit and double solenoid valve

## 8.4 Delay circuits using relays

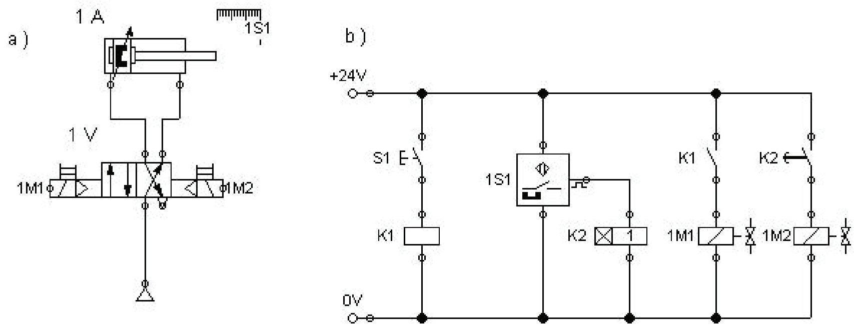
Many applications within automation technology require the piston rod of a pneumatic cylinder to remain in one position for a defined period of time. An example of such an application is the drive for a pressing device that presses two workpieces together until the adhesive has set and both parts are firmly stuck together.

Tasks such as this use relays with a switch-on or switch-off delay. These are relays that can trigger or interrupt a switching operation via a predefined time delay.

## 8.5 Controlling a cylinder via timing

The piston rod of a cylinder is to advance after the pushbutton S1 is briefly actuated, remain in the advanced end position for 10 seconds and then automatically retract.

Figure 8.9b shows the electrical circuit diagram for delayed retraction. The piston rod advances when the pushbutton S1 is actuated. If the advanced end position is reached, the limit switch 1S1 closes. Current flows through the coil of the relay K2. The contact K2 remains open until the set delay time (1 second in this case) has expired. It is then closed and the piston rod retracts.




a) Pneumatic circuit diagram
b) Electrical circuit diagram

Figure 8.9: Delayed retraction (relay with switch-on delay, storage by means of a double solenoid valve)

# 9 Programmable logic controllers (PLCs)

## 9.1 General information

These days complex control tasks are mainly handled using programmable logic controllers (PLCs). With this type of controller, the program is not realised through the linking of individual relays but rather using appropriate software. PLCs mainly process binary signals.

Their advantages over contact controllers or hard-wired programmed controllers are:

- just a few logic blocks in the software instead of numerous relays,
- less wiring,
- more flexible when it comes to changing the programs quickly and effectively,
- faults are easier to find,
- much more cost-effective.

The MecLab® learning system uses a PLC simulated in the FluidSIM® software instead of an actual PLC. The programming of this PLC is essentially the same as for a standard PLC such as the Siemens "LOGO!" controller shown in Figure 9.1, for example.

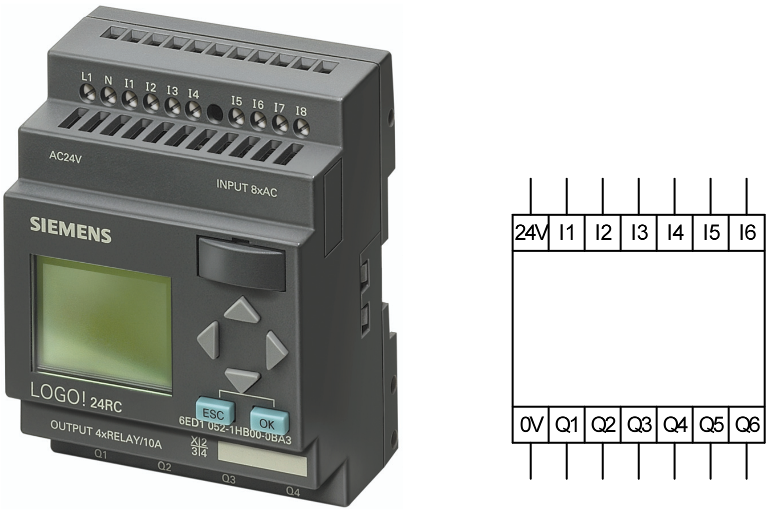



Figure 9.1: Picture of the "LOGO!" PLC from Siemens and the corresponding symbol in FluidSIM®

## 9.2 Logic symbols in the FluidSIM® control software

Using controllers in an application only makes sense if their sequences happen at precisely the right time, at the exact position and in the correct order. This calls not only for reliable hardware, but also software that enables complex technical sequences to be both planned and controlled and that has a user interface conforming to international standards. The FluidSIM® software meets these requirements.

FluidSIM® offers three options for developing a control system:

- pneumatic circuits,
- electrical circuits,
- logic circuits.

All of these circuit types can be combined together and the simulation mode enables controller functions to be put to the test before they are realised on the actual module. This advance testing of the developed solution on the computer means that damage to the technical system can be avoided.

The following table provides an overview of the most important logic symbols available in FluidSIM®.

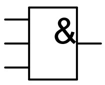
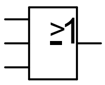
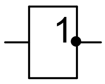
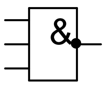
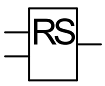
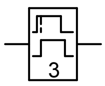
| Symbol | Designation | Function |
|---|---|---|
|   | AND | Switches the output to 1 when all inputs are 1. Unassigned inputs are always 1. |
|   | OR | Switches the output to 1 when at least one input is 1. Unassigned inputs are always 0. |
|   | NOT | Inverts the input. |
|   | NOT AND (NAND) | Switches the input to 0 when all inputs are 1. Unassigned inputs are always 1. |
|   | Latching element | Switches the input to 1 when the upper input is set to 1. The output is only reset to 0 when the lower input is set to 1. |
|   | Switch-on/off delay | When the input is set to 1, the output is set to 1 after the first set time has elapsed and reset to 0 after the second set time has elapsed. |

Table 9.1: Logic symbols in FluidSIM®

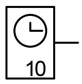
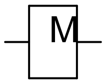
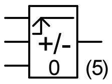
| Symbol | Designation | Function |
|---|---|---|
|  | Time delay clock | The output is set to 1 after the switch-on time has elapsed and reset to 0 after the switch-off time has elapsed. The process can be repeated. |
|  | Label | The output assumes the value of the input. This is necessary because some logic blocks cannot be connected with the output of another logic block. |
|  | Counter | Counts how often the value 1 was applied at the middle input. The output is set to 1 after a preset number of counting pulses is reached. The direction of counting (forwards/backwards) can be set using the lower input and the counter can be reset using the upper input. |

Table 9.1: Logic symbols in FluidSIM® (continued)

## 9.3 Programming a logic control system using a PLC

### 9.3.1 Example 1: Self-latching loop

Figure 9.2 shows a circuit with double-acting cylinder and 4/2-way single solenoid valve. A PLC program is to be created for it that enables the piston rod to advance when a pushbutton T1 is pressed. The piston rod should retract when the forward end position has been reached. The forward end position is detected via proximity sensor 1S1.

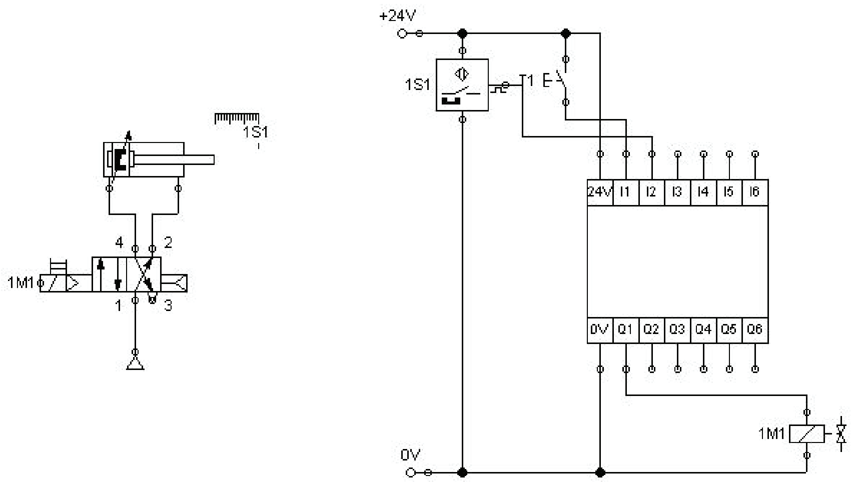



Figure 9.2: Pneumatic circuit diagram with solenoid valve and proximity sensor

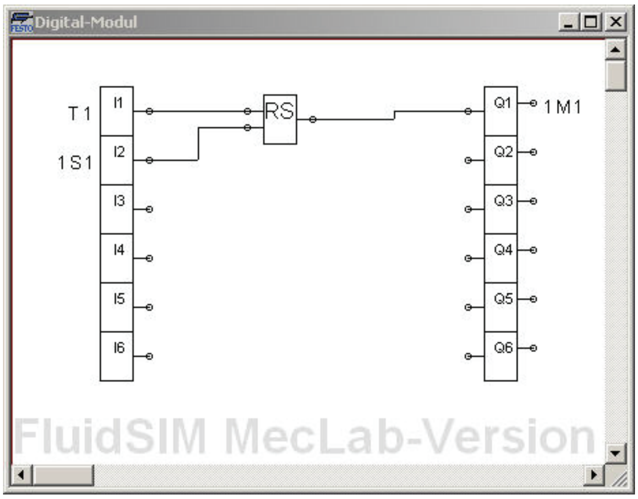



Figure 9.3: PLC program for Figure 9.2

Figure 9.3 shows the accompanying PLC program. The pushbutton T1 is connected to the input I1 of the PLC. This activates a latching element that switches on the valve solenoid 1M1 connected to the output Q1 of the PLC.

When the piston of the cylinder 1A (see Figure 9.2) reaches the forward end position, the sensor 1S1 connected to the input I2 of the PLC is activated. The latching element and thus also the output Q1 are reset. The valve returns to its normal position and the cylinder piston rod retracts.

### 9.3.2 Example 2: AND operation, timer

Figure 9.4 shows a modified pneumatic circuit. The cylinder is equipped with two proximity sensors, one at the forward end position and one at the retracted end position. A program is to be developed that lets the cylinder advance when it is in the retracted end position and the pushbutton is actuated. The piston rod should advance fully, stay in that position for exactly 3 seconds and then retract again.

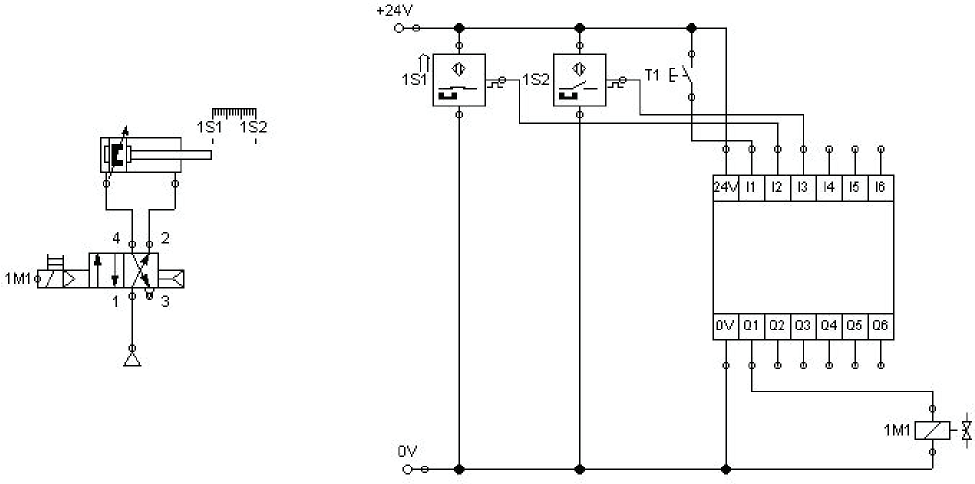



Figure 9.4: Cylinder with two proximity sensors

Figure 9.5 shows the accompanying PLC program. The inputs I1 and I2, to which the start button and the proximity sensor 1S1 are connected, have been linked using an AND operation (the high element sets the third, unused input to 1 also). If the cylinder is in the retracted end position and the pushbutton is actuated, all inputs of the AND operation are set to 1. The output of the AND operation as well as the required input of the latching element is likewise set to 1 and the cylinder advances.

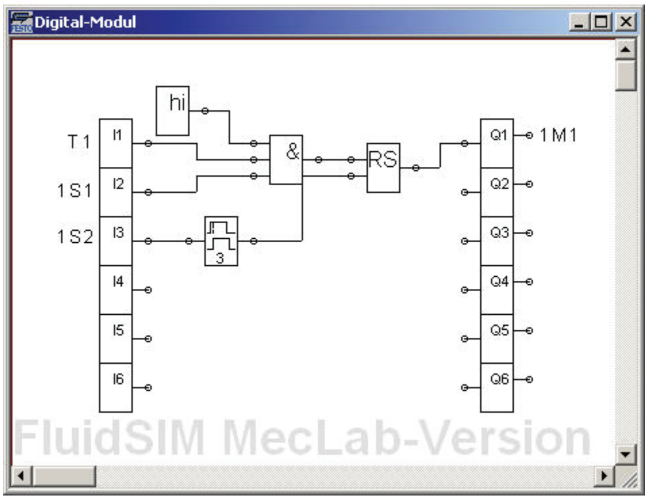



Figure 9.5: PLC program for Figure 9.4

When the cylinder reaches its forward end position, this activates the proximity sensor 1S2 that sets the input of the timer to 1. The output of the delay element is set to 1 after the set delay time expires, resetting the latching element. Current is no longer applied to the valve solenoid 1M1 and the cylinder retracts again.

### 9.4 Programming a control system using the sequencing method

The logic control systems described in the previous section are adequate for simple control problems. If, however, operations where complex steps are to be performed in sequence are to be controlled, this simple type of programming usually no longer suffices. Sequencing technology was developed for this application. With sequencing, the execution of one step is a condition for the next step. The information collected is buffered via latching elements.

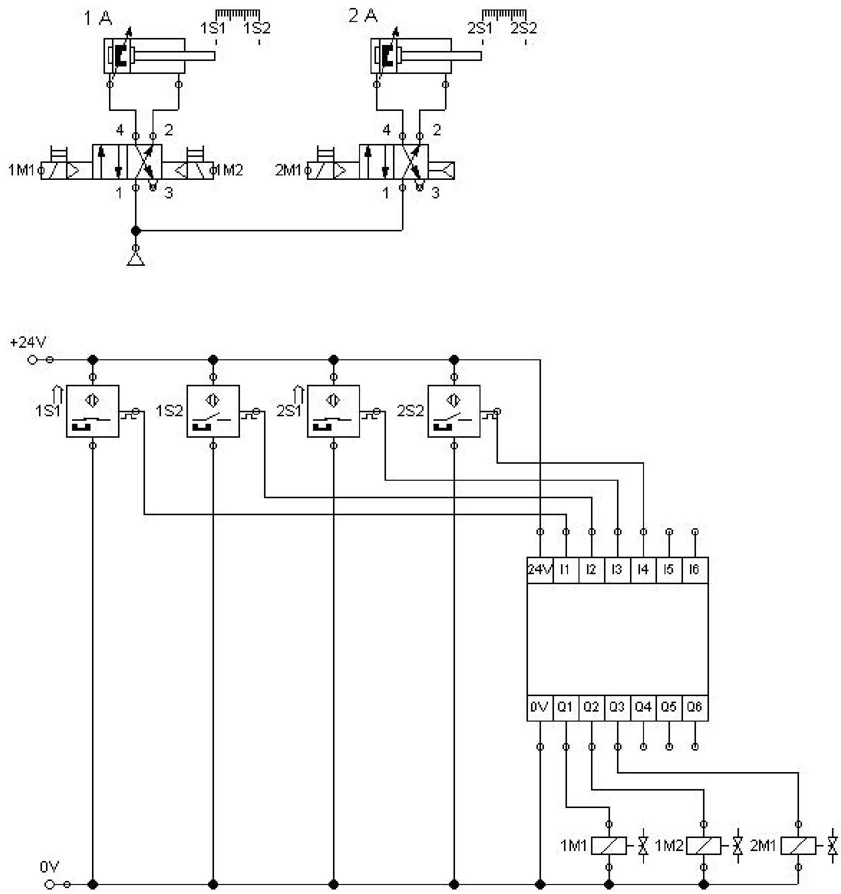



Figure 9.6: Circuit with two double-acting cylinders

Figure 9.6 shows a circuit diagram for two cylinders with two proximity sensors each for checking the end position.

Figure 9.7 shows the accompanying PLC program. The sequence can be described as follows:

- When the proximity sensors 1S1 and 2S1 are activated (both cylinders in their initial position), the latching element is activated via the AND operation. This energises the valve solenoid 1M1 and the cylinder advances (step 1).
- Once the cylinder 1A has reached its forward end position, the second AND operation activates the second latching element. This activates the valve solenoid 2M1 and the cylinder 2A advances (step 2). Step 2, however, can only be realised if step 1 has been executed since the output of the first latching element is connected to an input of the AND operation of the second circuit. When step 2 is executed, it resets step 1 via the label by resetting the latching element.
- Once step 2 has been executed and both cylinders have reached their forward end positions, step 3 is activated. This resets step 2, activates the valve solenoid 1M2 and de-energises the valve solenoid 2M1. Both cylinders return to their normal positions and the cycle begins again.

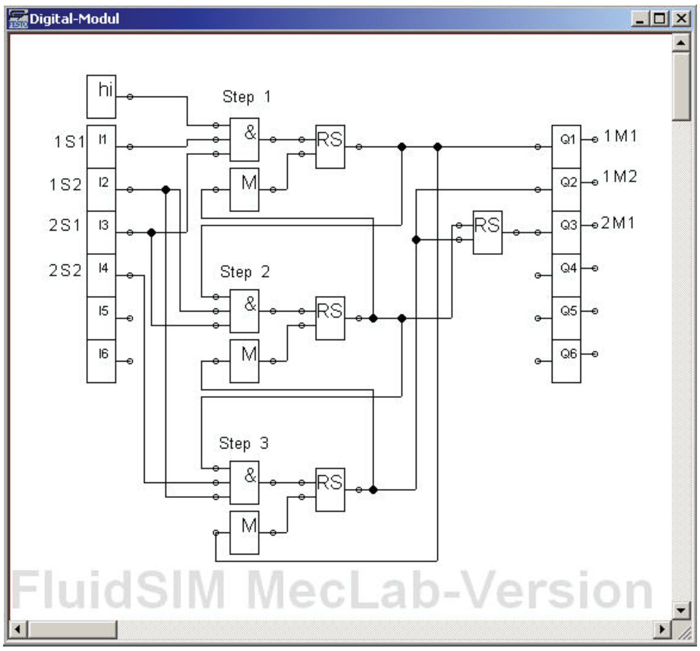



Figure 9.7: PLC program with sequencing

Note that the execution of each step is a condition for the execution of the next step and resets the preceding step. Any number of sequences can be combined in principle using this technique, enabling very complex operations.