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# Electropneumatics

**Basic Level**

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**Contents**

# Preface

Electropneumatics is successfully used in many areas of industrial automation. Production, assembly and packaging systems worldwide are driven by electropneumatic control systems.

The change in requirements together with technical advances have had a considerable impact on the appearance of controls. In the signal control section, the relay has increasingly been replaced by the programmable logic controller in order to meet the growing demand for more flexibility. Modern electropneumatic controls also implement new concepts in the power section to meet the needs of modern industrial practice. Examples of this are the valve terminal, bus networking and proportional pneumatics.

In introducing this topic, this textbook first looks at the structure and mode of operation of the components used for setting up an electropneumatic control. The following chapters then look at the approach to project planning and the implementation of electropneumatic controls using fully worked examples. Finally, the last chapter looks at trends and developments in Electropneumatics.

We would welcome your comments on this book and will certainly consider your tips, criticism and ideas in respect of improvement.

November 1997 The Authors

# Chapter 1

# Introduction

## 1.1 Applications of pneumatics

Pneumatics deals the use of compressed air. Most commonly, compressed air is used to do mechanical work – that is to produce motion and to generate forces. Pneumatic drives have the task of converting the energy stored in compressed air into motion.

Cylinders are most commonly used for pneumatic drives. They are characterized by robust construction, a large range of types, simple installation and favorable price/performance. As a result of these benefits, pneumatics is used in a wide range of applications.

*Fig. 1.1: Pneumatic linear cylinder and pneumatic swivel cylinder.*

Some of the many applications of pneumatics are

- Handling of workpieces (such as clamping, positioning, separating, stacking, rotating)
- Packaging
- Filling
- Opening and closing of doors (such as buses and trains)
- Metal-forming (embossing and pressing)
- Stamping

*Application example*

In the processing station in Fig. 1.2, the rotary indexing table, feed, clamping and ejecting devices and the drives for the various tools are pneumatic.

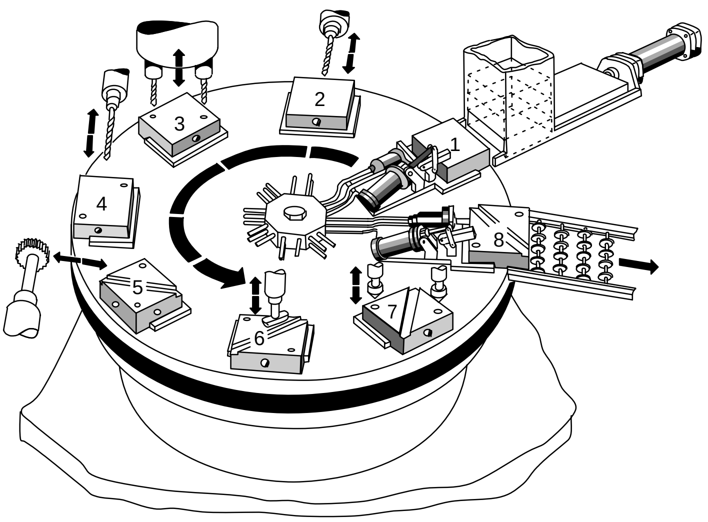



*Fig. 1.2: Processing station*

## 1.2 Basic control engineering terms

Pneumatic drives can only do work usefully if their motions are precise and carried out at the right time and in the right sequence. Coordinating the sequence of motion is the task of the controller.

Control engineering deals with the design and structure of controllers. The following section covers the basic terms used in control engineering.

***Control***
*(DIN 9226, Part 1)*

Controlling – open loop control – is that process taking place in a system whereby one or more variables in the form of input variables exert influence on other variables in the form of output variables by reason of the laws which characterize the system. The distinguishing feature of open loop controlling is the open sequence of action via the individual transfer elements or the control chain.

The term open loop control is widely used not only for the process of controlling but also for the plant as a whole.

*Application example*

A device closes metal cans with a lid. The closing process is triggered by operation of a pushbutton at the workplace. When the pushbutton is released, the piston retracts to the retracted end position.

In this control, the position of the pushbutton (pushed, not pushed) is the input variable. The position of the pressing cylinder is the output variable. The loop is open because the output variable (position of the cylinder) has no influence on the input variable (position of the pushbutton).

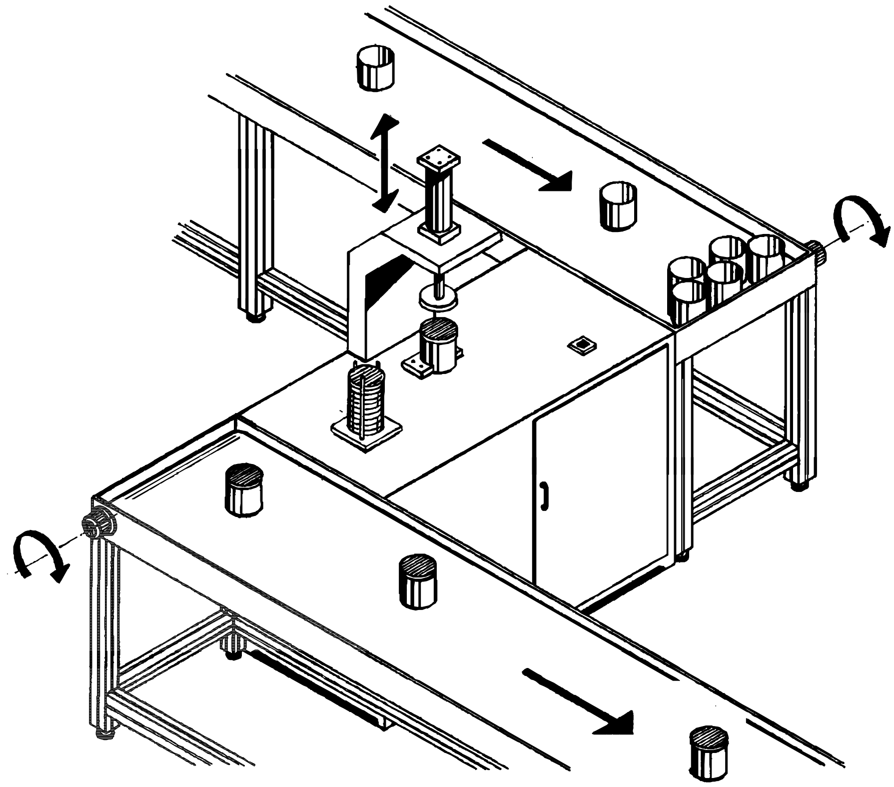
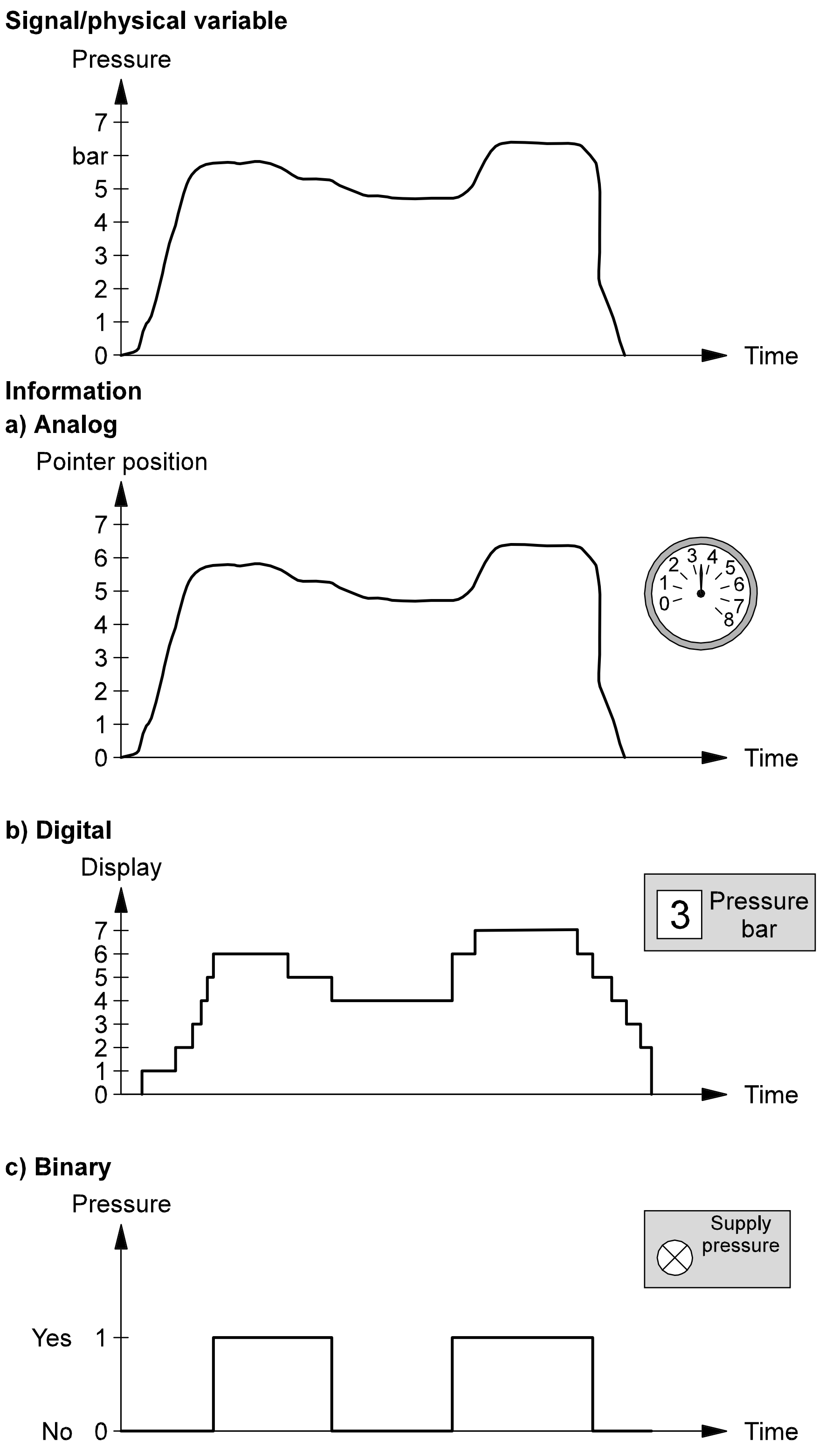


*Fig. 1.3:*
*Assembly device for mounting lids on cans*

Controls must evaluate and process information (for example, pushbutton pressed or not pressed). The information is represented by signals. A signal is a physical variable, for example

- The pressure at a particular point in a pneumatic system
- The voltage at a particular point in an electrical circuit

*Fig. 1.4:*
*Signal and information*



A signal is the representation of information The representation is by means of the value or value pattern of the physical variable.

***Analog signal***

An analog signal is a signal in which information is assigned point by point to a continuous value range of the signal parameter (DIN 19226, Part 5).

*Application example*

In the case of a pressure gauge, each pressure value (information parameter) is assigned a particular display value (= information). If the signal rises or falls, the information changes continuously.

***Digital signal***

A digital signal is a signal with a finite number of value ranges of the information parameter. Each value range is assigned a specific item of information (DIN 19226, Part 5).

*Application example*

A pressure measuring system with a digital display shows the pressure in increments of 1 bar. There are 8 possible display values (0 to 7 bar) for a pressure range of 7 bar. That is, there eight possible value ranges for the information parameter. If the signal rises or falls, the information changes in increments.

***Binary signal***

A binary signal is a digital signal with only two value ranges for the information parameter. These are normally designated o and 1 (DIN 19226, Part 5).

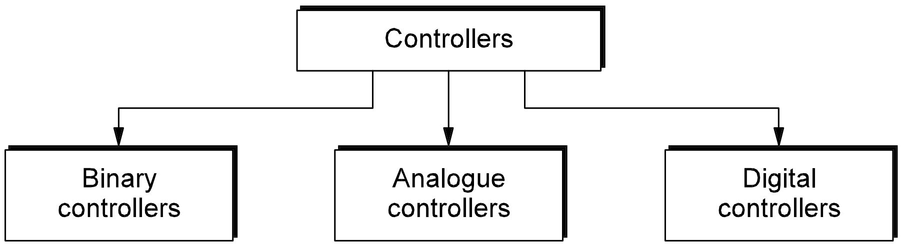
*Application example*

A control lamp indicates whether a pneumatic system is being correctly supplied with compressed air. If the supply pressure (= signal) is below 5 bar, the control lamp is off (0 status). If the pressure is above 5 bar, the control lamp is on (1 status).

*Classification of controllers by type of information representation*

Controllers can be divided into different categories according to the type of information representation, into analogue, digital and binary controllers (DIN 19226, Part 5).

*Fig. 1.5: Classification of controllers by type of information representation*




**Logic controller**

A logic controller generates output signals through logical association of input signals.

*Application example*

The assembly device in Fig. 1.3 is extended so that it can be operated from two positions. The two output signals are linked. The piston rod advances if either pushbutton 1 or 2 is pressed or if both are pressed.

**Sequence controller**

A sequence controller is characterized by its step by step operation. The next step can only be carried out when certain criteria are met.

*Application example*

Drilling station. The first step is clamping of the workpiece. As soon as the piston rod of the clamping cylinder has reached the forward end position, this step has been completed. The second step is to advance the drill. When this motion has been completed (piston rod of drill feed cylinder in forward end position), the third step is carried out, etc.

*Signal flow in a control system*

A controller can be divided into the functions signal input, signal processing, signal output and command execution. The mutual influence of these functions is shown by the signal flow diagram.

- Signals from the signal input are logically associated (signal processing). Signals for signal input and signal process are low power signals. Both functions are part of the signal control section.
- At the signal output stage, signals are amplified from low power to high power. Signal output forms the link between the signal control section and the power section.
- Command execution takes place at a high power level – that is, in order to reach a high speed (such as for fast ejection of a workpiece from a machine) or to exert a high force (such as for a press). Command execution belongs to the power section of a control system.

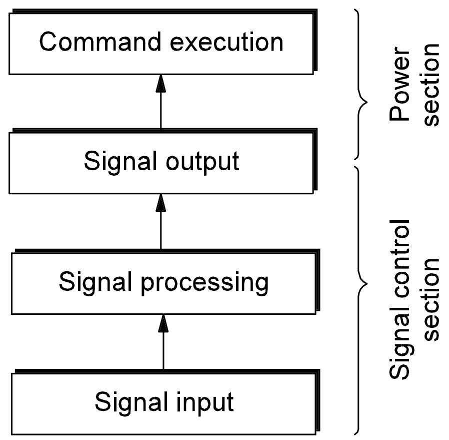



*Fig. 1.6: Signal flow in a control system*

The components in the circuit diagram of a purely pneumatic controller are arranged so that the signal flow is clear. Bottom up: input elements (such as manually operated valves), logical association elements (such as two-pressure valves), signal output elements (power valves, such as 5/2-way valves) and finally command execution (such as cylinders).

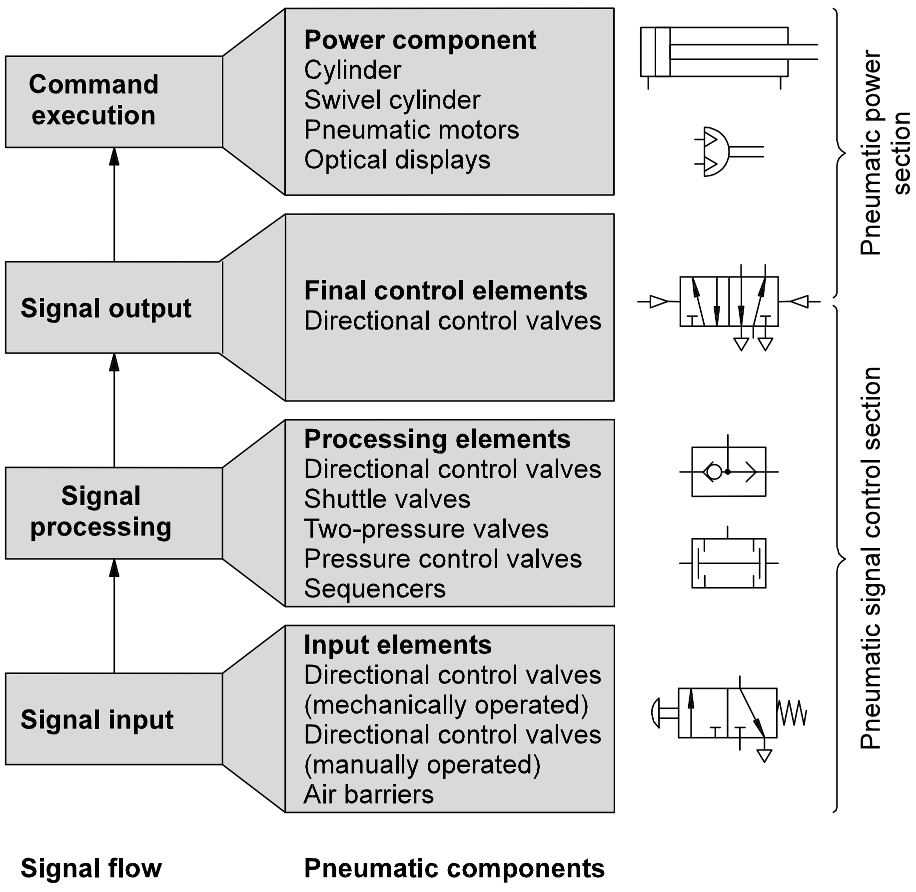
### 1.3 Pneumatic and electropneumatic control systems

Both pneumatic and electropneumatic controllers have a pneumatic power section (See Fig. 1.7 and 1.8). The signal control section varies according to type.

- In a pneumatic control pneumatic components are used, that is, various types of valves, sequencers, air barriers, etc.
- In an electro-pneumatic control the signal control section is made up of a electrical components, for example with electrical input buttons, proximity switches, relays, or a programmable logic controller.

The directional control valves form the interface between the signal control section and the pneumatic power section in both types of controller.

*Fig. 1.7: Signal flow and components of a pneumatic control system*



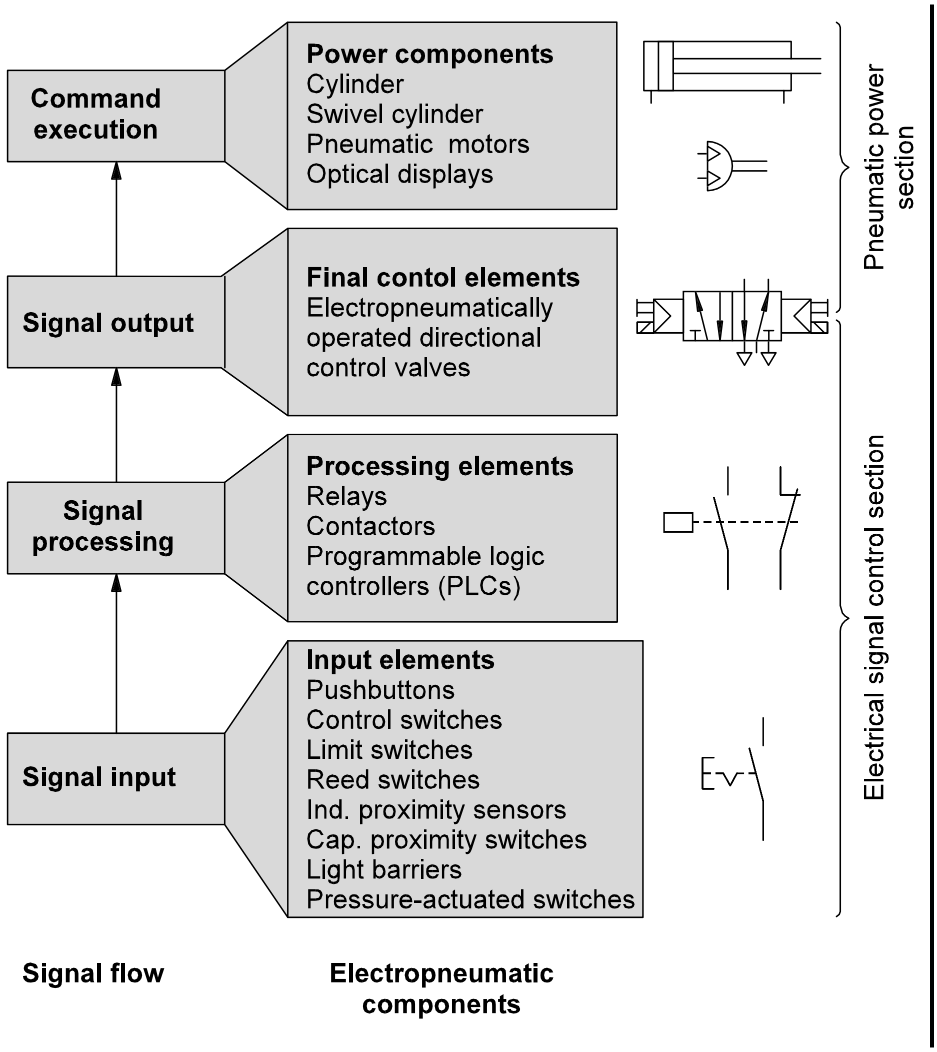



*Fig. 1.8: Signal flow and components of an electropneumatic control system*

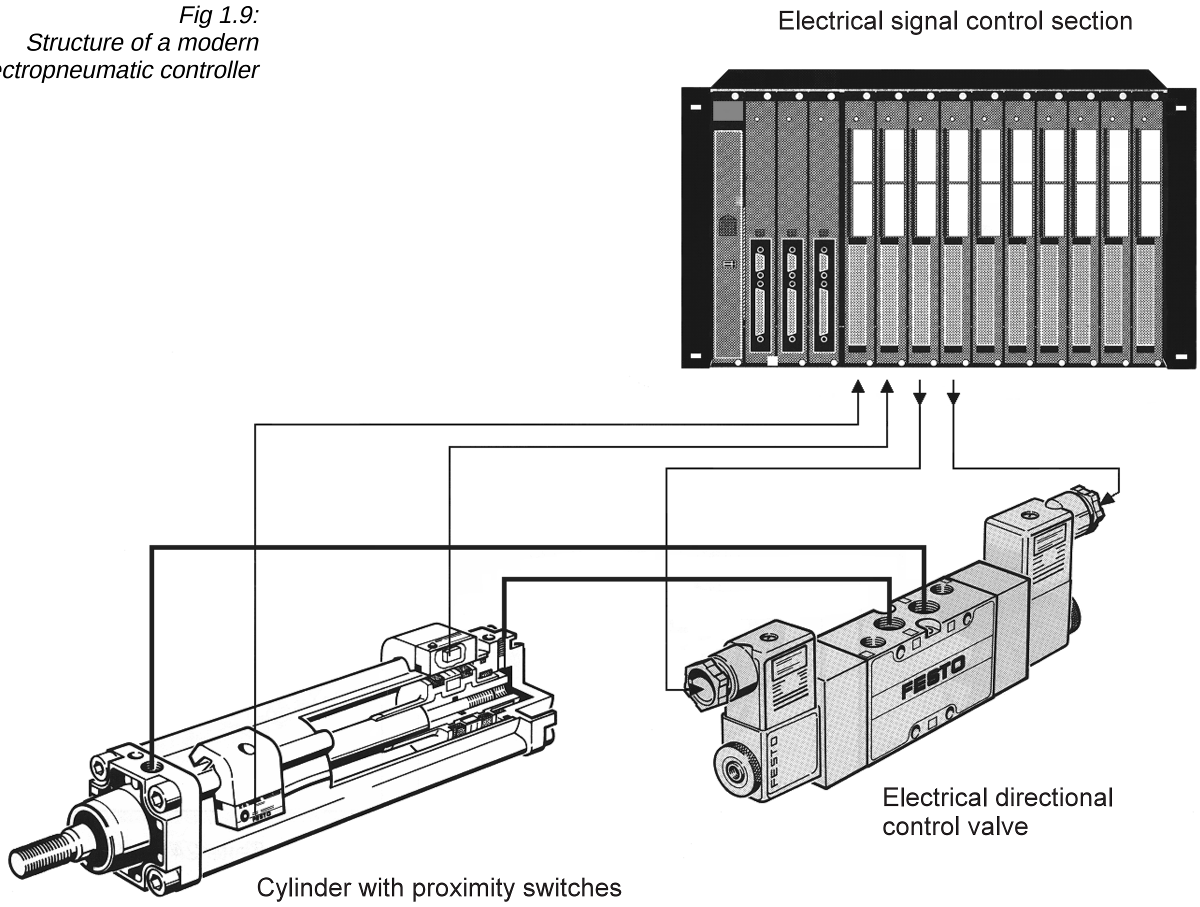
In contrast to a purely pneumatic control system, electropneumatic controllers are not shown in any single overall circuit diagram, but in two separate circuit diagrams - one for the electrical part and one for the pneumatic part. For this reason, signal flow is not immediately clear from the arrangement of the components in the overall circuit diagram.

*Structure and mode of operation of an electropneumatic controller*

Fig 1.9 shows at the structure and mode of operation of an electropneumatic controller.

- The electrical signal control section switches the electrically actuated directional control valves.
- The directional control valves cause the piston rods to extend and retract.
- The position of the piston rods is reported to the electrical signal control section by proximity switches.

*Fig 1.9: Structure of a modern electropneumatic controller*



### 1.4 Advantages of electropneumatic controllers

Electropneumatic controllers have the following advantages over pneumatic control systems:

- Higher reliability (fewer moving parts subject to wear)
- Lower planning and commissioning effort, particularly for complex controls
- Lower installation effort, particularly when modern components such as valve terminals are used
- Simpler exchange of information between several controllers

Electropneumatic controllers have asserted themselves in modern industrial practice and the application of purely pneumatic control systems is a limited to a few special applications.

# Chapter 2

# Fundamentals of electrical technology

## 2.1 Direct current and alternating current

A simple electrical circuit consists of a voltage source, a load, and connection lines.

Physically, charge carriers – electrons – move through the electrical circuit via the electrical conductors from the negative pole of the voltage source to the positive pole. This motion of charge carriers is called electrical current. Current can only flow if the circuit is closed.

There are two types of current - direct current and alternating current:

- If the electromotive force in an electrical circuit is always in the same direction, the current also always flows in the same direction. This is called direct current (DC) or a DC circuit.
- In the case of alternating current or an AC circuit, the voltage and current change direction and strength in a certain cycle.

*Fig. 2.1: Direct current and alternating current plotted against time*

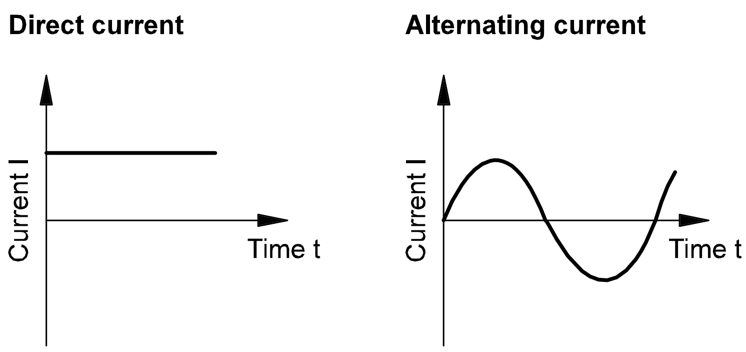


Fig. 2.2 shows a simple DC circuit consisting of a voltage source, electrical lines, a control switch, and a load (here a lamp).

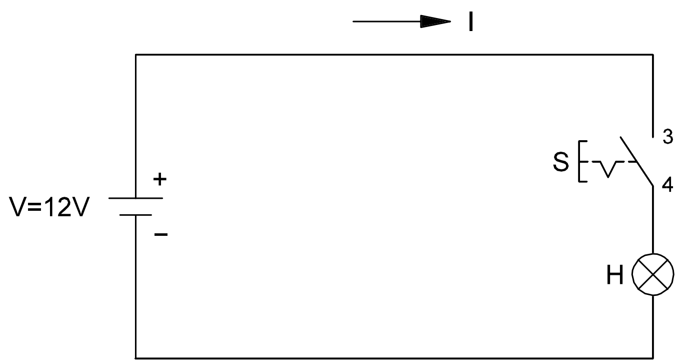



*Fig. 2.2:*
*DC circuit*

*Technical direction of flow*

When the control switch is closed, current I flows via the load. The electrons move from the negative pole to the positive pole of the voltage source. The direction of flow from quotes "positive" to "negative" was laid down before electrons were discovered. This definition is still used in practice today. It is called the technical direction of flow.

## 2.2 Ohm's Law

*Electrical conductors*

Electrical current is the flow of charge carriers in one direction. A current can only flow in a material if a sufficient number of free electrons are available. Materials that meet this criterion are called electrical conductors. The metals copper, aluminium and silver are particularly good conductors. Copper is normally used for conductors in control technology.

*Electrical resistance*

Every material offers resistance to electrical current. This results when the free-moving electrons collide with the atoms of the conductor material, inhibiting their motion. Resistance is low in electrical conductors. Materials with particularly high resistance are called insulators. Rubber- and plastic-based materials are used for insulation of electrical wires and cables.

*Source emf*

The negative pole of a voltage source has a surplus of electrons. The positive pole has a deficit. This difference results in source emf (electromotive force).

*Ohm's law*

Ohm's law expresses the relationship between voltage, current and resistance. It states that in a circuit of given resistance, the current is proportional to the voltage, that is

- If the voltage increases, the current increases.
- If the voltage decreases, the current decreases.

*Fig. 2.3: Ohm's law*

$$V = R \cdot I$$

| | | |
|---|---|---|
| V | = Voltage; | Unit: Volt (V) |
| R | = Resistance; | Unit: Ohm (Ω) |
| I | = Current; | Unit: Ampere (A) |

*Electrical power*

In mechanics, power can be defined by means of work. The faster work is done, the greater the power needed. So power is "work divided by time".

In the case of a load in an electrical circuit, electrical energy is converted into kinetic energy (for example electrical motor), light (electrical lamp), or heat energy (such as electrical heater, electrical lamp). The faster the energy is converted, the higher the electrical power. So here, too, power means converted energy divided by time. Power increases with current and voltage.

The electrical power of a load is also called its electrical power input.

$$P = V \cdot I$$

| | | |
|---|---|---|
| P | = Power; | Unit: Watt (W) |
| V | = Voltage; | Unit: Volt (V) |
| I | = Current; | Unit: Ampere (A) |

*Fig. 2.4:*
*Electrical power*

*Application example*

Power of a coil

The solenoid coil of a pneumatic 5/2-way valve is supplied with 24 VDC. The resistance of the coil is 60 Ohm. What is the power?

The current is calculated by means of Ohm's law:

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

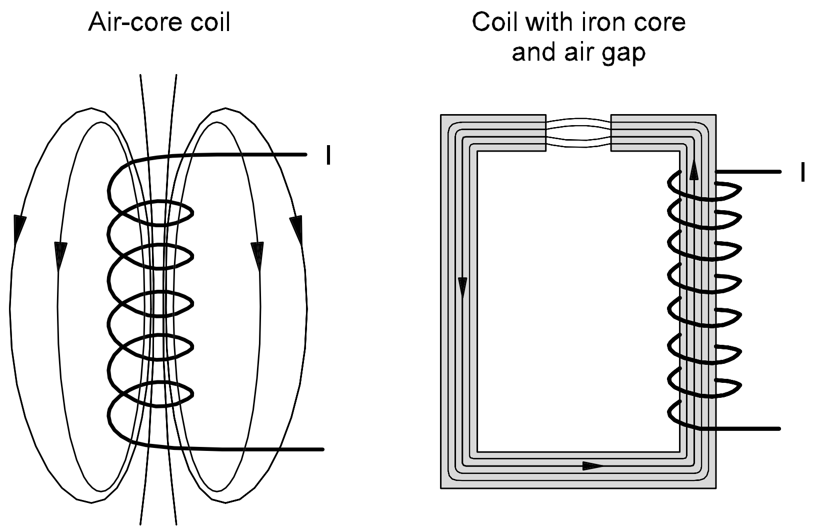
The electrical power is the product of current and voltage:

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

## 2.3 Function of a solenoid

A magnetic field is induced when a current is passed through an electrical conductor. The strength of the magnetic field is proportional to the current. Magnetic fields attract iron, nickel and cobalt. The attraction increases with the strength of the magnetic field.

*Fig. 2.6: Electrical coil and magnetic lines of force*




*Structure of a solenoid*

The solenoid has the following structure:

- The current-bearing conductor is wound around a coil. The overlapping of the lines of force of all loops increases the strength of the magnetic field resulting in a main direction of the field.
- An iron core is placed in the centre. When current flows, the iron is also magnetized. This allows a significantly higher magnetic field to be induced with the same current (compared to an air-core coil).

These two measures ensure that an solenoid exerts a strong force on ferrous (= containing iron) materials.

*Applications of solenoids*

In electropneumatic controls, solenoids are primarily used to control the switching of valves, relays or contactors. This can be demonstrated using the example of the spring-return directional control valve:

- If current flows through the solenoid coil, the piston of the valve is actuated.
- If the current is interrupted, a spring pushes the piston back into its initial position.

*Reactance in AC circuits*

If a AC voltage is applied to a coil, an alternating current flows (see Fig. 2.1). This means that the current and magnetic field are constantly changing. The change in the magnetic field induces a current in the coil. The induced current opposes the current that induced the magnetic field. For this reason, a coil offers "resistance" to an alternating current. This is called reactance.  The reactance increases with the frequency of the voltage and the inductance of the coil. Inductance is measured in Henry (H).

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

*Reactance in DC circuits*

In the case of DC circuits, the current, voltage and magnetic field only change when the current is switched on. For this reason reactance only applies when the circuit is closed (switching on the current).

In addition to reactance, the coil has ohmic resistance. This resistance applies both to AC circuits and DC circuits.

## 2.4 Function of a capacitor

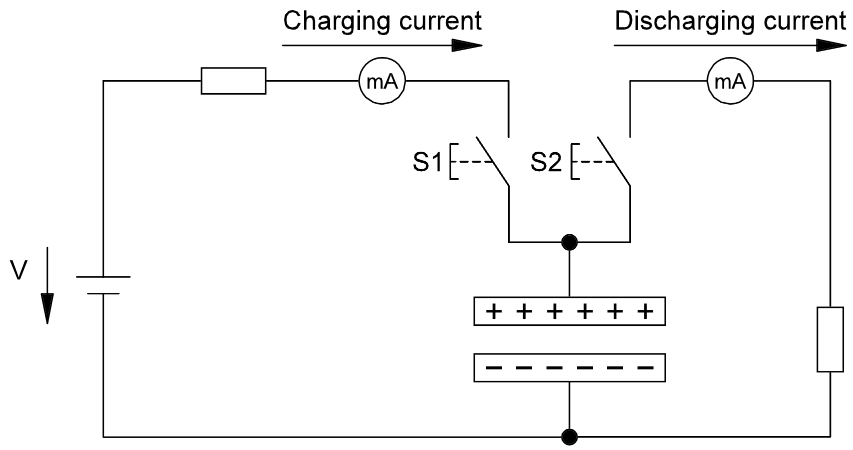
A capacitor consists of two metal plates with an insulating layer (dielectric) between them. If the capacitor is connected to a DC voltage source (closing the switch S1 in Fig. 2.6), a charging current flows momentarily. Both plates are electrically charged by this. If the circuit is then interrupted, the charge remains stored in the capacitor. The larger the capacitance of a capacitor, the greater the electrical charge it can store for a given voltage.

Capacitance is measured in Farad (F):

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

If the charged capacitor is now connected to a load (closing switch S2 in Fig. 2.6), the capacitor discharges. Current flows through the load until the capacitor is fully discharged.

*Fig. 2.6:*
*Function of a capacitor*



## 2.5 Function of a diode

Diodes are electrical components that only allows current to flow in one direction:

- In the flow direction, the resistance is so low that the current can flow unhindered.
- In the reverse direction, the resistance is so high that no current flows.

If a diode is inserted into a AC circuit, the current can only flow in one direction. The current is rectified.

The effect of a diode on an electrical circuit is comparable to the effect of a non-return valve on a pneumatic circuit.

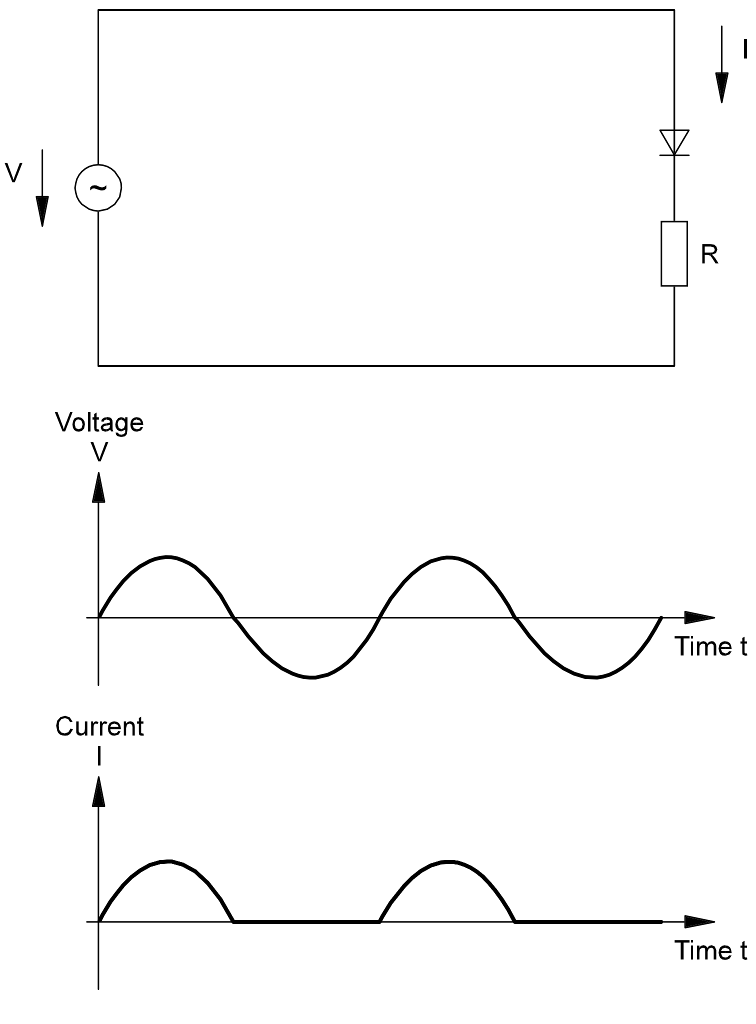



*Fig. 2.7:*
*Function of a diode*

## 2.6 Measurement in electrical circuits

Measurement means comparing an unknown variable (such as the length of a pneumatic cylinder) with a known variable (such as the scale of a measuring tape). A measuring device (such as a ruler) allows such measurements to be made. The result – the measured value – consists of a numeric value and a unit (such as 30.4 cm).

*Measurement*

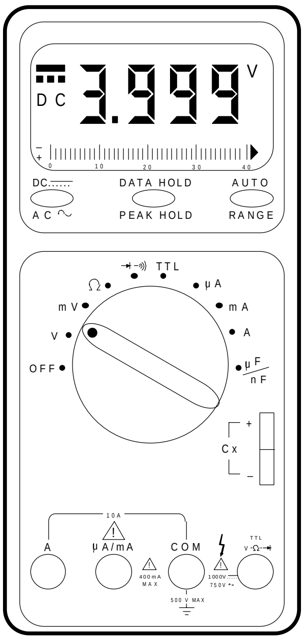
Electrical currents, voltages and resistances are normally measured with multimeters. These devices can be switched between various modes:

- DC current and voltage, AC current and voltage
- Current, voltage and resistance

The multimeter can only measure correctly if the correct mode is set.

Devices for measuring voltage are also called voltmeters. Devices for measuring current are also called ammeters.

*Fig. 2.8: Multimeter*



*Danger!*

Before carrying out a measurement, ensure that voltage of the controller on which you are working does not exceed 24 V! Measurements on parts of a controller operating at higher voltages (such as 230 V) may only be carried out by persons with appropriate training or instruction. Incorrect measurement methods can result in danger to life. Please read the safety precautions in Chapters 3 and 7!

*Procedure for measurements on electrical circuits*

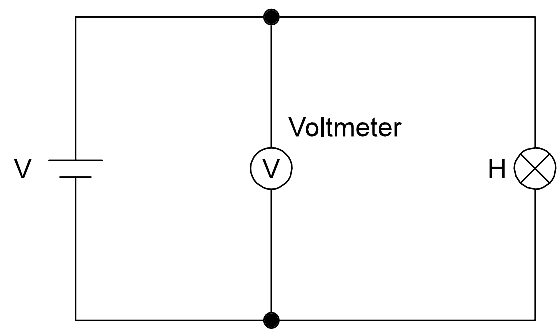
Follow the following steps when making measurements of electrical circuits.

- Switch off voltage source of circuit.
- Set multimeter to desired mode. (voltmeter or ammeter, AC or DC, resistance)
- Check zeroing for pointer instruments. Adjust if necessary.
- When measuring DC voltage or current, check for correct polarity. ("+" probe of device to positive pole of voltage source).
- Select largest range.
- Switch on voltage source.
- Observe pointer or display and step down to smaller range.
- Record measurement for greatest pointer deflection (smallest measuring range).
- For pointer instruments, always view from vertically above display in order to avoid parallax error.

*Voltage measurement*

For voltage measurement, the measuring device (voltmeter) is connected in parallel to the load. The voltage drop across the load corresponds to the voltage drop across the measuring device. A voltmeter has an internal resistance. In order to avoid an inaccurate measurement, the current flowing through the voltmeter must be as small as possible, so the internal resistance of the voltmeter must be as high as possible.

*Fig. 2.9:*
*Voltage measurement*

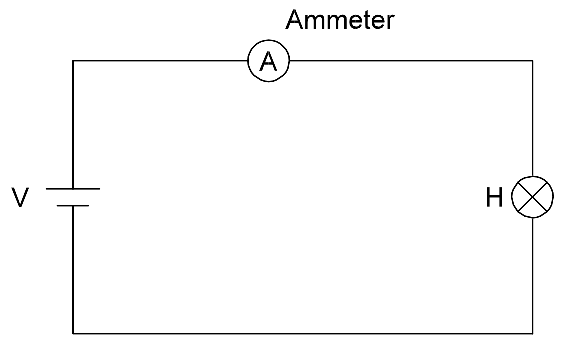



*Current measurement*

For current measurement, the measuring device (ammeter) is connected in series to the load. The entire current flows through the device.

Each ammeter has an internal resistance. In order to minimize the measuring error, the resistance of the ammeter must be as small as possible.

*Fig. 2.10*
*Current measurement*



*Resistance measurement*

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

- Indirect measurement measures the current through the load and the voltage across the load (Fig. 2.11a). The two measurements can either be carried out simultaneously or one after the other. The resistance is then measured using Ohm's law.
- For direct measurement the load is separated from the rest of the circuit (Fig. 2.11b). The measuring device (ohmmeter) is set to resistance measurement mode and connected to the terminals of the load. The value of the resistance is displayed.

If the load is defective (for example, the magnetic coil of a valve is burned out), the measurement of resistance either results in a value of zero (short-circuit) or an infinitely high value (open circuit).

**Warning:** The direct method must be used for measuring the resistance of a load in AC circuits.

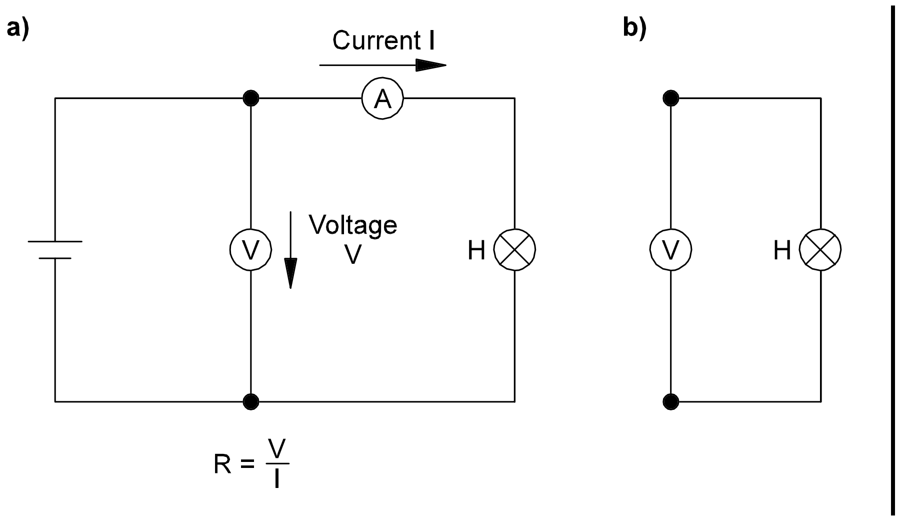



*Fig. 2.11: Measuring resistance*

*Sources of error*

Measuring devices cannot measure voltage, current and resistance to any desired degree of accuracy. The measuring device itself influences the circuit it is measuring, and no measuring device can display a value precisely. The permissible display error of a measuring device is given as a percentage of the upper limit of the effective range. For example, for a measuring device with an accuracy of 0.5, the display error must not exceed 0.5 % of the upper limit of the effective range.

*Application example*

Display error

A Class 1.5 measuring device is used to measure the voltage of a 9 V battery. The range is set once to 10 V and once to 100 V. How large is the maximum permissible display error for the two effective ranges?

*Table 2.1: Calculating the display error*

| Range | Permissible display error | Percentage error |
|---|---|---|
| 10 V | $10\text{ V} \cdot \frac{15}{100} = 0.15\text{ V}$ | $\frac{0.15}{9\text{ V}} \cdot 100 = 166\ \%$ |
| 100 V | $100\text{ V} \cdot \frac{15}{100} = 15\text{ V}$ | $\frac{15}{9\text{ V}} \cdot 100 = 16.6\ \%$ |

The example shows clearly that the permissible error is less for the smaller range. Also, the device can be read more accurately. For this reason, you should always set the smallest possible range.

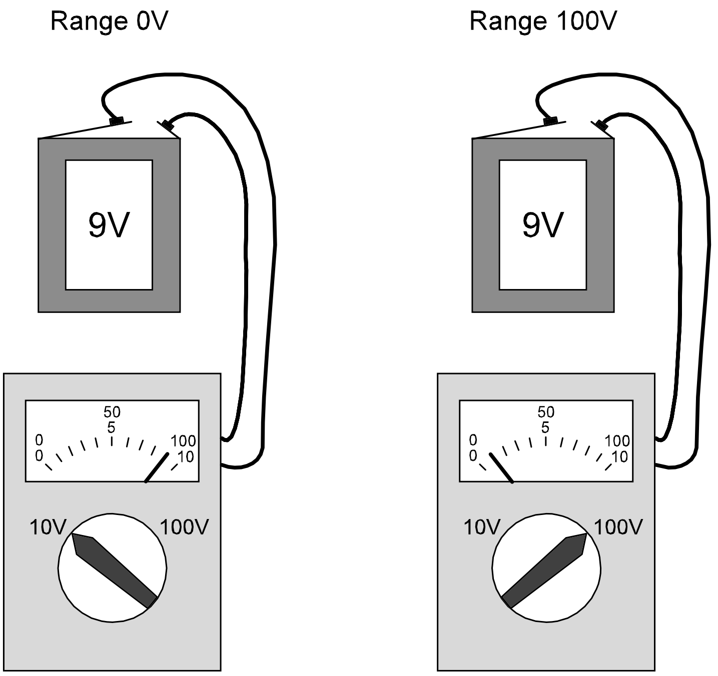



*Fig. 2.12:*
*Measuring battery voltage (with different range settings)*

# Chapter 3

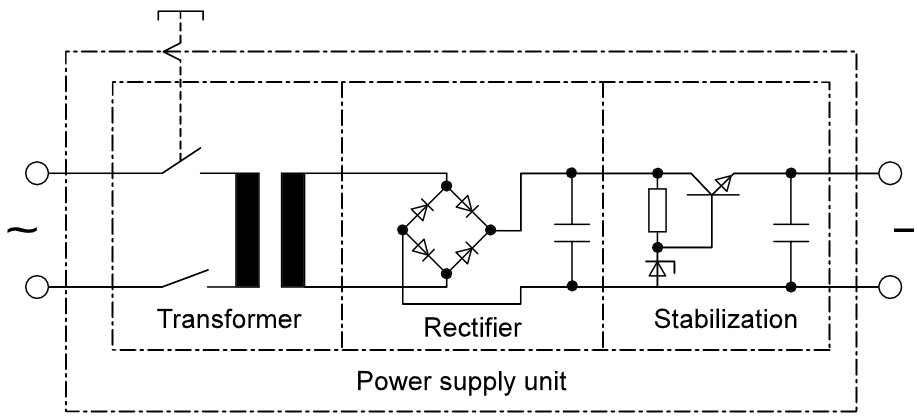
## Components and assemblies in the electrical signal control section

## 3.1 Power supply unit

The signal control section of an electropneumatic controller is supplied with power via the electrical mains. The controller has a power supply unit for this purpose (see Fig. 3.1). The individual assemblies of the power supply unit have the following tasks:

- The transformer reduces the operating voltage. The mains voltage (i. e. 230 V) is applied to the input of the transformer. A lower voltage (i. e. 24 V) is available at the output.
- The rectifier converts the AC voltage into DC voltage. The capacitor at the rectifier output smoothes the voltage.
- The voltage regulator at the output of the power supply unit is required to ensure that the electrical voltage remains constant regardless of the current flowing.

*Fig. 3.1: Component parts of a power supply unit for an electropneumatic controller.*




***Safety precaution***

> **Warning:** Because of the high input voltage, power supply units are part of the power installation (DIN/VDE 100). Safety regulations for power installations must be observed. Only authorized personnel may work on power supply units.

### 3.2 Push button and control switches

Switches are installed in circuits to apply a current to a load or to interrupt the circuit. These switches are divided into pushbuttons and control switches.

- Control switches are mechanically detented in the selected position. The switch position remains unchanged until a new switch position is selected. Example: Light switches in the home.
- Push button switches only maintain the selected position as long as the switch is actuated (pressed). Example: Bell push.

*Normally open contact (make)*

In the case of a normally open contact, the circuit is open if the switch is in its initial position (not actuated). The circuit is closed by pressing the push button – current flows to the load. When the plunger is released, the spring returns the switch to its initial position, interrupting the circuit.

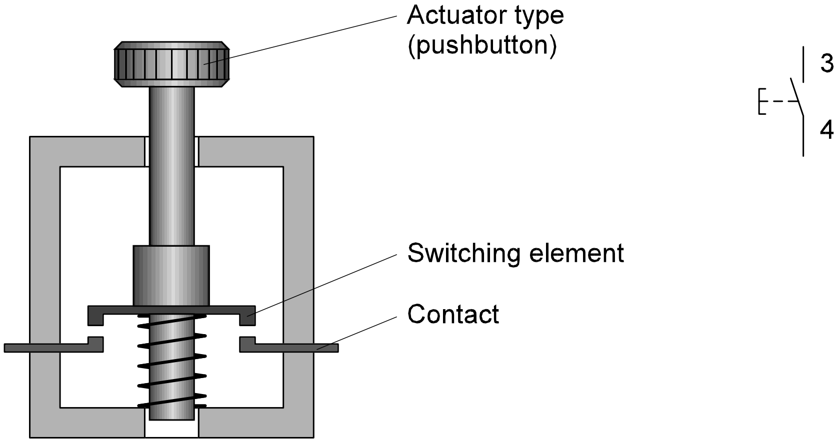
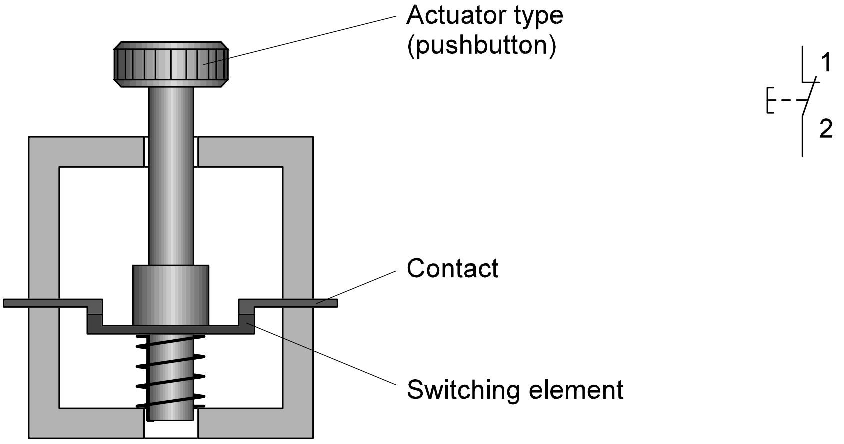



*Fig. 3.2:*
*Normally open contact (make)*
*– section and symbol*

*Normally closed contact (break)*

In this case, the circuit is closed when the switch is in its initial position. The circuit is interrupted by pressing the pushbutton.

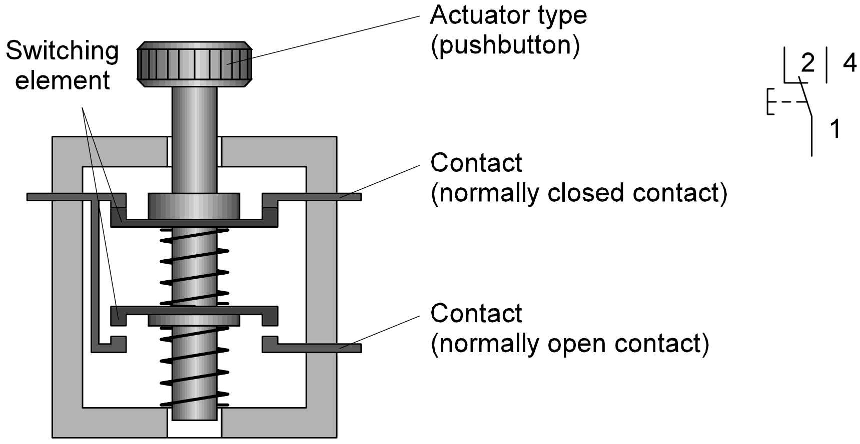
*Fig. 3.3: Normally open contact (break) – section and symbol*




*Changeover contact*

The changeover contact combines the functions of the normally open and normally closed contacts in one device. Changeover contacts are used to close one circuit and open another in one switching operation. The circuits are momentarily interrupted during changeover.

*Fig. 3.4: Changeover contact – section and symbol*



## 3.3 Sensors for measuring displacement and pressure

Sensors have the task of measuring information and passing this on to the signal processing part in a form that can easily be processed. In electropneumatic controllers, sensors are primarily used for the following purposes:

- To detect the advanced and retracted end position of the piston rod in cylinder drives
- To detect the presence and position of workpieces
- To measure and monitor pressure

*Limit switches*

A limit switch is actuated when a machine part or workpiece is in a certain position. Normally, actuation is effected by a cam. Limit switches are normally changeover contacts. They can then be connected – as required – as a normally open contact, normally closed contact or changeover contact.

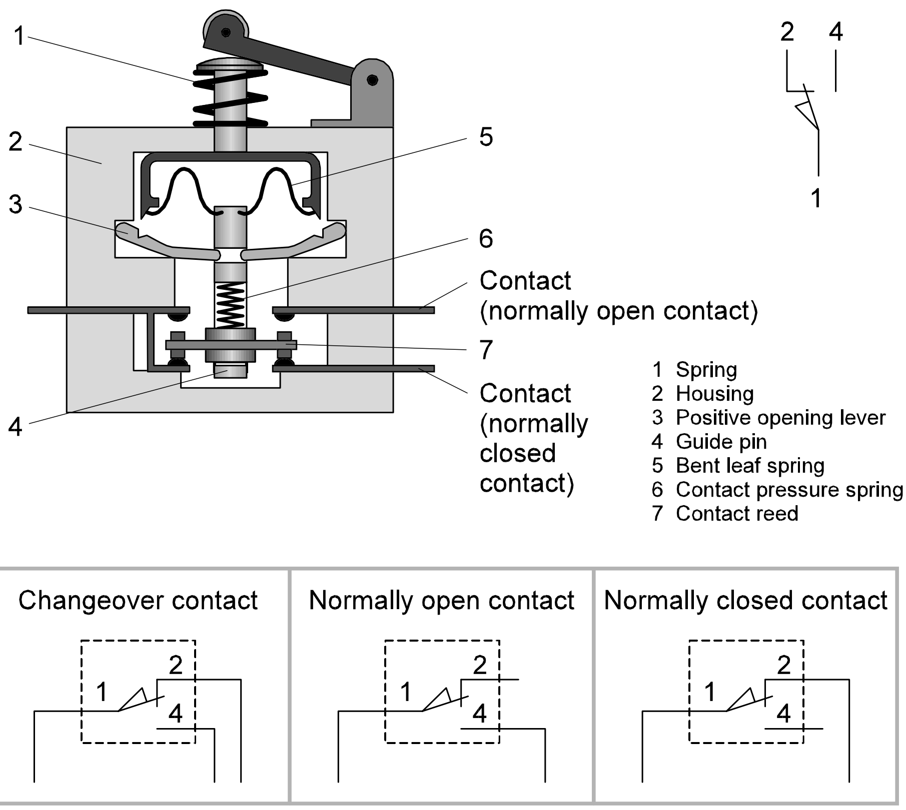



*Fig. 3.5:*
*Mechanical limit switch: construction and connection possibilities*

**Proximity switches**

In contrast to limit switches, proximity switches operated contactlessly (non-contact switching) and without an external mechanical actuating force.

As a result, proximity switches have a long service life and high switching reliability. The following types of proximity switch are differentiated:

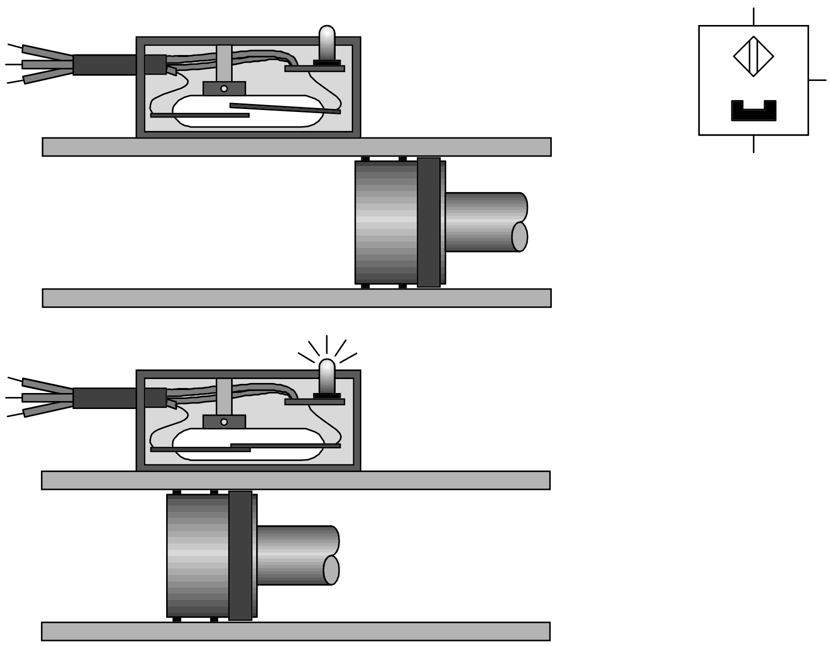
- Reed switch
- Inductive proximity switch
- Capacitive proximity switch
- Optical proximity switch

*Reed switch*

Reed switches are magnetically actuated proximity switches. They consist of two contact reeds in a glass tube filled with inert gas. The field of a magnet causes the two reeds to close, allowing current to flow. In reed switches that act as normally closed contacts, the contact reeds are closed by small magnets. This magnetic field is overcome by the considerably stronger magnetic field of the switching magnets.

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

*Fig. 3.6: Reed switch (normally open contact)*



*Electronic sensors*

Inductive, optical and capacitive proximity switches are electronic sensors. They normally have three electrical contacts.

- Contact for supply voltage
- Contact for ground
- Contact for output signal

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

*Positive and negative switching sensors*

There are two types of electronic sensor with regard to the polarity of the output voltage.

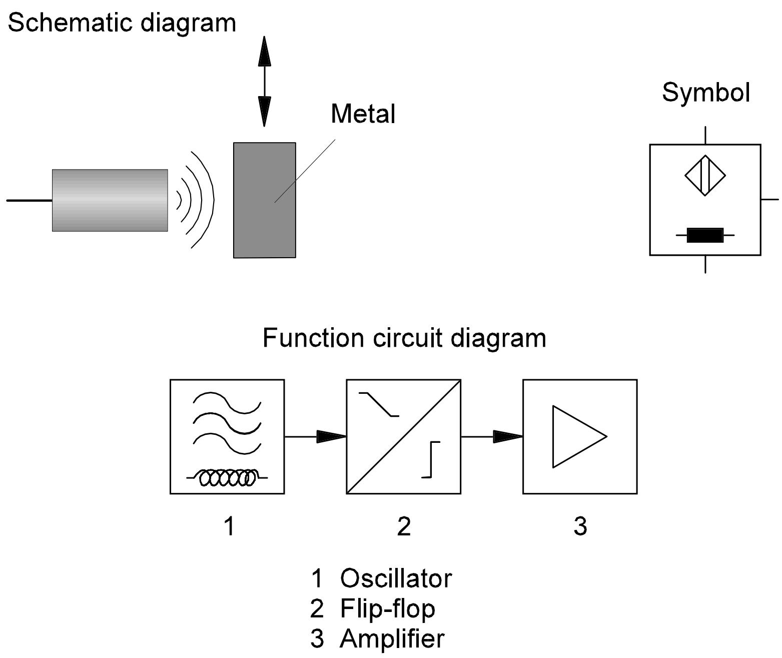
- In positive switching sensors, the output voltage is zero if no part is detected in the proximity. The approach of a workpiece or machine part leads to switchover of the output, applying the supply voltage.
- In negative switching sensors, the supply voltage is applied to the output if no part is detected in the proximity. The approach of a workpiece or machine part leads to switchover of the output, switching the output voltage to 0 V.

*Inductive proximity sensors*

An inductive proximity sensor consists of an electrical oscillator (1), a flip-flop (2) and an amplifier (3). When a voltage is applied, the oscillator generates a high-frequency alternating magnetic field that is emitted from the front of the sensor. If an electrical circuit is introduced into this field, the oscillator is attenuated. The downstream circuitry, consisting of a flip-flop and an amplifier, evaluates the behavior of the oscillator and actuates the output.

Inductive proximity sensors can be used for the detection of all good electrical conductors (materials). In addition to metals, these include, for example, graphite.

*Fig. 3.7: Inductive proximity sensor*



*Capacitive proximity sensor*

A capacitive proximity sensor consists of a capacitor and an electrical resistance that together form an RC oscillator, and a circuit for evaluation of the frequency. An electrostatic field is generated between the anode and the cathode of the capacitor. A stray field forms at the front of the sensor. If an object is introduced into this stray field, the capacitance of the capacitor changes. The oscillator is attenuated. The circuitry switches the output.

Capacitive proximity sensors not only react to highly conductive materials (such as metals) but also to insulators of high dielectric strength (such as plastics, glass, ceramics, fluids and wood).

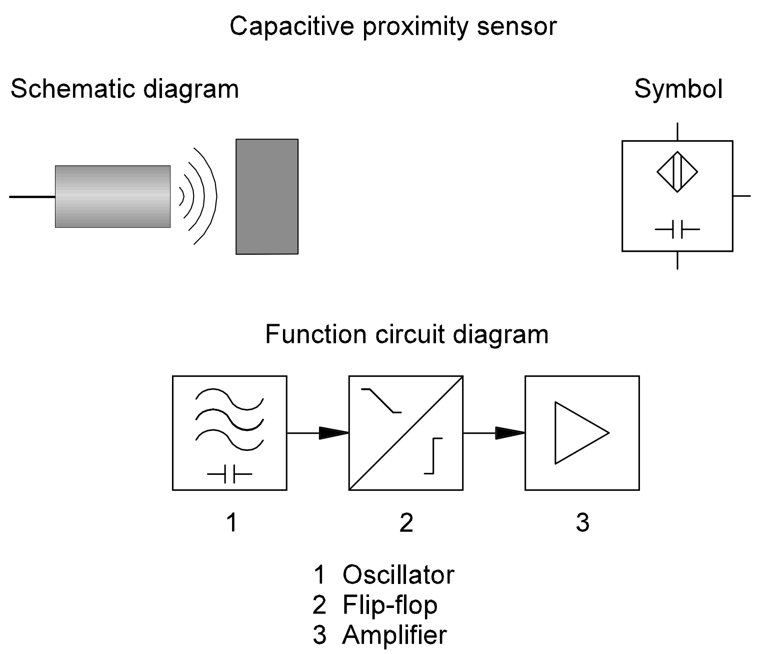



*Fig. 3.8:*
*Capacitive proximity sensor*

*Optical proximity sensor*

Optical proximity sensors use optical and electronic means for object detection. Red or infrared light is used. Semiconductor light-emitting diodes (LEDs) are particularly reliable sources of red or infrared light. They are small and rugged, have a long service life and can be simply modulated. Photodiodes or phototransistors are used as a receiver. Red light has the advantage that the light beam can be seen during adjustment of the optical axes of the proximity switch. Polymer optical fibres can also be used because of their low attenuation of light of this wavelength.

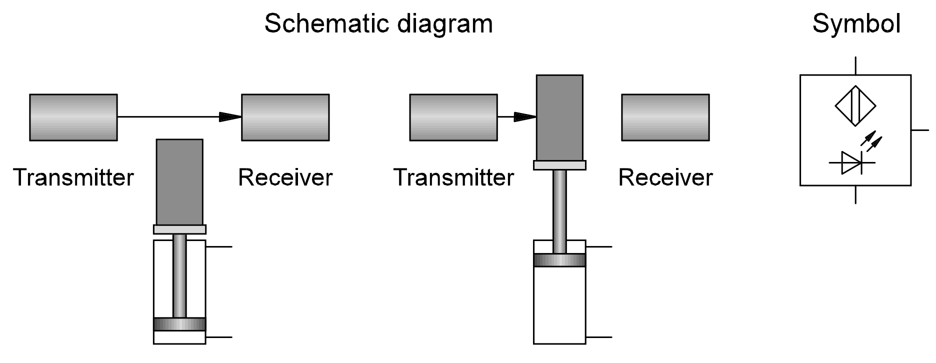
Three different types of optical proximity switch are differentiated:

- One-way light barrier
- Reflective light barrier
- Diffuse reflective optical sensor

*One-way light barrier*

The one-way light barrier has spatially separate transmitter and receiver units. The parts are mounted in such a way that the transmitter beam is directed at the receiver. The output is switched if the beam is interrupted.

*Fig. 3.9: One-way light barrier*



*Reflective light barrier*

In the reflective light barrier, the transmitter and receiver are mounted together in one housing. The reflector is mounted in such a way that the light beam transmitted by the transmitter is practically completely reflected to the receiver. The output is switched if the beam is interrupted.

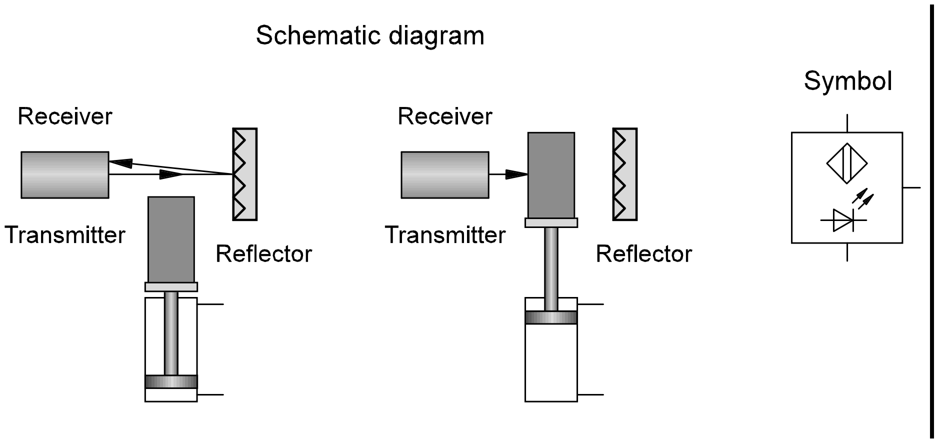



*Fig. 3.10:*
*Reflective light barrier*

*Diffuse reflective optical sensor*

In the diffuse reflective optical sensor, the transmitter and receiver are mounted together in one unit. If the light hits a reflective object, it is redirected to the receiver and causes the output of the sensor to switch. Because of the functional principle, the diffuse reflective optical sensor can only be used if the material or machine part to be detected is highly reflective (for example polished metal surfaces, bright paint).

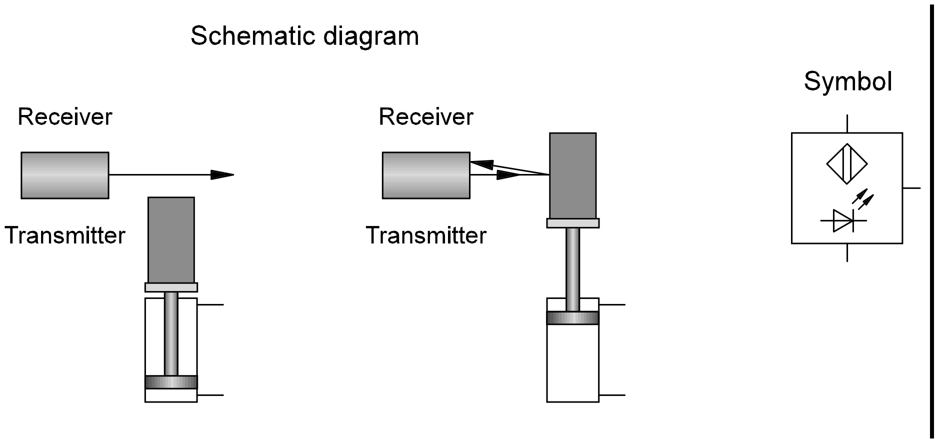



*Fig. 3.11*
*Diffuse reflective optical sensor*

**Pressure sensors**

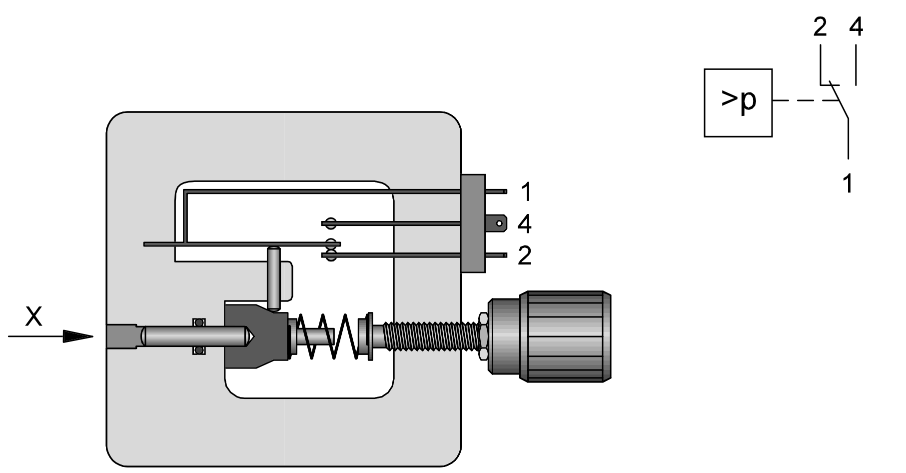
There are various types of pressure-sensitive sensors:

- Pressure switch with mechanical contact (binary output signal)
- Pressure switch with electronic switching ( binary output signal)
- Electronic pressure sensor with analogue output signal

*Mechanical pressure switch*

In the mechanically actuated pressure switch, the pressure acts on a cylinder surface. If the pressure exerted exceeds the spring force of the return spring, the piston moves and operates the contact set.

*Fig. 3.12: Piston-actuated pressure switch*



*Electronic pressure switches*

Diaphragm pressure switches are of increasing importance. Instead of actuating a mechanical contact, the output is switched electronically. Pressure or force sensitive sensors are attached to the diaphragm. The sensor signal is evaluated by an electronic circuit. As soon as the pressure exceeds a certain value, the output is switched.

*Analogue pressure sensors*

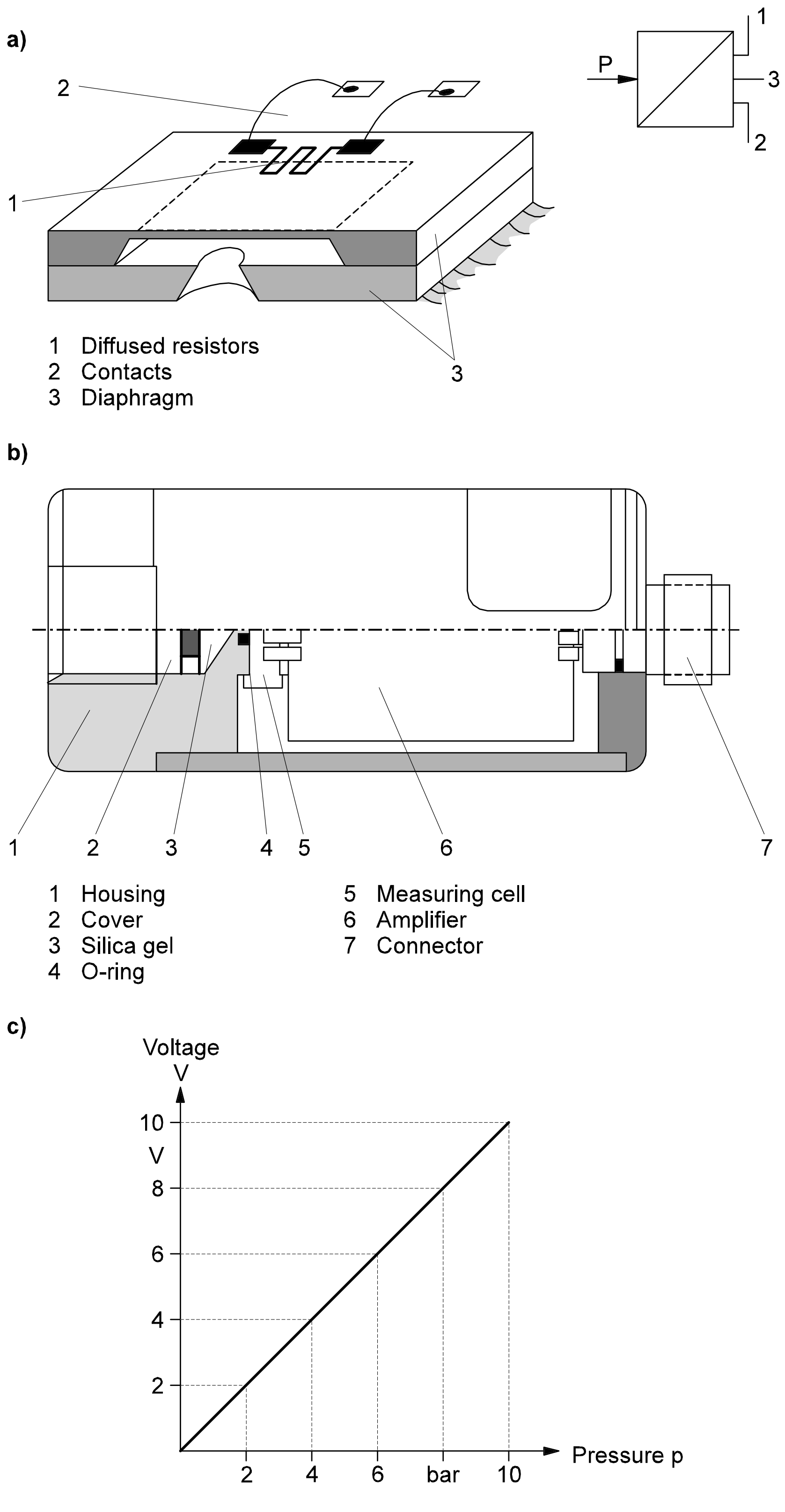
The design and mode of operation of an analogue pressure sensor is demonstrated using the example of the Festo SDE-10-10V/20mA sensor.

Fig. 3.13a shows the piezoresistive measuring cell of a pressure sensor. Variable resistor 1 changes its value when pressure is applied to the diaphragm. Via the contacts 2, the resistor is connected to the electronic evaluating device, which generates the output signal.

Fig. 3.13b represents the overall construction of the sensor.

Fig. 3.13c illustrates the sensor characteristics, representing the correlation between the pressure and the electrical output signal. Increasing pressure results in increasing voltage at the sensor output. A pressure of 1 bar causes a voltage or 1V, a pressure of 2 bar a voltage of 2 V etc.

*Fig. 3.13:*
*Construction and characteristic curve of an analogue pressure sensor (Festo SDE-10-10V/20mA)*



### 3.4 Relays and contactors

*Construction of a relay*

A relay is an electromagnetically actuated switch. When a voltage is applied to the solenoid coil, an electromagnet field results. This causes the armature to be attracted to the coil core. The armature actuates the relay contacts, either closing or opening them, depending on the design. A return spring returns the armature to its initial position when the current to the coil is interrupted.

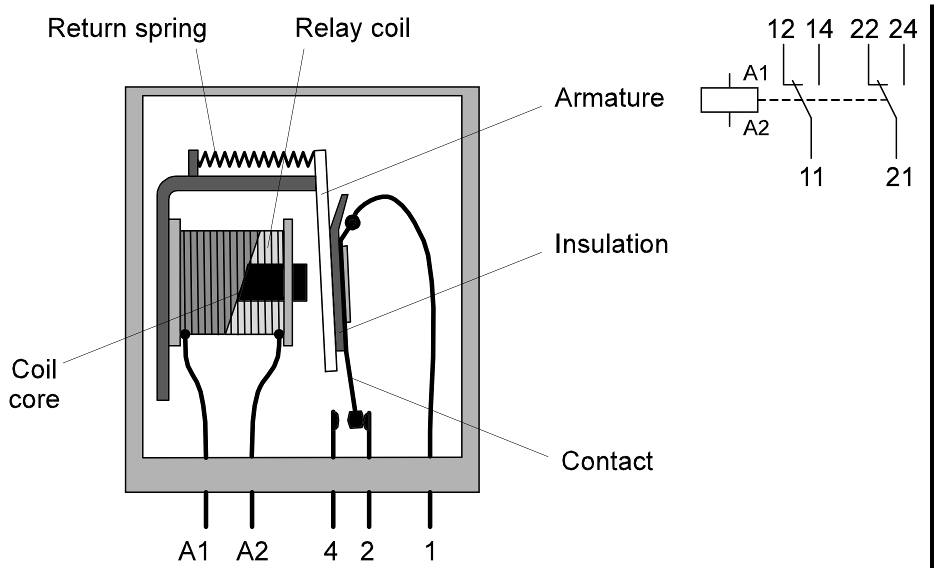



*Fig. 3.14:*
*Construction of a relay*

A relay coil can switch one or more contacts. In addition to the type of relay described above, there are other types of electromagnetically actuated switch, such as the retentive relay, the time relay, and the contactor.

*Applications of relays*

In electropneumatic control systems, relays are used for the following functions:

- Signal multiplication
- Delaying and conversion of signals
- Association of information
- Isolation of control circuit from main circuit

In purely electrical controllers, the relay is also used for isolation of DC and AC circuits.

*Retentive relay*

The retentive relay responds to current pulses:

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

The behavior of a retentive relay is analogous to that of a pneumatic double pilot valve, which responds to pressure pulses.

*Time relay*

There are two types of time relay – pull-in delay and drop-out delay. With pull-in delay, the armature is energised after a set delay; drop-out however, is effeced without delay. The reverse applies in the case of the drop-out delay relay, whereby the contacts switch accordingly - (see Figs. 3.15, 3.16). The time delay $t_d$ can be set.

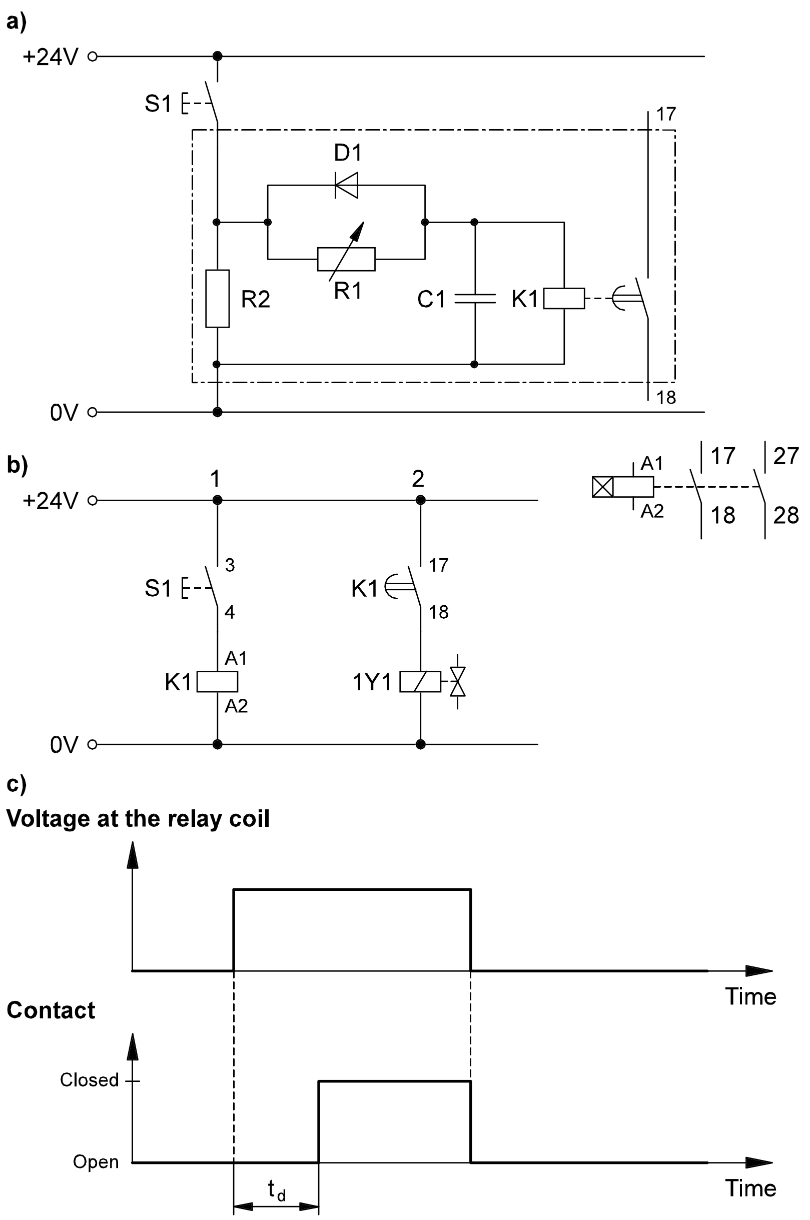



*Fig. 3.15*
*Relay with pull-in delay*

*a) Internal construction*
*b) Circuit diagram*
*c) Signal behavior*

*Functional principle*

When switch S1 is actuated, current flows via the variable resistor R1 to capacitor C1. Diode D1 – connected in parallel – does not allow current to flow in this direction. Current also flows via discharge resistor R2 (which is initially not of importance). When capacitor C1 has charged in the switched position of relay K1, the relay switches.

When S1 is released, the circuit is interrupted and the capacitor discharges rapidly via diode D1 and the resistor R2. As a result, the relay returns immediately to its initial position.

Variable resistor R1 allows the charging current to the capacitor to be adjusted – thus also adjusting the time until the switching voltage for K1 is reached. If a large resistance is set, a small current flows with the result that the delay is long. If the resistance is low, a large current flows and the delay is short.

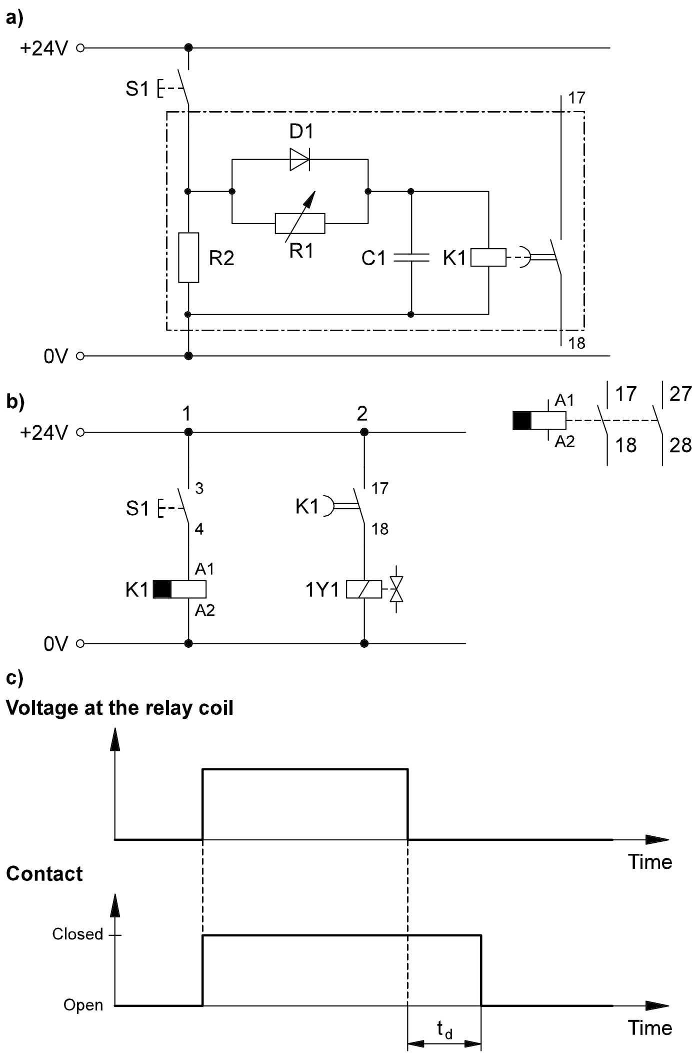



*Fig. 3.16:*
*Relay with drop-out delay*

*a) Internal construction*
*b) Circuit diagram*
*c) Signal behavior*

*Construction of a contactor*

Contactors operate in the same way as a relay. Typical features of a contactor are:

- Double switching (dual contacts)
- Positive-action contacts
- Closed chambers (arc quenching chambers)

These design features allow contactors to switch much higher currents than relays.

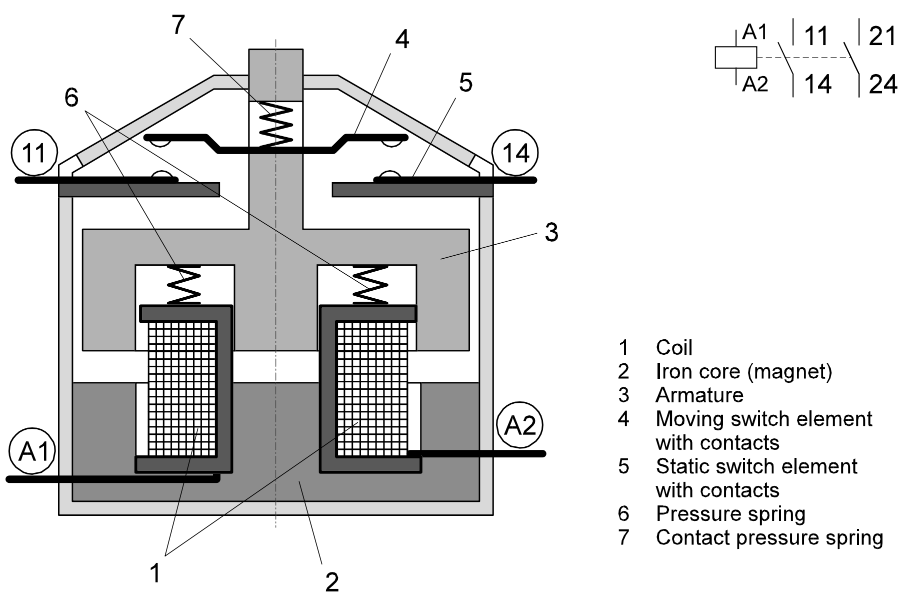



*Fig. 3.17:*
*Construction of a contactor*

A contactor has multiple switching elements, normally four to ten contacts. For contactors – as for relays – there are various types with combinations of normally open contact, normally closed contact, changeover contact, delayed normally closed contact etc. Contactors that only switch auxiliary contacts (control contacts) are called contactor relays. Contactors with main and auxiliary contacts are called main or power contactors.

*Applications of contactors*

Contactors are used for the following applications:

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

In electropneumatic controllers, electrical currents and power are low. For this reason, they can be implemented with auxiliary contactors. Main or power contactors are not required.

### 3.5 Programmable logic controllers

Programmable logic controllers (PLCs) are used for processing of signals in binary control systems. The PLC is particularly suitable for binary control systems with numerous input and output signals and requiring complex signal combinations.


*Fig. 3.18:*
*PLC (Festo 101)*

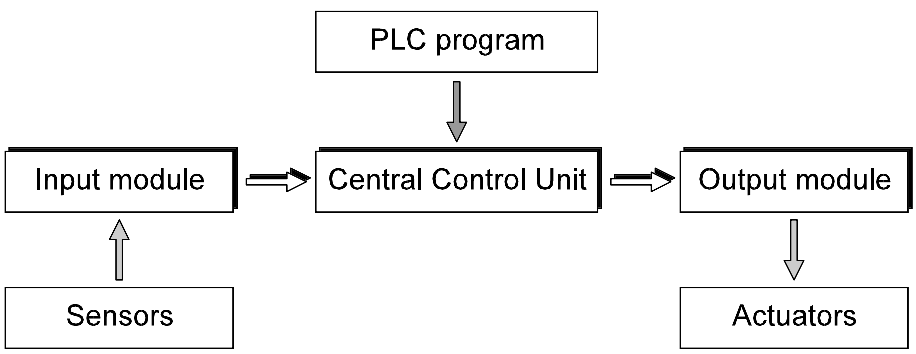



*Fig. 3.19:*
*System components of a PLC*

*Structure and mode of operation of a PLC*

Fig. 3.19 is in the form of a box diagram illustrating the system components of a PLC. The main element (CCU)is a microprocessor system. Programming of the microprocessors determines:

- Which control inputs (I1, I24 etc.) are read in which order
- How these signals are associated
- Which outputs (O1, O2 etc.) receive the results of signal processing.

In this way, the behavior of the controller is not determined by the wiring (hardware), but by the program (software).

### 3.6 Overall structure of the signal processing part

The signal processing part of an electropneumatic controller consists of three function blocks. Its structure is shown in Fig. 3.20.

- Signal input takes place via two sensors or via push button or control switches. Fig. 3.20 shows two proximity switches for signal input.
- Signal processing is normally undertaken by a relay control system or a programmable logic controller. Other types of controller can be neglected. In Fig. 3.20 control is undertaken by a relay control system.
- Signal output is via solenoid-actuated directional control valves.

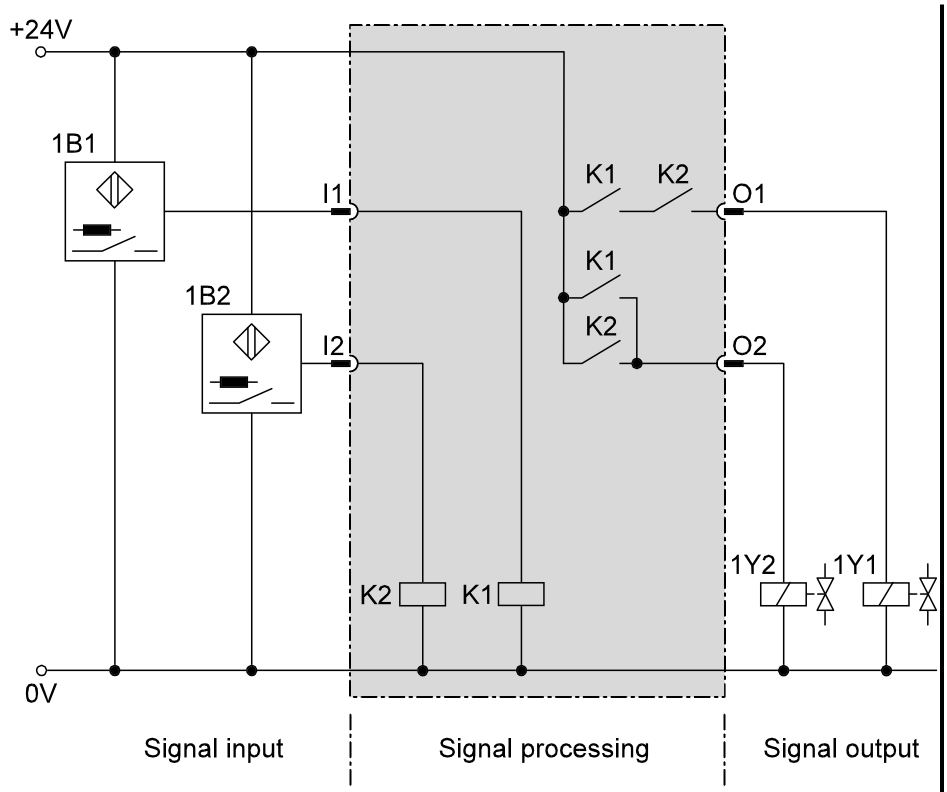



*Fig. 3.20.*
*Signal control section of relay control system (schematic, circuit diagram not compliant with standard)*

Fig. 3.20 shows a schematic representation of a signal control section of an electropneumatic control system, in which relays are used for signal processing.

- The components for signal input (in Fig. 3.20: inductive proximity switches 1B1 and 1B2 are connected via the controller inputs (I1, I2 etc.) to the relay coils (K1, K2 etc. )
- Signal processing is implemented by means of suitable wiring of several relay coils and contacts.
- The components for signal output (in Fig. 3.20: solenoids of directional control valves 1Y1 and 1Y2) are connected to the controller outputs (O1, O2 etc.). They are actuated via the relay contacts.

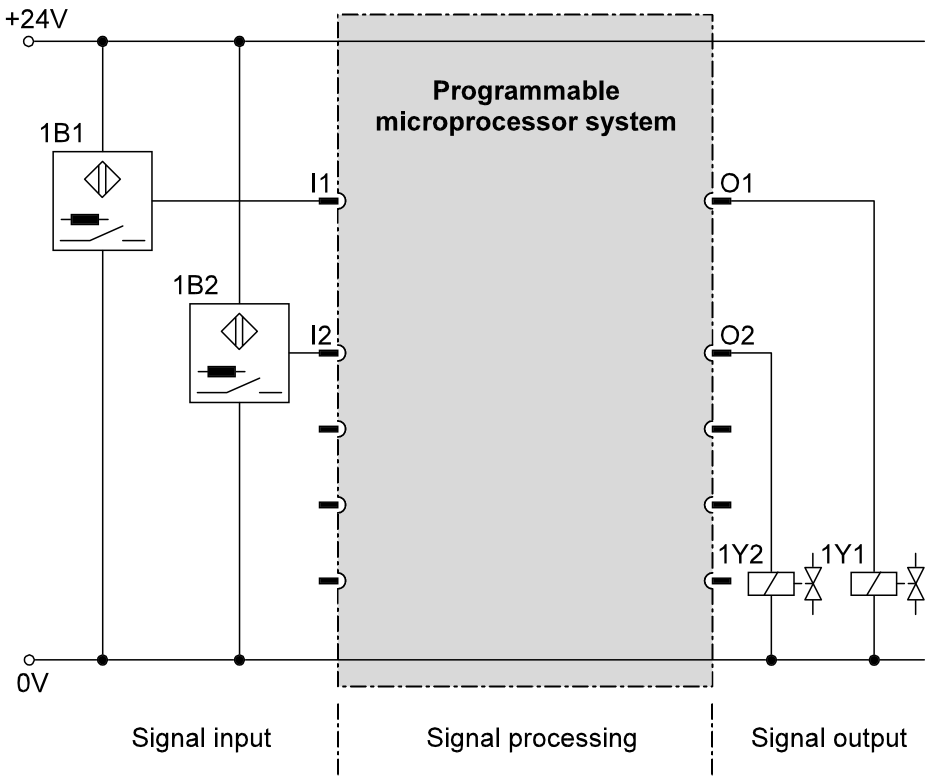



*Fig. 3.21:
Signal control section with programmable logic controller (PLC)*

Fig. 3.21 shows the signal control section of an electropneumatic control system in which a PLC is used for signal processing.

- The components for signal input (in Fig. 3.21: inductive proximity switches 1B1 and 1B2 are connected to the inputs of the PLC (I1, I2).
- The programmable microprocessor system of the PLC undertakes all signal processing tasks.
- The components for signal output (in Fig. 3.21: solenoids of directional control valves 1Y1 and 1Y2) are connected to the PLC outputs (O1, O2 etc.). They are actuated by electronic circuits that are part of the microprocessor system.

Electropneumatic control systems with relays are covered in Chapter 8. Electropneumatic control systems with PLCs are covered in Chapter 9.

# Chapter 4

## Electrically actuated directional control valves

## 4.1 Functions

An electropneumatic control system works with two forms of energy:

- Electrical energy in the signal control section
- Compressed air in the power section

Electrically actuated directional control valves form the interface between the two parts of an electropneumatic control. They are switched by the output signals of the signal control section and open or close connections in the power section. The most important tasks of electrically actuated directional control valves include:

- Switching supply air on or off
- Extension and retraction of cylinder drives

*Actuation of a single-acting cylinder*

Fig. 4.1a shows an electrically actuated valve that controls the motion of a single-acting cylinder. It has three ports and two switching positions:

- If no current is applied to the solenoid coil of the directional control valve, the cylinder chamber above the directional control valve is vented. The piston rod is retracted.
- If current is applied to the solenoid coil, the directional control valve switches and the chamber is pressurized. The piston rod extends.
- When the current is interrupted, the valve switches back. The cylinder chamber is vented and the piston rod retracts.

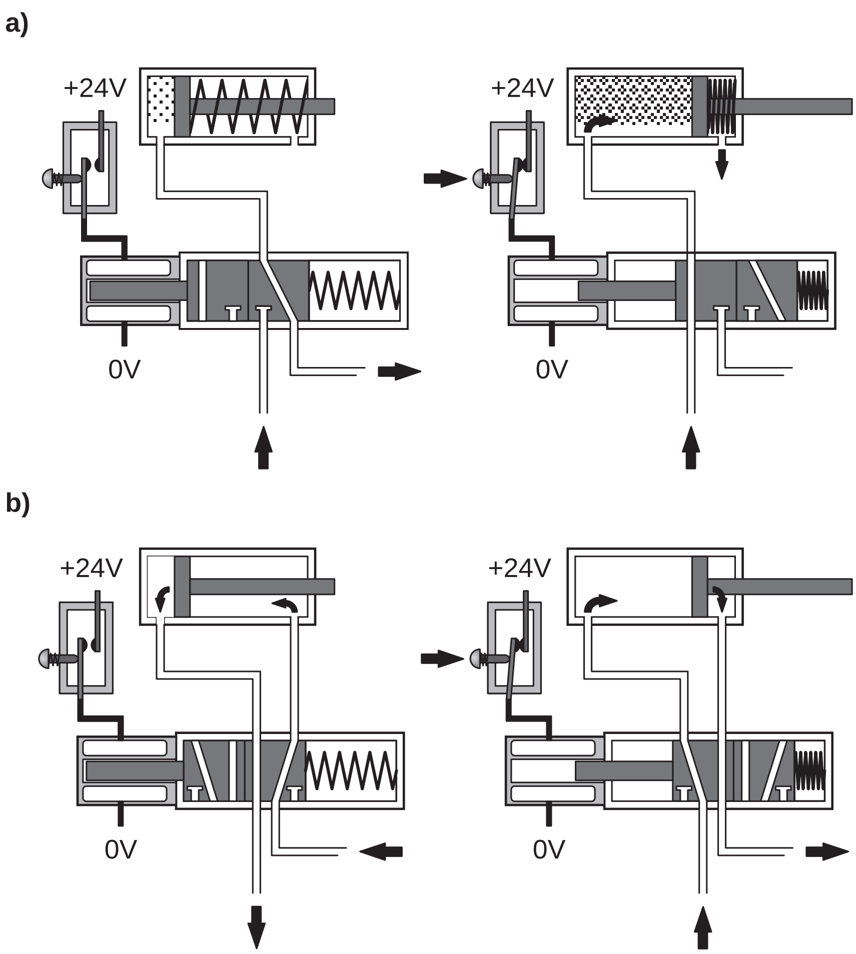



*Fig. 4.1: Actuation of a pneumatic cylinder a) Single-acting b) Double-acting*

*Actuation of a double-acting cylinder*

The double-acting cylinder drive in Fig. 4.1b is actuated by a directional control valve with five ports and two switching positions.

- If no current is applied to the solenoid coil, the left cylinder chamber is vented, the right chamber pressurized. The piston rod is retracted.
- If current is applied to the solenoid coil, the directional control valve switches. The left chamber is pressurized, the right chamber vented. The piston rod extends.
- When the current is interrupted, the valve switches back and the piston rod retracts.

## 4.2 Construction and mode of operation

Electrically actuated directional control valves are switched with the aid of solenoids. They can be divided into two groups:

- Spring-return valves only remain in the actuated position as long as current flows through the solenoid.
- Double solenoid valves retain the last switched position even when no current flows through the solenoid.

*Initial position*

In the initial position, all solenoids of an electrically actuated directional control valve are de-energised and the solenoids are inactive. A double solenoid valve has no clear initial position, as it does not have a return spring.

*Port designation*

Directional control valves are also differentiated by the number of ports and the number of switching positions. The valve designation results from the number of ports and positions, for example:

- Spring-return 3/2-way valve
- 5/2-way double solenoid valve

The following section explains the construction and mode of operation of the major types of valve.

*Directly controlled 3/2-way valve*

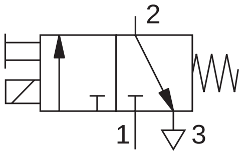
Fig. 4.2 shows two cross-sections of a directly controlled electrically actuated 3/2-way valve.

- In its initial position, the working port 2 is linked to the exhaust port 3 by the slot in the armature (see detail) (Fig. 4.2a).
- If the solenoid is energised, the magnetic field forces the armature up against the pressure of the spring (Fig. 4.2b). The lower sealing seat opens and the path is free for flow from pressure port 1 to working port 2. The upper sealing seat closes, shutting off the path between port 1 and port 3.
- If the solenoid coil is deenergized, the armature is retracted to its initial position by the return spring (Fig. 4.2a). The path between port 2 and port 3 is opened and the path between port 1 and port 2 closed. The compressed air is vented via the armature tube at port 3.

*Manual override*

The manual override A allows the path between port 1 and port 2 to be opened even if the solenoid is not energized. When the screw is turned, the eccentric cam actuates the armature. Turning the screw back returns the armature to its initial position.

*Fig. 4.2:*
*3/2-way solenoid valve with manual override (normally closed)*



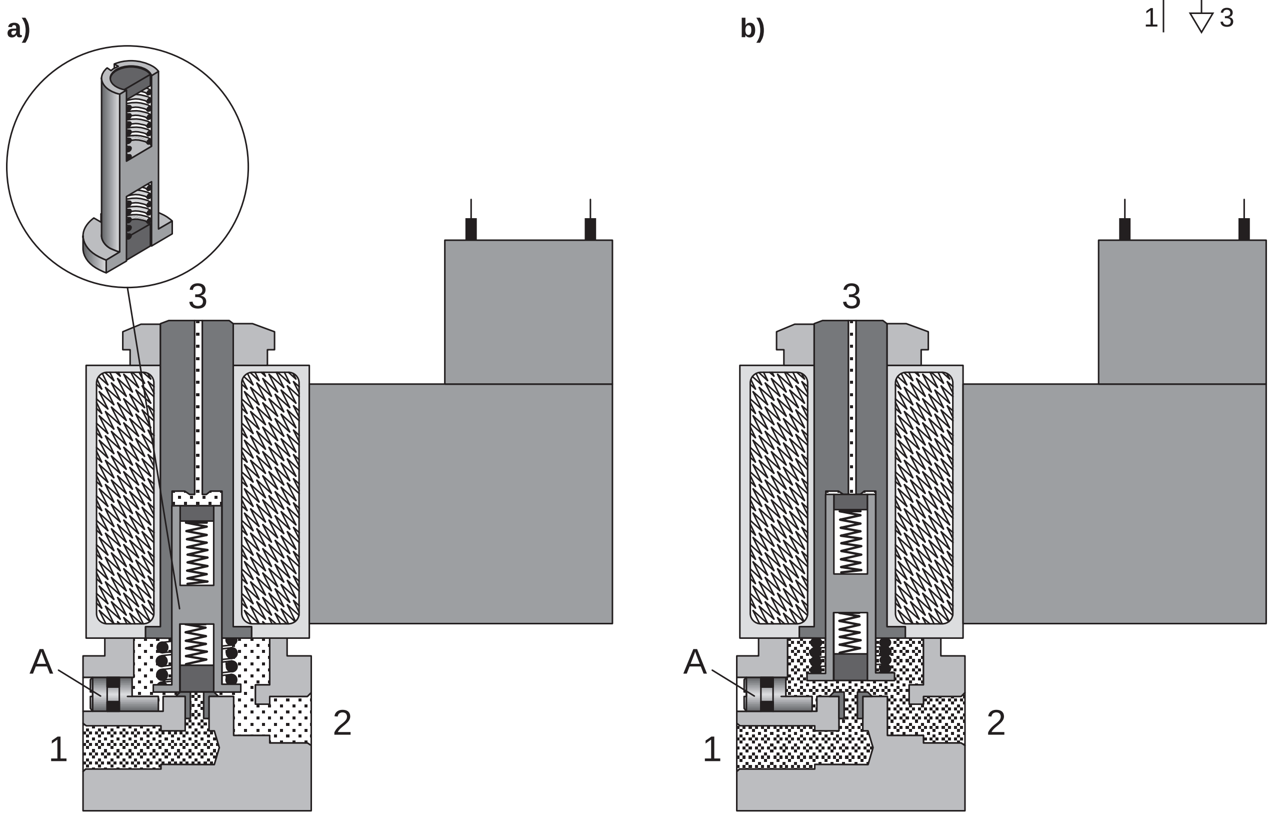
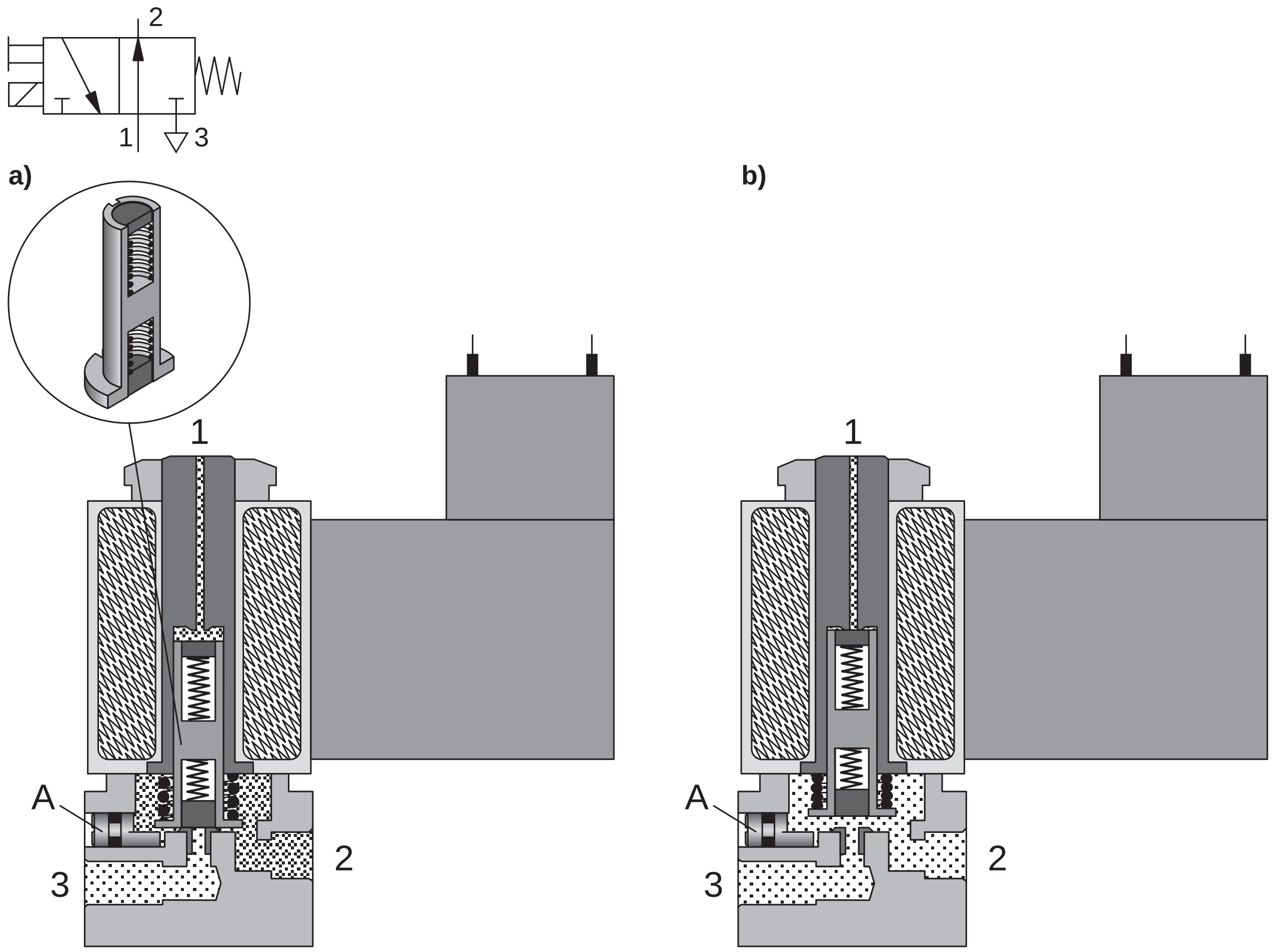



Fig. 4.3 shows an electrically actuated 3/2-way valve, normally open. Fig. 4.3a shows the valve in its initial position, Fig. 4.3b actuated. Compared to the initial position of the closed valve (fig. 4.2) the pressure and exhaust ports are reversed.

*Fig. 4.3:*
*3/2-way valve with manual override (normally open)*



*Pilot controlled directional control valve*

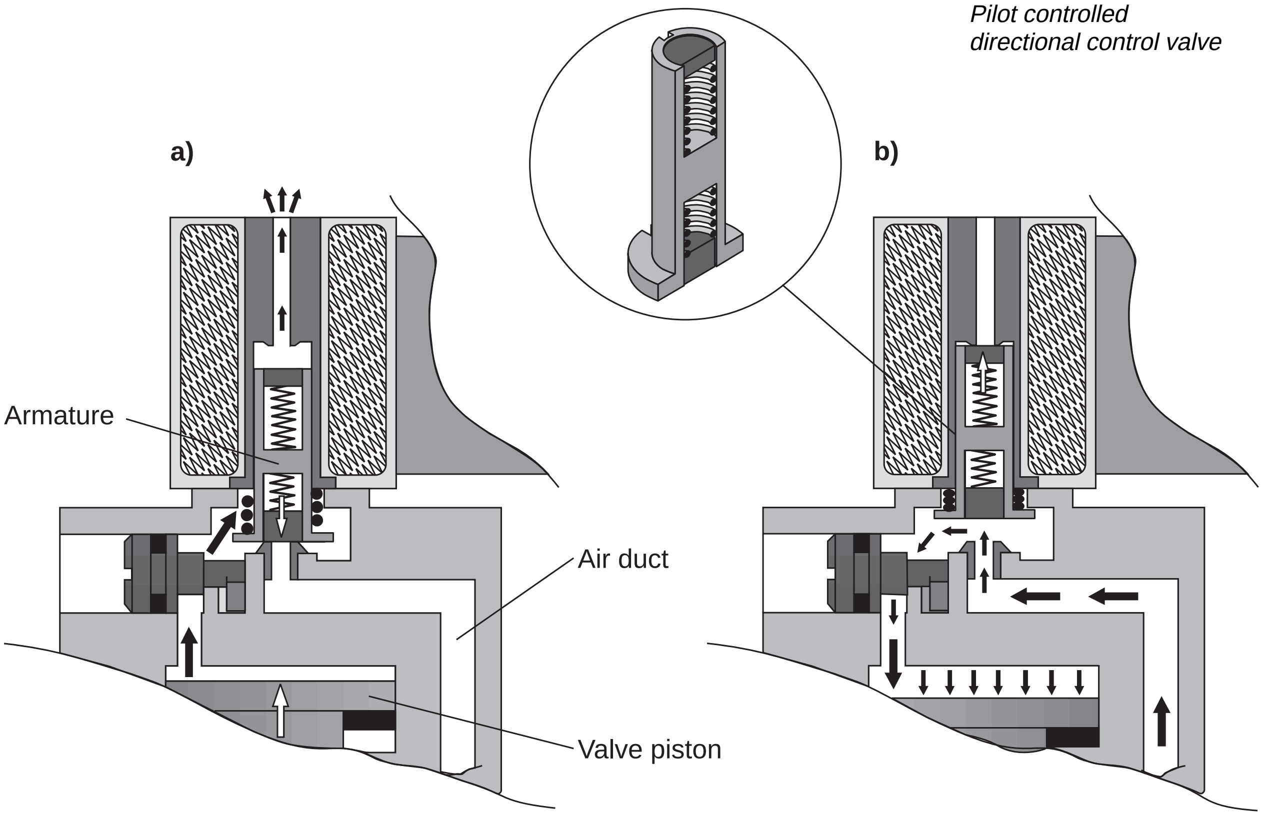
In pilot controlled directional control valves, the valve piston is indirectly actuated.

- The armature of a solenoid opens or closes an air duct from port 1.
- If the armature is open, compressed air from port 1 actuates the valve piston.

Fig. 4.4 explains the mode of operation of the pilot control.

- If the coil is de-energized, the armature is pressed against the lower sealing seat by the spring. The chamber of the upper side of the piston is vented (Fig. 4.4a).
- If the coil is energized, the solenoid pulls the armature down. The chamber on the upper side of the piston is pressurized (Fig. 4.4b).

*Fig. 4.4: Pilot controlled directional control valve*



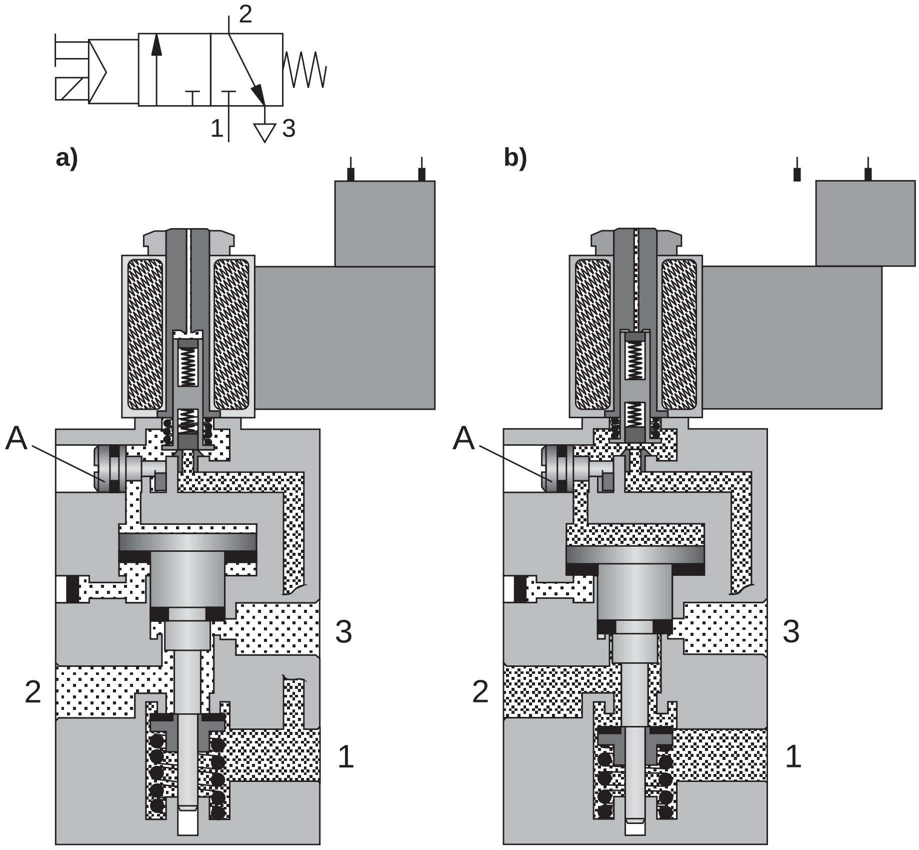
*Pilot controlled 3/2-way valve*

Fig. 4.5 shows two cross-sections of an electrically actuated pilot controlled 3/2-way valve.

- In its initial position, the piston surface is only subject to atmospheric pressure, so the return spring pushes the piston up (Fig. 4.5a). Ports 2 and 3 are connected.
- If the solenoid coil is energized, the chamber below the valve piston is connected to pressure port 1 (Fig. 4.5b). The force on the upper surface of the valve piston increases, pressing the piston down. The connection between ports 2 and 3 is closed, the connection between ports 1 and 2 opened. The valve remains in this position as long as the solenoid coil is energized.
- If the solenoid coil is de-energized, the valve switches back to its initial position.

A minimum supply pressure (control pressure) is required to actuate the pilot controlled valve against the spring pressure. This pressure is given in the valve specifications and lies – depending on type – in the range of about 2 to 3 bar.

*Fig. 4.5: Pilot controlled 3/2-way solenoid valve (normally closed, with manual override)*



*Comparison of pilot controlled and directly actuated valves*

The greater the flow rate of a directional control valve, the higher the flow.

In the case of a directly actuated valve, flow to the consuming device is released by the armature (see Fig. 4.2). In order to ensure a sufficiently large opening and sufficient flow rate, a relatively large armature is required. This in turn requires a large return spring – against which the solenoid must exert a large force. This results in relatively large component size and high power consumption.

In a pilot controlled valve, flow to the consuming device is switched by the main stage (Fig. 4.5). The valve piston is pressurized via the air duct. A relatively small airflow is sufficient, so the armature can be comparatively small with low actuation force. The solenoid can also be smaller than for a directly actuated valve. Power consumption and heat dissipation are lower.

The advantages with regard to power consumption, size of solenoids and heat dissipation have led to almost exclusive use being made of pilot controlled directional control valves in electropneumatic control systems.

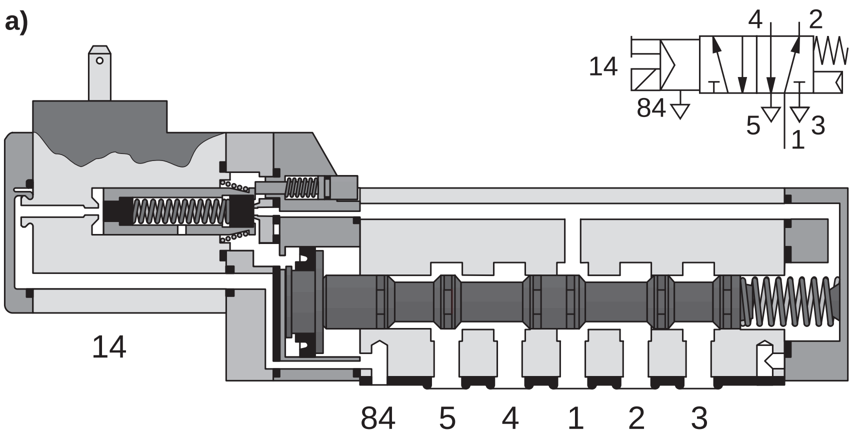
*Pilot controlled 5/2-way valve*

Fig. 4.6 shows the two switching positions of an electrically actuated pilot controlled 5/2-way valve.

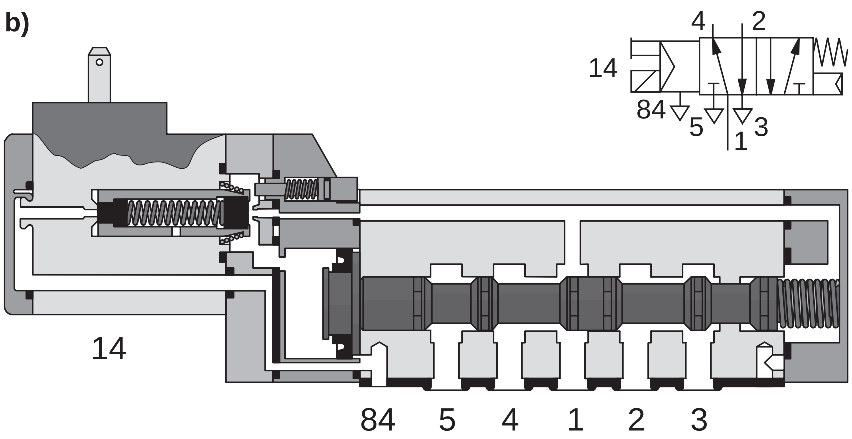
- In its initial position, the piston is at the left stop (Fig. 4.6a). Ports 1 and 2 and ports 4 and 5 are connected.
- If the solenoid coil is energized, the valve spool moves to the right stop (Fig. 4.6b). In this position, ports 1 and 4 and 2 and 3 are connected.
- If the solenoid is de-energized, the return spring returns the valve spool to its initial position.
- Pilot air is supplied via port 84.

*Fig. 4.6:*
*Pilot controlled*
*5/2-way solenoid valve*

**a)**




**b)**



*Pilot controlled 5/2-way double solenoid valvePilot controlled*

Fig. 4.7 shows two cross-sections of a pilot controlled 5/2-way double solenoid valve.

- If the piston is at the left stop, ports 1 and 2 and 4 and 5 are connected (Fig. 4.7a).
- If the left solenoid coil is energized, the piston moves to the right stop and ports 1 and 4 and 2 and 3 are connected (Fig. 4.7b).
- If the valve is to be retracted to its initial position, it is not sufficient to de-energized the left solenoid coil. Rather, the right solenoid coil must be energized.

If neither solenoid coil is energized, friction holds the piston in the last position selected. This also applies if both solenoids coils are energized simultaneously, as they oppose each other with equal force.

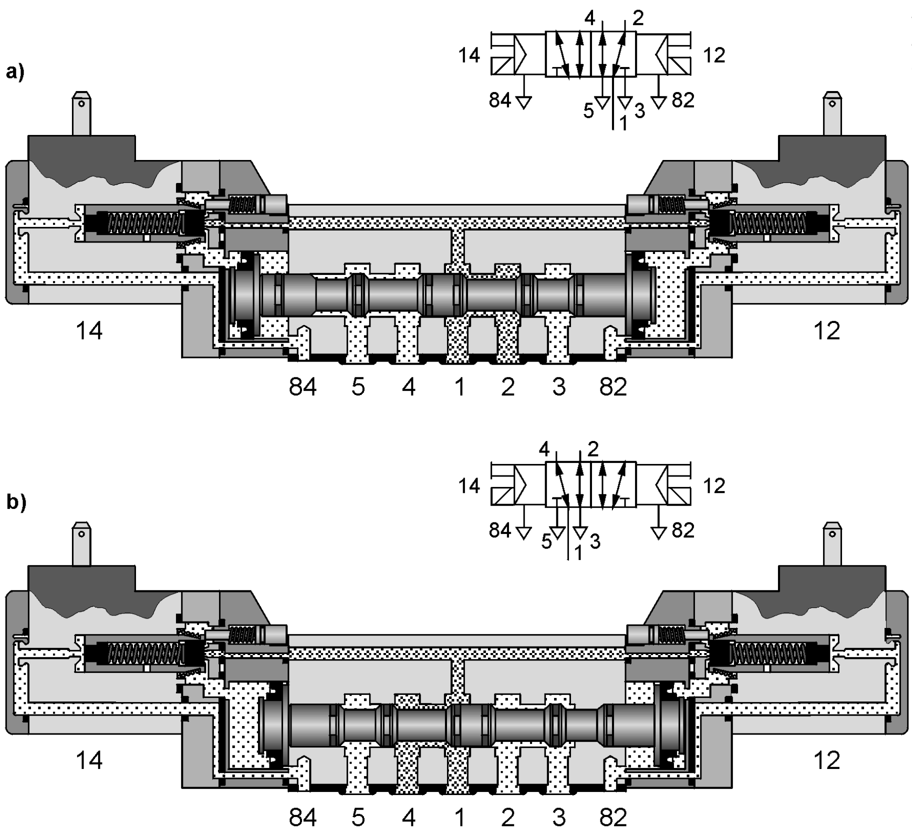


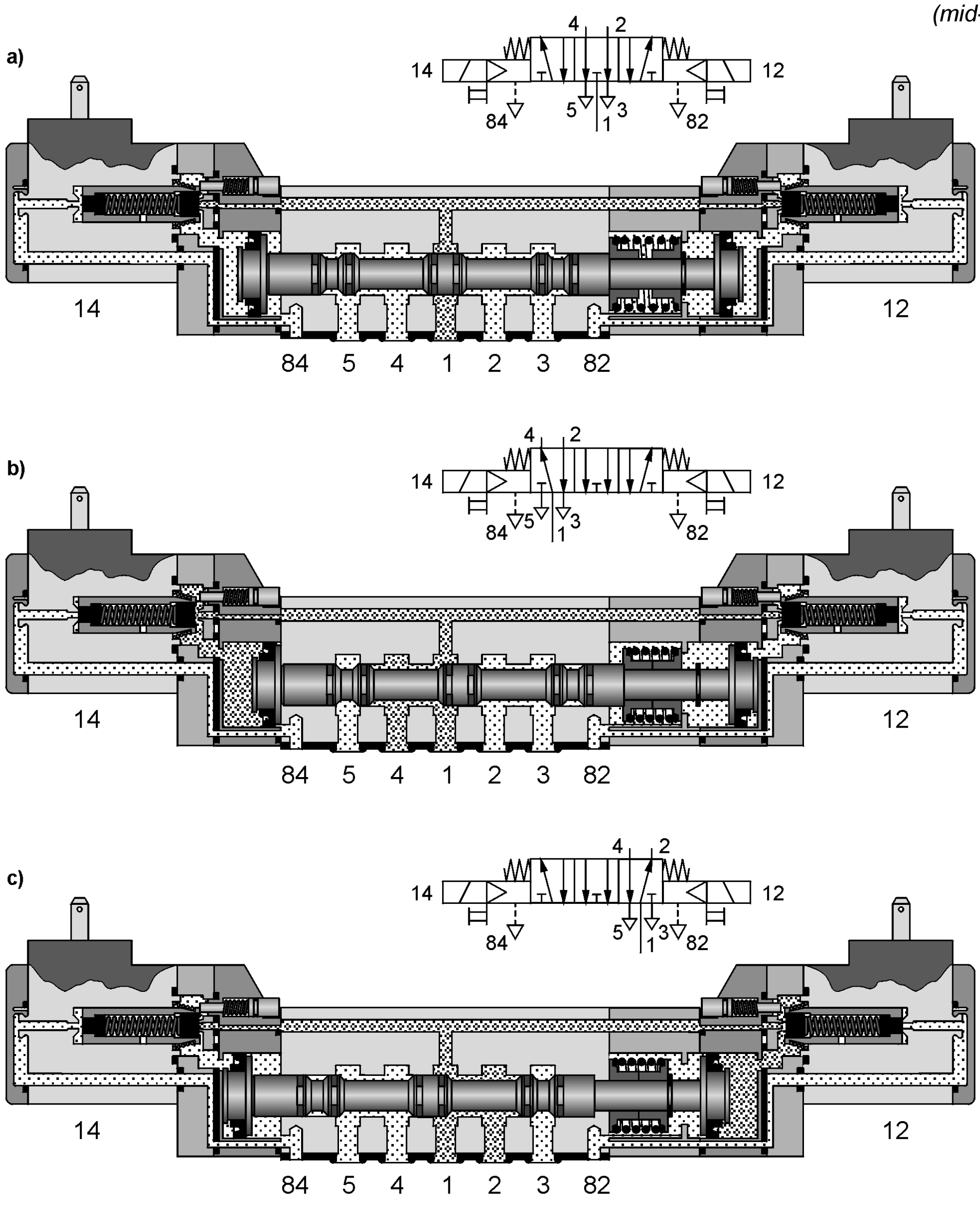

*Fig. 4.7: Pilot controlled 5/2-way double solenoid valve*

*5/3-way valve with exhausted initial position*

Fig. 4.8 shows the three switching positions of an electrically actuated, pilot controlled 5/3-way valve.

- In its initial position, the solenoid coils are de-energized and the piston spool is held in the mid-position by the two springs (Fig. 4.8a). Ports 2 and 3 and 4 and 5 are connected. Port 1 is closed.
- If the left solenoid coil is energized, the piston moves to its right stop (Fig. 4.8b). Ports 1 and 4 and 2 and 3 are connected.
- If the right solenoid coil is energized, the piston moves to its left stop (Fig. 4.8c). In this position, ports 1 and 2 and 4 and 5 are connected.
- Each position is held as long as the appropriate coil is energized. If neither coil is energized, the valve returns to the initial mid-position.

*Fig. 4.8:*
*Pilot-actuated 5/3-way double solenoid valve (mid-position exhausted)*



*Influence of mid-position*

Directional control valves with two positions (such as 3/2-way or 5/2-way valves) allow the extension or retraction of a cylinder. Directional control valves with three positions (such as 5/3-way valves) have a mid-position offering additional options for cylinder actuation. This can be demonstrated using the example of three 5/3-way valves with different mid-positions. We will look at the behavior of the cylinder drive when the directional control valve is in mid-position.

- If a 5/3-way valve is used in which the working ports are exhausted, the piston of the cylinder drive does not exert any force on the piston rod. The piston rod can be moved freely (Fig. 4.9a).
- If a 5/3-way valve is used in which the all ports are closed, the piston of the cylinder drive is held in position. This also applies ifthe piston rod is not at a stop (Fig. 4.9b)
- If a 5/3-way valve is used in which the working ports are pressurized, the piston rod extends with reduced force (Fig. 4.9c).

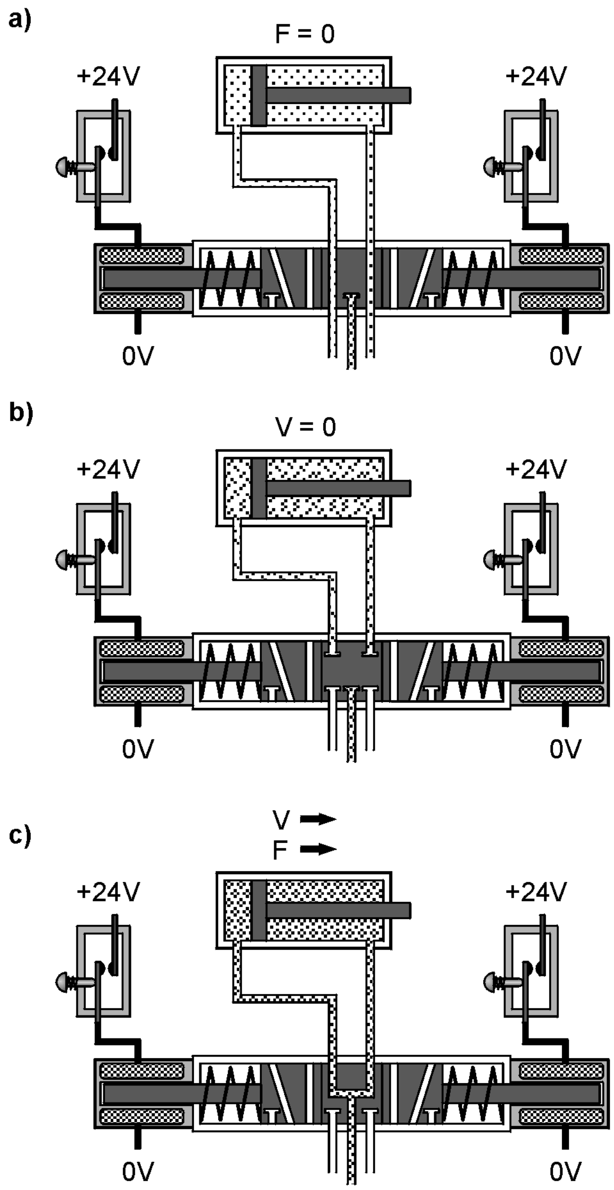



*Fig. 4.9:*
*Influence of mid-position of 5/3-way double solenoid valves*

### 4.3 Types and pneumatic performance data

Electrically actuated directional control valves are manufactured in a wide range of variants and sizes to meet different requirements in industrial practice.

A step by step approach is useful when selecting a suitable valve:

- First establish the required valve type based on the task, required behavior in the event of power failure (for example, spring-return 5/2-way valve).
- In a second step, the manufacturer's catalogue is used to establish which valve meets the required performance at the lowest cost. Here, not only the cost of the valve, but also for installation, maintenance, spare parts inventory etc. must be taken into account.

Tables 4.1 and 4.2 summarize the most commonly used valve types with their symbols and applications.

*Table 4.1:*
*Applications and symbols for spring-return electrically actuated directional control valves*

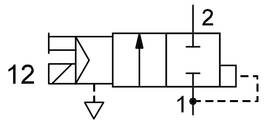
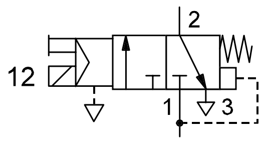
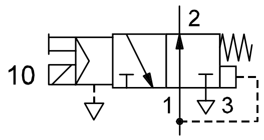
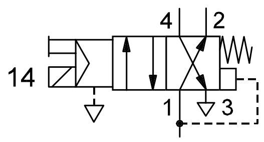
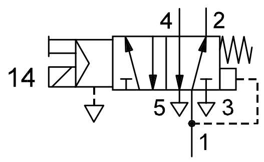
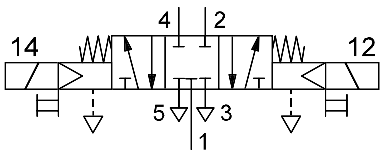
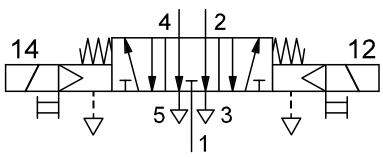
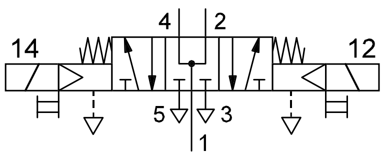
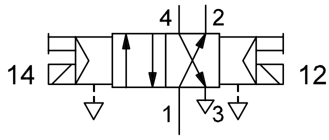
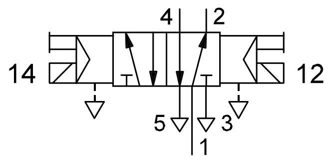
| *Valve type* | *Symbol* | *Applications* |
|---|---|---|
| Pilot controlled spring-return 2/2-way valve |   | Shut-off function |
| Pilot controlled spring-return 3/2-way valve, normally closed |   | Single-acting cylinders |
| Pilot controlled spring-return 3/2-way valve, normally open |   | Switching compressed air on and off |
| Pilot controlled spring-return 4/2-way valve |   | Double-acting linear or swivel cylinders |
| Pilot controlled spring-return 5/2-way valve |   | |
| Pilot controlled spring-return 5/2-way valve (normally closed, ex-hausted or pressurized) |       | Double-acting linear or swivel cylinders with intermediate stop, with special requirements regarding behavior in event of power failure. |

*Table 4.2: Applications and symbols for double solenoid valves*

| *Valve type* | *Symbol* | *Applications* |
|---|---|---|
| Pilot controlled 4/2-way double solenoid valve |  | Double-acting linear or swivel cylinders |
| Pilot controlled 5/2-way double solenoid valve |  | |

If no valve with all required properties is available, often a valve with a different number of ports can be used.

- 4/2-way valves and 5/2-way valves fulfill the same function. They are exchangeable.
- To implement the function of a 3/2-way double-solenoid valve, the working port of a 4/2-way or 5/2-way double solenoid valve is fitted with a plug.

*Power failure and cable breakage*

An electropneumatic control system should be designed in such a way that workpieces are not damaged by uncontrolled motion in the event of a power failure or cable break. The behavior of the pneumatic cylinder under such circumstances can be determined by the choice of directional control valve:

- A spring-return 3/2-way or 5/2-way valve switches to its initial position and the piston rod of the cylinder returns to its initial position.
- A spring-centered 5/3-way valve also switches to its initial position. If the working ports are exhausted in the initial position, the cylinder is not subject to force. If the ports are pressurized, the piston rod extends at reduced force. If the ports are closed, the motion of the piston rod is interrupted.
- A double-solenoid valve retains its current position. The piston rod completes the current motion.

*Modular design of an electrically actuated directional control valve*

Electrically actuated directional control valves are of modular design. The following components are required for their operation:

- Directional control valve
- One or two solenoids for actuation
- One or two plugs for cable connections to the signal control section

A 3/2-way valve is shown in Fig. 4.10 as an example of this design principle.

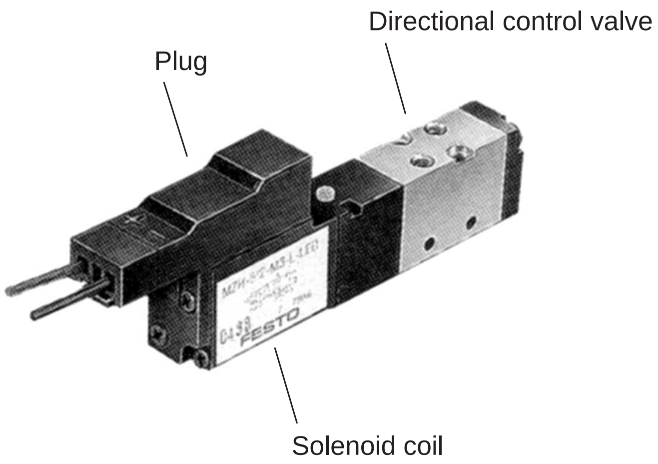



*Fig. 4.10: Modular design of an electrically actuated directional control valve (Festo)*

The performance data of a valve are determined by all three components in combination (Fig. 4.11). The mechanical components of a valve primarily affect the pneumatic performance data, whereas the solenoid coil and cable connection mainly influence the electrical performance data.

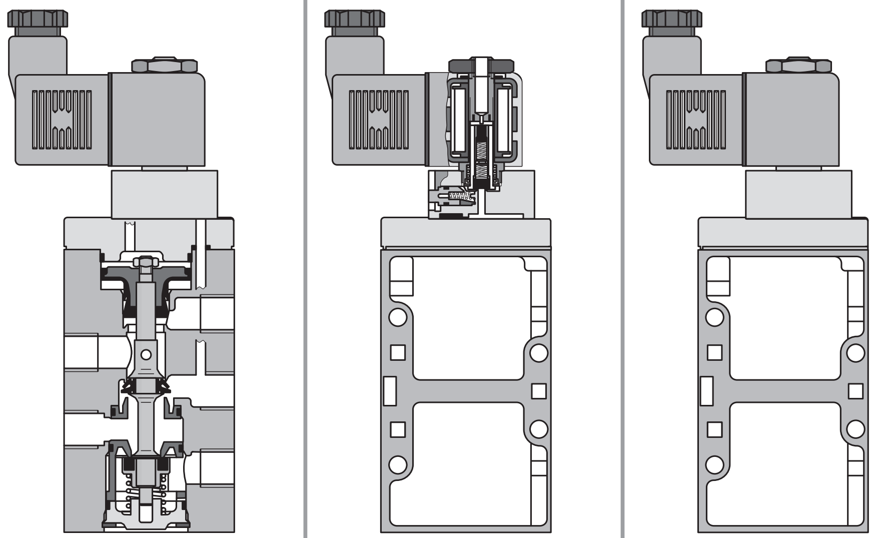



*Fig. 4.11: Performance data of a directional control valve*

*Arrangement of valve ports*

To allow for different installation situations, electrically actuated directional control valves are available with two different port configurations.

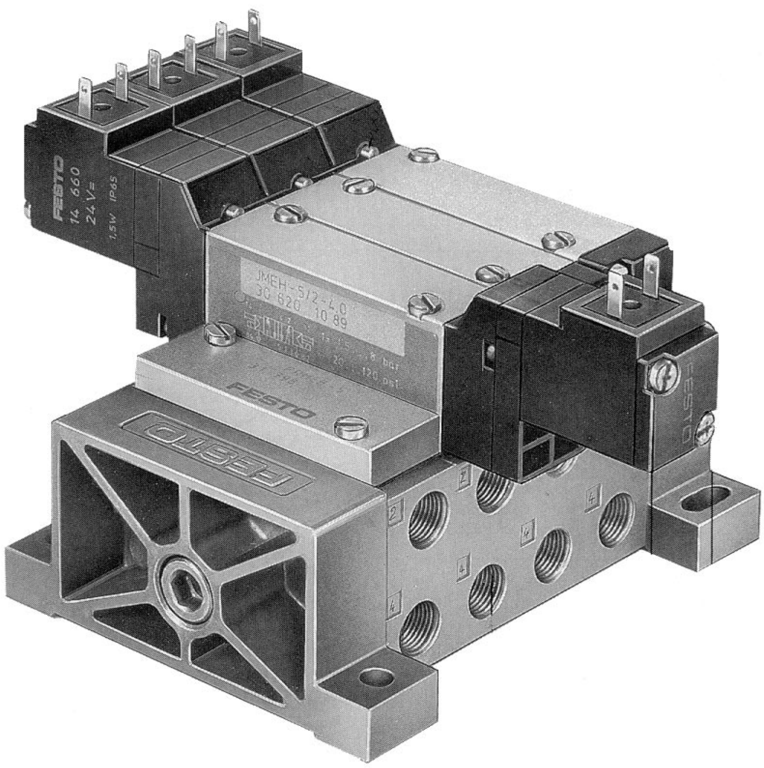
- On an in-line valve all pneumatic ports are threaded so that the tubes and silencers can be fitted directly on the valve. Valves can be mounted individually, but several valves can also be mounted together in a single manifold.
- On a sub-basevalve all valve ports are brought out to one side, and the holes for the ports in the valve housing are unthreaded. Sub-base valves are mounted individually or in groups on sub-bases or manifolds.

*Application example*

Fig. 4.12 shows a valve manifold block with assembled sub-base valves. A double solenoid valve is shown in the foreground, behind which are two spring-return directional control valves with just one solenoid for valve actuation. The spare valve position in the foreground is sealed with a blanking plate. The ports for the consuming devices are visible in the foreground at the lower right.

The supply air and exhaust ports are located on the end plate facing the rear right (not visible in the photograph).

*Fig. 4.12: Mounting of electrically actuated directional control valves on a valve manifold block (Festo)*



*ISO valves*

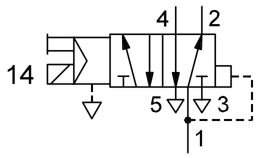
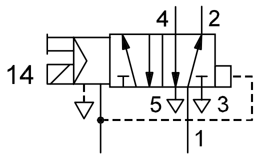
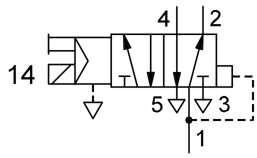
Certain sub-base valves are standardized in accordance with ISO. They have standardized dimensions, thus enabling valves from different manufacturers to be mounted on an ISO sub-base.

It is often of benefit to use manufacturer-specific, non-standardized valves. This is particularly the case if the proprietary valves are more compact than comparable ISO valves and can be installed at less expense.

*Performance data of 5/2-way valves*

The pneumatic performance data and operating conditions of three 5/2-way valves are summarized in Table 4.3.

*Table 4.3: Pneumatic performance data of electrically actuated directional control valves (Festo)*

| *Valve type* | *Pilot controlled spring-return 5/2-way valve* | *Pilot controlled spring-return 5/2-way valve with auxiliary pilot air* | *Pilot controlled spring-return 5/2-way valve* |
|---|---|---|---|
| Port arrangement | Sub-base valve | Sub-base valve with auxiliary pilot air | Individual valve |
| Graphical symbol |   |   |   |
| Nominal size | 4.0 mm | 4.0 mm | 14.0 mm |
| Nominal flow rate | 500 l/min | 500 l/min | 2000 l/min |
| Pressure range | 2.5 to 8 bar | 0.9 to 8 bar (auxiliary pilot air: 2.5 to 8 bar) | 2.5 to 10 bar |
| Response times - On/off | 20/30 ms | 20/30 ms | 30/55 ms |

*Nominal size and nominal flow rate*

Whether a directional control valve with a high or low flow rate should be used is dependent on the cylinder being actuated.

A cylinder with a large piston surface or a high speed of motion calls for the use of a valve with a high flow rate. A cylinder with a small piston surface or a low speed of motion can be actuated by a valve with a low flow rate. The nominal size and nominal flow rate are measures of the valve's flow characteristics.

To determine the nominal size of the valve, the narrowest valve cross section through which air flows must be found. The corresponding cross-sectional area is converted into a circular area. The diameter of this area is the valve's nominal size.

A large nominal size results in a high flow rate, and a small nominal size in a low flow rate.

The nominal flow rate of a valve is measured under specified conditions. A pressure of 6 bar is maintained upstream of the valve for the measurement, and a pressure of 5 bar downstream of the valve.

On account of their flow rates, the valves described in Table 4.3 with a nominal size of 4 mm are mostly used for cylinders with a piston diameter of up to 50 mm. The valve with a nominal size of 14 mm, on the other hand, is suitable for cylinders with a large piston diameter where the piston rod is expected to reach high advance and retract speeds.

*Pressure range*

The pressure range is the range of supply pressure at which the valve can be operated. The upper limit of the pressure is determined by the strength of the housing, the lower limit by the pilot control stage (see Section 4.2).

If the valve actuates a drive that only operates at low pressure (such as a vacuum suction cup), the pressure is not sufficient to actuate the pilot control stage. A valve with separate pilot pressure supply is therefore necessary.

*Response times*

The response times indicate the length of time that elapses between actuation of the contact and the valve switching over.

In spring-return valves, the response time for switching from the initial position to the actuated position is usually shorter than for the switching operation in the opposite direction.

A long response time slows down the performance of an electropneumatic control system because pressurizing and/or venting of the cylinders is delayed by the length of the response time.

## 4.4 Performance data of solenoid coils

An electrically actuated directional control valve can be equipped with various different solenoid coils. The valve manufacturer usually offers one or more series of solenoid coils for each type of directional control valve, with connection dimensions to match the valve. The choice of solenoid coil is made on the basis of the electrical performance data (Table 4.4).

*Table 4.4: Performance data of DC and AC solenoid coils (Festo)*

| *Coil type* | | *DC voltage* | *AC voltage* |
|---|---|---|---|
| Voltages | Normal | 12, 24, 42, 48 V | 24, 42, 110, 230 V, 50 Hz |
| | Special | On request | On request |
| Voltage fluctuation | | max. +- 10 % | Max. +- 10 % |
| Frequency fluctuation | | – | Max. +- 5 %<br>at nominal voltage |
| Power consumption for normal voltages | | 4.1 W at 12 V<br>4.5 W at 24 V | Pickup: 7.5 VA<br>Hold: 6 VA |
| Power factor | | – | 0.7 |
| Duty cycle | | 100 % | 100 % |
| Degree of protection | | IP 65 | IP 65 |
| Cable conduit fitting | | PG9 | PG9 |
| Ambient temperature | | 5 to + 40 °C | 5 to + 40 °C |
| Medium temperature | | 10 to + 60 °C | 10 to + 60 °C |
| Average pickup time | | 10 ms | 10 ms |

*Specification of operating voltage*

The voltage specification in Table 4.4 relates to the voltage supplied to the solenoid coils. The solenoid coils are chosen to match the signal control section of the electropneumatic control system. If the signal control section operates with a DC voltage of 24 V, for example, the corresponding type of coil should be chosen.

To ensure proper operation of the solenoid coil, the voltage supplied to it from the signal control section must be within certain limits. For the 24 V coil type, the limits are as follows:

Minimum voltage: $V_{min} = 24\ V \cdot (100\% - 10\%) = 24\ V \cdot 0.9 = 21.6\ V$

Maximum voltage: $V_{max} = 24\ V \cdot (100\% + 10\%) = 24\ V \cdot 1.1 = 26.4\ V$

If the signal control section operates with AC voltage and therefore AC solenoid coils are used, the frequency of the AC voltage must be within a specified range. For the AC coils described in the table, frequencies up to 5 % above or below 50 Hz are permissible; in other words the permitted frequency range is between 47.5 and 52.5 Hz.

*Electrical power data*

The power data (power consumption and power factor) must be taken into account when specifying the rating of the power supply unit for the signal control section. It is prudent to design the power supply unit such that it is not overloaded even if all solenoid coils are actuated simultaneously.

*Duty cycle (VDE 530)*

When a solenoid is actuated, a current flows through the coil. The temperature of the coil rises because of its ohmic resistance. The duty cycle indicates the maximum percentage of the operating time for which the solenoid coil is allowed to be actuated. A solenoid coil with a 100 % duty cycle may be energized throughout the entire operating duration.

If the duty cycle is less than 100 %, the coil would become too hot in continuous operation. The insulation would melt, and the coil would be destroyed. The duty cycle is specified in relation to an operating time of 10 minutes. If the permissible duty cycle of a coil is 60 %, for example, the coil may be energized for no more than 6 minutes during an operating time of 10 minutes.

*Class of protection and cable conduit fitting*

The class of protection indicates how well a solenoid coil is protected against the ingress of dust and water. The coils described in Table 4.4 have class of protection IP 65, i.e. they are protected against the ingress of dust and may be operated in an environment in which they are exposed to water jets. The various degrees of protection are explained in detail in Chapter 7.

The specification of the cable conduit fitting relates to the electrical connection of the solenoid coils (see Section 4.5).

*Temperature data*

Reliable operation of the solenoid coil can only be guaranteed if the ambient temperature and the medium temperature, i.e. the temperature of the compressed air, are within the specified limits.

*Average pickup time*

When a solenoid coil is actuated, the coil's magnetic field and hence the power of the solenoid are built up, but with a delay. The average pickup time indicates the length of time between the instant at which current flows through the coil and the instant at which the armature picks up. The average pickup time is typically between 10 and 30 ms.

The longer the pickup time of a solenoid coil, the greater the response time of the actuated directional control valve.

## 4.5 Electrical connection of solenoid coils

The solenoid coil of a directional control valve is connected to the signal control section of an electropneumatic control system via a two-core cable. There is a removable plug connector between the cable and the solenoid. When the connector is inserted it is screwed down to protect the plug contacts against the ingress of dust and water. The type of plug connector and cable conduit fitting are specified in the technical documentation for the solenoid coil (such as PG9 in Table 4.4).

*Protective circuit of a solenoid coil*

The electric circuit is opened or closed by a contact in the signal control section of the control system. When the contact is opened, the current through the solenoid coil suddenly decays. As a result of the rapid change in current intensity, in conjunction with the inductance of the coil, a very high voltage is induced briefly in the coil. Arcing may occur at the opening contact. Even after only a short operating time, this leads to destruction of the contact. A protective circuit is therefore necessary.

Fig. 4.13 shows the protective circuit for a DC coil. While the contact is closed, current $I_1$ flows through the solenoid and the diode is de-energized (Fig. 4.13a). When the contact is opened, the flow of current in the main circuit is interrupted (Fig. 4.13b). The circuit is now closed via the diode. In that way the current can continue flowing through the coil until the energy stored in the magnetic field is dissipated.

As a result of the protective circuit, current $I_M$ is no longer subject to sudden decay, instead it is continuously reduced over a certain length of time. The induced voltage peak is considerably lower, ensuring that the contact and solenoid coil are not damaged.

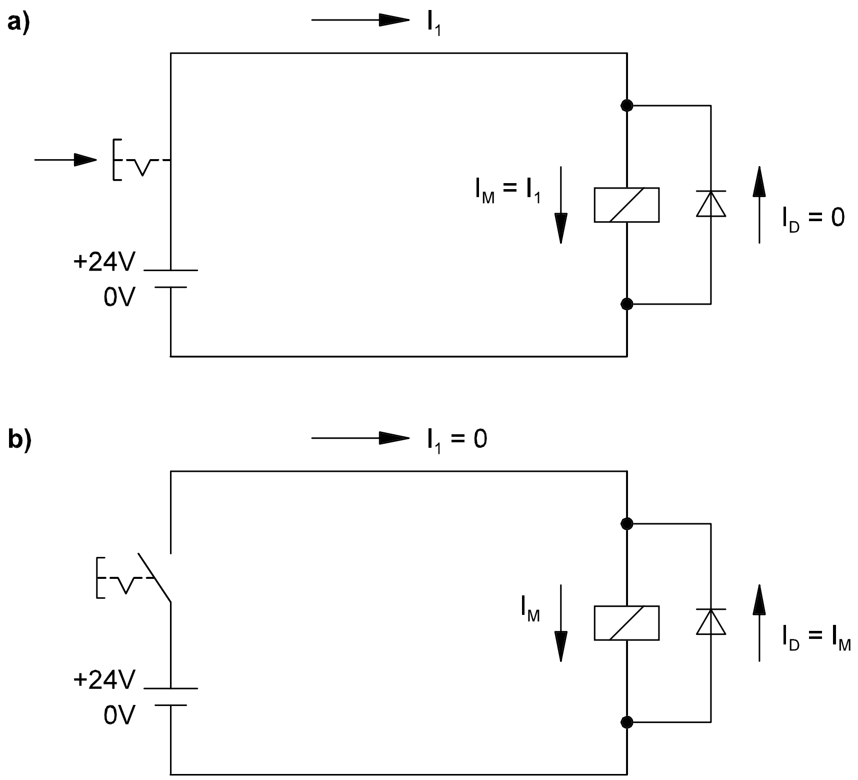



*Fig. 4.13: Protective circuit of a solenoid coil*

*Auxiliary functions*

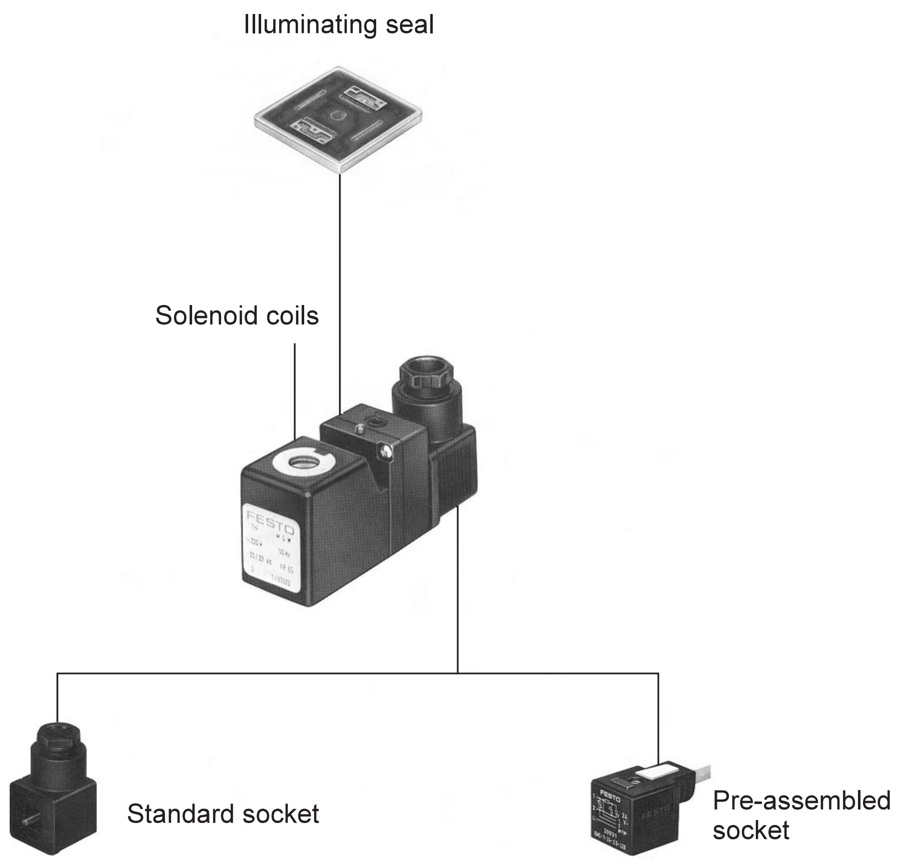
In addition to the protective circuit required for operation of the valve, further auxiliary functions can be integrated in the cable connection, for example:

- Indicator lamp (lights up when the solenoid is actuated)
- Switching delay (to allow delayed actuation)

*Adapters and cable sockets*

The protective circuit and auxiliary functions are integrated either into the cable socket or in the form of adapter inserts i. e. illuminating seal (Fig. 4.14). Appropriate adapters and cable sockets must be chosen to match the voltage at which the signal control section operates (for example 24 V DC).

*Fig. 4.14: Solenoid coil, adapter and socket*




*Class of protection*

Plugs, sockets and adapters are sealed in order to prevent either dust or moisture from entering the plug connection. If the adapter, solenoid coil and valve have different classes of protection, the lowest of the three classes of protection applies to the assembled valve, coil and cable conduit.

*Explosion protection*

If it is intended to use electrically actuated directional control valves in an environment subject to explosion hazards, special solenoid coils approved for such applications are required; these have molded cables.

# Chapter 5

## Developing an electropneumatic control system

## 5.1 Procedure for developing a control system

The field of application for electropneumatic controls ranges from partially automated workstations to fully automated production facilities with numerous stations. Accordingly, the design and range of functions of such control systems varies greatly. Electropneumatic control systems are therefore developed individually, tailored to a particular project. Development of a control system entails:

- Project design (preparation of the necessary plans and documents)
- Selection and configuration of the electrical and pneumatic equipment
- Implementation (setting up and commissioning)

A systematic, step-by-step procedure helps to avoid mistakes. It also makes it easier to stay within budget and keep to time schedules. Fig. 5.1 provides an overview of the individual steps in control development.

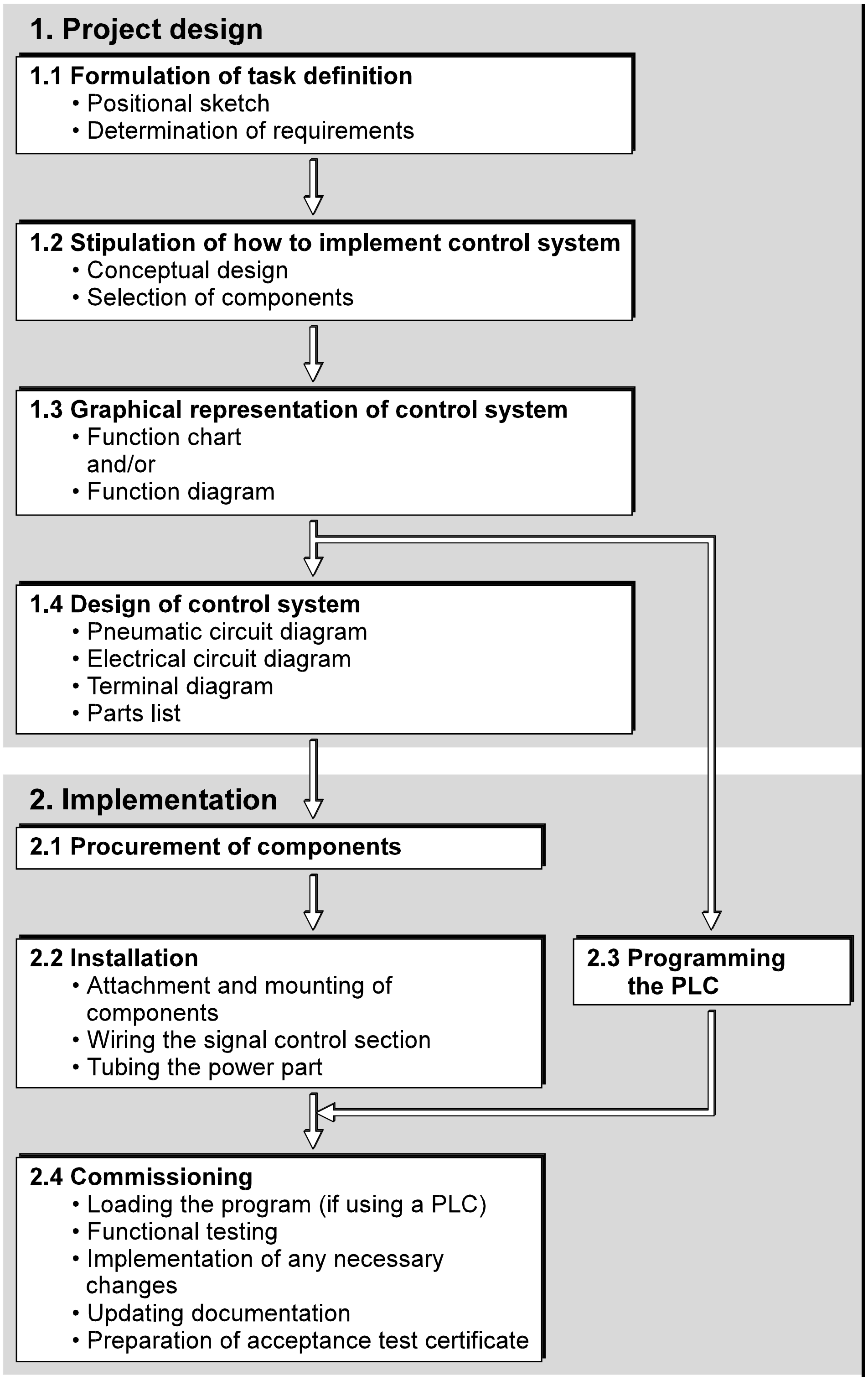



*Fig. 5.1:*
*Procedure for development and implementation of an electropneumatic control system*

## 5.2 Project design procedure

Project design for an electropneumatic control system involves the following (see Fig. 5.1):

- Formulation of the control task and stipulation of the requirements to be met by the control system
- Conceptual design of the control system and selection of the necessary components
- Graphical representation of the control task
- Planning of the control system and preparation of diagrams and parts lists

The various steps in project design are explained in the following, illustrated with the aid of an example.

*Formulation of task definition and requirements*

The design of a control project begins with written formulation of the control task. All requirements must be carefully, precisely and clearly defined. The following aids have proved useful in this work:

- Lists or forms which help to record all requirements quickly and completely (Table 5.1)
- Tables listing drive units, valves and sensors
- A positional sketch showing the spatial arrangement of the drive units

The requirements to be met by the control system must be agreed upon jointly by the developer and operator of the control system. It is also of benefit if the developer of the control system familiarizes him- or herself with the ambient conditions and installation circumstances on location.

*Table 5.1: List for specifying requirements to be met by an electropneumatic control system*

| | |
|---|---|
| Operator control | Necessary control elements |
| | Necessary operating modes |
| | Indicators, displays and warning lights |
| Drive units | Number of drives |
| | For each drive<br>- Function<br>- Necessary force<br>- Necessary stroke<br>- What speeds of motion need to be available?<br>- Braking of motions<br>- Spatial arrangement<br>- Additional functions (such as linear guide)<br>- Initial position |
| Motion sequence | Order of drive motions |
| | Number of steps in motion sequence |
| | Step enabling conditions |
| | Necessary waiting times |
| | Necessary cycle times |
| | Communication with other control systems |
| Sensors / signals | Necessary proximity switches |
| | Necessary pressure switches, pressure sensors |
| | Other sensors |
| | Other input and output signals |
| Constraints | Installation space |
| | Behavior in event of power failure |
| | Behavior in event of emergency stop |
| | Behavior in response to other faults |
| | Ambient conditions (temperature, dust, moisture) |
| | Necessary protective measures |
| | Other requirements |

*Conceptual design of an electropneumatic control system*

Electropneumatic control systems can be designed according to widely differing concepts. Examples include:

- With a PLC or with relays for signal processing
- With separately installed directional control valves or with directional control valves mounted in a valve terminal
- With standard cylinders or with cylinders featuring auxiliary functions (such as linear guides, end position cushioning, slots for attachment)

The conceptual design of the control system has a decisive influence on the expense of further development, i.e. the cost of planning, setting up and commissioning the control system. Measures to reduce expenditure include:

- Modular control system design (use of identical circuit and program modules for different control configurations)
- Using state-of-the-art components and assemblies (such as bus systems and valve terminals; see Chapter 9)

*Selection of components*

Once the overall concept of the control system is in place, the necessary components can be chosen. These include:

- Pneumatic drive units
- Pneumatic valves
- Control elements
- Proximity switches, pressure switches etc.
- PLC or types of relays to be used

*Graphical representation of the control task*

Before work is started on drawing up the circuit diagrams, certain points have to be clarified:

- How many steps are needed in the sequence
- Which drives are actuated in each step
- Which sensor signals or what length of waiting time triggers the next step in the sequence

Clarification and illustration of the sequence is most easily done using graphical methods, for example with a displacement-step diagram, a displacement-time diagram, a function diagram or a function chart. The various methods are explained in Sections 6.1 and 6.2.

*Control system planning, diagrams and parts list*

The last stage of project engineering involves compiling all documents that are necessary for setting up the control system. These include:

- Parts list
- Pneumatic circuit diagram
- Electrical circuit diagram
- Terminal diagram

The presentation of circuit and terminal diagrams in accordance with the relevant standards is explained in Sections 6.3 to 6.7. Chapter 8 deals with the design of circuit diagrams for relay control systems.

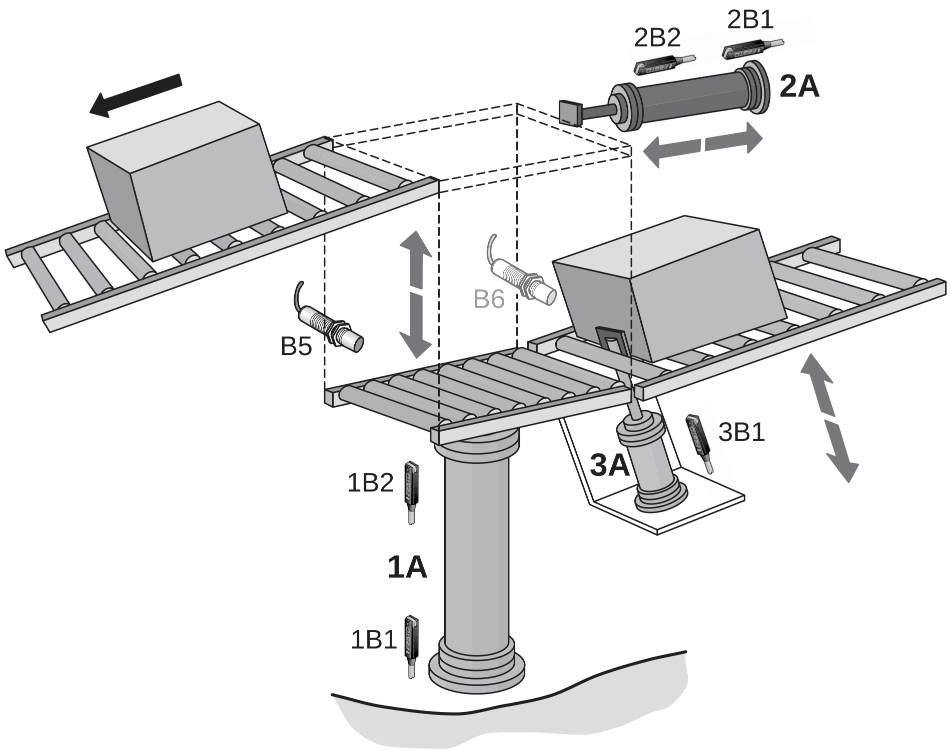
### 5.3 Sample application: project design ofa lifting device

A lifting device transfers workpieces from one roller conveyor to another at a different height. The task is to carry out the project engineering for the associated electropneumatic control system.

A positional sketch of the lifting device is shown in Fig. 5.2. There are three pneumatic drives:

- Drive 1A lifts the workpieces.
- Drive 2A pushes the workpieces onto the upper roller conveyor.
- Drive 3A is used as a stopper, for releasing and interrupting the supply of workpieces.

*Fig. 5.2: Positional sketch of the lifting device*




The packages first have to be separated to be fed singly; this is done at an upstream facility. The optical proximity switch B6 is not taken into account for the purposes of further project engineering of the lifting device.

*Drives for the lifting device*

Cylinder 1A requires a stroke of 500 mm and a force of at least 600 N, cylinder 2A a stroke of 250 mm and a force of at least 400 N. Cylinder 3A requires a stroke of 20 mm and a force of 40 N. On cylinders 1A and 2A the advance and retract speeds of the piston rods need to be variable. The control system must allow soft braking of drives 1A and 2A.

To prevent the possibility of secondary damage, in the event of an electrical power failure the piston rods of cylinders 1A and 2A are to be braked immediately and remain at a standstill. The piston rod of the stopper cylinder 3A is meant to extend in these circumstances.

*Movement cycle of the lifting device*

The movement cycle of the lifting device is described in Table 5.2 (see positional sketch, Fig. 5.2). It comprises four steps.

*Table 5.2: Movement cycle of the lifting device*

| *Step* | *Movement piston rod cylinder 1A* | *Movement piston rod cylinder 2A* | *Movement piston rod cylinder 3A* | *End of step, step enabling condition* | *Comments* |
|---|---|---|---|---|---|
| 1 | None | None | Retract | B5 triggered (package present) | Open device |
| 2 | Advance | None | Advance | 1B2 triggered | Lift package |
| 3 | None | Advance | None | 2B2 triggered | Push out package |
| 4 | Retract | Retract | None | 1B1, 2B1 triggered | Retract drives to initial position |

*Operator control*

The control system of the lifting device must enable the device to be run in a continuous cycle (continuous operation). A single cycle operating mode is also necessary in which the sequence is processed precisely once.

The operator control equipment for the system must conform to the relevant standards (see Section 7.4). The control panel for the lifting device is shown in Fig. 5.3.

The following operating functions are specified in more detail in relation to the lifting device:

- "EMERGENCY STOP": When this is actuated, not only the electrical power supply, also the pneumatic power supply must be shut down.
- "Reset": This returns the system to the initial position, i.e. the piston rods of cylinders 1A and 2A retract, the piston rod of cylinder 3A extends.
- "Continuous cycle OFF": This stops the continuous cycle process. If there is already a workpiece in the device, it is transferred to the upper roller conveyor. The piston rods of cylinders 1A and 2A retract. The device is subsequently in its initial position.

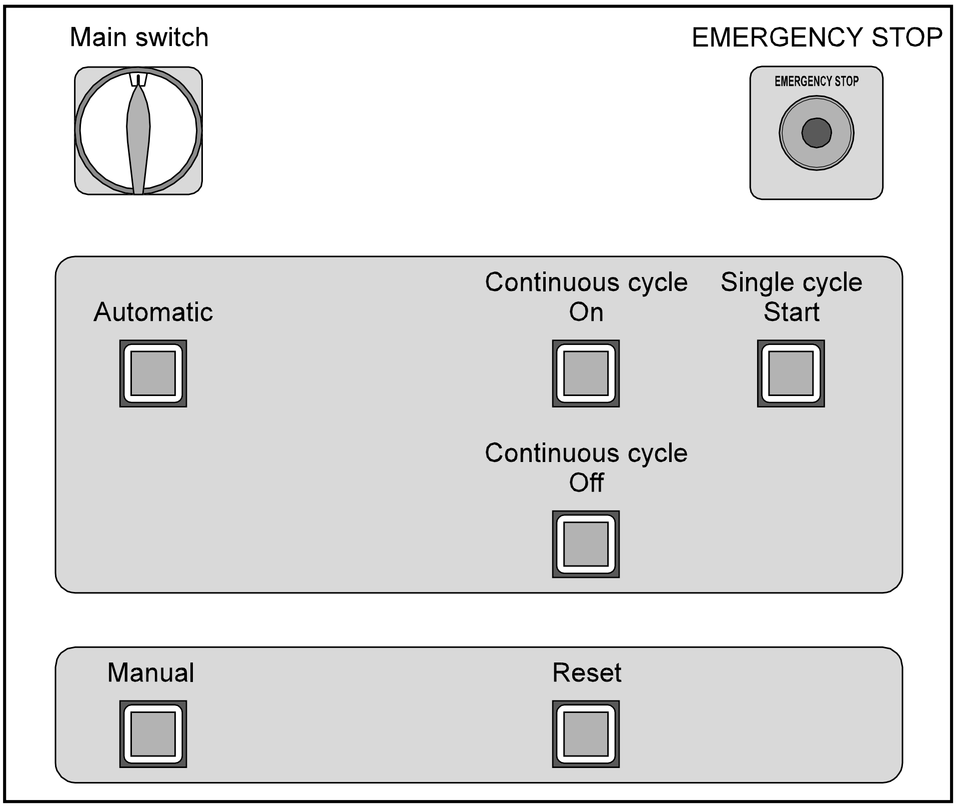



*Fig. 5.3: Control panel of the control system for the lifting device*

*Ambient conditions*

The lifting device is used in a production shop in which the temperature fluctuates between 15 and 35 degrees Centigrade. The pneumatic components of the power section and the electrical connections of the valves are to be dust-tight and splash-proof. The electrical components of the signal control section are installed in a control cabinet and must conform to the relevant safety regulations (see Chapter 7).

*Power supply*

The following power supply networks are available:

- Compressed air network (p = 0.6 MPa = 6 bar)
- Electrical network (V = 230 V AC)

The electrical signal control section and the main circuit are to be operated with 24 V DC. A power supply unit therefore needs to be provided to supply this voltage.

*Overall conceptual design of the control system*

The signal processing aspect of the lifting device is implemented as a relay control system. In view of the small number of drive units, the valves are mounted separately.

As the linear guides of the lifting platform and of the pushing device are already part of the station, cylinders without integrated guides are used. Double-acting cylinders are used for drives 1A and 2A. Drive 3A takes the form of a single-acting stopper cylinder.

*Selection of cylinders*

The cylinders are chosen on the basis of the requirements in terms of force and stroke, using catalogues obtained from pneumatics manufacturers.

On account of the required drive force, cylinder 1A must have a piston diameter of at least 40 mm, and cylinder 2A a piston diameter of at least 32 mm.

To ensure soft braking, cylinders with integrated adjustable end position cushioning are used for drives 1A and 2A. The following cylinders would be suitable, for example:

- Cylinder 1A: Festo DNGUL-40-500-PPV-A
- Cylinder 2A: Festo DNGUL-32-250-PPV-A

A stopper cylinder is used for drive 3A; it is extended if the compressed air supply fails. This requirement is met by a Festo STA-32-20-P-A type cylinder, for example.

*Selection of directional control valves for the control chain*

In order to obtain the required behavior for drives 1A and 2A in the event of a power failure, the valves used are spring-centered 5/3-way valves with a closed mid-position. As the movements of the piston rods are relatively slow, valves of a comparatively small nominal size are adequate. Valves with 1/8-inch ports are used to match the smaller of the two cylinders. Directional control valves of the Festo MEH-5/3G-1/8 type would be suitable, for example.

A spring-return 3/2-way valve of the Festo MEH-3/2-1/8 type is used for actuation of stopper cylinder 3A.

*Pressure sequence valve*

The supply of compressed air for all three control chains must be shut off as soon as the electrical power supply fails or an EMERGENCY STOP is triggered. An additional, electrically actuated, spring-return 3/2-way valve is therefore necessary which enables the supply of compressed air only when the electrical power supply is functioning properly and no EMERGENCY STOP device has been actuated. In order to ensure that there is adequate flow, a Festo CPE14-M1H-3GL-1/8 type valve is used.

*Speed regulation*

The advanceand retract speeds of drives 1A and 2A are regulated by means of exhaust air flow control. Function connectors reduce tubing work, because they are screwed directly into the cylinder bore. The type of connectors required are those with a one-way flow control function, for example Festo GRLA-1/4 (cylinder 1A) or GFLA-1/8 (cylinder 2A).

*Selection of proximity switches*

The proximity switches are selected to match the cylinders. It makes sense to use positive-switching sensors. For example, inductive sensors of type SMTO-1-PS-K-LED-24 are suitable for cylinders 1A and 2A, and type SMT-8-PS-KL-LED-24 for cylinder 3A.

For controlling the device (see movement sequence) two proximity switches are needed for each of cylinders 1A and 2A in order to detect the forward and retracted end positions. In the case of cylinder 3A it is sufficient to have one sensor to detect the forward end position.

Positive-switching optical sensors, for example Festo type SOEG-RT-M18-PS-K, are used to detect whether there is a workpiece ahead of the stopper cylinder or on the lifting platform.

*Allocation table for the lifting device*

The subsequent steps of the project design process are made easier by listing the cylinders, solenoids, sensors, control elements and indicators (Table 5.3). Components belonging to an individual control chain are shown on the same line of the table.

*Table 5.3: Allocation table for the lifting device*

| *Drive / function* | *Actuated solenoid* | | | *Proximity switch* | | | *Control element* | *Comments* |
|---|---|---|---|---|---|---|---|---|
| | Advance | Retract | Other | Advanced | Retracted | Other | | |
| Cyl. 1A | 1Y1 | 1Y2 | – | 1B2 | 1B1 | | | Control chain 1 |
| Cyl. 2A | 2Y1 | 2Y2 | – | 2B2 | 2B1 | | | Control chain 2 |
| Cyl. 3A | | | – | 3B1 | | | | Control chain 3 |
| Comp. air | | | 0Y1 | | | | | Pressure sequence valve |
| | | | | | | B5 | | Package on lifting platform |
| | | | | | | | S1 | Main switch |
| | | | | | | | S2 | EMERGENCY STOP (normally closed contact) |
| | | | | | | | S3 | Manual (MAN) |
| | | | | | | | S4 | Automatic (AUT) |
| | | | | | | | S5 | RESET |
| | | | | | | | S6 | Continuous cycle ON |
| | | | | | | | S7 | Single cycle START |
| | | | | | | | S8 | Continuous cycle OFF |

*Displacement-step diagram for the lifting device*

The displacement-step diagram for the lifting device is shown in Fig. 5.4. It illustrates the steps in which the piston rods of the three cylinders advance and retract, and when the proximity switches respond.

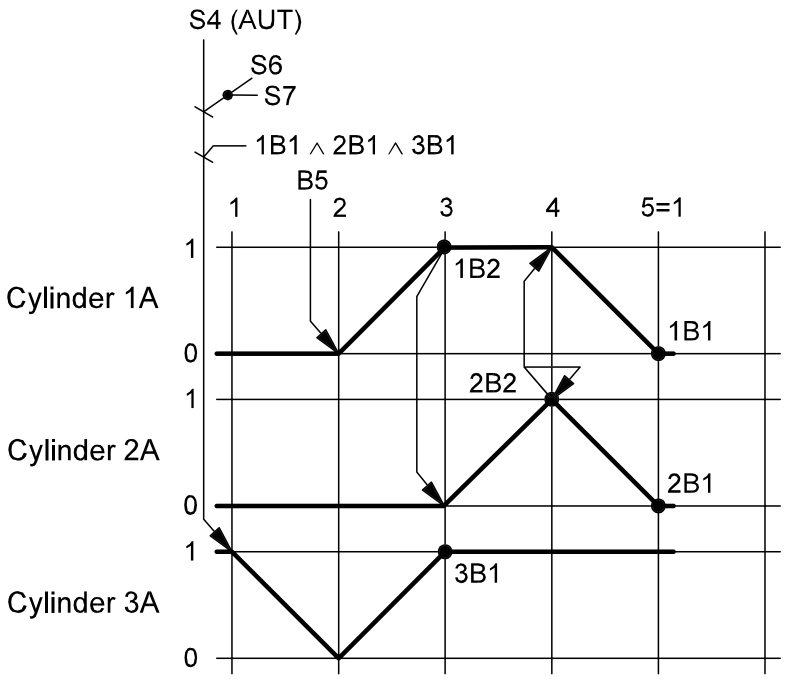
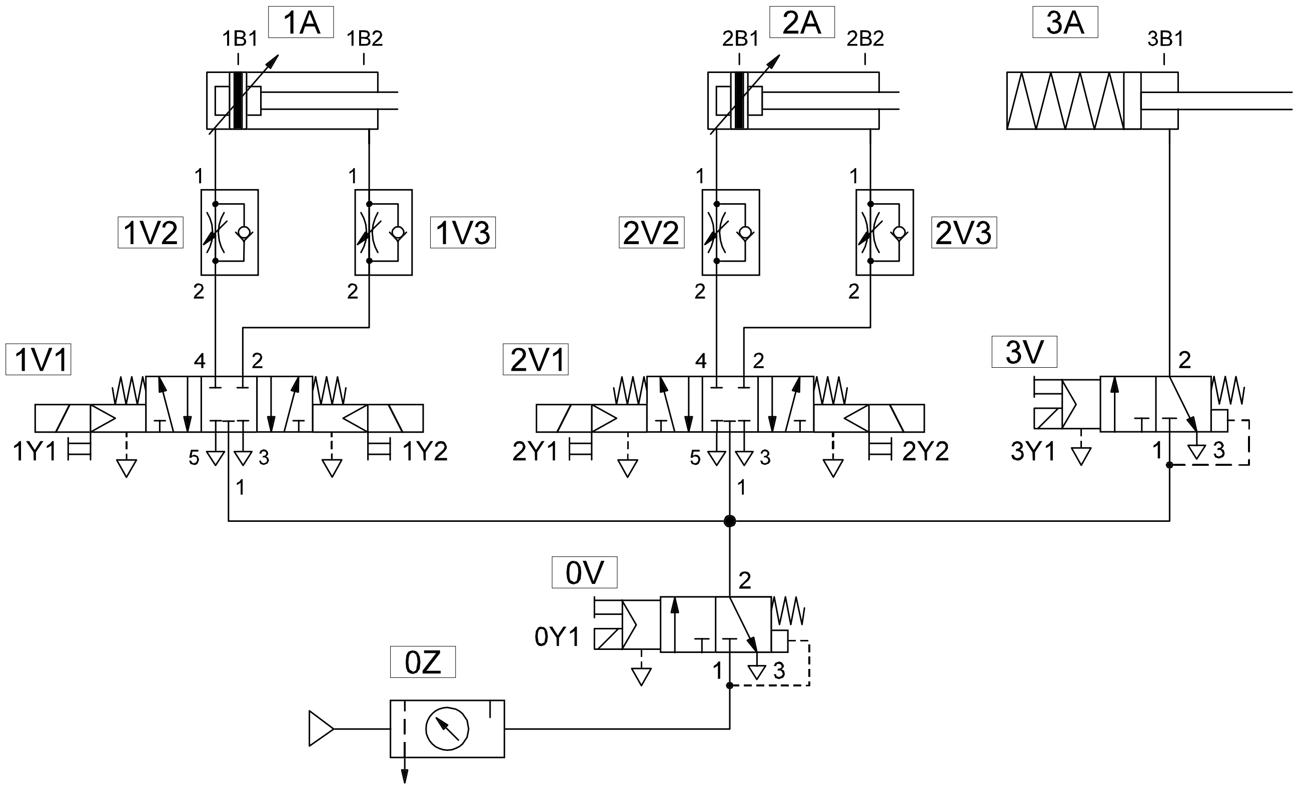



*Fig. 5.4: Displacement-step diagram for the lifting device*

*Circuit diagrams for the lifting device*

The electrical and pneumatic circuit diagrams for the lifting device are shown in Figs. 5.5 and 5.6. Each drive is actuated by a directional control valve. The additional directional control valve, actuated by coil 0Y1, switches on the compressed air.

*Fig. 5.5: Pneumatic circuit diagram of the lifting device*




The procedure for drawing up the electrical circuit diagram for the control system of the lifting device is explained in Section 8.8. The electrical circuit diagram is shown in Figs. 8.22, 8.25 to 8.27, 8.29 and 8.30.

*Fig. 5.6a:*
*Electrical circuit diagram of the lifting device - control elements*

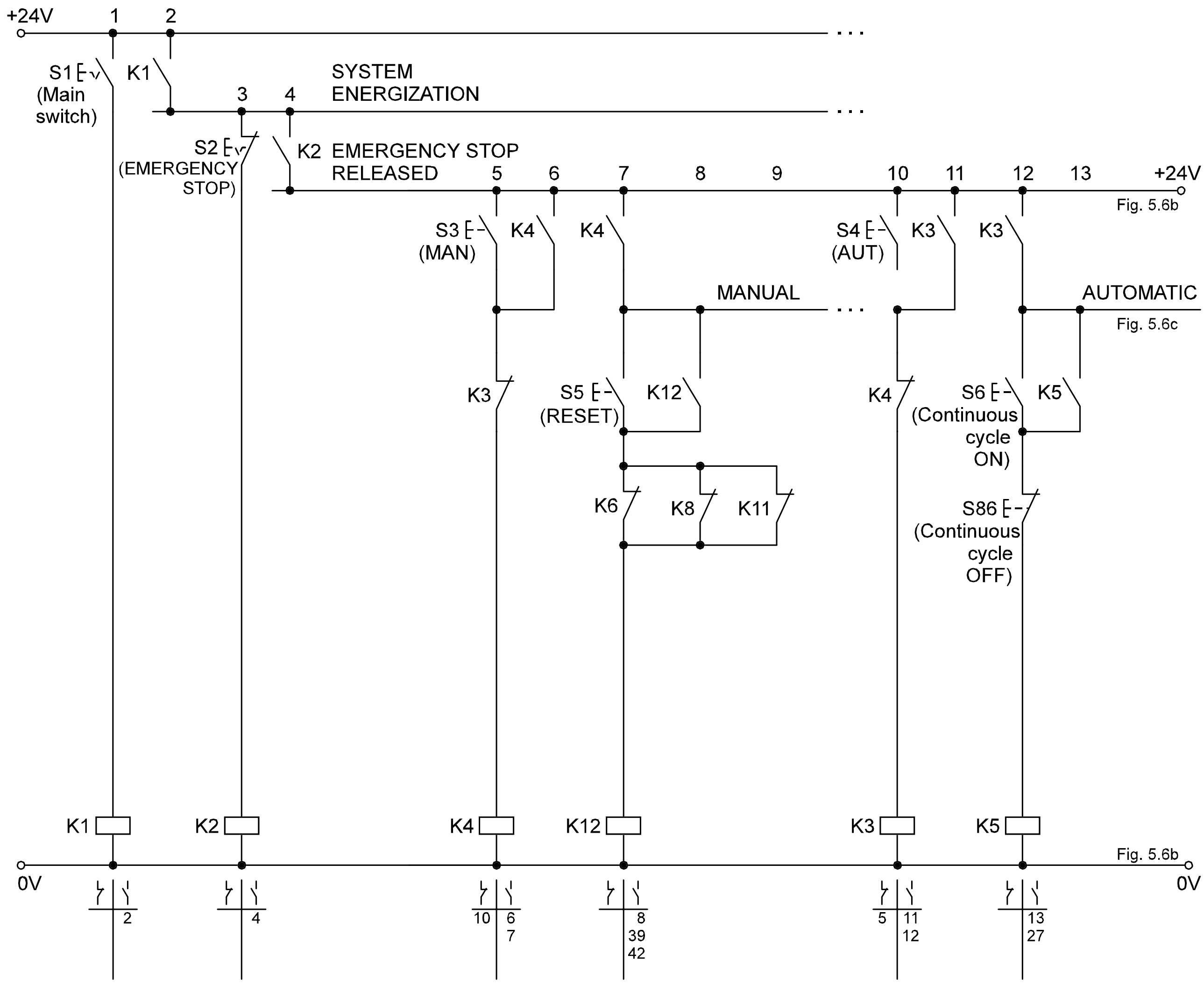


*Fig. 5.6b:
Electrical circuit diagram
of the lifting device -
sensor evaluation*

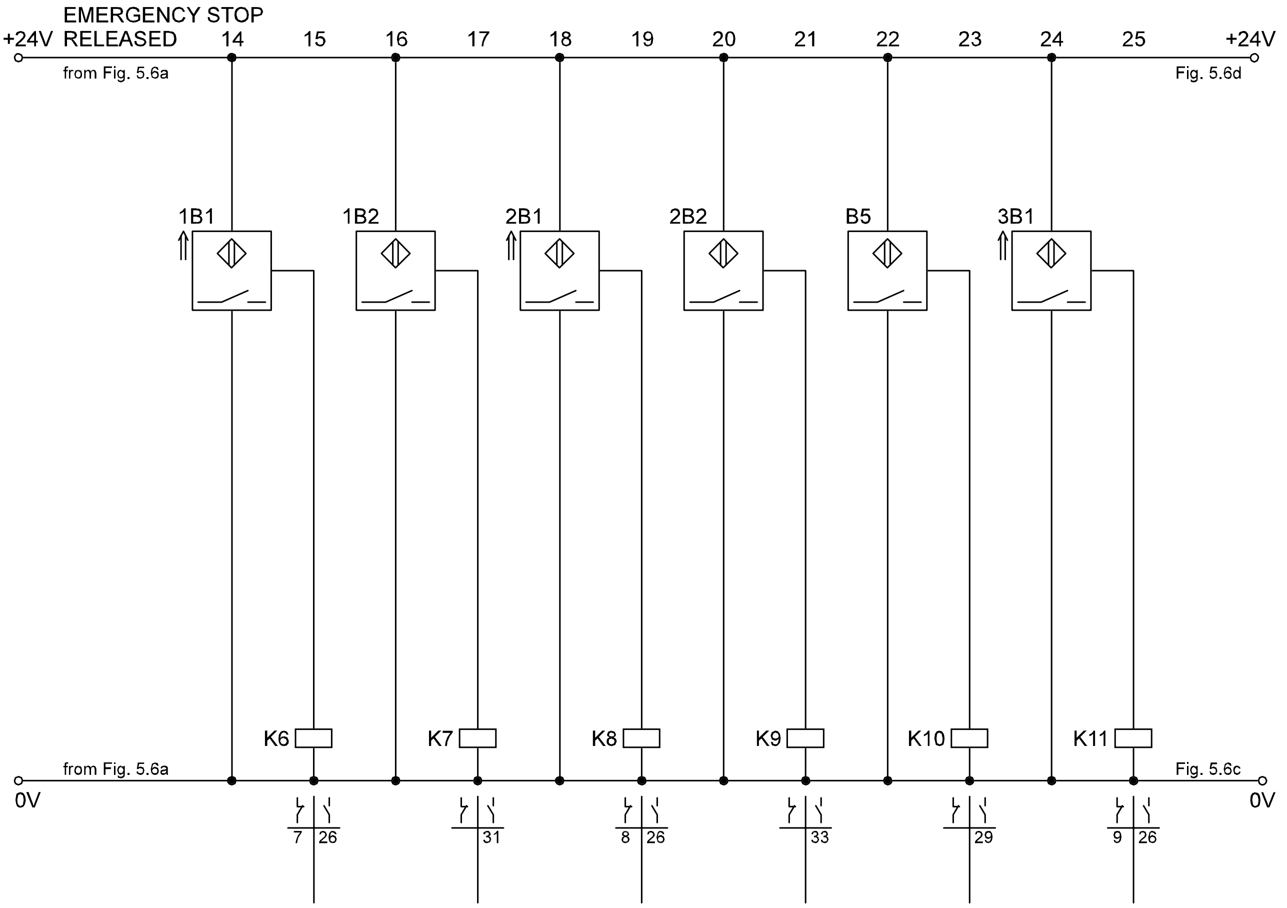


*Fig. 5.6c:*
*Electrical circuit diagram of the lifting device - switching of sequence steps*

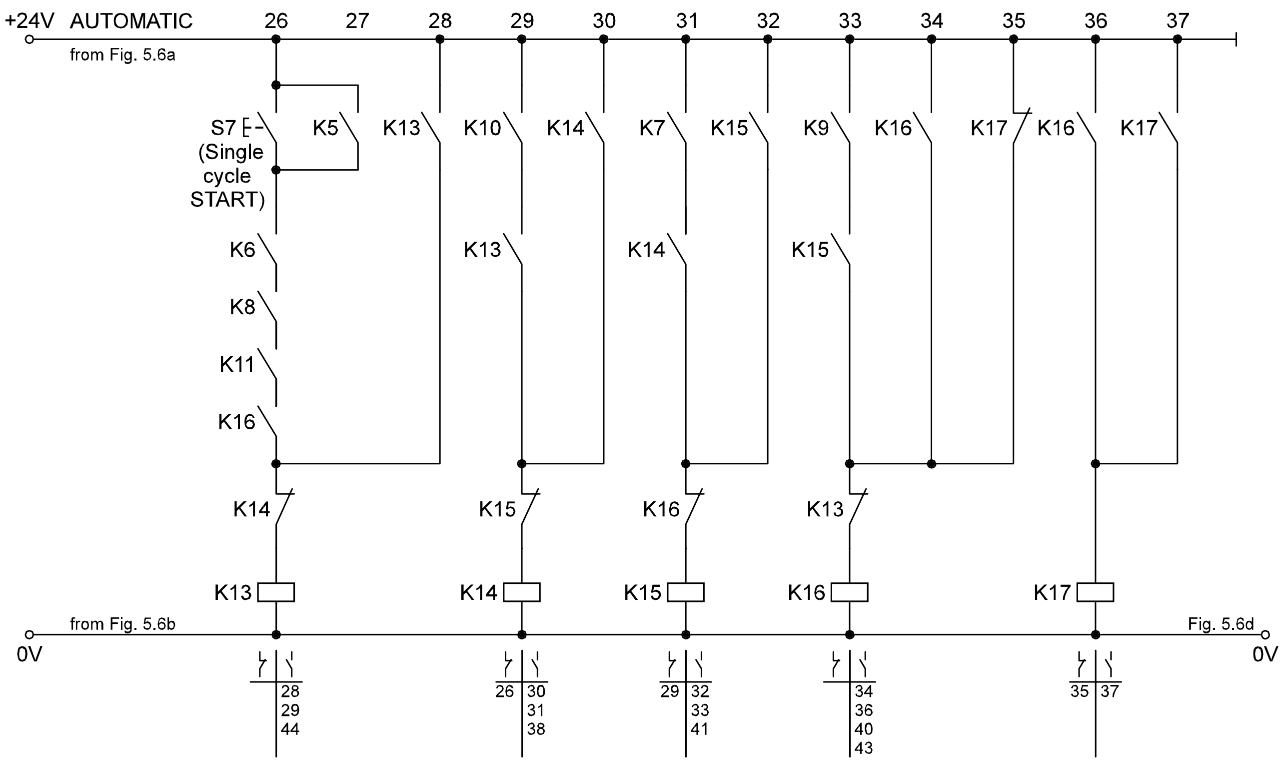
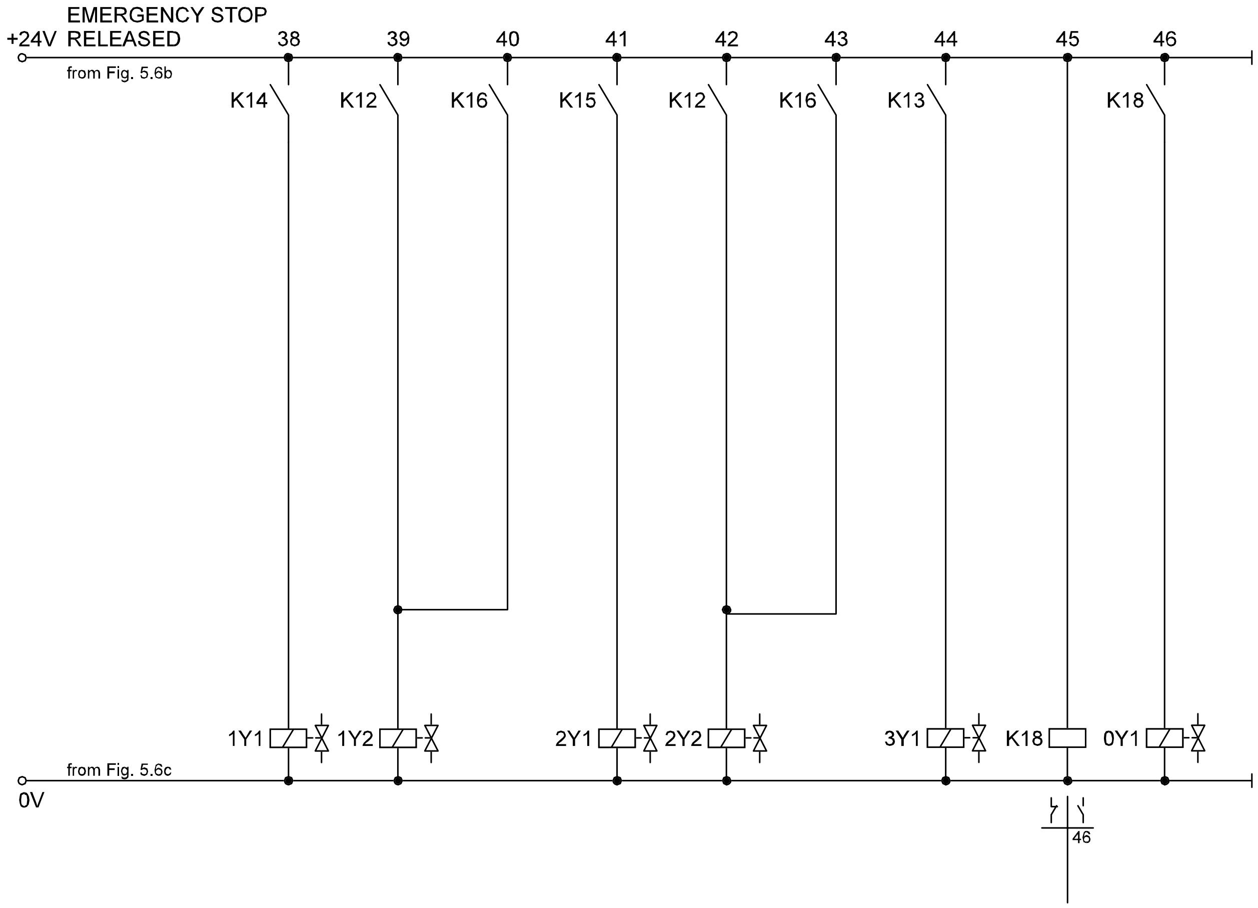


*Fig. 5.6d:
Electrical circuit diagram
of the lifting device -
circuitry of solenoid coils*



## 5.4 Procedure for implementing the control system

Implementation of an electropneumatic control system entails:

- Procuring all necessary components
- Installing the control system
- Programming (if a PLC is being used)
- Commissioning the control system

*Procedure for installing the control system*

The following items must be available before installing the control system:

- Complete circuit diagrams and terminal diagrams
- All electrical and pneumatic components in accordance with the parts list

In order to prevent errors being made in assembly, tube connection and wiring, the work is carried out in a fixed, invariable sequence. One possibility, for example, is always to connect the tubing in the pneumatic power section starting from the power supply via the valves through to the cylinders.

*Programming a PLC*

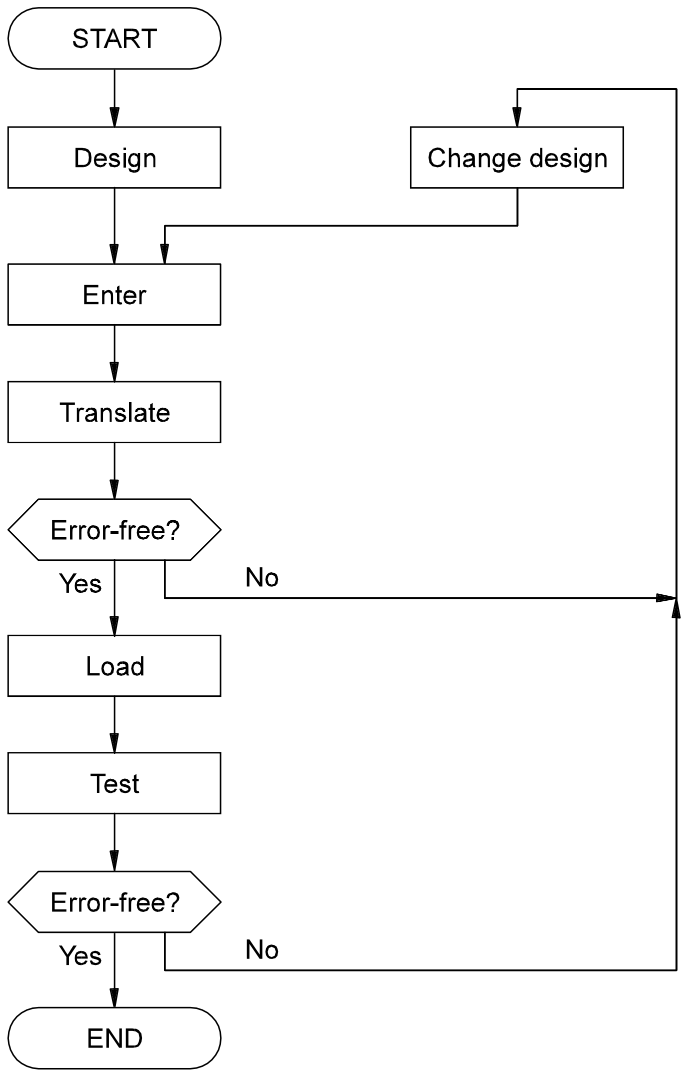
If a programmable logic controller (PLC) is used, the motion sequence of the pneumatic drives is determined by the program. The basis for developing the PLC program is provided by either a function diagram or a function chart. Program development can be carried out concurrently with setting up the control system.

Either a personal computer or a programming unit can be used as the tool for program development. The procedure comprises the following steps (Fig. 5.7):

- Design the program
- Enter the program in the personal computer or the programming unit
- Translate the program
- Test the program (initially in simulation, as far as possible, i.e. on the personal computer or with the programming unit)

Any program errors revealed in translation or during testing must be corrected. The following program development steps must subsequently be run through again. This process must be repeated until all detectable errors have been eliminated (Fig. 5.7).

*Fig. 5.7: Development of a PLC program*



The final functional test for the program cannot be carried out until the electropneumatic control system as a whole is commissioned. When installation of the control system and program development is completed, the program is loaded into the main memory of the PLC. The electropneumatic control system is then prepared for commissioning.

*Commissioning*

Commissioning has three main purposes:

- Testing operation of the control system under all conditions occurring in practice
- Carrying out the necessary settings on the control system (adjustment of proximity switches, setting of throttles etc.)
- Correcting errors in the control system

The pneumatic power section should initially be operated with reduced supply pressure. This reduces the risk of personnel coming to harm and/or the installation being damaged (for example if two piston rods collide) if there are faults in the control system.

To complete the commissioning procedure, the documentation must be updated. This means:

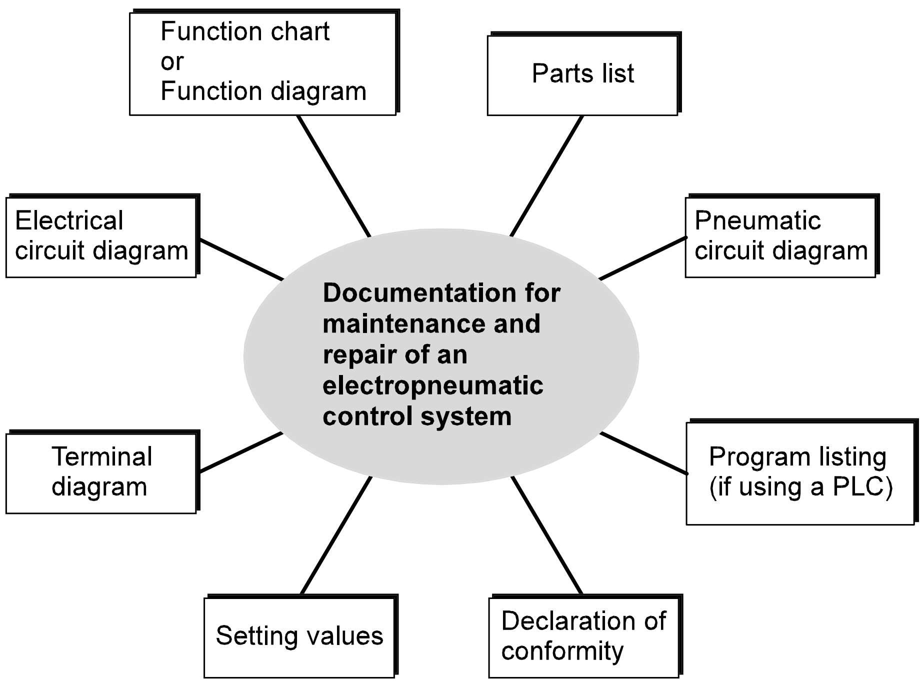
- Entering current setting values
- Correcting circuit diagrams and terminal diagrams where appropriate
- If necessary, printing out the revised PLC program

*Familiarization of maintenance staff and acceptance test certificate*

Once the control system is working faultlessly and the operator of the control system is convinced that it is functioning properly, development is completed. Handover of the control system from the developer to the operator involves the following:

- The declaration of conformity
- Familiarization of maintenance and operating staff
- Handover to maintenance staff of the documents necessary for maintenance, service and repair (Fig. 5.8)
- Preparation of an acceptance test certificate to be countersigned by the responsible developer and the operator of the control system

*Fig. 5.8: Documentation for maintenance, service and repair of an electro-pneumatic control system*




*Maintenance, service and repair*

Malfunctions and failures in a control system prove very expensive because production or parts of production are at a standstill for the duration of the failure. In order to avert failure, maintenance and service work is carried out at specified intervals. Components susceptible to wear are replaced as a preventive measure. If faults occur despite this action, the failed components have to be repaired or replaced. Maintenance, service, troubleshooting and repair are made easier if all components of the control system are arranged in a clear, easily accessible layout.

# Chapter 6

# Documentation for an electropneumatic control system

Minimal downtimes are a basic prerequisite for economic operation of an electropneumatic control system. The components of the system are therefore designed for high reliability and long service life. Nevertheless, maintenance, service and repair work is necessary, and needs to be carried out as quickly as possible. Maintenance staff therefore require accurate and complete documentation of the control system. In design work, though, too, detailed information is necessary in order to be able to choose which components to use.

Systematic documentation accompanying a project also plays a part in reducing the cost of developing a control system. This applies in particular to installation and testing of the control system.

The set of documentation for an electropneumatic control system comprises a range of documents:

- Function diagram or function chart (representation of the control sequence, Sections 6.1 and 6.2)
- Pneumatic and electrical circuit diagram (representation of the interaction of all components, Sections 6.3 and 6.4)
- Terminal allocation list (representation of the wiring allocation of terminal strips in switchboxes and terminal boxes, Section 6.5)
- Parts lists
- Positional sketch

It is essential for the circuit diagrams and terminal diagram to be available to the maintenance staff so that malfunctions and faults can be quickly located and corrected. In many cases troubleshooting is made easier if a function diagram or function chart, positional sketch and parts lists are available. These records should therefore be included with the documentation of each control system.

All documentation must be drawn up in accordance with the relevant guidelines and standards. This is the only way of ensuring that all documents are clear, unambiguous and easily readable.

## 6.1 Function diagram

The sequence of motions of an electropneumatic control system is illustrated in graphical form by means of a Function diagram.

*Application example*

A sheet-metal bending device (positional sketch: Fig. 6.1) has two double-acting pneumatic cylinder drives that are actuated with spring-return 5/2-way valves.

- Cylinder 1A is used to clamp the workpiece. Proximity switches 1B2 (forward end position) and 1B1 (retracted end position) and a 5/2-way valve with solenoid coil 1Y1 are assigned to this cylinder.
- Cylinder 2A (forward end position: proximity switch 2B2, rear end position: proximity switch 2B1, 5/2-way valve with solenoid coil 2Y1) executes the bending process.

Four steps are required for the bending operation:

- Step 1:
  Advance piston rod of cylinder 1A (clamp workpiece)
- Step 2:
  Advance piston rod of cylinder 2A (bend metal sheet)
- Step 3:
  Retract piston rod of cylinder 2A (retract bending fixture)
- Step 4:
  Retract piston rod of cylinder 1A (release workpiece)

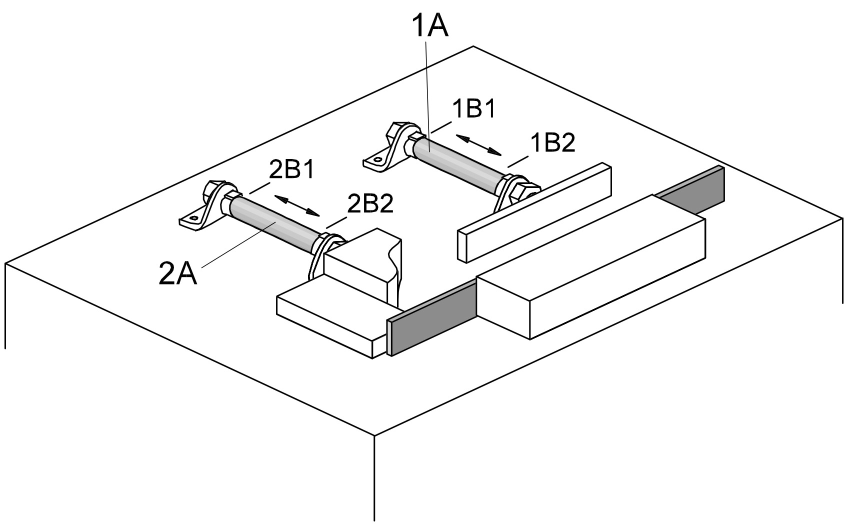
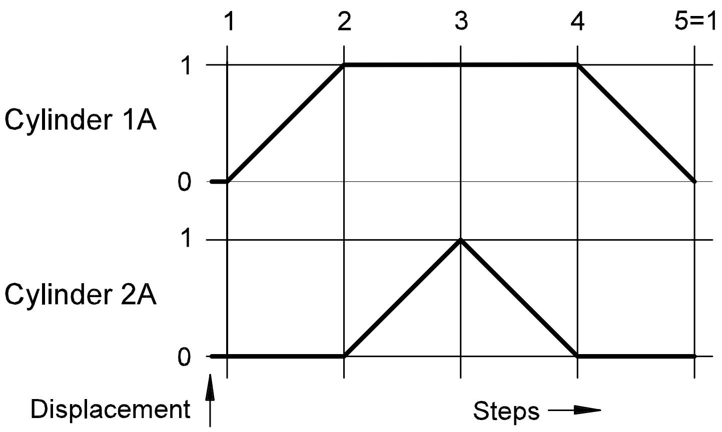



*Fig. 6.1:*
*Positional sketch of a sheet-metal bending device*

*Displacement-step diagram*

The movements of the piston rods are shown in the displacement-step diagram. The individual movement steps are numbered consecutively from left to right. If there is more than one power component, the movements of the piston rods are plotted one below the other (Fig. 6.2). This diagram illustrates how the various movements follow on from each other.

*Fig. 6.2: Displacement-step diagram for the sheet-metal bending device*




VDI standard 3260 "Function diagrams of driven machines and production facilities" has been withdrawn. In this book it is still used to illustrate control sequences.

*Displacement-time diagram*

In a displacement-time diagram the movements of the piston rods are plotted as a function of time. This form of representation highlights the different lengths of time needed for individual steps. The displacement-time diagram for the sheet-metal bending device (Fig. 6.3) shows that advancing the piston rod of cylinder 2A (step 2) takes considerably longer than retracting it (step 3).

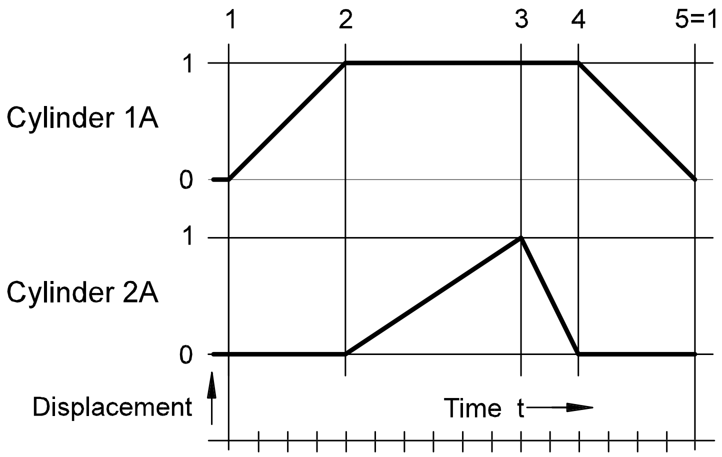



*Fig. 6.3:*
*Displacement-time diagram for the sheet-metal bending device*

*Advantages and disadvantages of the Function diagram*

The mode of operation of an electropneumatic control system can be represented very vividly with a function diagram. Although Function diagrams are no longer standardized, they are still frequently used in practice. They are predominantly suited to simple control systems with few control chains.

Logical associations and mutual influencing of the various control chains can be represented by signal lines in the function diagram. For the application examined here it is more appropriate to represent only the drive movements in a displacement-step or displacement-time diagram. The sequence and signal logic are better documented by other means, for example a function chart (Section 6.2).

## 6.2 Function chart

A function chart in accordance with DIN/EN 40719/6 can be used for graphical representation of a control system irrespective of the technology used. Function charts are used in many fields of automation for planning and documenting sequence controls, for example in power stations, industrial process engineering facilities or material flow systems.

*Structure of a function chart*

Function charts have a sequence-oriented structure. They comprise the following (Fig. 6.4):

- Representation of the steps in the sequence by step fields and command fields
- Representation of transitions by connection lines and transition conditions

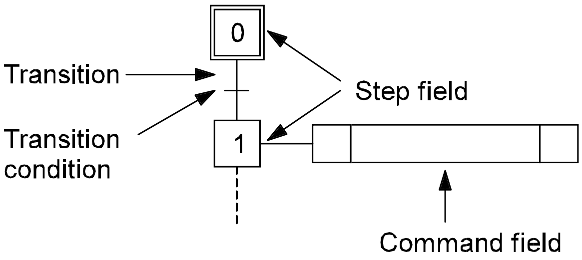



*Fig. 6.4:*
*Structure of a function chart*

*Step field*

Each step field is numbered in accordance with the sequence. The initial state of the sequence (basic setting of the control system) is identified by a step field with a double frame.

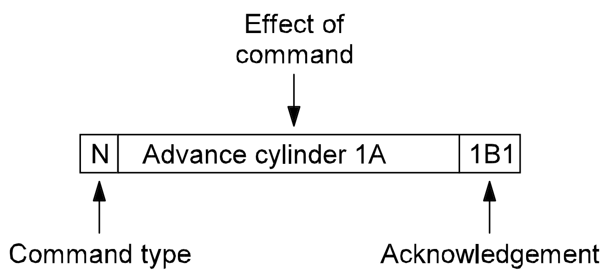
*Command field*

Each command field identifies an operation that is executed in a particular step, and is sub-divided into three parts. (Fig. 6.5):

- The nature of the command is shown in the left-hand part. Non-storing (N), for example, means that the output is actuated for this step only. Table 6.1 gives an overview of the possible types of commands.
- The effect of the command, for example to advance a cylinder drive, is shown in the central part.
- The feedback signal acknowledging execution of the command is entered in the right-hand part (for example in the form of a number or by specifying the corresponding sensor).

If more than one operation is executed in one step, there will be more than one command field associated with the step.

*Fig. 6.5:*
*Example of a command field*



| | | | |
|---|---|---|---|
| S | Stored | D | Delayed |
| L | Time-limited | P | Pulse-type |
| C | Conditional | N | Non-stored, non-conditional |
| F | Enable-dependent | | |
| Example: DP | Delayed, pulse-type command | | |

*Table 6.1: Indication of types of commands in a function chart*

*Transition conditions*

Transition from one step to the next does not take place until the associated transition condition has been satisfied. In order to improve the overall clarity of the function chart, the transition conditions are numbered. The numbering refers to the step and the command whose acknowledgement is evaluated (Fig. 6.6).

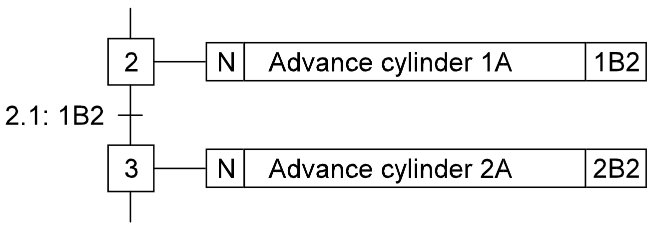
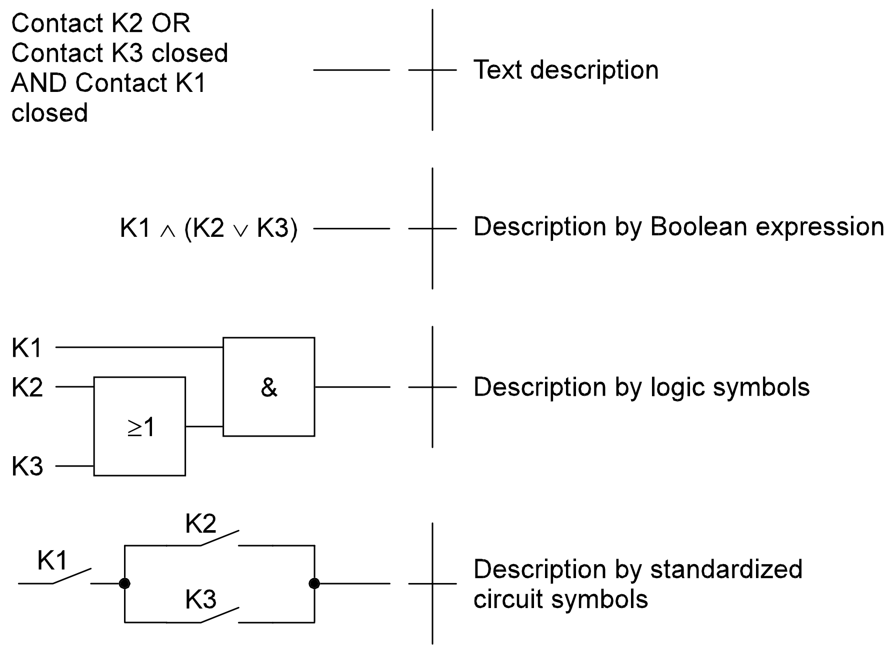



*Fig. 6.6: Representation of a transition condition in a function chart*

*Logical association of transition conditions*

Logical associations between transition conditions can be represented by text, Boolean expressions, logic symbols or standardized circuit symbols (Fig 6.7).

*Fig. 6.7: Means of representing transition conditions in a function chart*



*Parallel branching and parallel union*

Parallel branching and parallel union are used in function charts when more than two or more part sequences have to be executed in parallel. Fig. 6.8 shows a branch with two parallel sequences. When transition condition 1 is met, both part sequences are started simultaneously. The step after the reunion is only activated when both part sequences have been completed and when transition condition 2 is met.

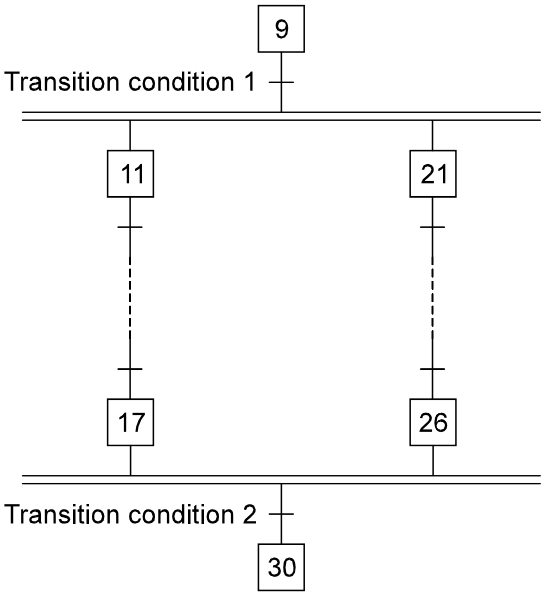
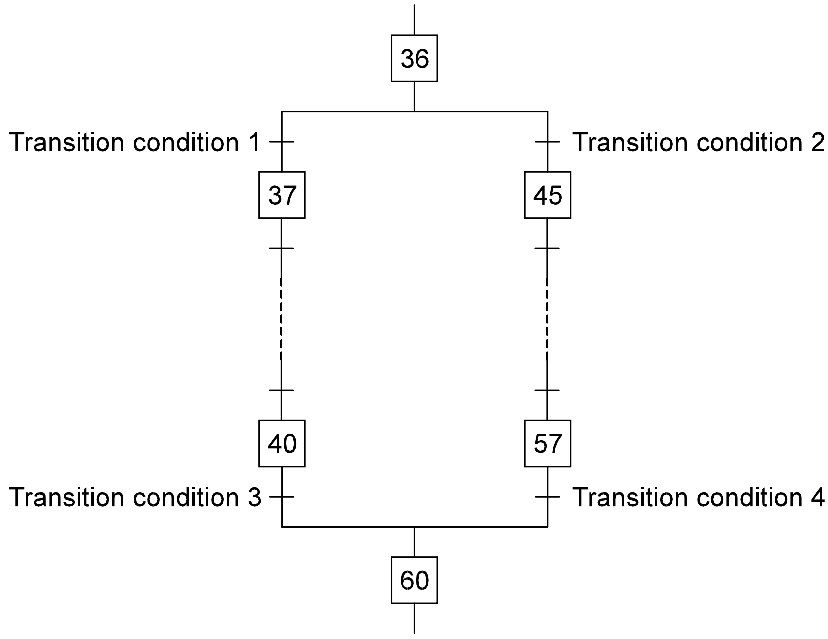



*Fig. 6.8: Parallel branching and parallel union in a function chart*

*Sequence selection and convergence*

If it is necessary to process different sequences depending on the state of the control system, this is represented in the function chart by sequence selection and sequence convergence. In Fig. 6.9 there are two branches available for selection. If transition condition 2 is met after completion of step 36, only the right-hand branch is executed. As soon as step 57 has been processed and transition condition 4 is met, the sequence is continued with step 60 following convergence.

*Fig. 6.9: Sequence selection and convergence in a function chart*



*Application example*

Fig. 6.10 shows the function chart for the sheet-metal bending device (positional sketch: Fig. 6.1). Four sequence steps are executed during one movement cycle (see Section 6.1, Function diagram Fig. 6.2).

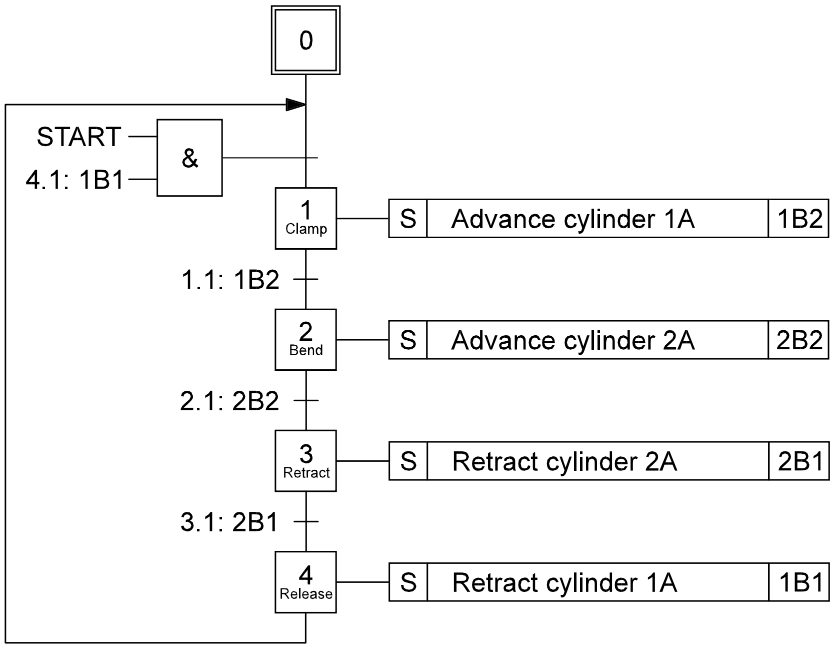



*Fig. 6.10:*
*Function chart for the bending device*

*Advantages and disadvantages of the function chart*

As an aid to planning and troubleshooting, the function chart has the following advantages:

- The mode of operation of the signal control section can be documented down to the last detail.
- The key characteristics of a control system can be visualized in graphical form (important especially when planning and documenting large control systems).
- The sequence-oriented structure makes it easy to determine when which step enabling conditions are necessary and when which output signals are set.
- The finalized control system can be implemented at relatively low cost on the basis of a detailed function chart.

In relation to electropneumatic control systems, the major disadvantage of function charts is that the movement pattern of the drives is not represented in graphical form. As a result, a function chart is less visually clear than a function diagram. It is therefore often useful to prepare a displacement-step or displacement-time diagram in addition to a function chart.

## 6.3 Pneumatic circuit diagram

The pneumatic circuit diagram of a control system shows how the various pneumatic components are connected to each other and how they interact. The graphical symbols representing the components are arranged so as to obtain a clear circuit diagram in which there is as little crossing of lines as possible. A pneumatic circuit diagram therefore does not reveal the actual spatial arrangement of the components.

In a pneumatic circuit diagram the components are represented by graphical (circuit) symbols, which are standardized according to DIN/ISO 1219-1. It must be possible to recognize the following characteristics from a graphical symbol:

- Type of actuation
- Number of ports and their designations
- Number of switching positions

The symbols shown on the following pages are only those for components which are used frequently in electropneumatic control systems.

*Graphical symbols for compressed air supply*

The compressed air supply system can be represented by the graphical symbols of the individual components, by a combined symbol or by a simplified symbol (Fig. 6.11).

*Fig. 6.11: Graphical symbols for the power supply section*

**Supply**

- Compressor with constant displacement volume
- Accumulator, air reservoir
- Pressure source

**Maintenance**

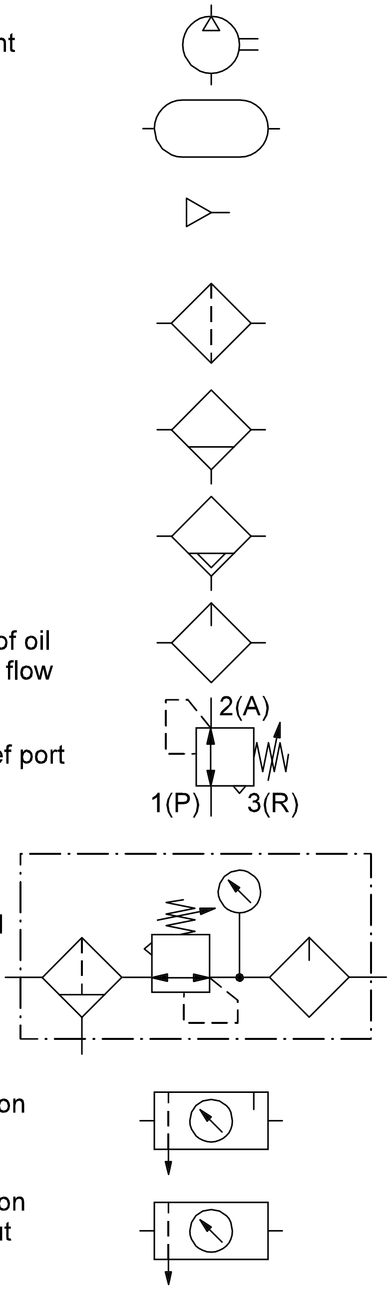
- Filter — Filtration of dirt particles
- Water separator, manually actuated
- Water separator, automatic
- Lubricator — Metered quantities of oil are added to the air flow
- Pressure regulating valve — Adjustable with relief port

**Combined symbols**

- Service unit — Consisting of water separator, compressed air filter, pressure regulating valve, pressure gauge and lubricator

  Simplified representation of a service unit.

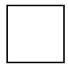
  Simplified representation of a service unit without lubricator.



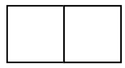
### *Graphical symbols for valves*

The symbols for pneumatic valves are composed of one or more squares (Fig. 6.12).

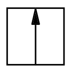
Switching positions are represented by squares



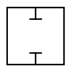
The number of squares corresponds to the number of switching positions



Lines indicate flow paths, arrows indicate flow direction



Closed ports are represented by two lines drawn at right angles to each other



Connecting lines for supply air and exhaust air are drawn on the outside of a square

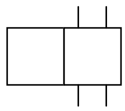


*Fig. 6.12: Building blocks for valve symbols*

*Graphical symbols for directional control valves*

The ports, switching positions and flow path are represented in the graphical symbol of a directional control valve (Fig. 6.13). In the case of an electrically actuated directional control valve the ports are drawn at the switching position assumed by the valve when the electrical power supply is switched off.

*Fig. 6.13: Directional control valves: ports and switching positions*

Number of ports

Number of switching positions

2/2 – way valve in flow position

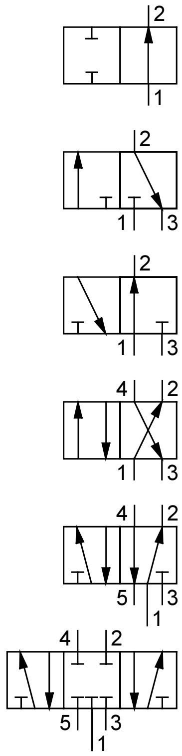
3/2 – way valve in closed position

3/2 – way valve in flow position

4/2 – way valve
Flow from 1 → 2 and from 4 → 3

5/2 – way valve
Flow from 1 → 2 and from 4 → 5

5/3 – way valve
Closed in mid-position



*Types of directional control valve actuation*

The following information is required in order to fully represent a directional control valve in a pneumatic circuit diagram:

- Basic type of valve actuation
- Reset method
- Pilot control (if applicable)
- Additional forms of actuation (such as manual override, if available)

Each actuation symbol is drawn on the side of the switching position corresponding to its direction of action.

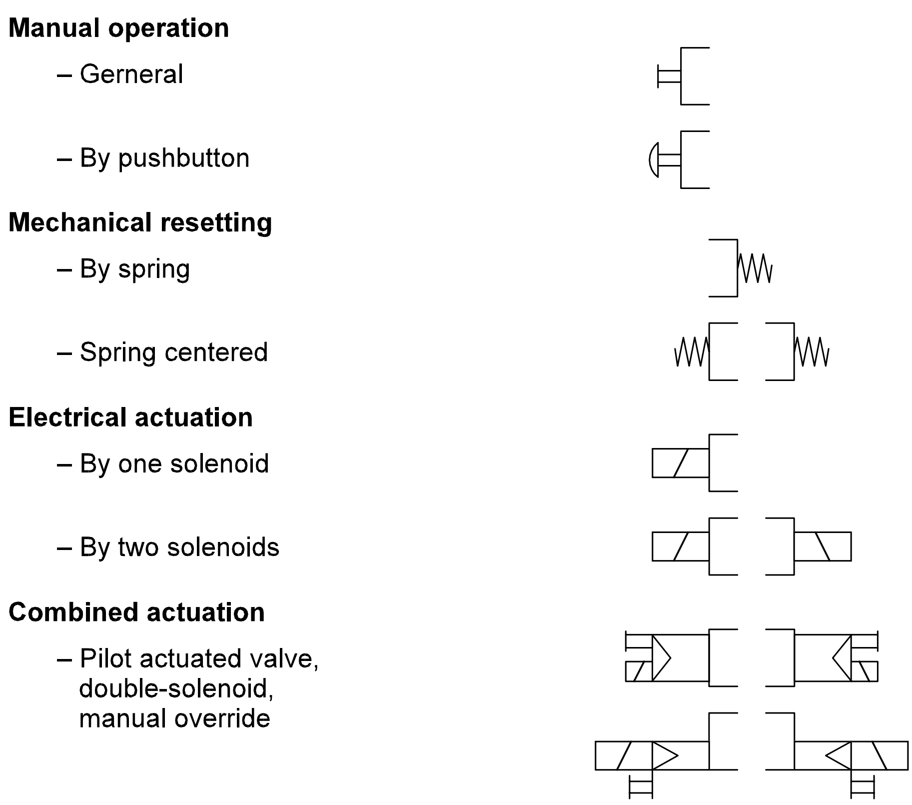



*Fig. 6.14: Types of actuation for electropneumatic directional control valves*

*Designation of ports and actuation on directional control valves*

In order to prevent incorrect connection of tubing on directional control valves, the valve ports are identified in accordance with ISO 5599-3 both on the valve itself and on the circuit diagram. Where actuation is by compressed air, the effect of actuation is represented in the circuit diagram either on the corresponding pilot line or, in the case of valves with internal pilot air supply, alongside the actuation symbol. A summary of the relevant details is shown in Table 6.2.

*Table 6.2: Designation of working lines and pilot lines on directional control valves*

| *Connection* | *Function* | *Designation* |
|---|---|---|
| Working lines (all valve types) | Supply port<br>Working ports<br>Exhaust ports | 1<br>2, 4<br>3, 5 |
| Pilot lines/actuation for pilot actuated or pneumatically actuated directional control valves | Close supply port<br>Connection between ports 1 and 2<br>Connection between ports 1 and 4<br>Auxiliary pilot air | 10<br>12<br>14<br>81, 91 |

Examples of graphical symbols of directional control valves are shown in Figs. 4.2, 4.3, 4.5 to 4.7 and 4.9, and in Tables 4.1 to 4.3.

*Graphical symbols for non-return valves, flow control valves and quick exhaust valves*

Non-return valves determine the direction of flow, and flow control valves determine the flow rate in a pneumatic control circuit. With quick exhaust valves it is possible to achieve particularly high motion speeds with pneumatic drives because the compressed air can escape virtually unthrottled. The associated graphical symbols are shown in Fig. 6.15.

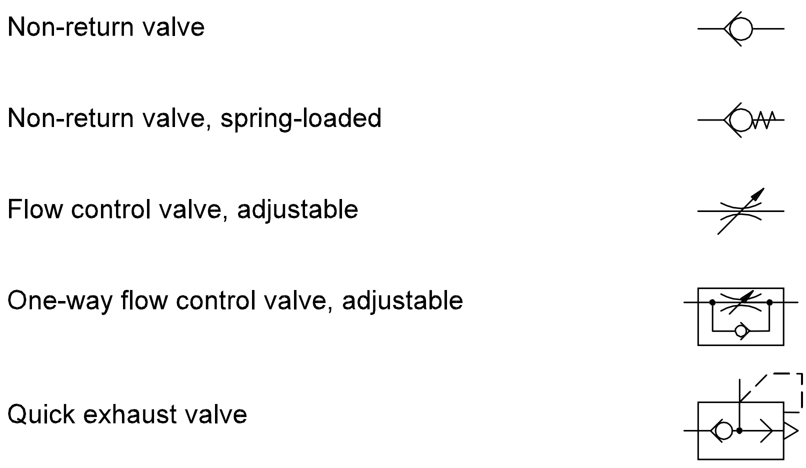



*Fig. 6.15:*
*Graphical symbols for non-return valves, flow control valves and quick exhaust valve*

*Graphical symbols for pressure control valves*

Pressure control valves are used for the following functions:

- Maintaining a constant pressure (pressure regulating valve)
- Pressure-dependent changeover (pressure sequence valve)

The graphical symbols for pressure control valves are shown in Fig. 6.16.

As an alternative to a pressure control valve in an electropneumatic control system it is also possible to use a directional control valve that is actuated by a signal from a pressure switch or pressure sensor.

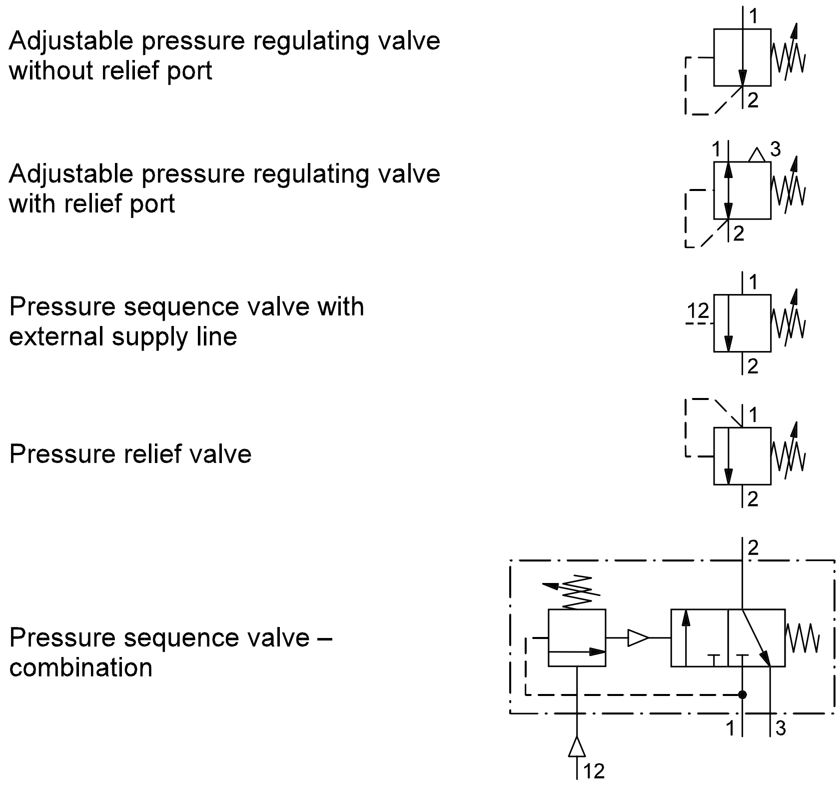



*Fig. 6.16: Graphical symbols for pressure control valves*

*Graphical symbols for proportional valves*

Proportional valves serve the purpose of quickly and accurately adjusting the pressure or flow rate to the required value with an electrical signal. Applications and the mode of operation are explained in Section 9.9. The graphical symbols for proportional valves are shown in Fig. 6.17.

5/3–way proportional valve

5/3–way proportional valve with double-acting linear motor and valve slide positional control

Pilot actuated proportional pressure valve

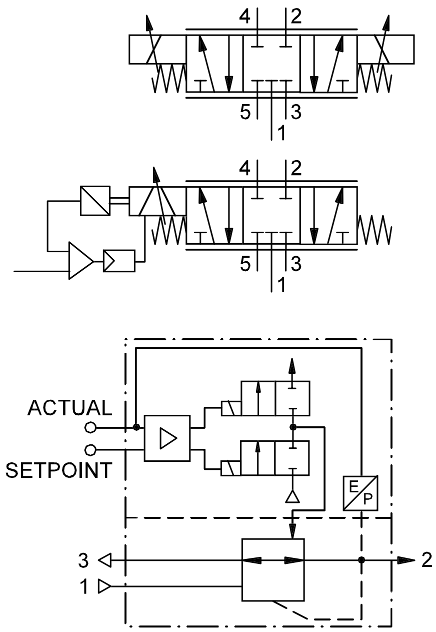



*Fig. 6.17: Graphical symbols for proportional valves*

*Graphical symbols for power components*

The following power components are used in electropneumatic control systems:

- Pneumatic cylinders for linear motions (single-acting cylinders, double-acting cylinders, rodless cylinders (linear drive units) etc.; see Section 9.2)
- Swivel cylinders
- Motors for continuous rotary motions (such as vane motor for compressed air screwdriver)
- Vacuum generator units

The graphical symbols for pneumatic power components are shown in Fig. 6.18.

*Fig. 6.18:*
*Graphical symbols for pneumatic power components*

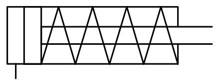
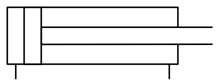
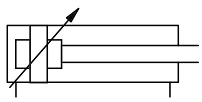
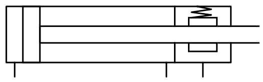
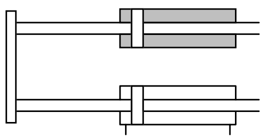
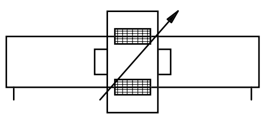
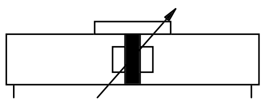
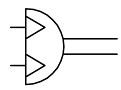
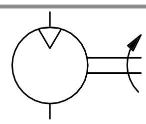
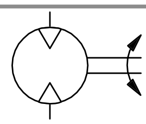
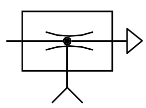
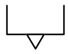
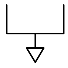
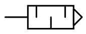
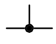
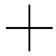
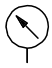
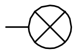
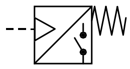
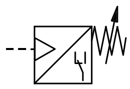
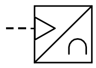
| Function | Description | Symbols |
|---|---|---|
| Single-acting cylinder | Extend by pneumatic power.<br>Return by return spring. |  |
| Double-acting cylinder | Extend and return by pneumatic power. |  |
| Double-acting cylinder | Adjustable end position cushioning for forward and reverse stroke. |  |
| Double-acting cylinder with clamping unit | Mechanical clamping unit with pneumatic unlocking. |  |
| Double-acting cylinder with hydraulic slave cylinder | Cylinder is pneumatically controlled.<br>The hydraulic slave cylinder provides for even movement. |  |
| Rodless cylinder with adjustable end position cushioning | Usually cylinder with long stroke lengths.<br>Power transmission by permanent magnet. |  |
| Rodless cylinder with adjustable end position cushioning | Power transmission by mechanical means. |  |
| Vane drive, pneumatic | Rotary drive with limited swiveling range. |  |
| Compressed air motor, pneumatic | Compressed air motor with constant capacity and one direction of rotation. |  |
| Compressed air motor | Pneumatic motor with two directions of rotation. |  |
| Vacuum generator | Vacuum input via ejector. |  |

*Fig. 6.19:*
*Other graphical symbols for pneumatic and electropneumatic components*

| | |
|---|---|
| Exhaust port with no facility for connection |  |
| Exhaust port with thread for connection |  |
| Silencer |  |
| Line connection |  |
| Crossing lines |  |
| Pressure gauge |  |
| Visual indicator |  |
| Pressure switch – P/E-converter |  |
| Pressure switch,  adjustable with changeover switch |  |
| Pressure sensor (analogue electrical output signal) |  |

*Arrangement of graphical symbols in a pneumatic circuit diagram*

The layout of a pneumatic circuit diagram, the arrangement of the graphical symbols and the identification and numbering of the components are standardized according to DIN/ISO 1219-2. In the case of an electropneumatic control system, the symbols are arranged in the circuit diagram as follows:

- Power components at the top
- Beneath those, valves with an influence on speed (such as flow control valves, non-return valves)
- Beneath those, control elements (directional control valves)
- Power supply at the bottom left

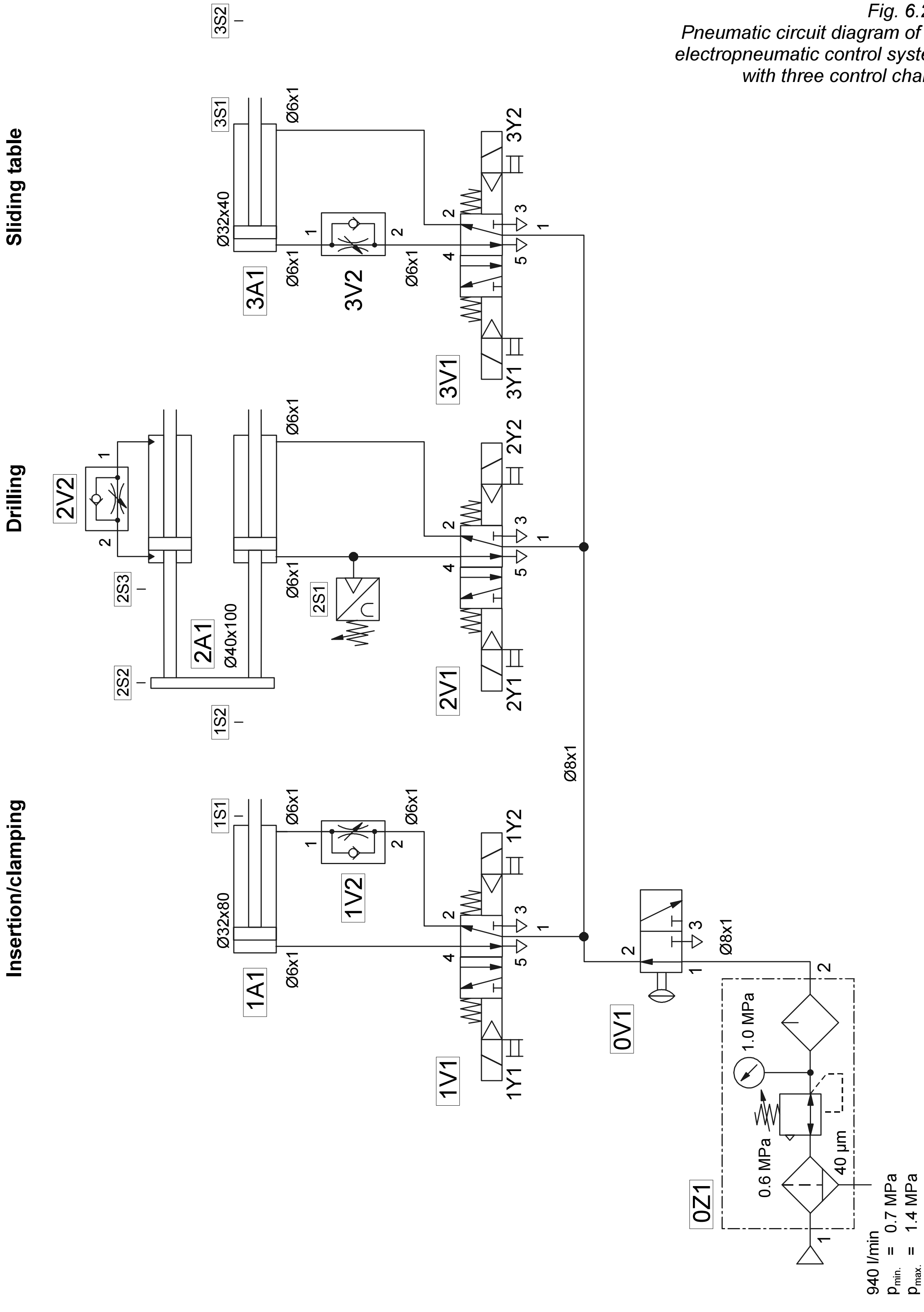
For control systems with several power components, the symbols for the various drive units are drawn alongside each other. The symbols for the associated valves are arranged beneath each drive symbol (Fig. 6.20).

*Positions of cylinders and directional control valves*

All components in a pneumatic circuit diagram are represented as if the electrical signal control section is in the de-energized condition. This means:

- The solenoid coils of the directional control valves are not actuated.
- The cylinder drives are in the initial position.

Fig. 6.20:
*Pneumatic circuit diagram of an electropneumatic control system with three control chains*



*Identification code for components*

Every component (apart from connection lines and connecting tubes) is identified in accordance with Fig. 6.21. The identification code contains the following information:

- Unit number
  (digit; may be omitted if the entire circuit consists of one unit)
- Circuit number (digit, mandatory)
- Component identification (letter, mandatory)
- Component number (digit, mandatory)

The identification code should be enclosed within a frame.

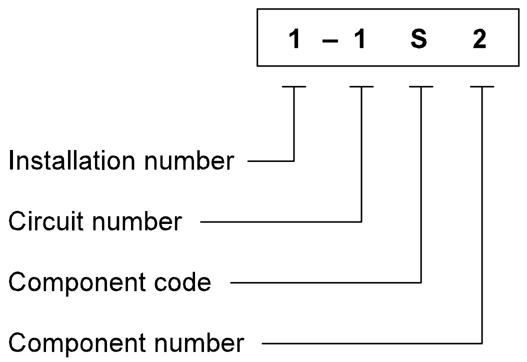



*Fig. 6.21:*
*Identification code for components in pneumatic circuit diagrams*

*Unit number*

If there are several units and electropneumatic control systems in a particular plant, the unit number helps to clarify the assignment between circuit diagrams and control systems. All pneumatic components of a control system (unit) are identified by the same unit number. In the example circuit diagram (Fig. 6.20) the unit number is not shown in the identification code.

*Circuit number*

Preferably all components belonging to the power supply should be identified by circuit number 0. The other circuit numbers are then assigned to the various control chains (= circuits). The following assignments apply to the control system shown in Fig. 6.20.

- Power supply and main switch: number 0
- Control chain "Insertion/clamping": circuit number 1
- Control chain "Drilling": circuit number 2
- Control chain "Sliding table": circuit number 3

*Component identification and number*

Every component in an electropneumatic control system is assigned a component identification (identification codes: Table 6.3) and a component number in the circuit diagram. Within each circuit, components with the same component identification are numbered consecutively from the bottom to the top and from left to right. The valves in the "Insertion/clamping" control chain (circuit 1 in the circuit diagram in Fig. 6.26) are therefore identified as follows:

- Directional control valve: 1V1 (circuit number 1, component identification V, component number 1)
- One-way flow control valve: 1V2 (circuit number 1, component identification V, component number 2)

*Table 6.3: Identification codes for components in a pneumatic circuit diagram*

| *Components* | *Identification* |
|---|---|
| Compressors | P |
| Power components | A |
| Drive motors | M |
| Sensors | S |
| Valves | V |
| Valve coils | Y* |
| Other components | Z** |

* national supplement in German standard
** or any other letter not included in the list

*Technical information*

In order to facilitate assembly of a control system and the replacement of components when carrying out maintenance, certain components in a pneumatic circuit diagram are identified by additional information (see Fig. 6.20):

- Cylinders:
  piston diameter, stroke and function (such as "Insertion/clamping")
- Compressed air supply:
  supply pressure range in megapascals or bar, rated volumetric flow rate in l/min
- Filters:
  nominal size in micrometers
- Tubes:
  nominal internal diameter in mm
- Pressure gauges:
  pressure range in megapascals or bar

## 6.4 Electrical circuit diagram

The electrical circuit diagram of a control system shows how the electrical control components are interconnected and how they interact. Depending on the task definition, the following types of circuit diagram are used in compliance with DIN/EN 61082-2:

- Overview diagram
- Function diagram
- Circuit diagram

*Overview diagram*

An overview diagram provides an overview of the electrical apparatus of a relatively large system, for example a packing machine or an assembly unit. It shows only the most important interdependencies. The various subsystems are shown in greater detail in other diagrams.

*Function diagram*

A function diagram illustrates the individual functions of a system. No account is taken of how these functions are executed.

*Circuit diagram*

A Circuit diagram shows the details of the design of systems, installations, apparatus etc. It contains:

- Graphical symbols for the items of equipment
- Connections between these items
- Equipment identifiers
- Terminal identifiers
- Other details necessary for tracing the paths
  (signal identifiers, notes on the representation location)

*Consolidated and distributed representation in a circuit diagram*

If consolidated representation is used for a circuit diagram, each device is represented as a single coherent symbol, i.e. for example even a relay that has more than one normally open and normally closed contact.

If distributed representation is used for a circuit diagram, the various components of a device may be drawn at different locations. They are arranged in such a way as to obtain a clear representation with straight lines and few line intersections. The normally closed and normally open contacts of a relay, for example, can be distributed throughout the circuit diagram as appropriate.

*Electrical circuit diagram of an electropneumatic control system*

A circuit diagram with distributed representation is used to represent the signal control section in electropneumatics. It is only if control systems are very large that an overview diagram or function diagram is prepared in addition.

In practice, the term "electrical circuit diagram of a electropneumatic control system" always refers to the circuit diagram within the meaning of DIN/EN 61082-2.