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Electropneumatics

Basic Level

FESTO

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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 In the signal control section, the relay has increasingly been replaced by the programmable logic controller in order to meet the growing demand for more flexibility.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.

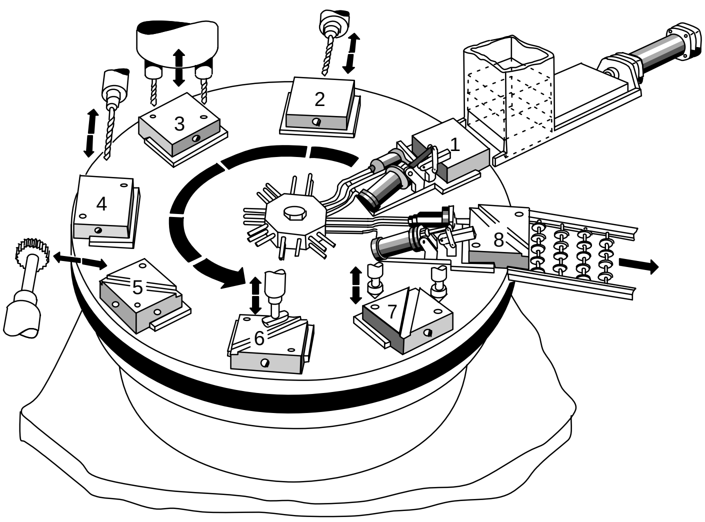


Fig. 1.2:
Processing station

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).

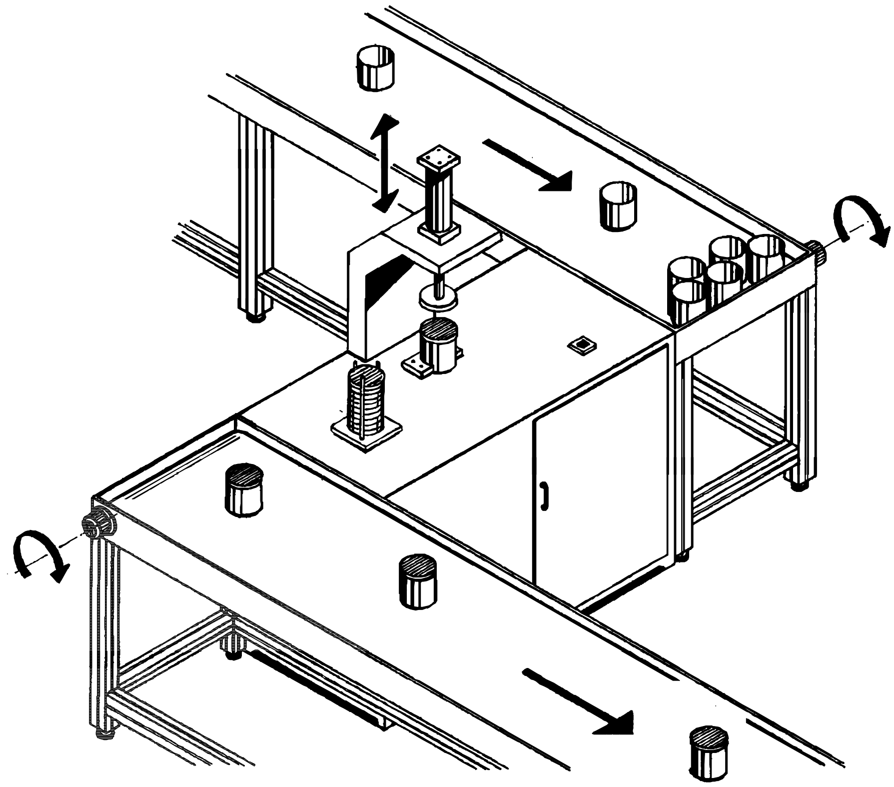
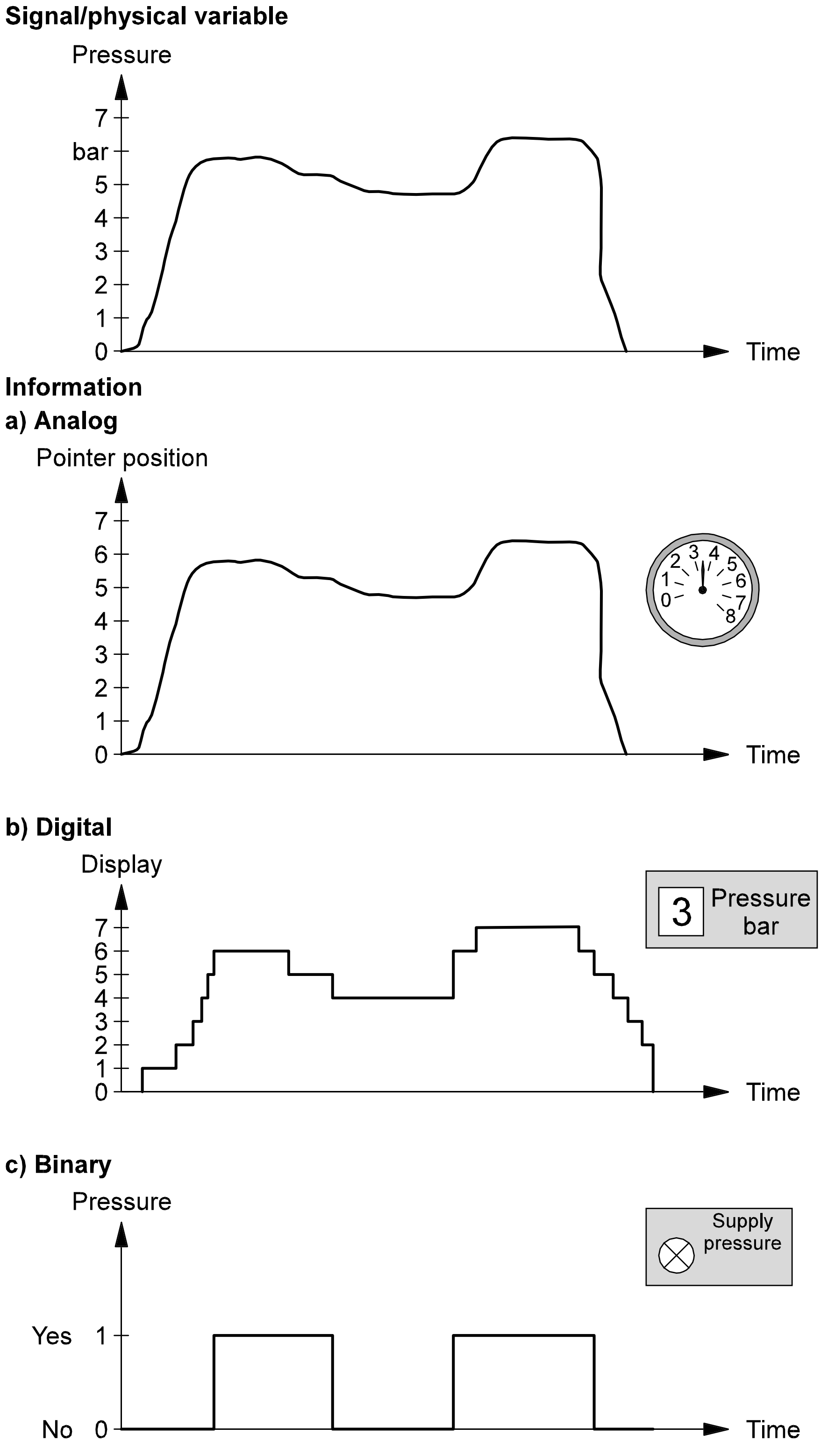


Fig. 1.3:
Assembly device for mounting lids on cans

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).

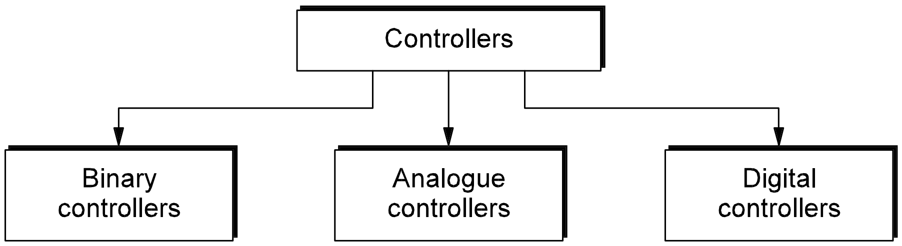


Fig. 1.5: Classification of controllers by type of information representation

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.

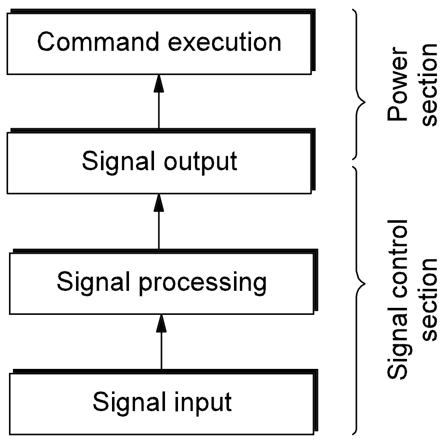


Fig. 1.6: Signal flow in a control system

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.

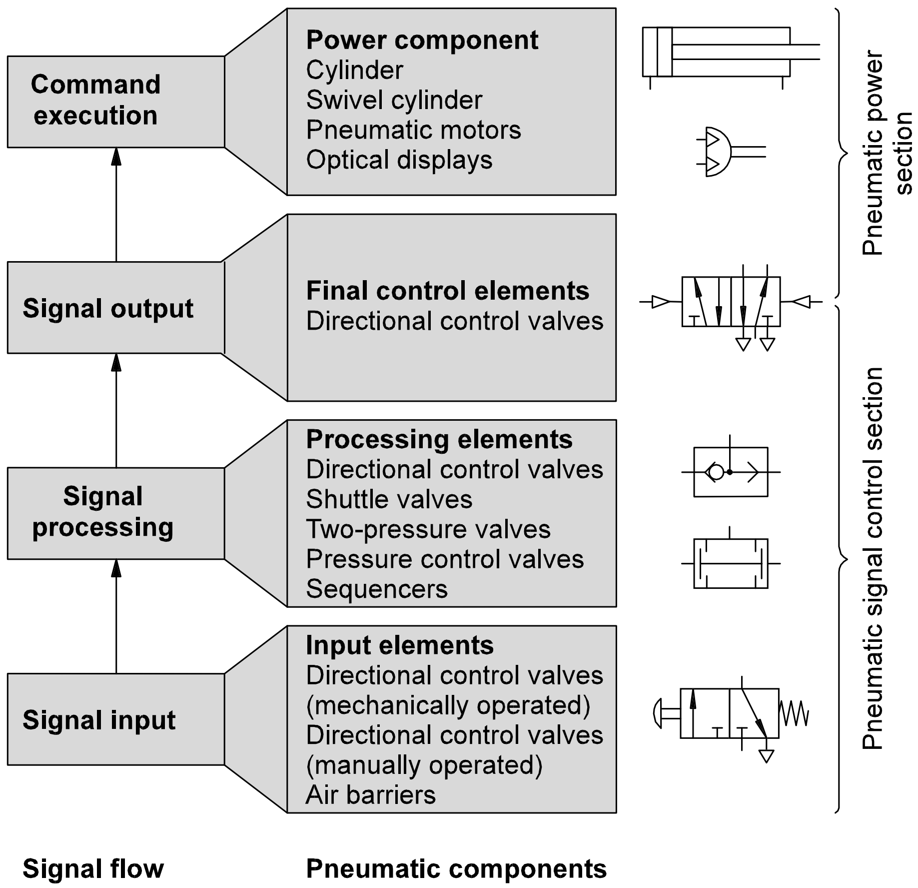


Fig. 1.7:
Signal flow and components of a pneumatic control system

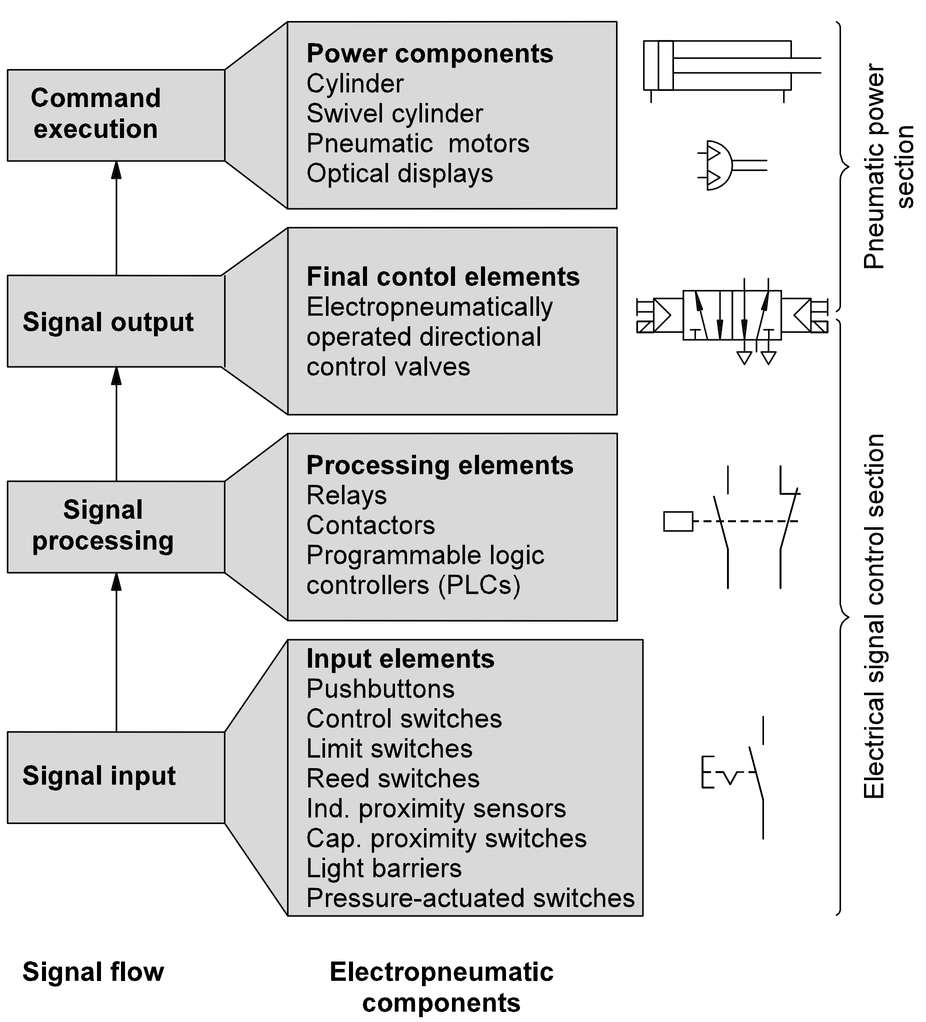


Fig. 1.8:
Signal flow and components of an electropneumatic control system

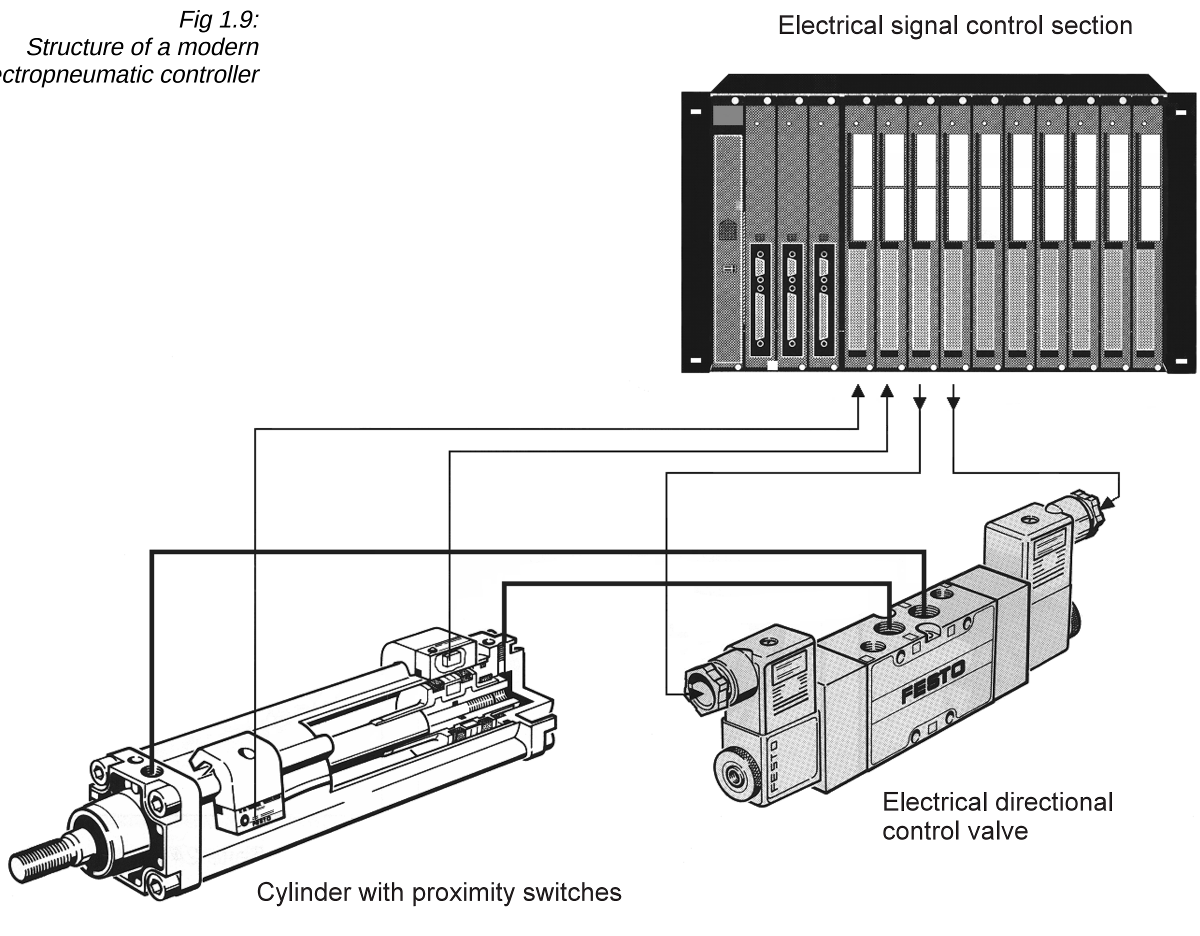
In contrast to a purely pneumatic control system, electropneumatic controllers are not shown in any single overall circuit diagram, but in two separate circuit diagrams - one for the electrical part and one for the pneumatic part. For this reason, signal flow is not immediately clear from the arrangement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

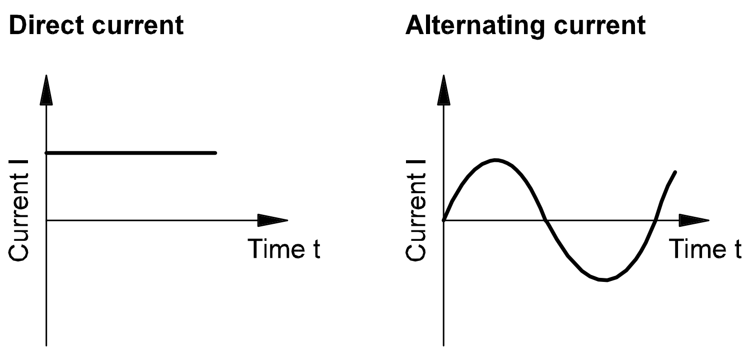


Fig. 2.2 shows a simple DC circuit consisting of a voltage source, electrical lines, a control switch, and a load (here a lamp).

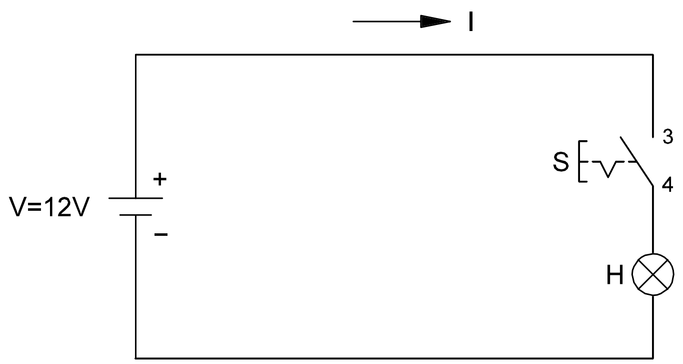


Fig. 2.2:
DC circuit

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 = Power;	Unit: Watt (W)
$P = V \cdot I$	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:

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

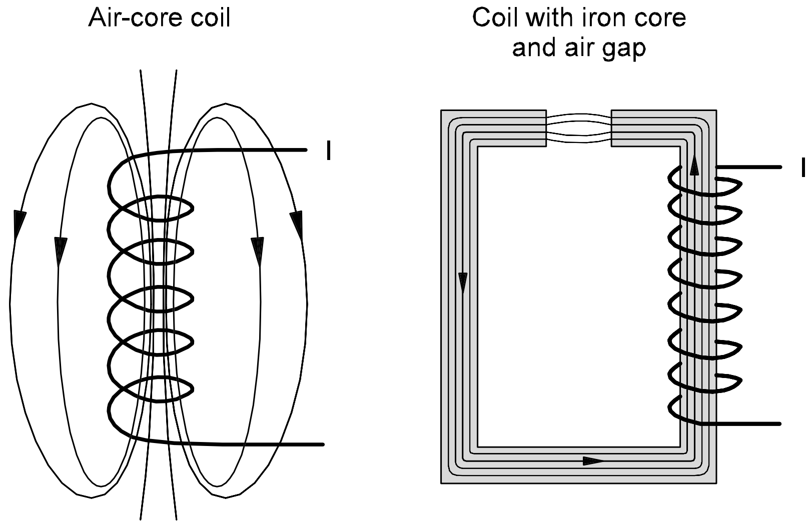
The electrical power is the product of current and voltage:

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

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

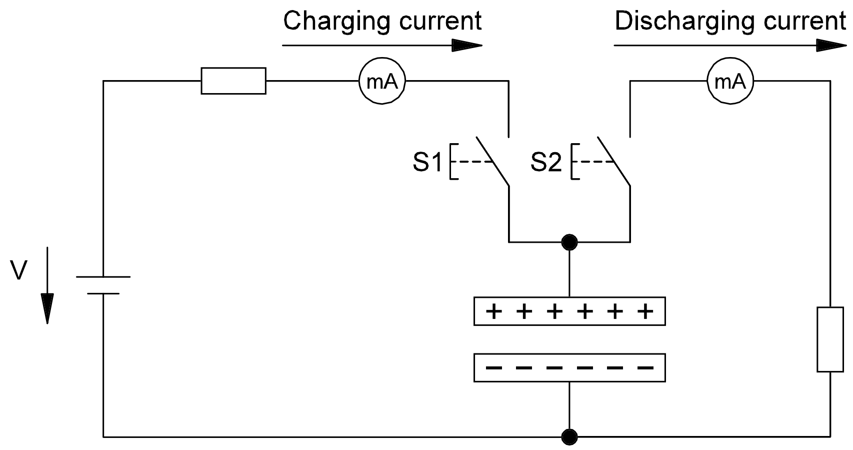
A capacitor consists of two metal plates with an insulating layer (dielectric) between them. If the capacitor is connected to a DC voltage source (closing the switch S1 in Fig. 2.6), a charging current flows momentarily. Both plates are electrically charged by this. If the circuit is then interrupted, 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.

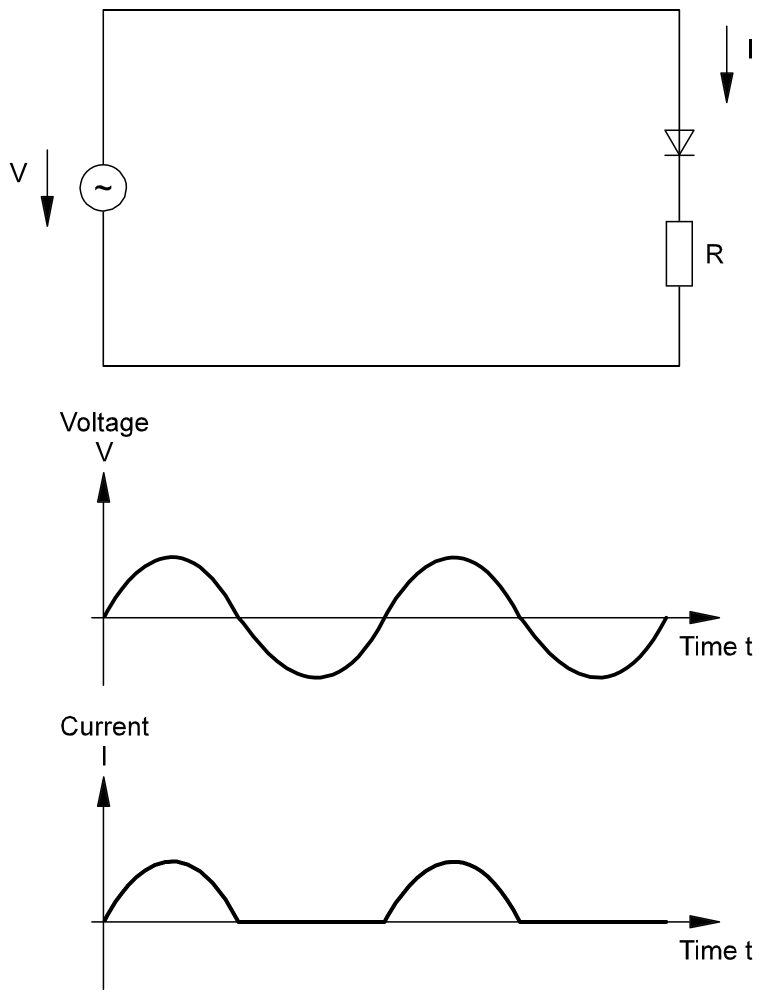


Fig. 2.7:
Function of a diode

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

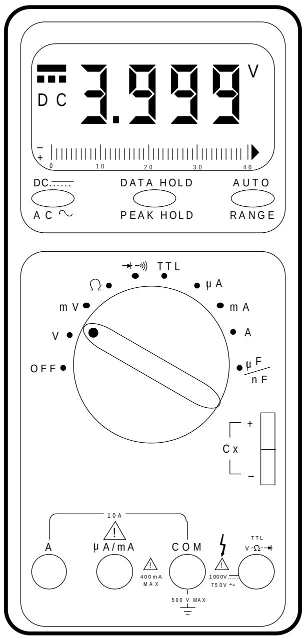
Electrical currents, voltages and resistances are normally measured with multimeters. These devices can be switched between various modes:

- 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

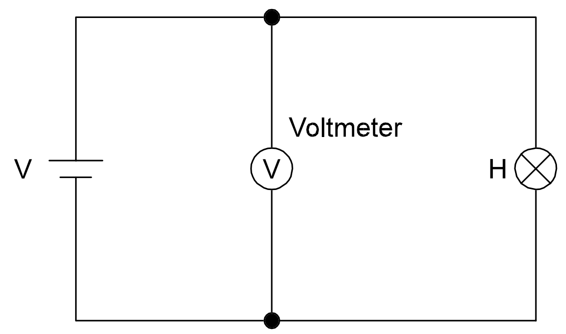
Follow the following steps when making measurements of electrical circuits.

- 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

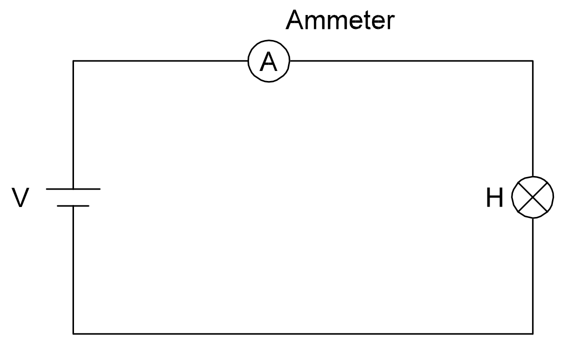


Current measurement

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.

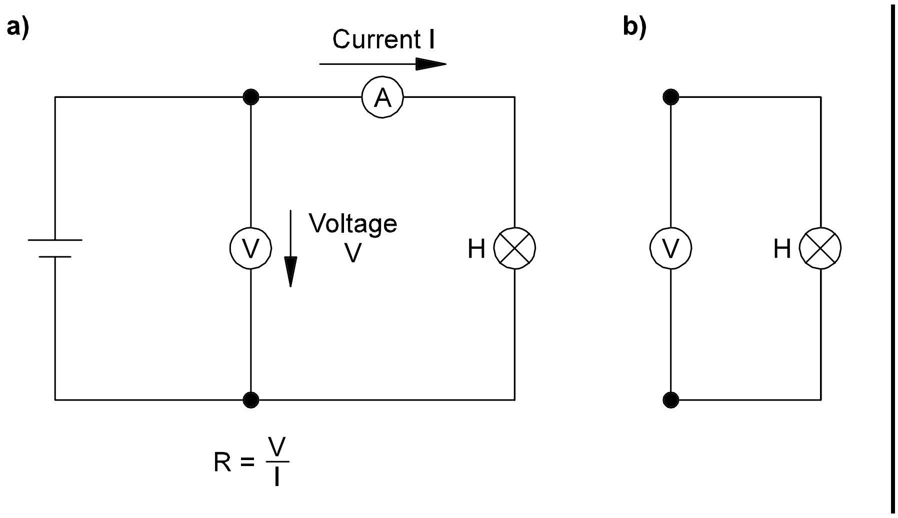


Fig. 2.11: Measuring resistance

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.

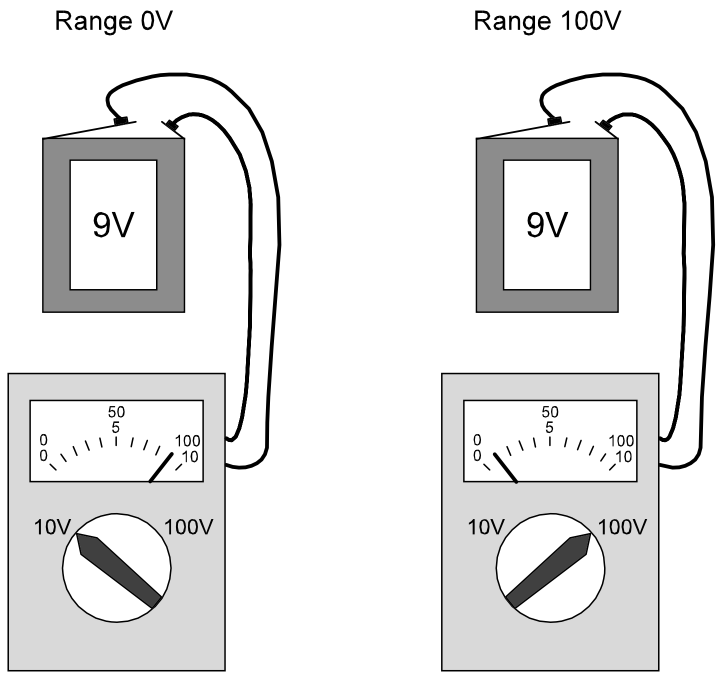


Fig. 2.12:
Measuring battery voltage (with different range settings)

Chapter 3

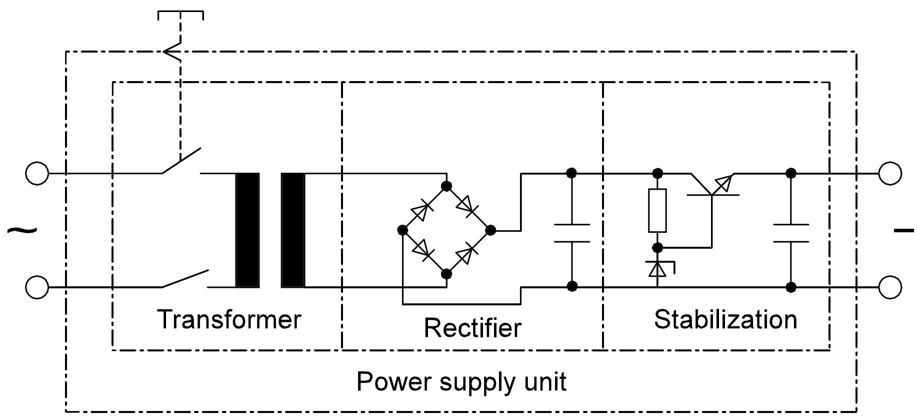
Components and assemblies in the electrical signal control section

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 electro-pneumatic 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.

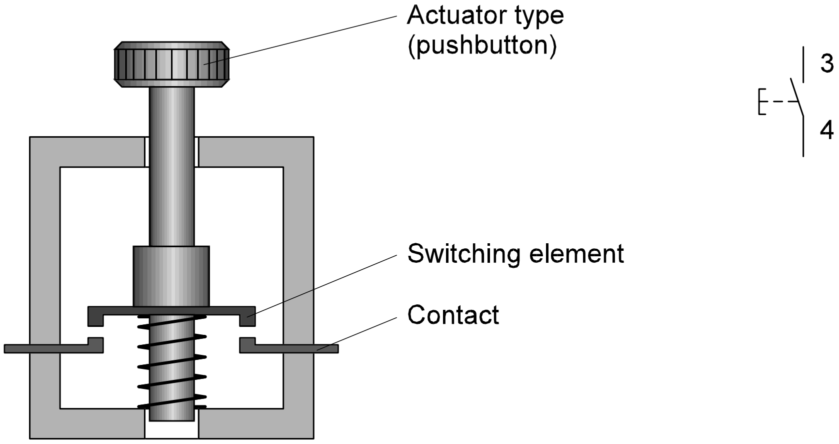
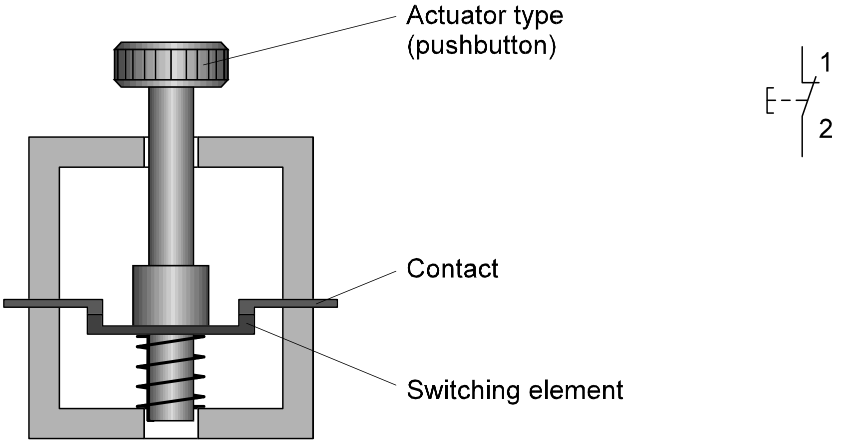


Fig. 3.2:
Normally open contact (make)
– section and symbol

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.

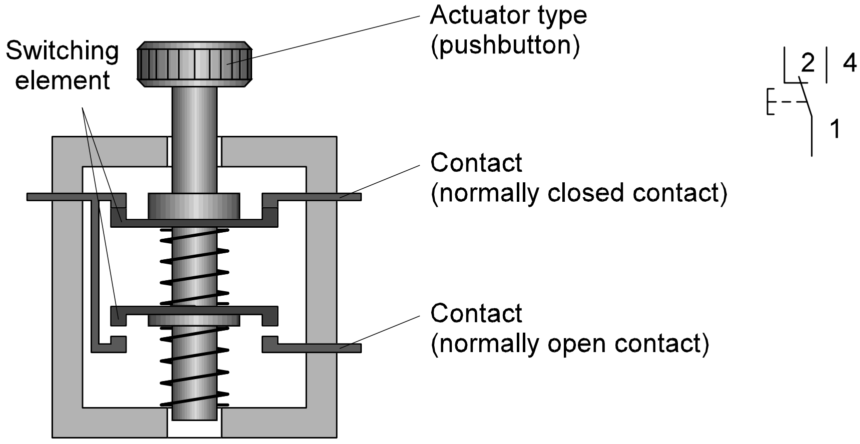
Fig. 3.3: Normally open contact (break) – section and symbol



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.

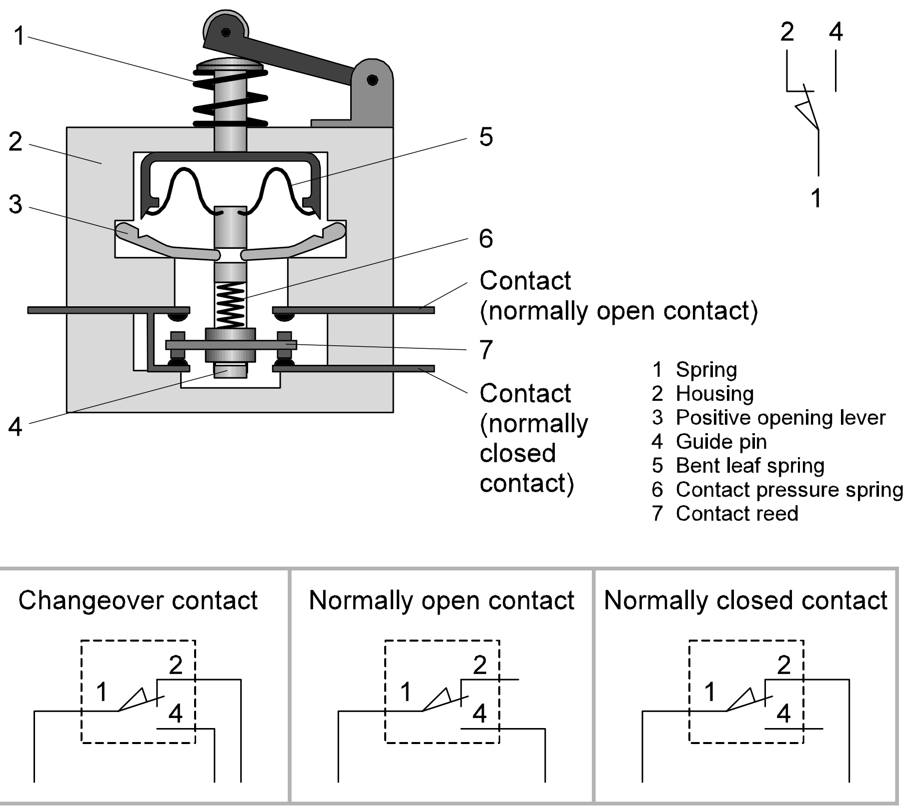


Fig. 3.5:
Mechanical limit switch: construction and connection possibilities

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:

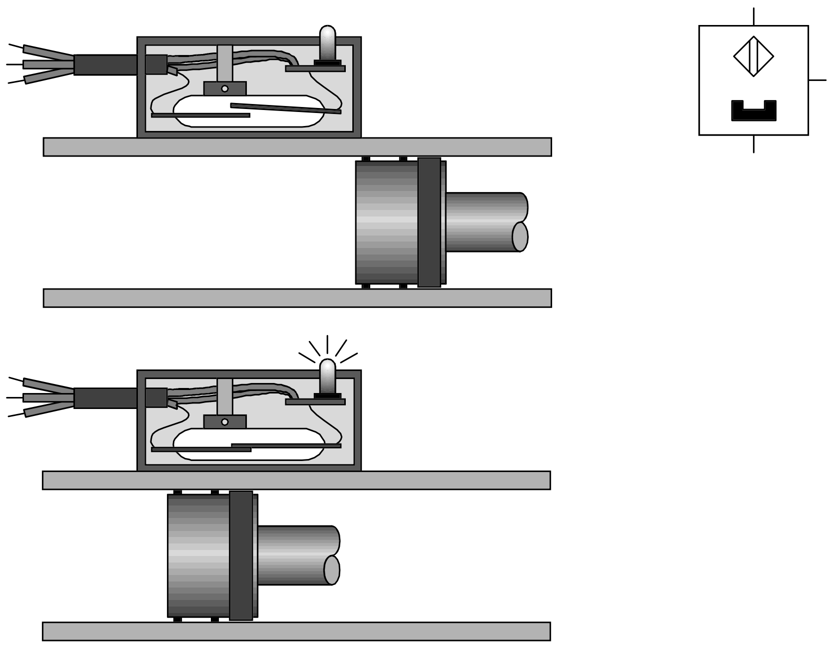
- Reed switch
- Inductive proximity switch
- Capacitive proximity switch
- Optical proximity switch

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.

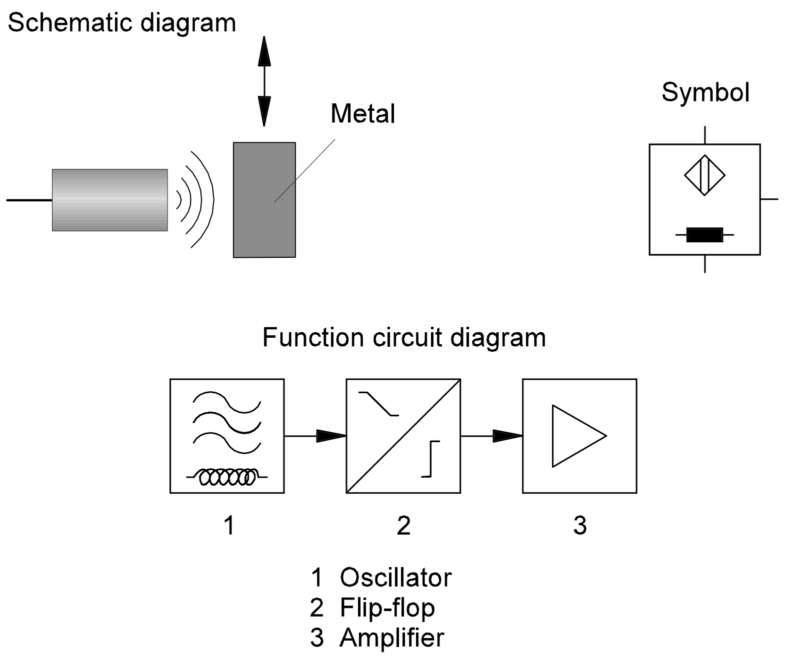
- In positive switching sensors, the output voltage is zero if no part is detected in the proximity. The approach of a workpiece or machine part leads to switchover of the output, applying the supply voltage.
- In negative switching sensors, the supply voltage is applied to the output if no part is detected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

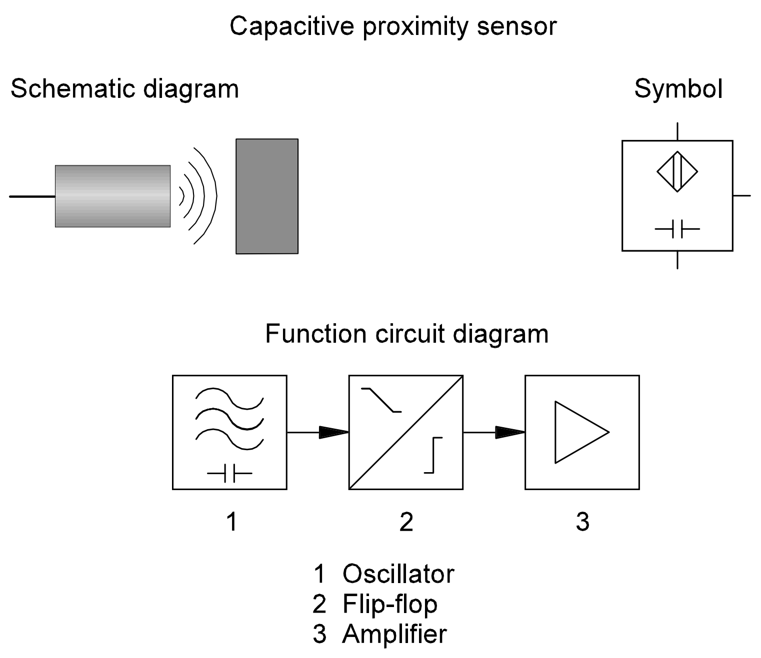


Fig. 3.8:
Capacitive proximity sensor

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.

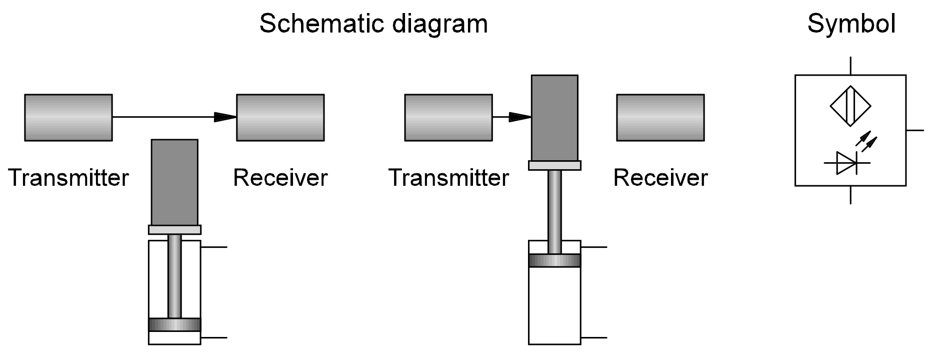
Three different types of optical proximity switch are differentiated:

- 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.

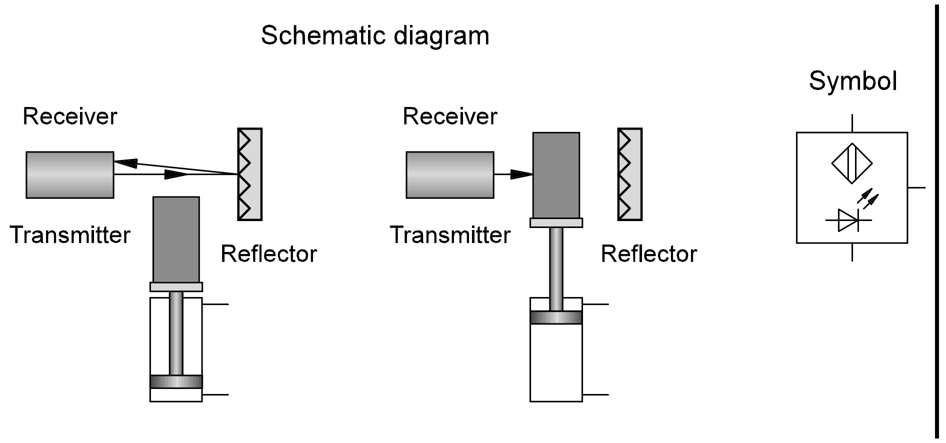


Fig. 3.10:
Reflective light barrier

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).

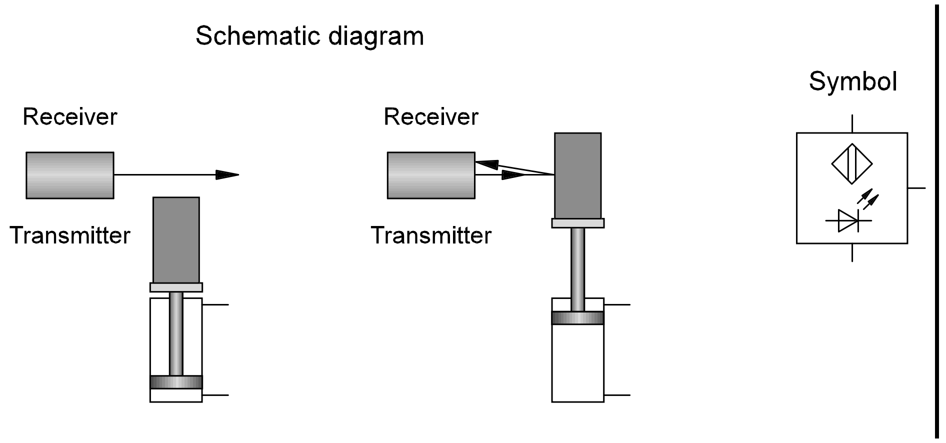


Fig. 3.11
Diffuse reflective optical sensor

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.

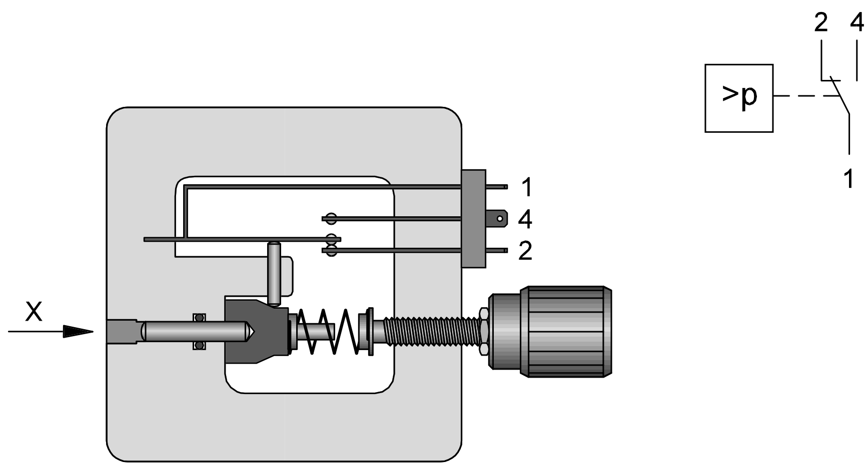


Fig. 3.12: Piston-actuated pressure switch

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

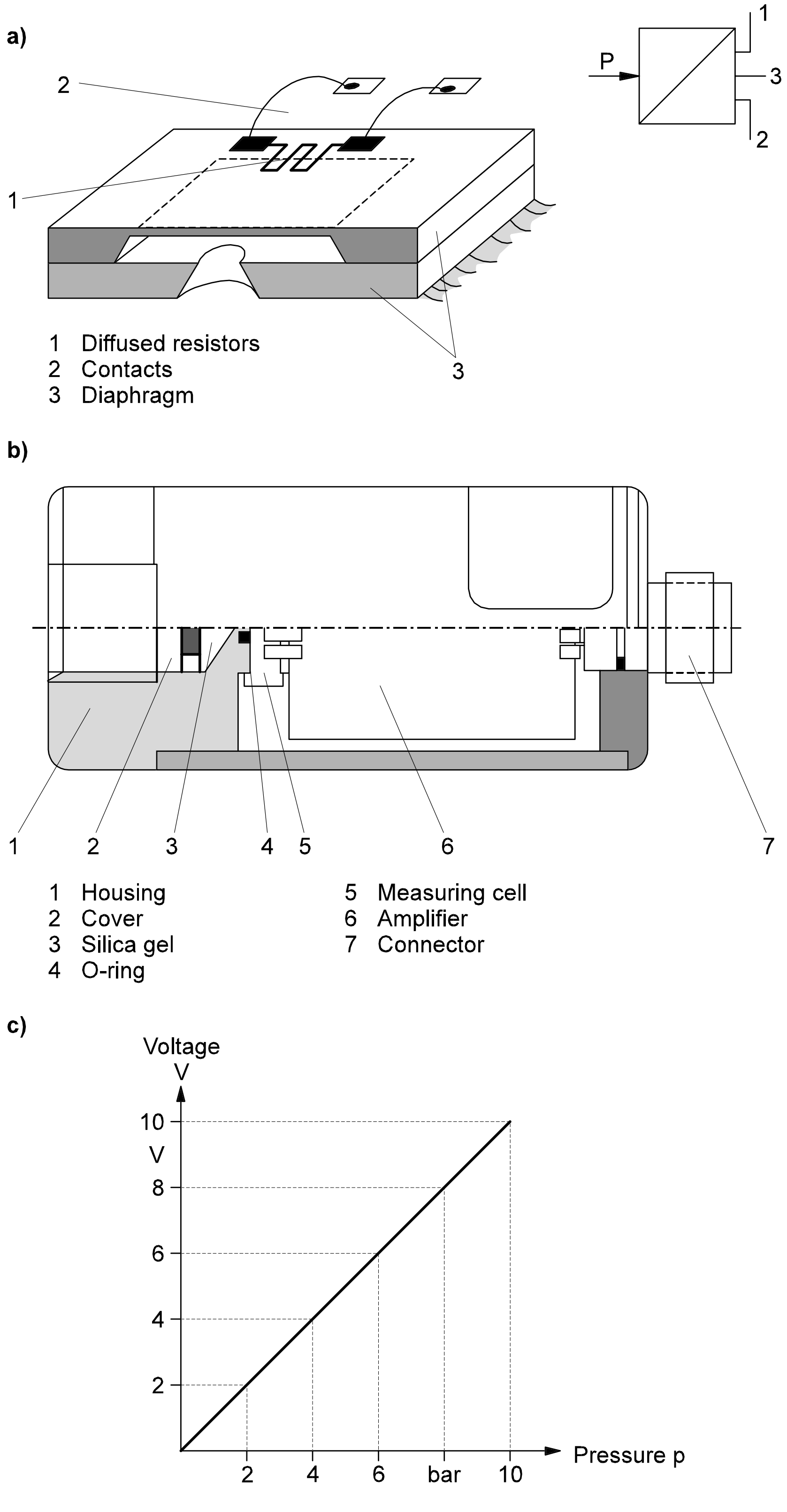
The design and mode of operation of an analogue pressure sensor is demonstrated using the example of the Festo SDE-10-10V/20mA sensor.

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.

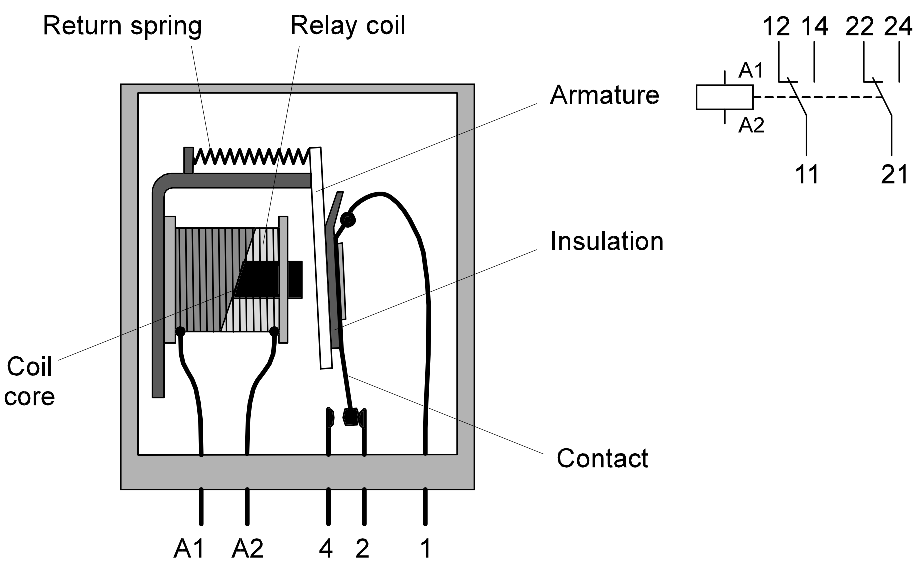


Fig. 3.14: Construction of a relay

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.

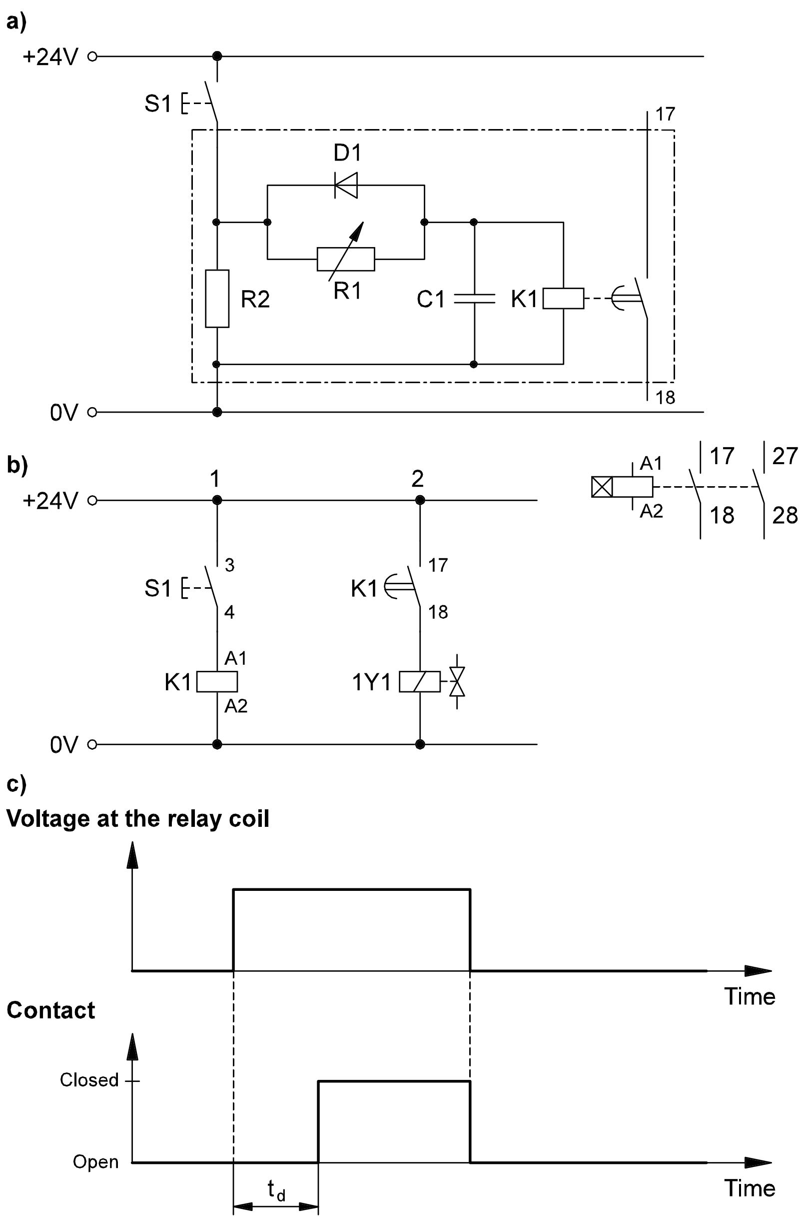


Fig. 3.15
Relay with pull-in delay

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.

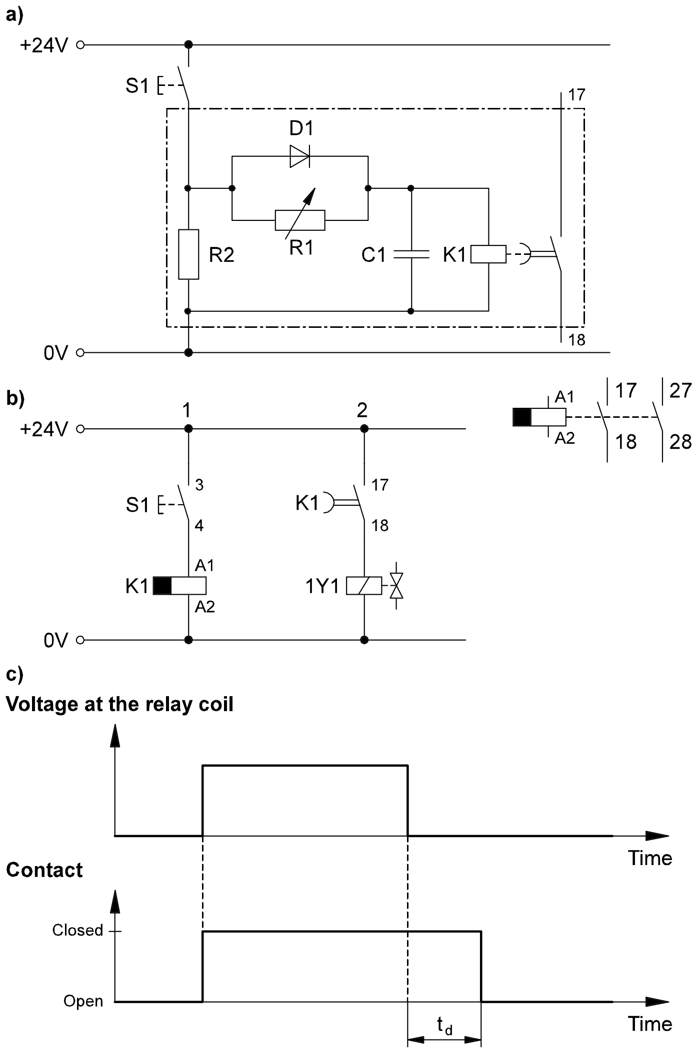


Fig. 3.16:
Relay with drop-out delay

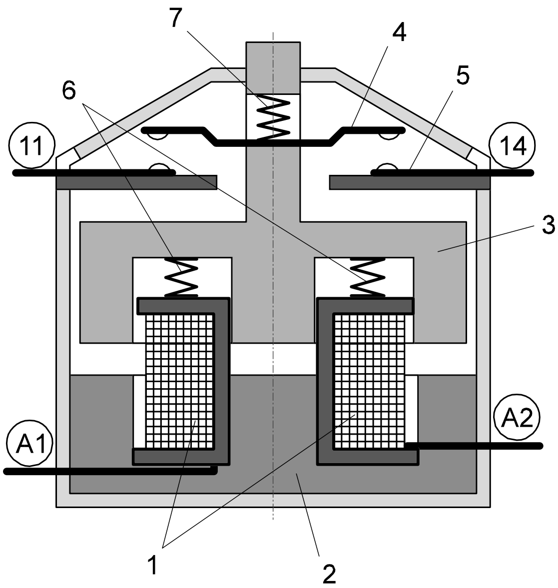
a) Internal construction
b) Circuit diagram
c) Signal behavior

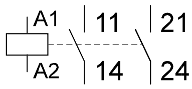
Construction of a contactor

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.





1 Coil
2 Iron core (magnet)
3 Armature
4 Moving switch element with contacts
5 Static switch element with contacts
6 Pressure spring
7 Contact pressure spring

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)

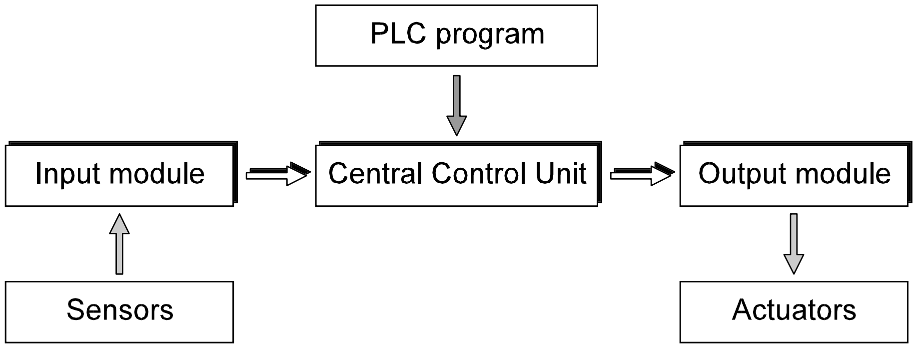


Fig. 3.19:
System components of a PLC

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.

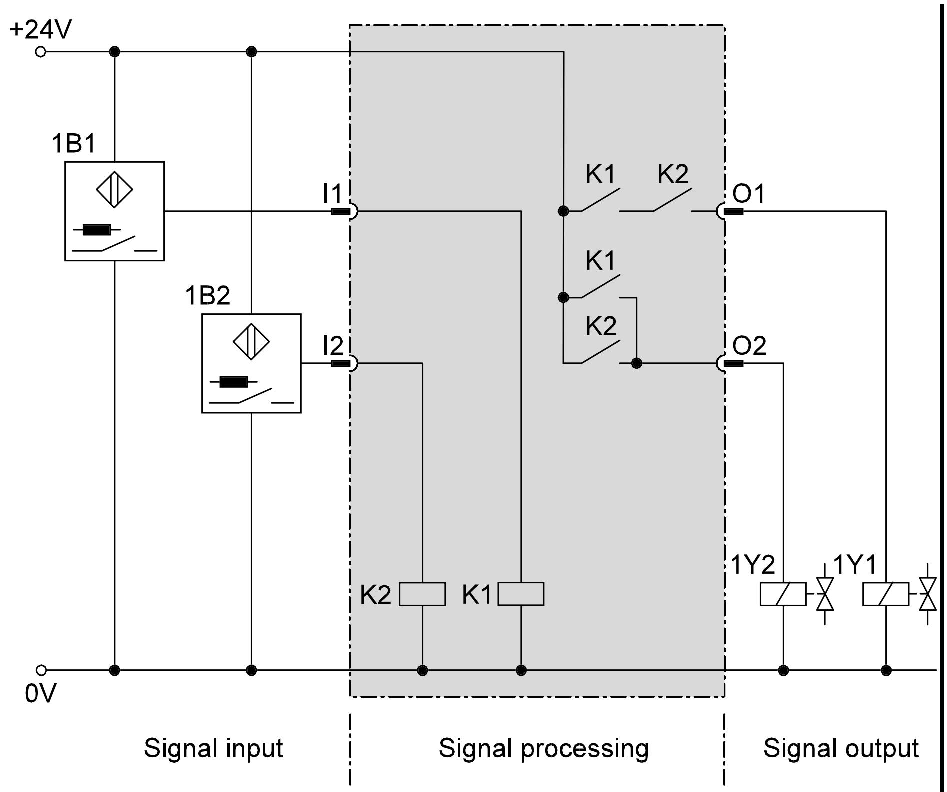


Fig. 3.20.
Signal control section of relay control system (schematic, circuit diagram not compliant with standard)

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)*

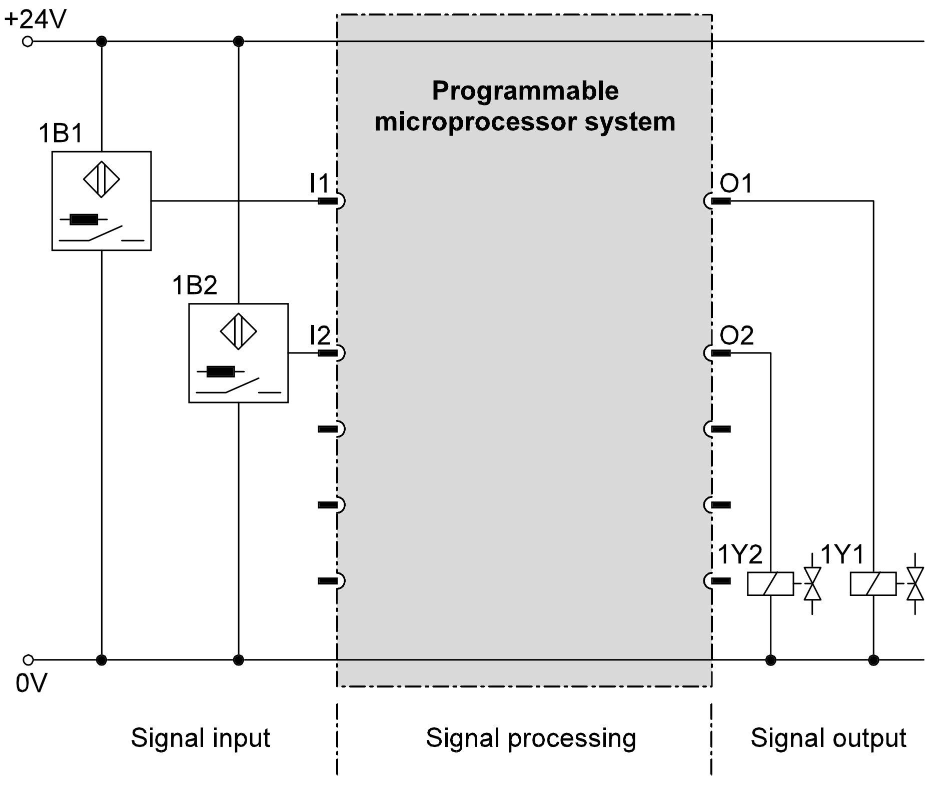


Fig. 3.21 shows the signal control section of an electropneumatic control system in which a PLC is used for signal processing.

- 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.

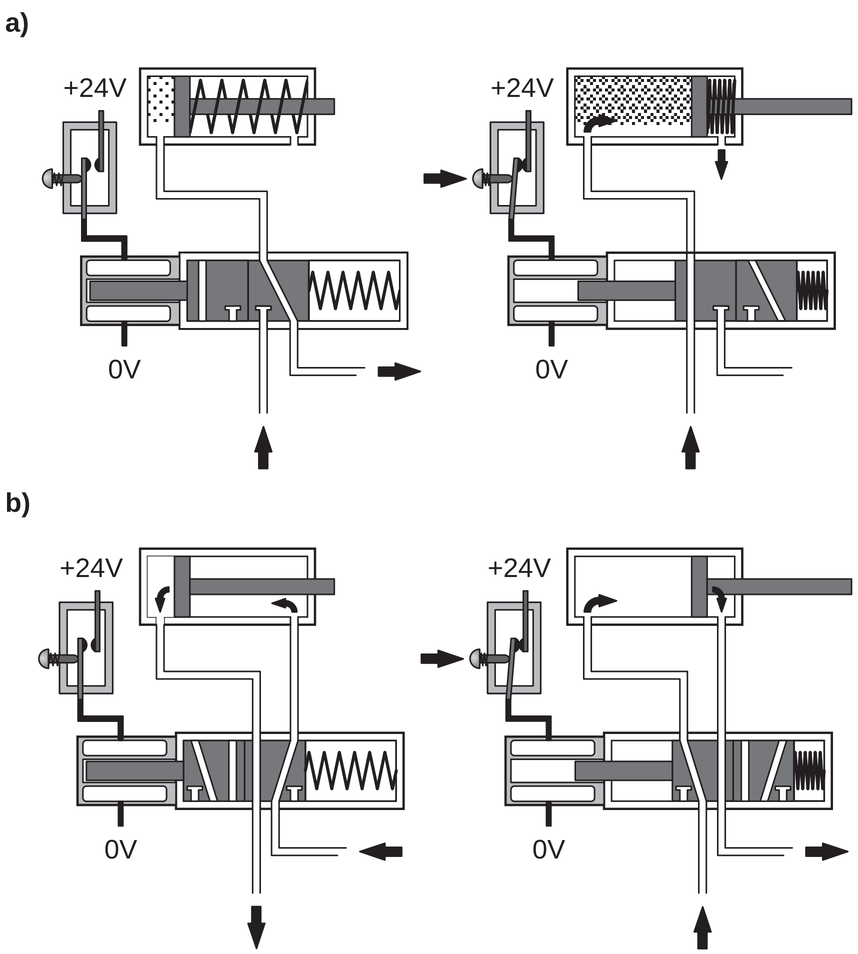


Fig. 4.1: Actuation of a pneumatic cylinder a) Single-acting b) Double-acting

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

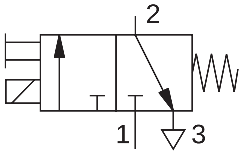
Fig. 4.2 shows two cross-sections of a directly controlled electrically actuated 3/2-way valve.

- 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)



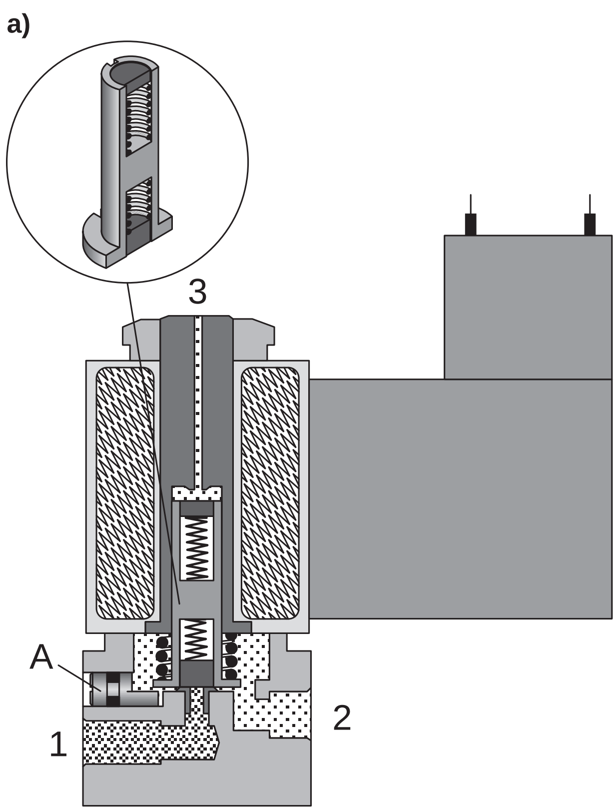
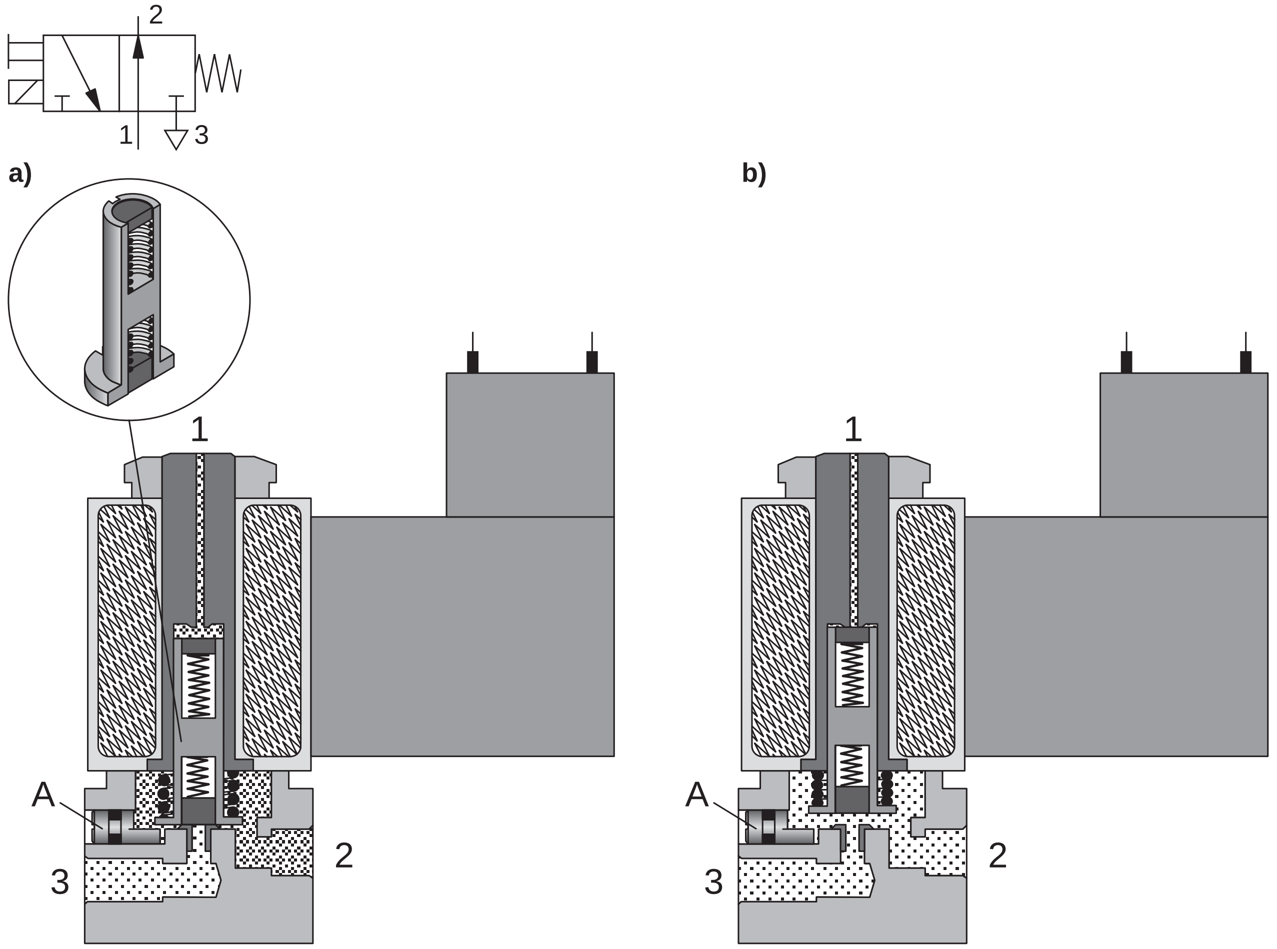


Fig. 4.3 shows an electrically actuated 3/2-way valve, normally open. Fig. 4.3a shows the valve in its initial position, Fig. 4.3b actuated. Compared to the initial position of the closed valve (fig. 4.2) the pressure and exhaust ports are reversed.

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



Pilot controlled directional control valve

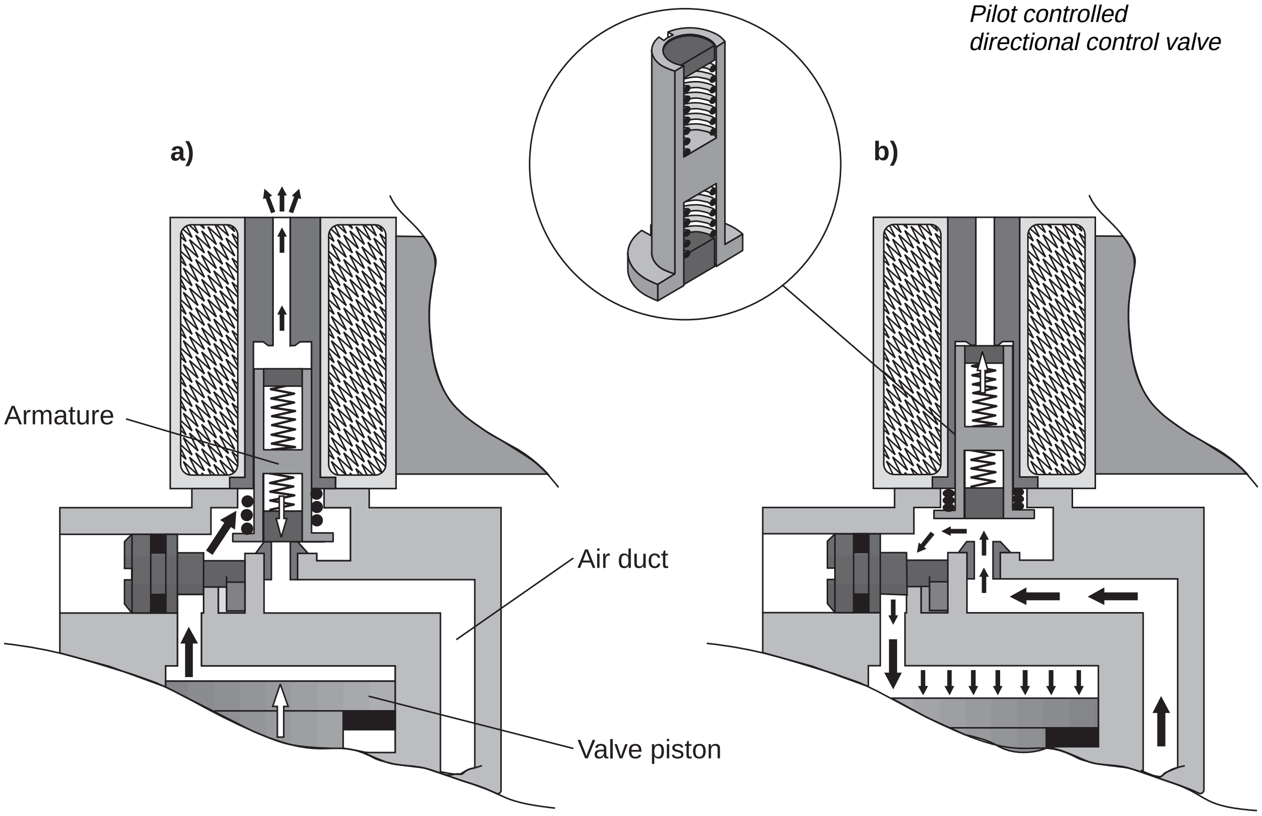
In pilot controlled directional control valves, the valve piston is indirectly actuated.

- 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



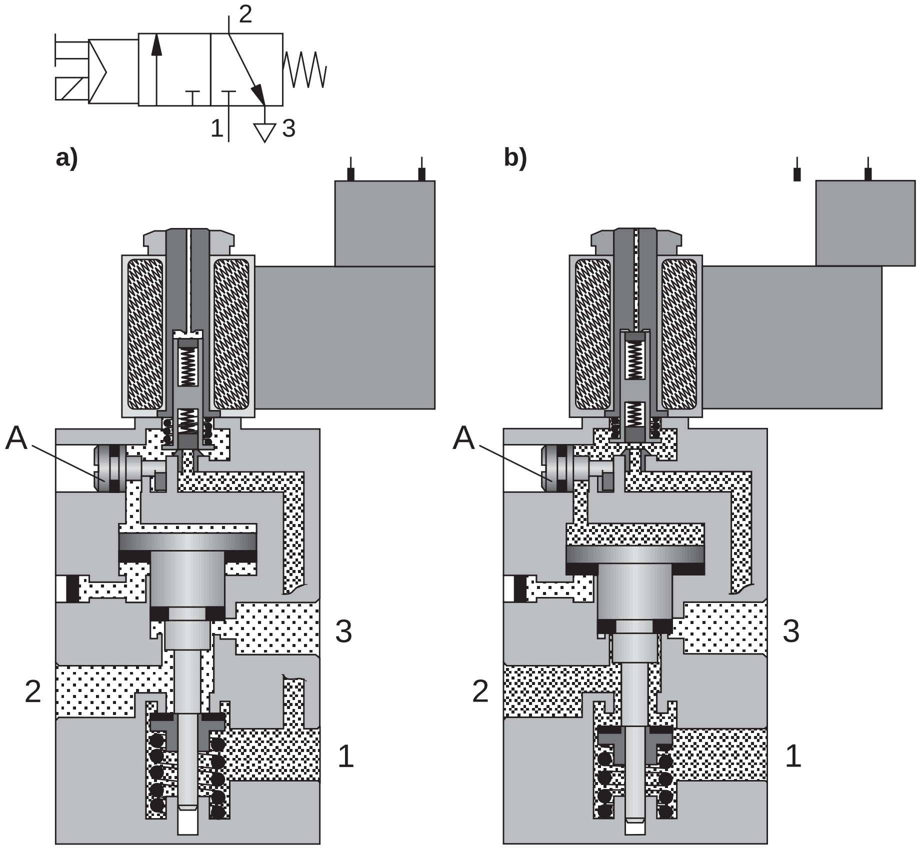
Pilot controlled 3/2-way valve

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.

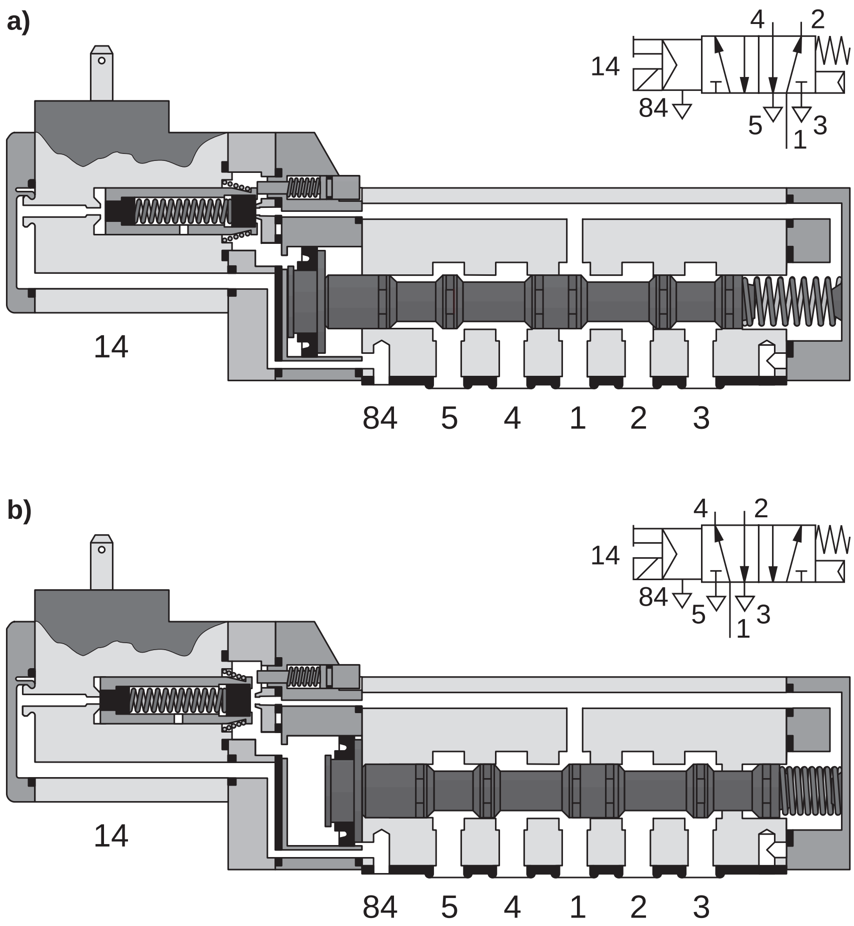
The advantages with regard to power consumption, size of solenoids and heat dissipation have led to almost exclusive use being made of pilot controlled directional control valves in electropneumatic control systems.

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



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.

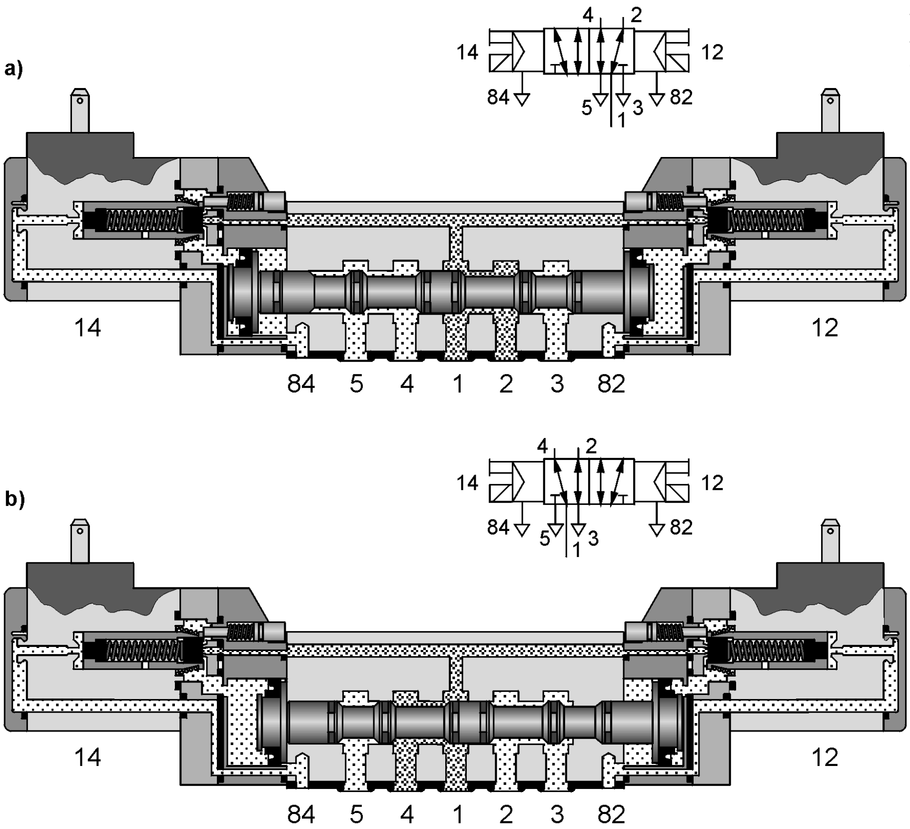


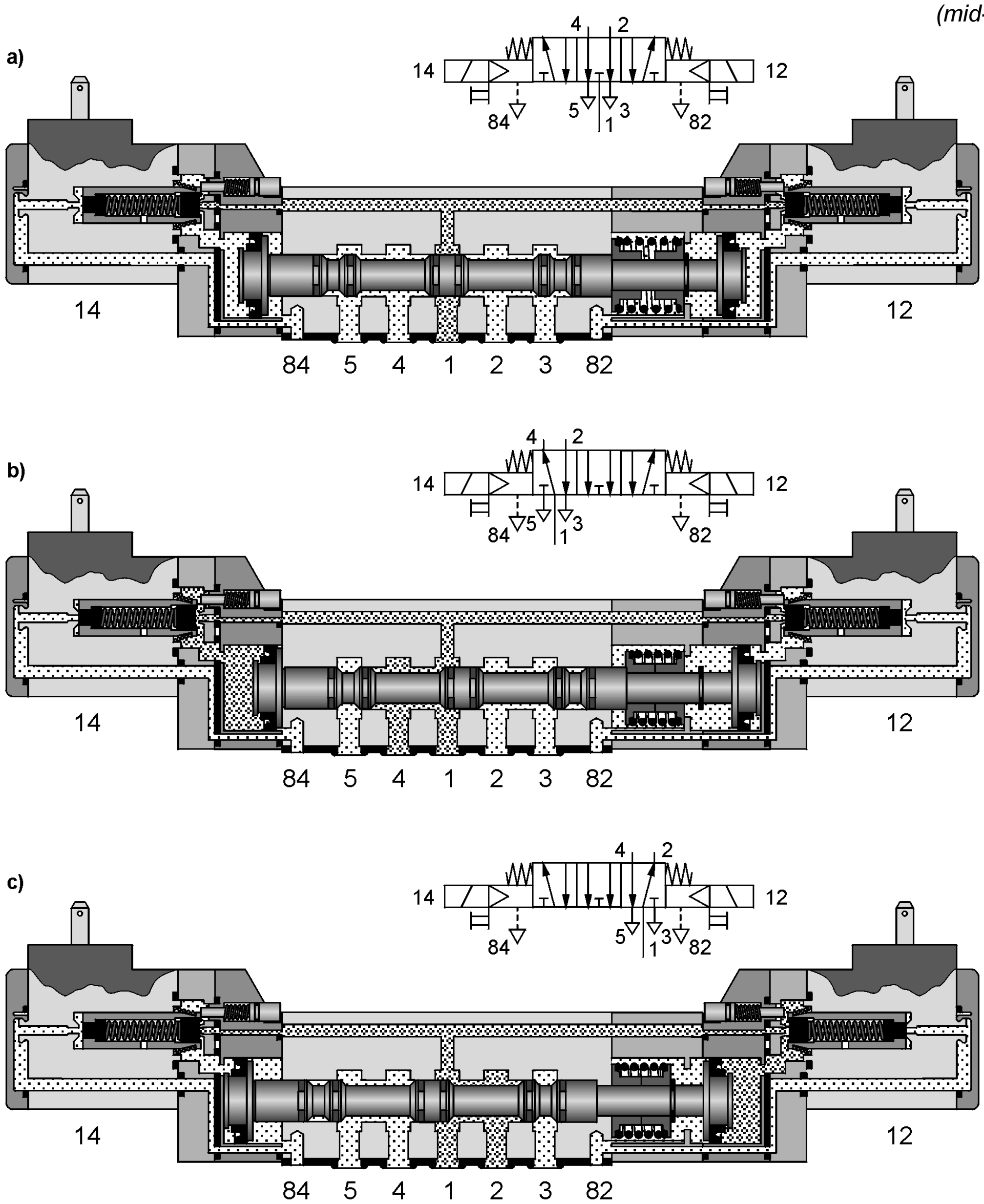
Fig. 4.7:
Pilot controlled 5/2-way double solenoid valve

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).

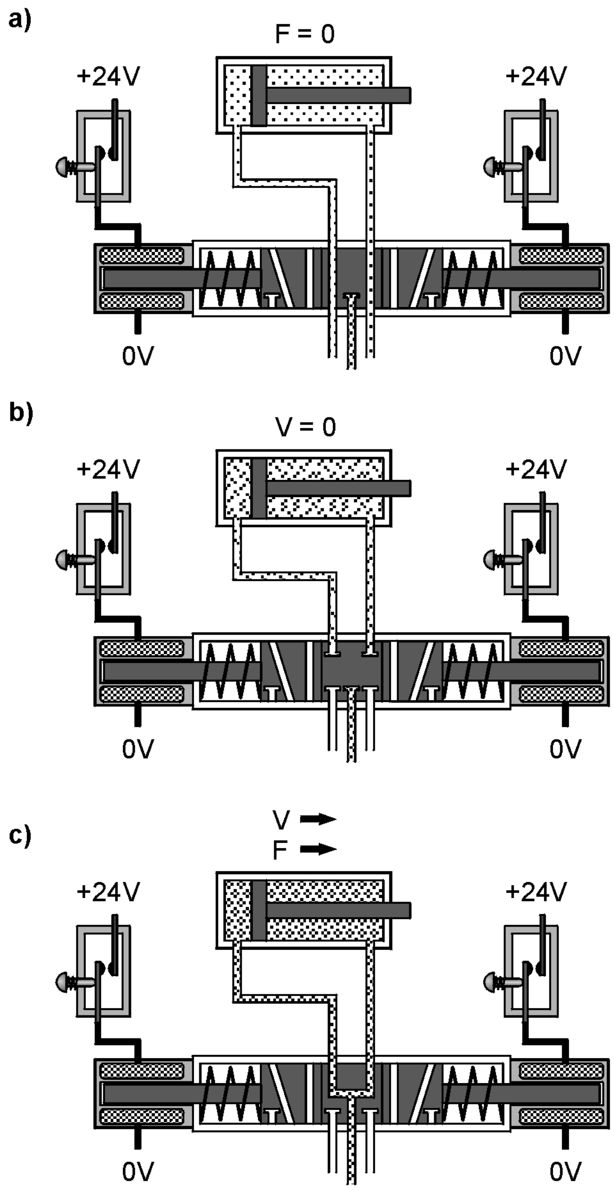


Fig. 4.9:
Influence of mid-position of 5/3-way double solenoid valves

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

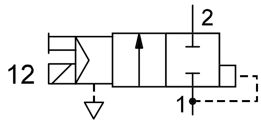
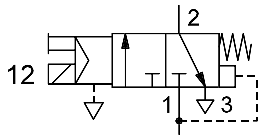
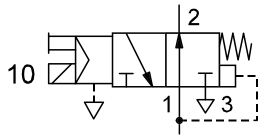
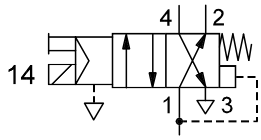
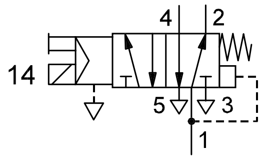
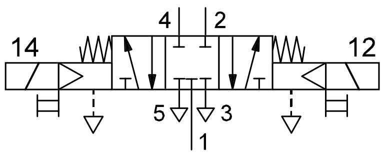
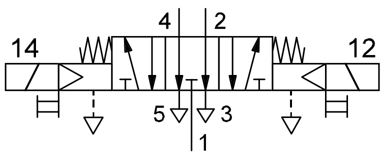
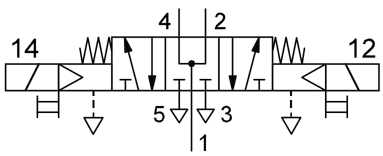
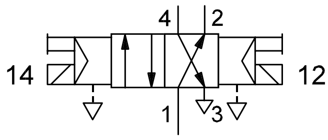
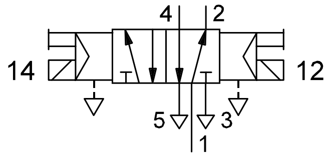
Valve type	*Symbol*	*Applications*
Pilot controlled spring-return 2/2-way valve		Shut-off function
Pilot controlled spring-return 3/2-way valve, normally closed		Single-acting cylinders
Pilot controlled spring-return 3/2-way valve, normally open		Switching compressed air on and off
Pilot controlled spring-return 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.

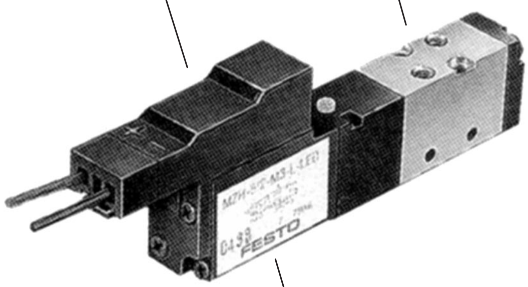
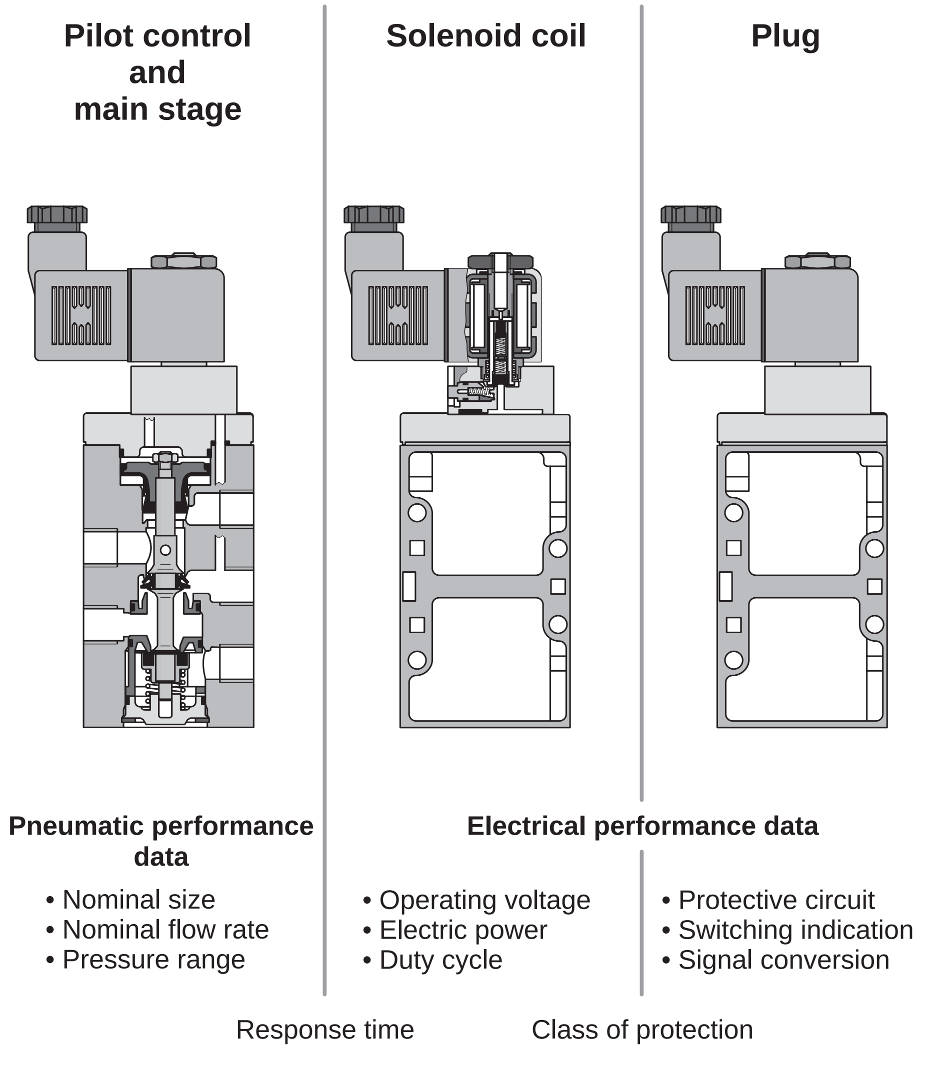


Fig. 4.10:
Modular design of an electrically actuated directional control valve (Festo)

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.

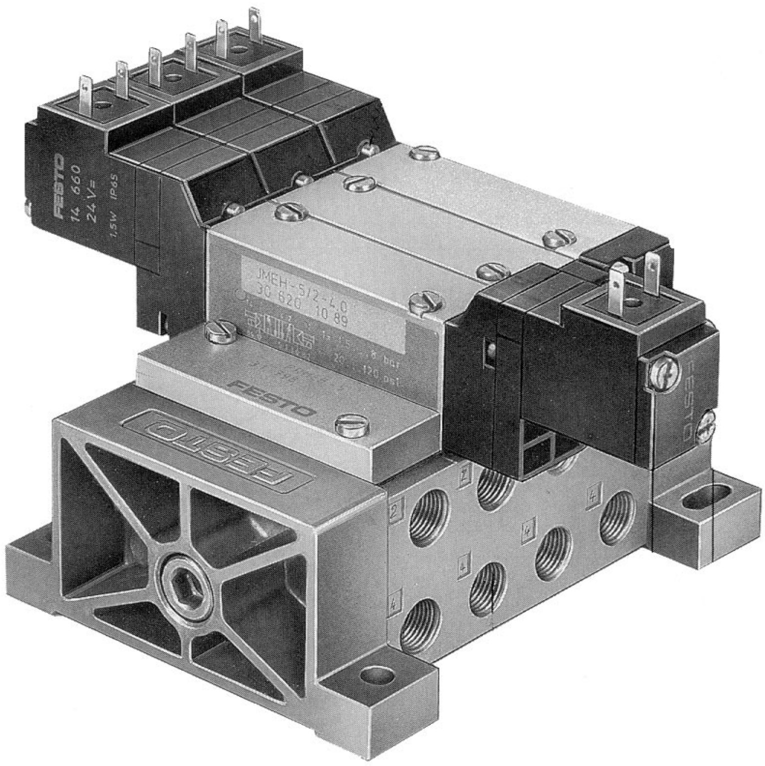
- On an in-line valve all pneumatic ports are threaded so that the tubes and silencers can be fitted directly on the valve. Valves can be mounted individually, but several valves can also be mounted together in a single manifold.
- On a sub-basevalve all valve ports are brought out to one side, and the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

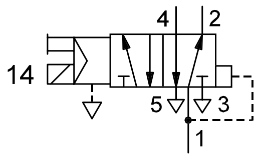
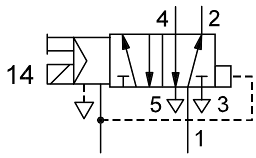
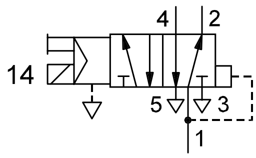
Certain sub-base valves are standardized in accordance with ISO. They have standardized dimensions, thus enabling valves from different manufacturers to be mounted on an ISO sub-base.

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 % at nominal voltage
Power consumption for normal voltages		4.1 W at 12 V 4.5 W at 24 V	Pickup: 7.5 VA 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.

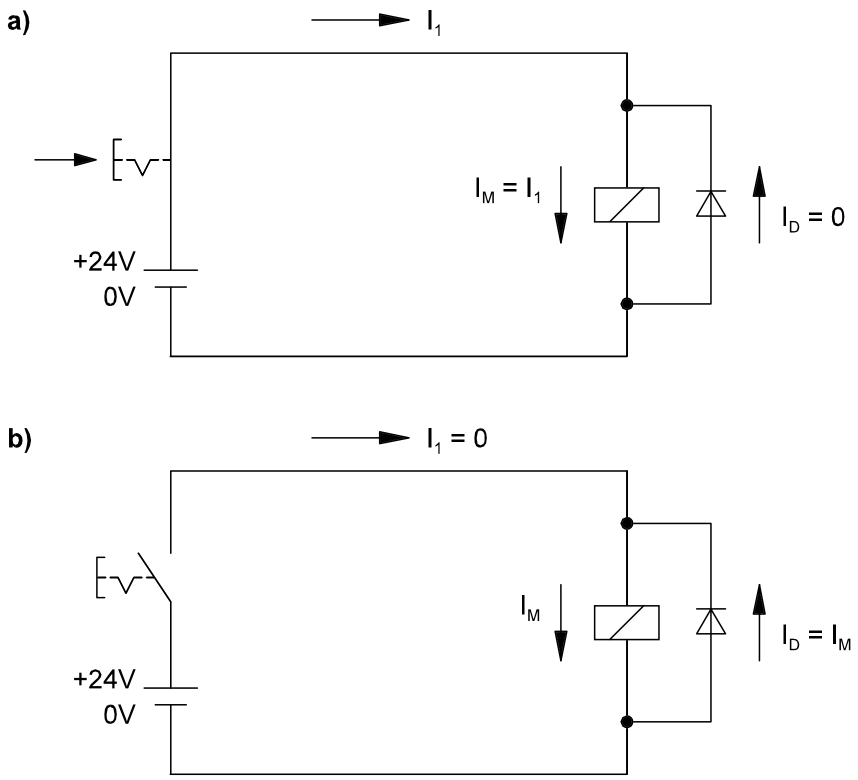


Fig. 4.13: Protective circuit of a solenoid coil

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).

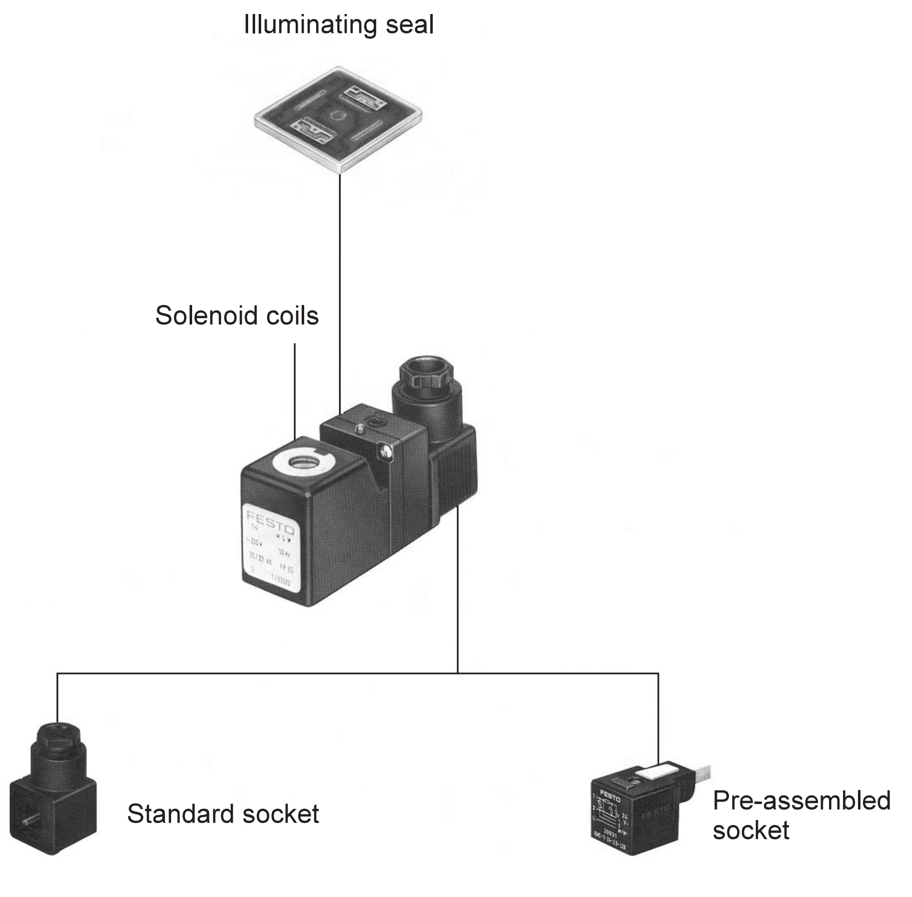


Fig. 4.14: Solenoid coil, adapter and socket

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.

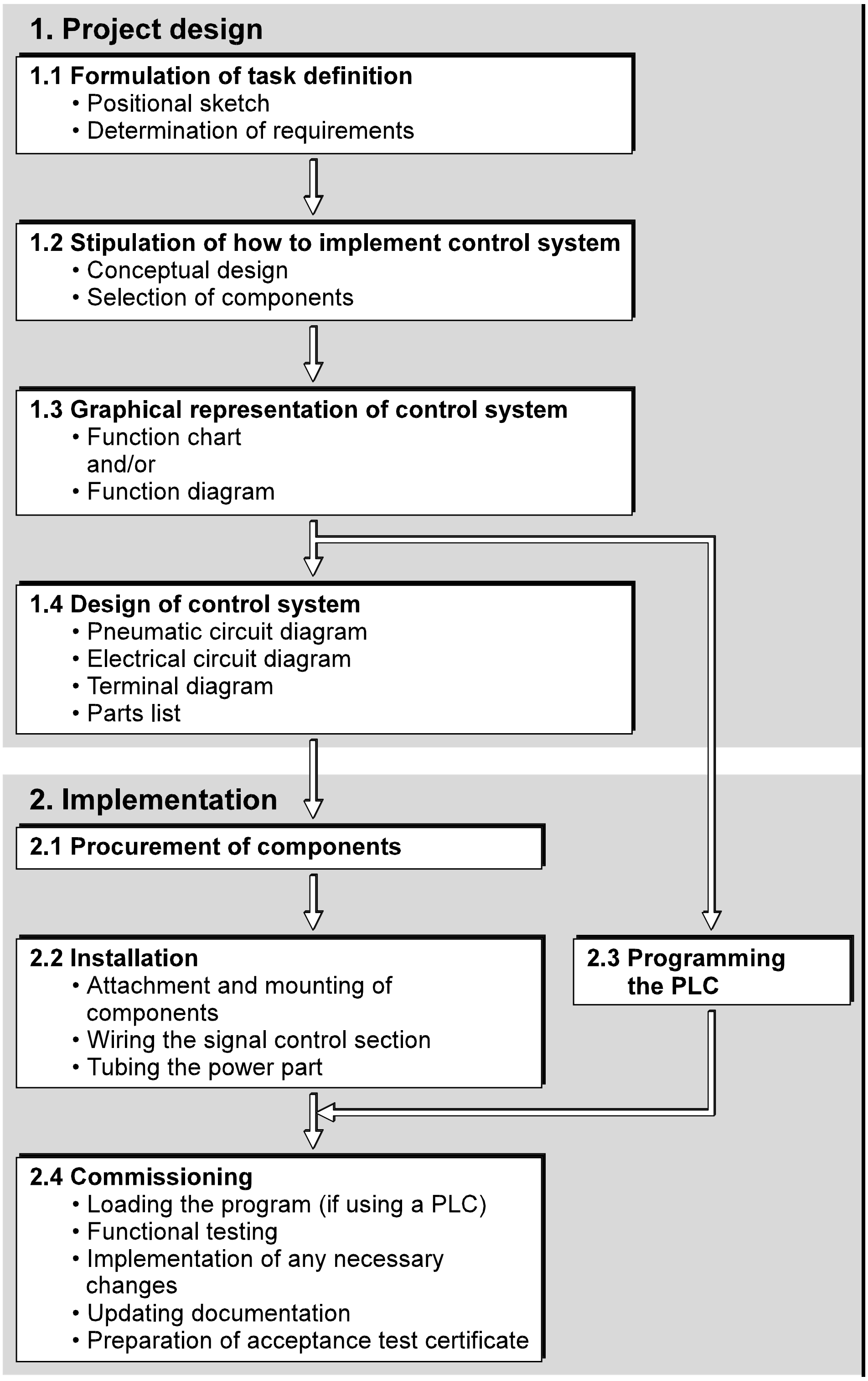


Fig. 5.1:
Procedure for development and implementation of an electropneumatic control system

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 - Function - Necessary force - Necessary stroke - What speeds of motion need to be available? - Braking of motions - Spatial arrangement - Additional functions (such as linear guide) - 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.

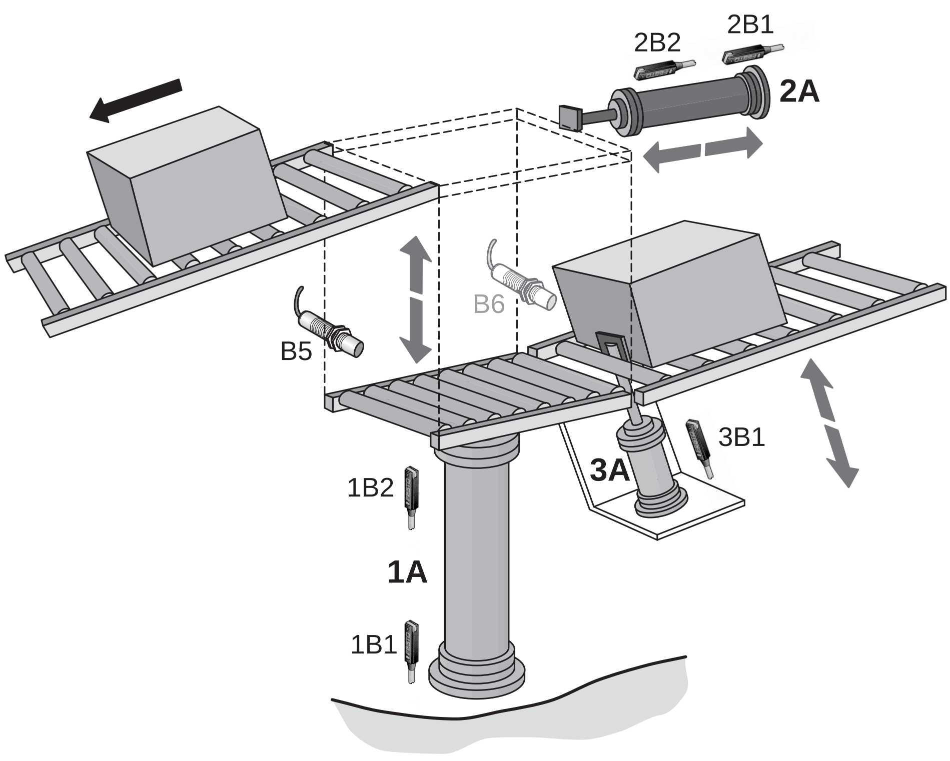
5.3 Sample application: project design ofa lifting device

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

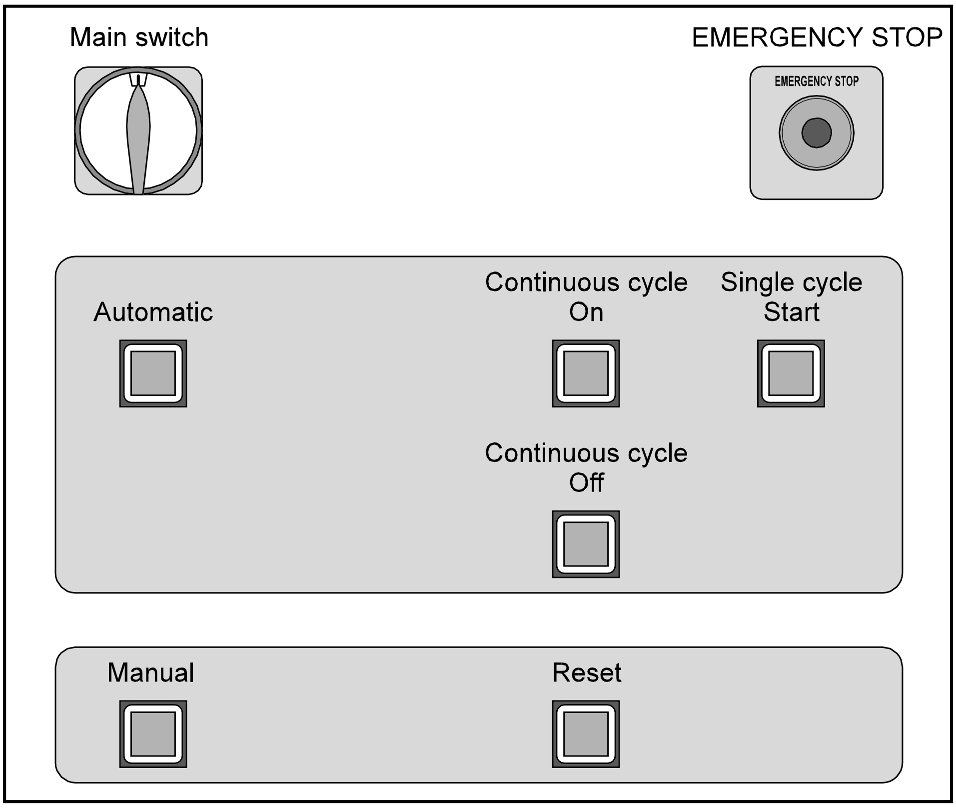
The control system of the lifting device must enable the device to be run in a continuous cycle (continuous operation). A single cycle operating mode is also necessary in which the sequence is processed precisely once.

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.

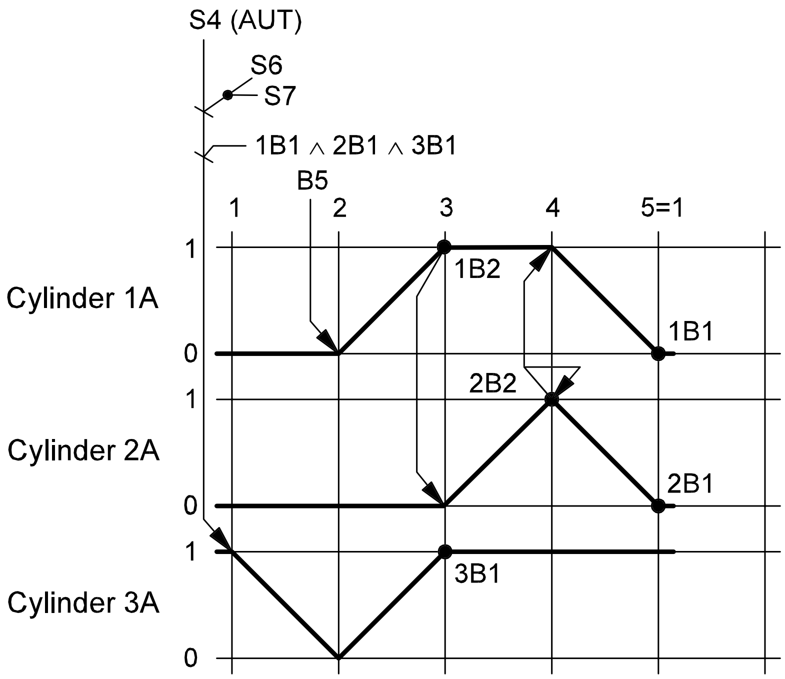
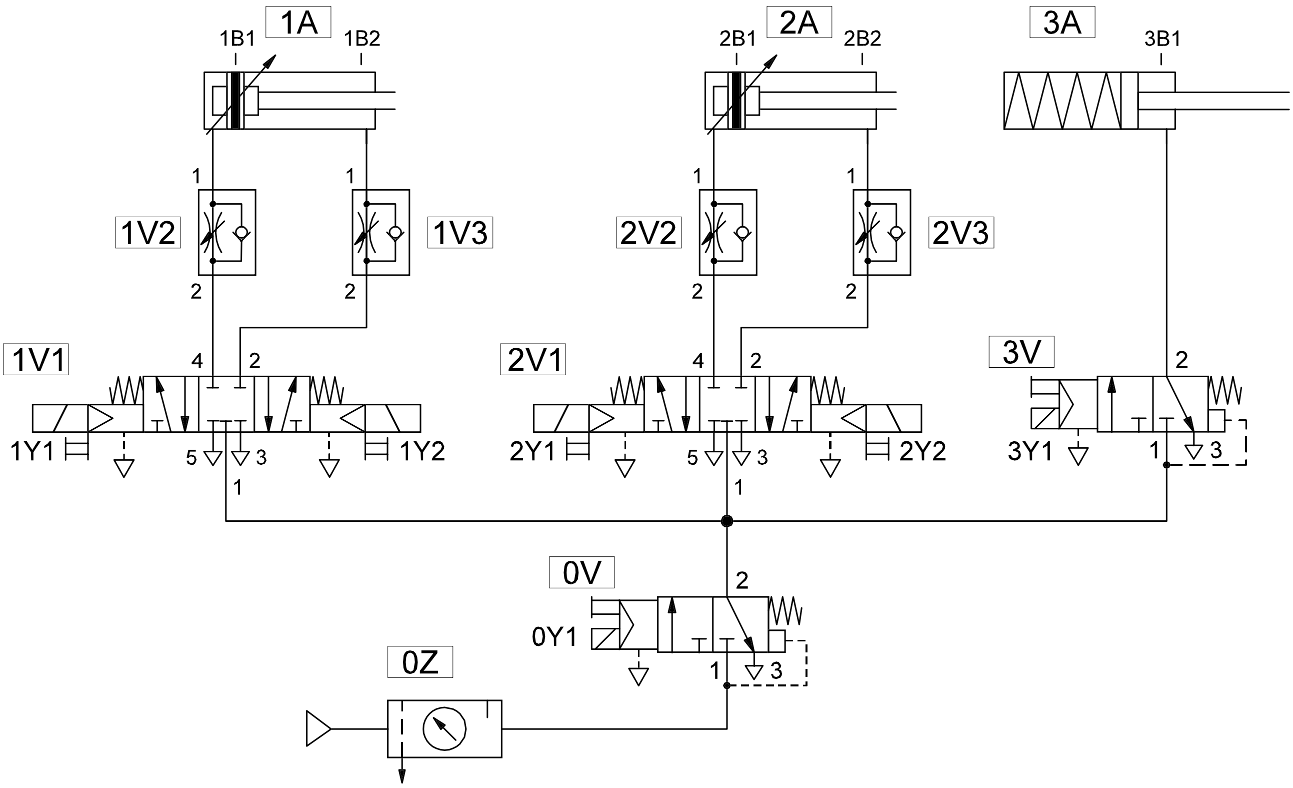


Fig. 5.4: Displacement-step diagram for the lifting device

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

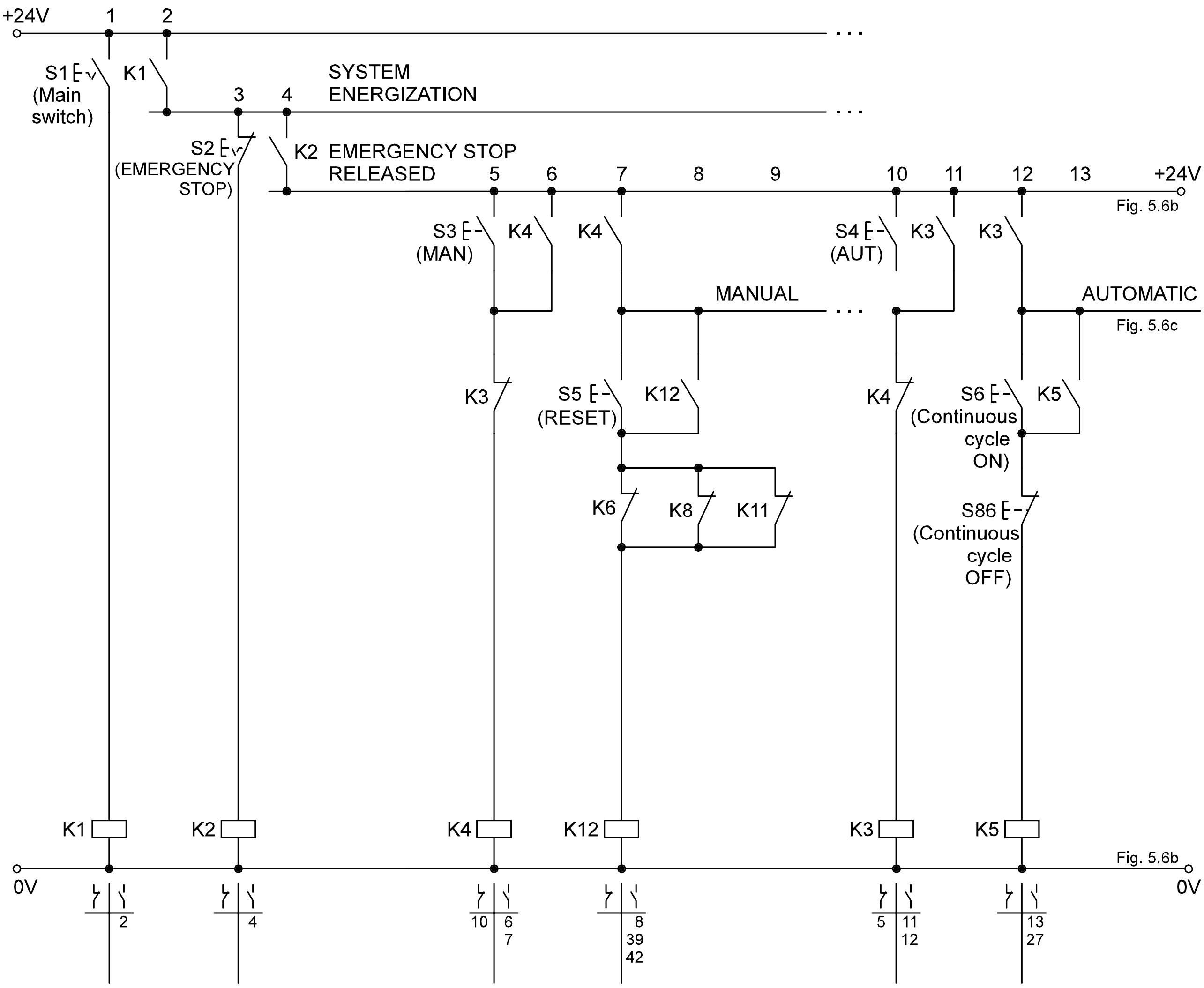


Fig. 5.6b:
Electrical circuit diagram of the lifting device - sensor evaluation

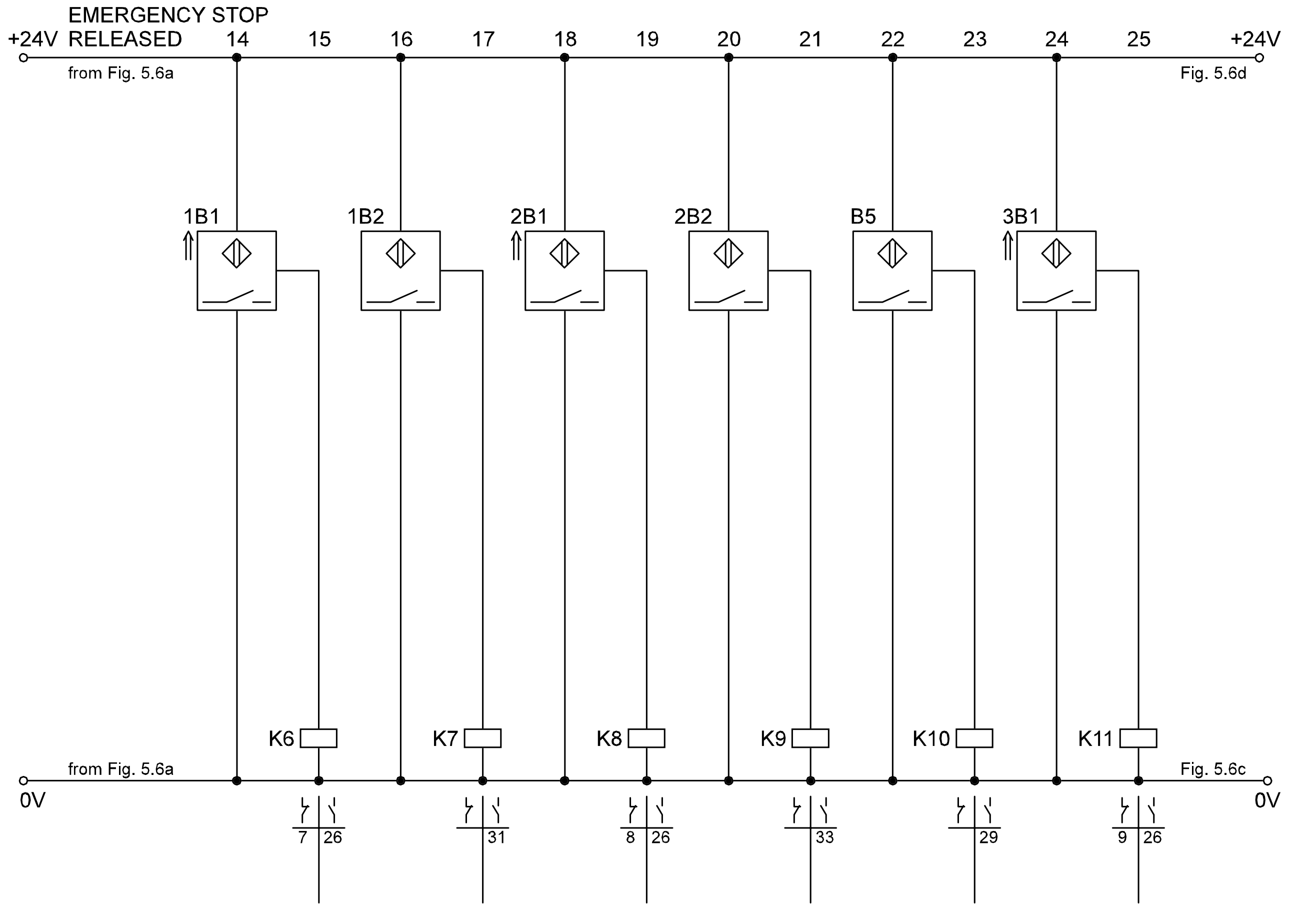


Fig. 5.6c:
Electrical circuit diagram
of the lifting device -
switching of sequence steps

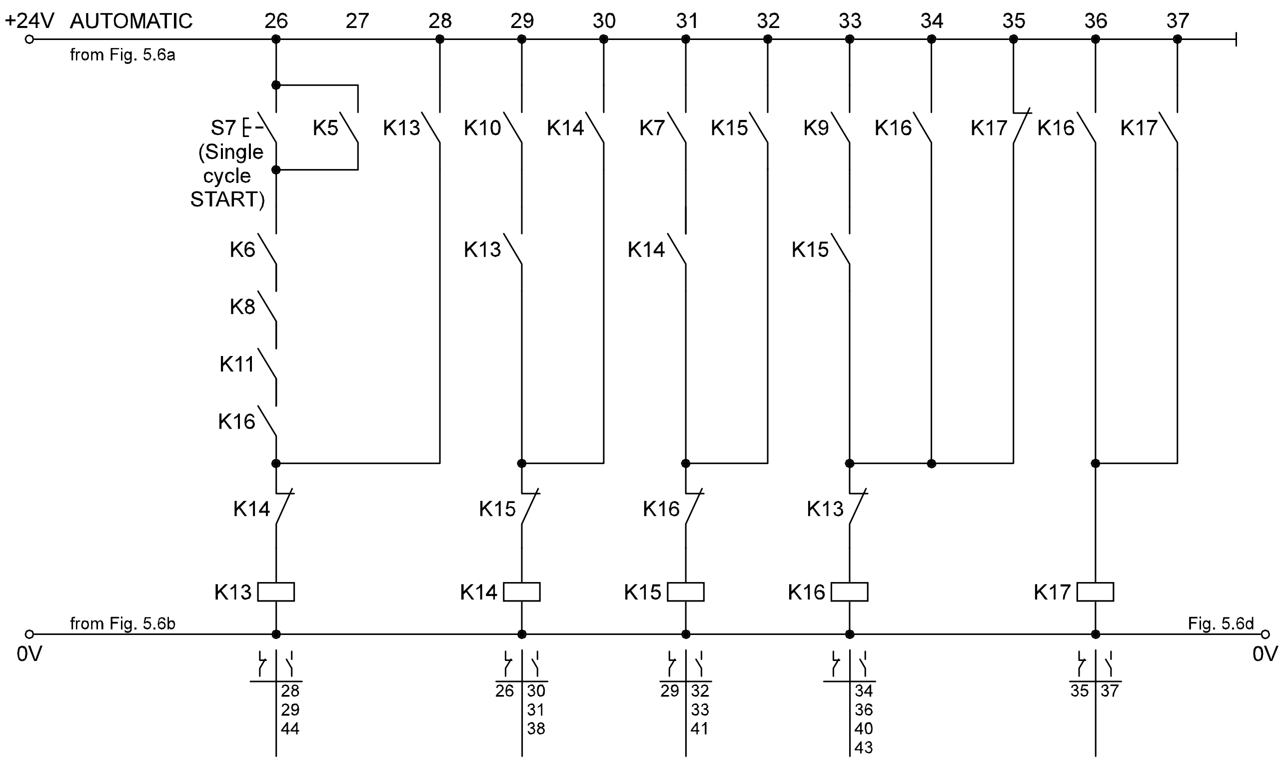
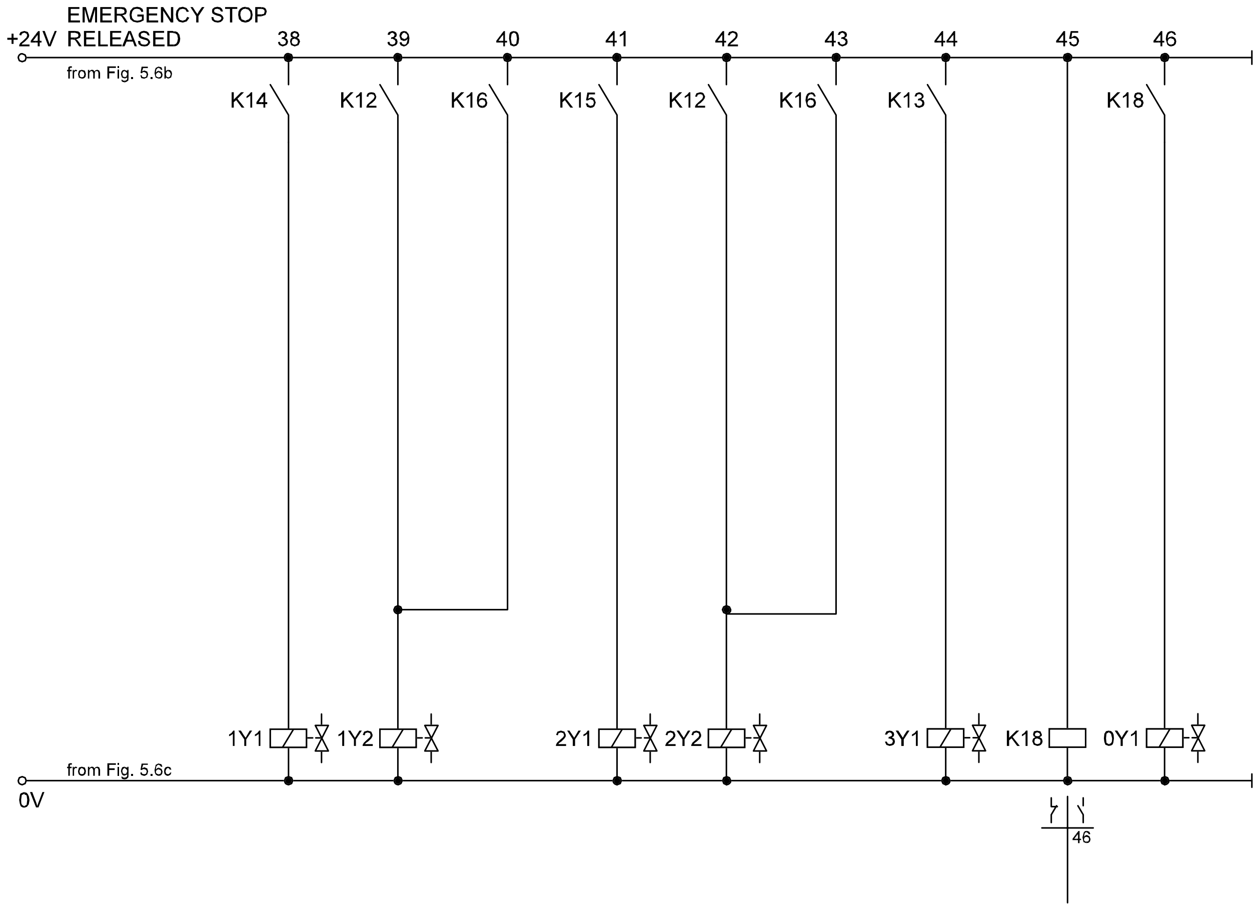


*Fig. 5.6d:
Electrical circuit diagram
of the lifting device -
circuitry of solenoid coils*



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

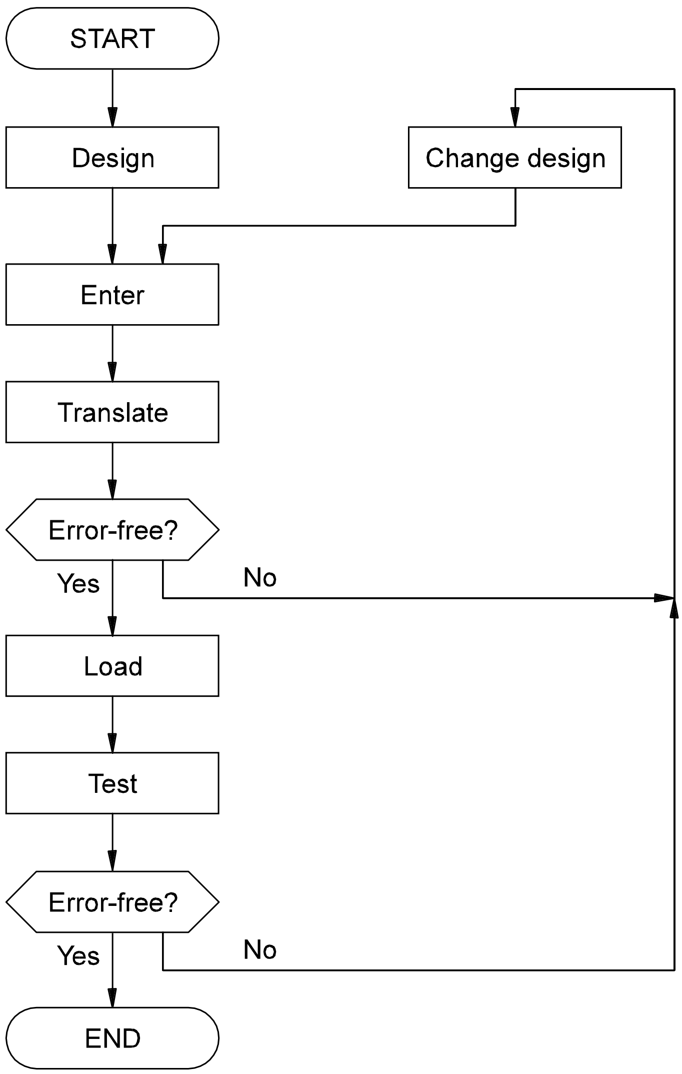
If a programmable logic controller (PLC) is used, the motion sequence of the pneumatic drives is determined by the program. The basis for developing the PLC program is provided by either a function diagram or a function chart. Program development can be carried out concurrently with setting up the control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

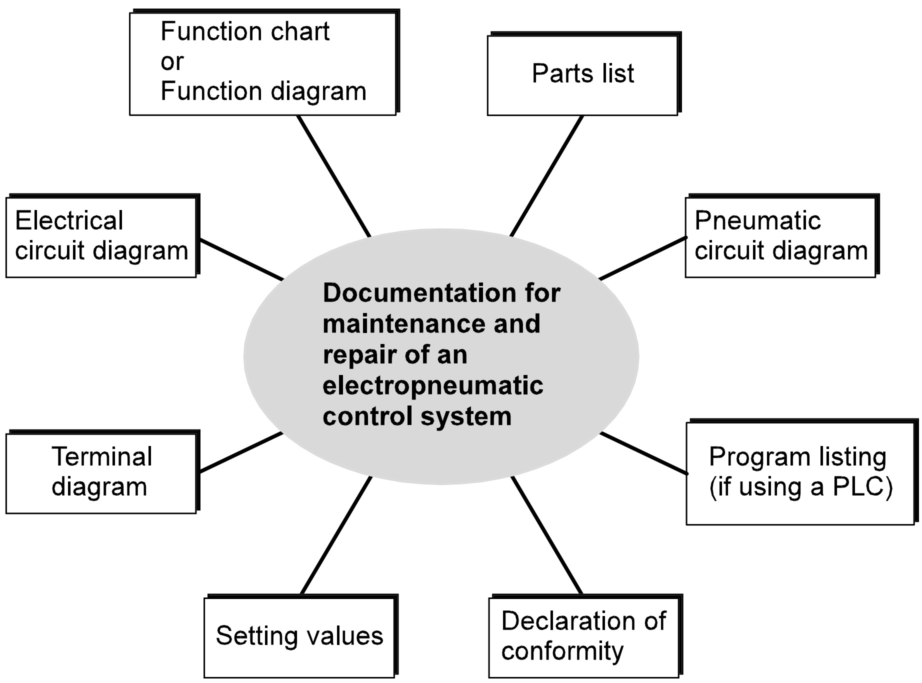


Fig. 5.8: Documentation for maintenance, service and repair of an electro-pneumatic control system

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)

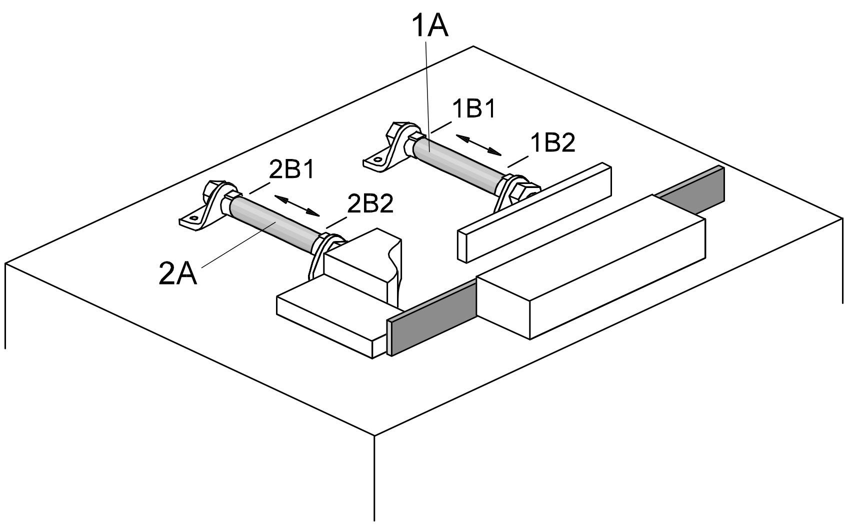
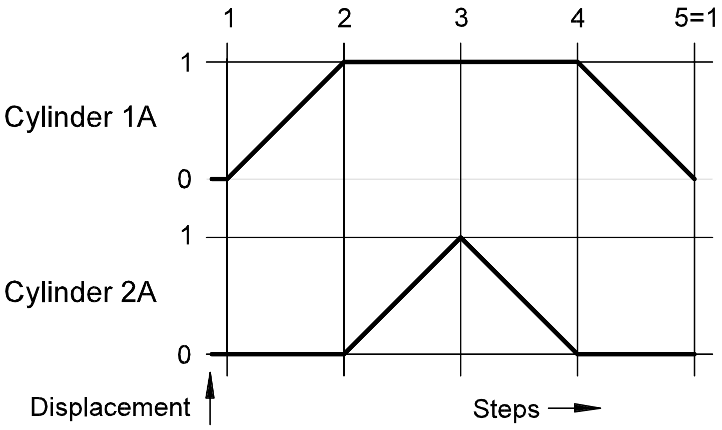


Fig. 6.1:
Positional sketch of a sheet-metal bending device

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).

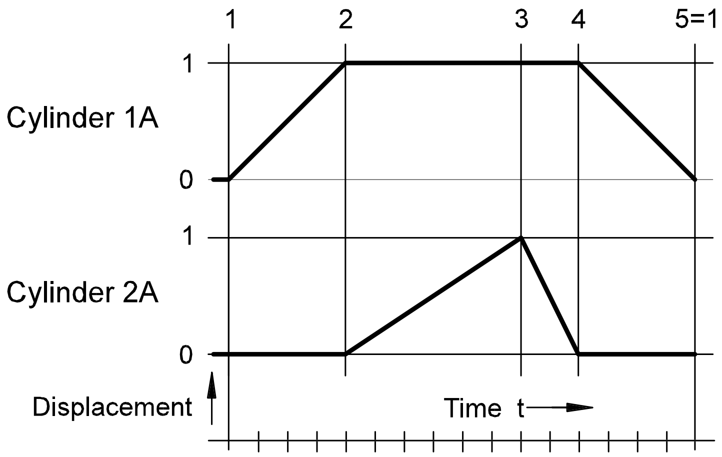


Fig. 6.3:
Displacement-time diagram for the sheet-metal bending device

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

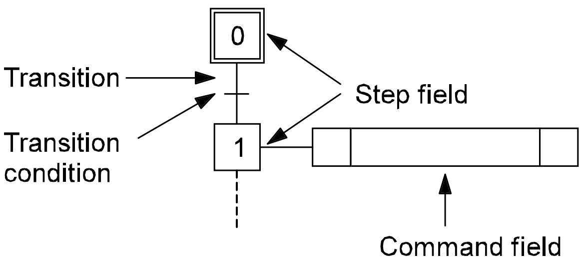


Fig. 6.4:
Structure of a function chart

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.

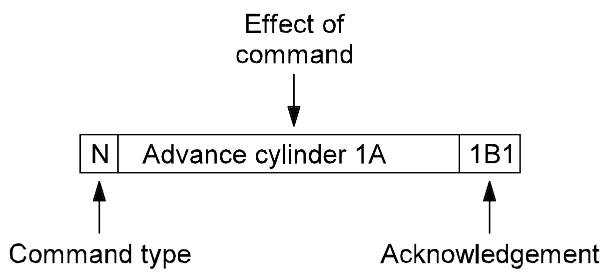
Command field

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).

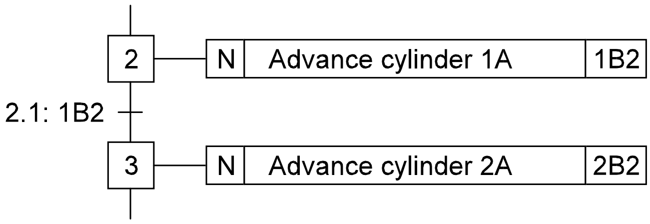
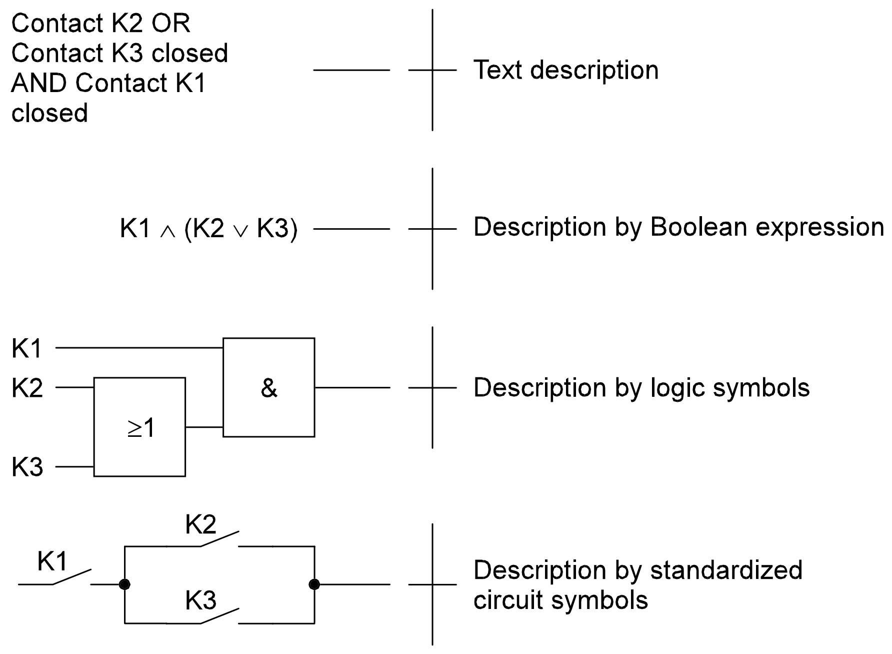


Fig. 6.6: Representation of a transition condition in a function chart

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.

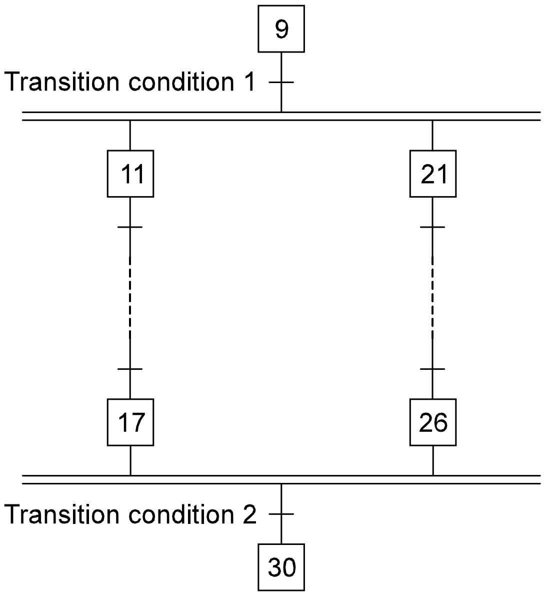
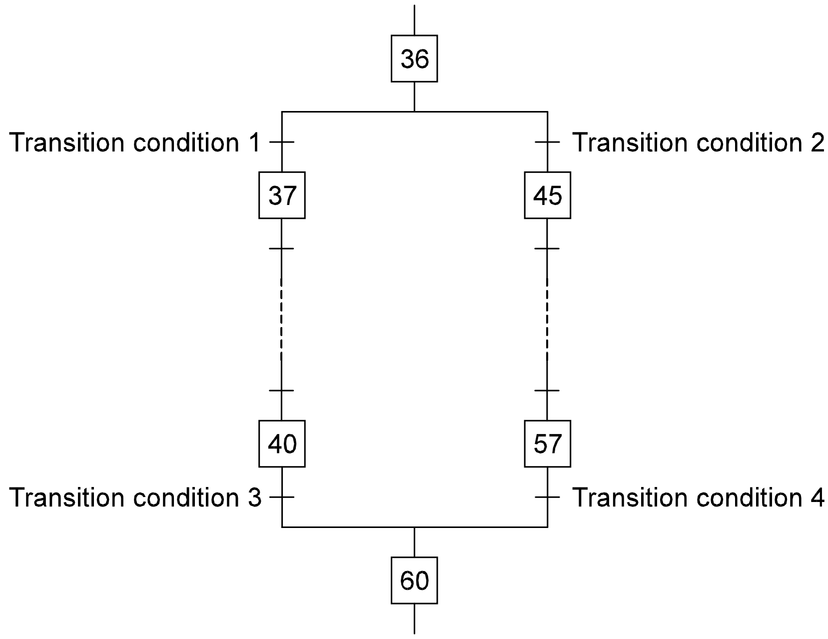


Fig. 6.8:
Parallel branching and parallel union in a function chart

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).

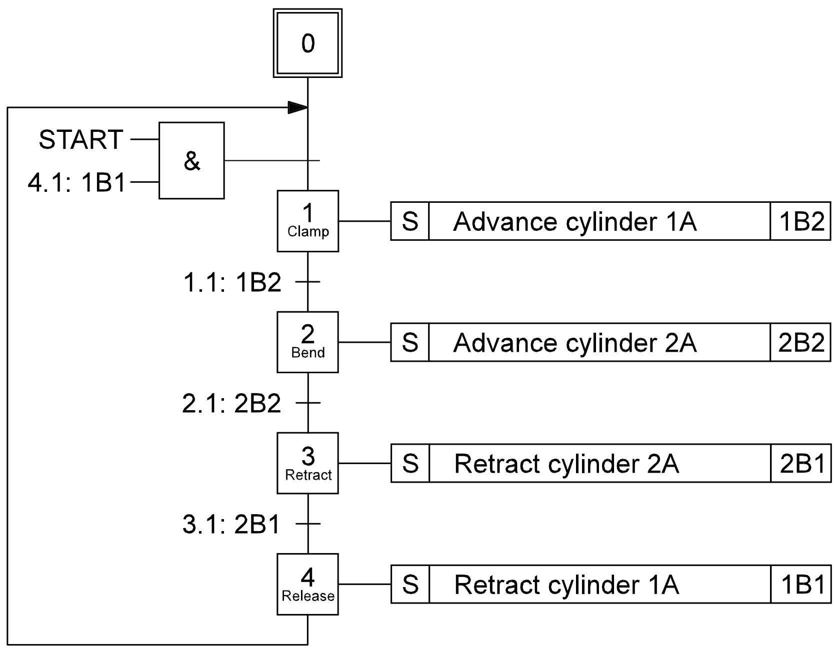


Fig. 6.10: Function chart for the bending device

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.

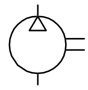
Graphical symbols for compressed air supply

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).

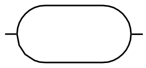
Fig. 6.11: Graphical symbols for the power supply section

Supply

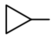
– Compressor with constant displacement volume



– Accumulator, air reservoir

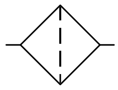


– Pressure source

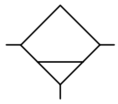


Maintenance

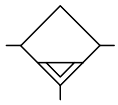
– Filter — Filtration of dirt particles



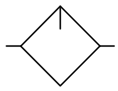
– Water separator, manually actuated



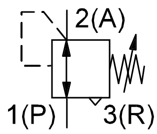
– Water separator, automatic



– Lubricator — Metered quantities of oil are added to the air flow

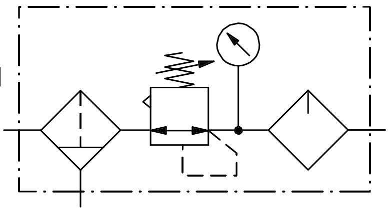


– Pressure regulating valve — Adjustable with relief port

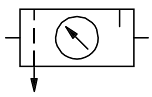


Combined symbols

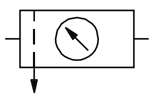
– Service unit — Consisting of water separator, compressed air filter, pressure regulating valve, pressure gauge and lubricator



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

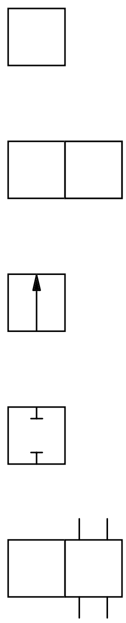


Fig. 6.12: Building blocks for valve symbols

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

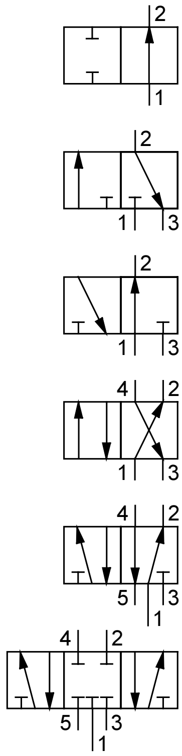
3/2 – way valve in closed position

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.

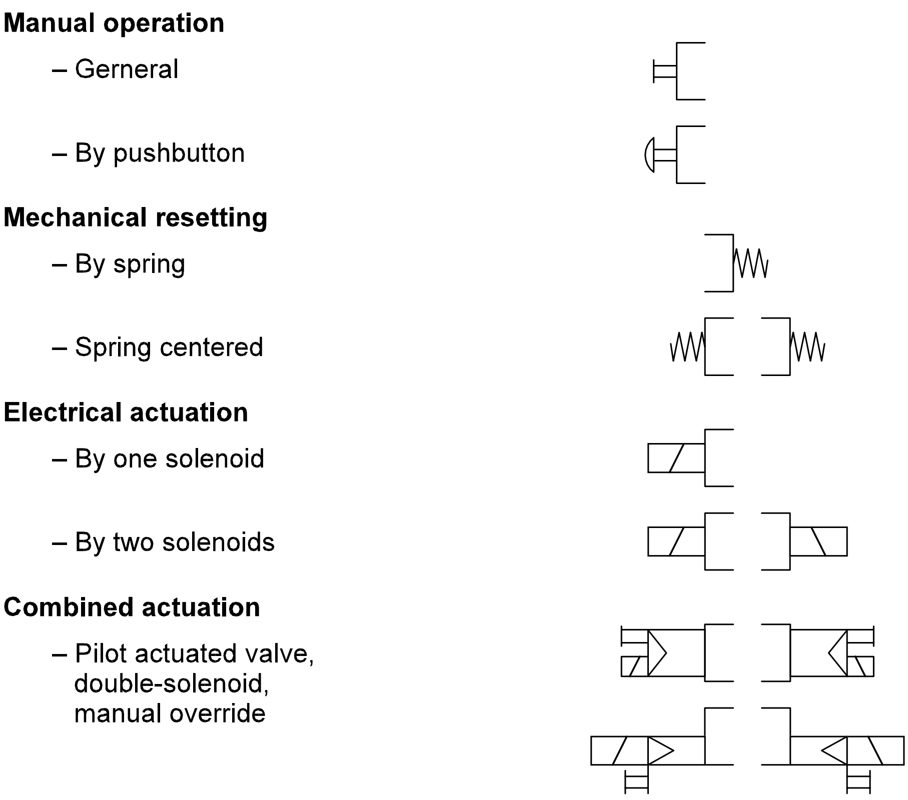


Fig. 6.14:
Types of actuation for electropneumatic directional control valves

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 Working ports Exhaust ports	1 2, 4 3, 5
Pilot lines/actuation for pilot actuated or pneumatically actuated directional control valves	Close supply port Connection between ports 1 and 2 Connection between ports 1 and 4 Auxiliary pilot air	10 12 14 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 un-throttled. The associated graphical symbols are shown in Fig. 6.15.

Non-return valve

Non-return valve, spring-loaded

Flow control valve, adjustable

One-way flow control valve, adjustable

Quick exhaust valve

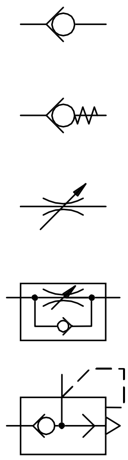


Fig. 6.15: Graphical symbols for non-return valves, flow control valves and quick exhaust valve

Graphical symbols for pressure control valves

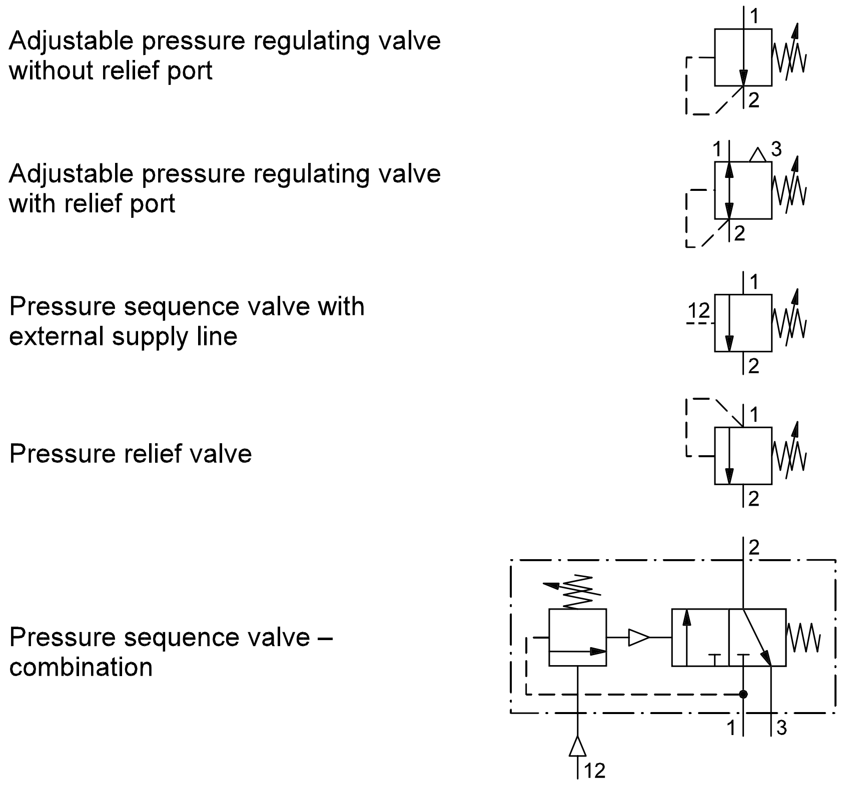
Pressure control valves are used for the following functions:

- 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

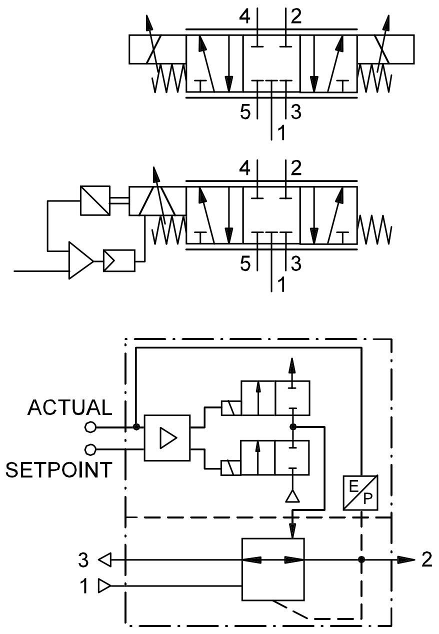


Fig. 6.17: Graphical symbols for proportional valves

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

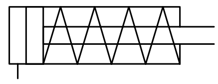
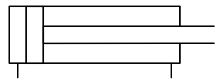
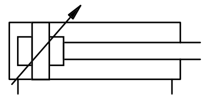
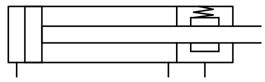
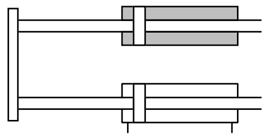
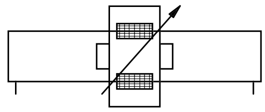
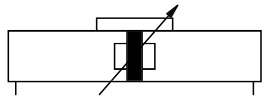
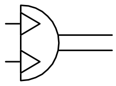
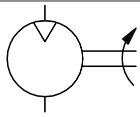
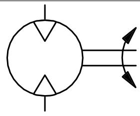
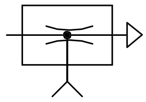
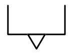
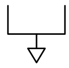
Function	**Description**	**Symbols**
Single-acting cylinder	Extend by pneumatic power. Return by return spring.	
Double-acting cylinder	Extend and return by pneumatic power.	
Double-acting cylinder	Adjustable end position cushioning for forward and reverse stroke.	
Double-acting cylinder with clamping unit	Mechanical clamping unit with pneumatic unlocking.	
Double-acting cylinder with hydraulic slave cylinder	Cylinder is pneumatically controlled. The hydraulic slave cylinder provides for even movement.	
Rodless cylinder with adjustable end position cushioning	Usually cylinder with long stroke lengths. Power transmission by permanent magnet.	
Rodless cylinder with adjustable end position cushioning	Power transmission by mechanical means.	
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

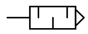
Exhaust port with no facility for connection



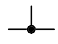
Exhaust port with thread for connection



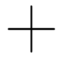
Silencer



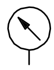
Line connection



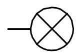
Crossing lines



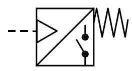
Pressure gauge



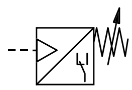
Visual indicator



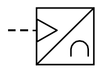
Pressure switch – P/E-converter



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.

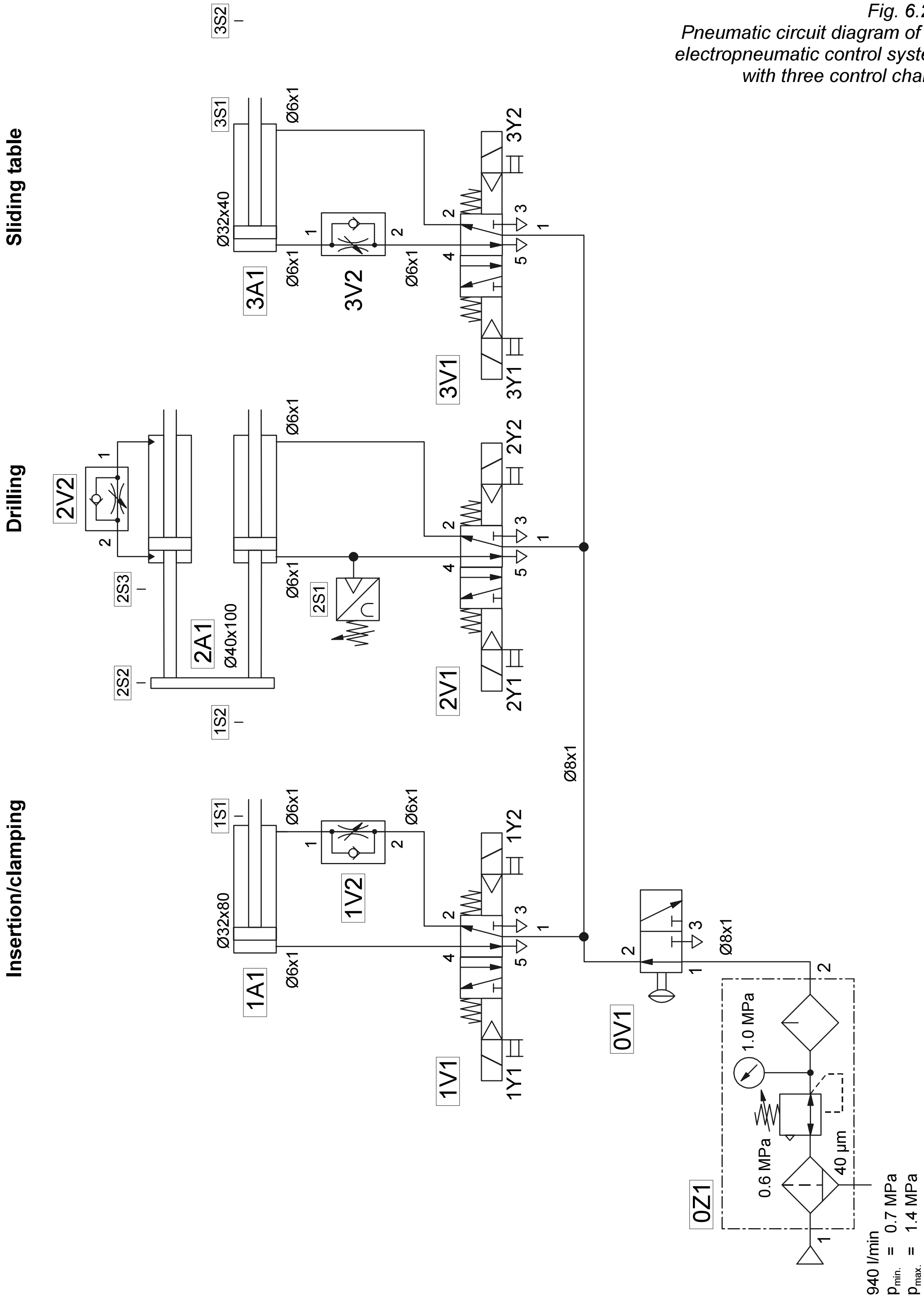


Fig. 6.20:
Pneumatic circuit diagram of an electropneumatic control system with three control chains

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.

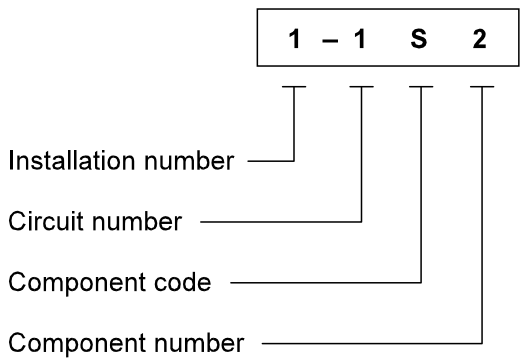


Fig. 6.21:
Identification code for components in pneumatic circuit diagrams

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

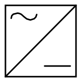
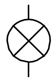
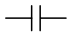
A circuit diagram with distributed representation is used to represent the signal control section in electropneumatics. It is only if control systems are very large that an overview diagram or function diagram is prepared in addition.

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.

Electrical symbols

In a circuit diagram the components are represented by graphical symbols that are standardized according to DIN 40900. Symbols used to represent electrical components that are frequently found in electropneumatic control systems are shown in Figs. 6.22 to 6.27.

Fig. 6.22:
Electrical symbols:
basic functions

Direct current, DC voltage	—
Alternating current, AC voltage	~
Rectifier (power supply unit)	
Permanent magnet	
Resistor, general	
Coil (inductivity)	
Indicator light	
Capacitor	
Grounding, general	

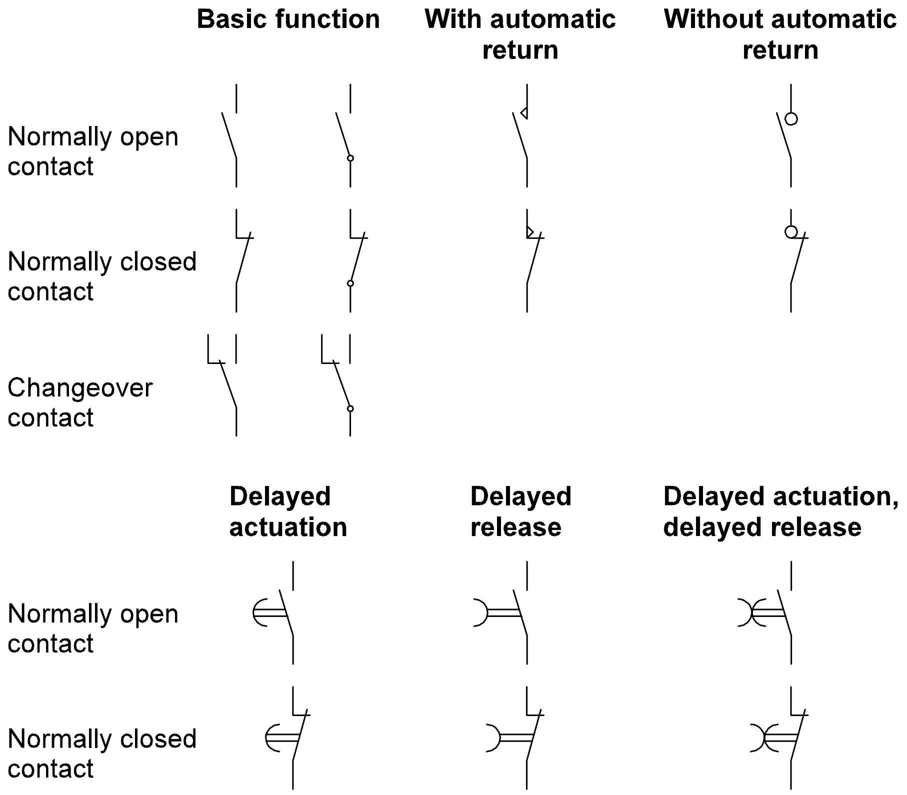


Fig. 6.23:
Graphical symbols for contacts: basic functions and delayed actuation

Fig. 6.24: Graphical symbols for manually operated switching devices

	Momentary-contact switch	Latching-type switch
Normally open contact, manually operated		
Normally open contact, manually operated by pressing		
Normally closed contact, manually operated by pulling		
Normally open contact, manually operated by turning		

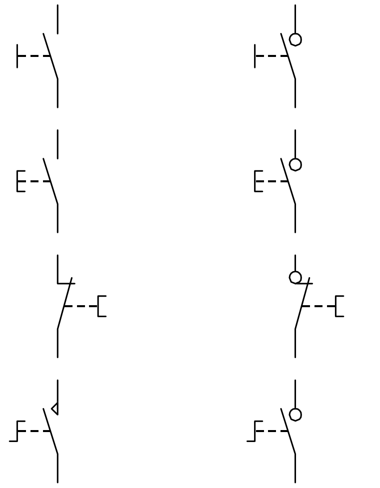


Fig. 6.25: Graphical symbols for electromechanical drives

General

– Electromechanical drive

Actuation of relays and contactors

– Electromechanical drive with two parallel windings

– Electromechanical drive with two opposed windings

– Electromechanical drive with pickup delay

– Electromechanical drive with dropout delay

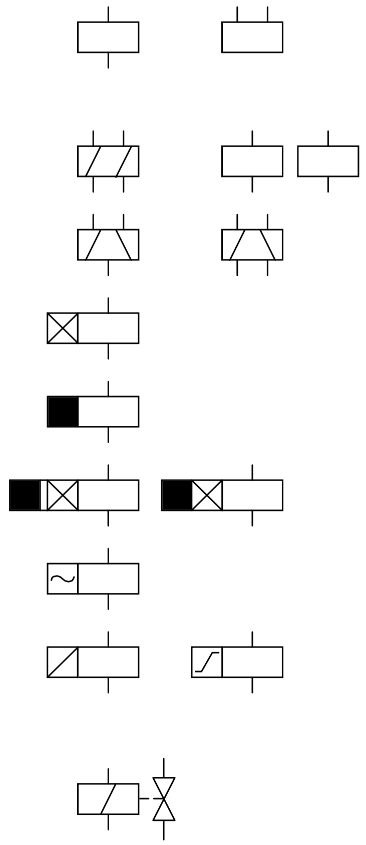
– Electromechanical drive with pickup and dropout delay

– Electromechanical drive of an AC relay

– Electromechanical drive of a retentive relay

Valve actuation

– Electromechanical drive of a directional control valve



Relays

- Relay with three normally open contacts and one normally closed contact
- Relay with dropout delay
- Relay with pickup delay
- Retentive relay
- Flasher relay

Contactor

- Contactor with one normally closed contact and one normally open contact

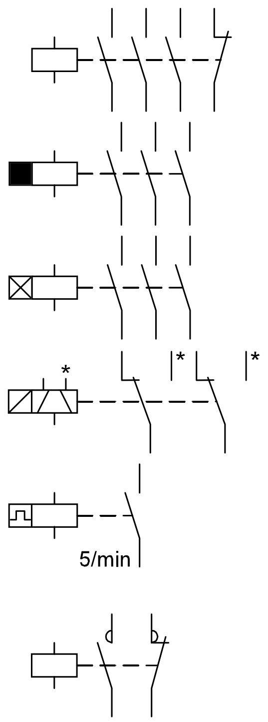


Fig. 6.26:
Graphical symbols for relays and contactors (consolidated representation)

When a voltage is applied to the winding termination marked by *, contact labels are placed at the positions of the contact elements marked by *.

Fig. 6.27: Graphical symbols for sensors

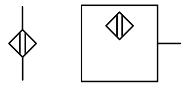
Limit switches

– Normally open contact

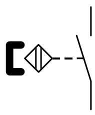
– Normally closed contact

Proximity switches, proximity sensors

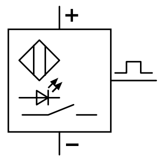
– Proximity sensor, proximity-sensitive device



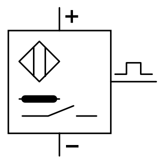
– Proximity switch (normally open contact), actuated by magnets (standardized)



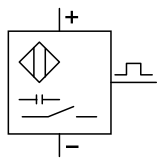
– Proximity switch, optical



– Proximity switch, inductive

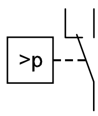


– Proximity switch, capacitive

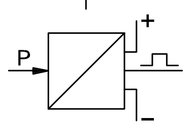


Pressure switches, pressure sensors

– Pressure switch, electromechanical



– Pressure switch, electronic



Circuit diagram of an electropneumatic control system

In the circuit diagram of an electropneumatic control system the graphical symbols of the components required to implement logic circuits and sequences are entered consecutively from the top to the bottom and from left to right. Relay coils and valve coils are always drawn beneath the contacts (Fig. 6.28).

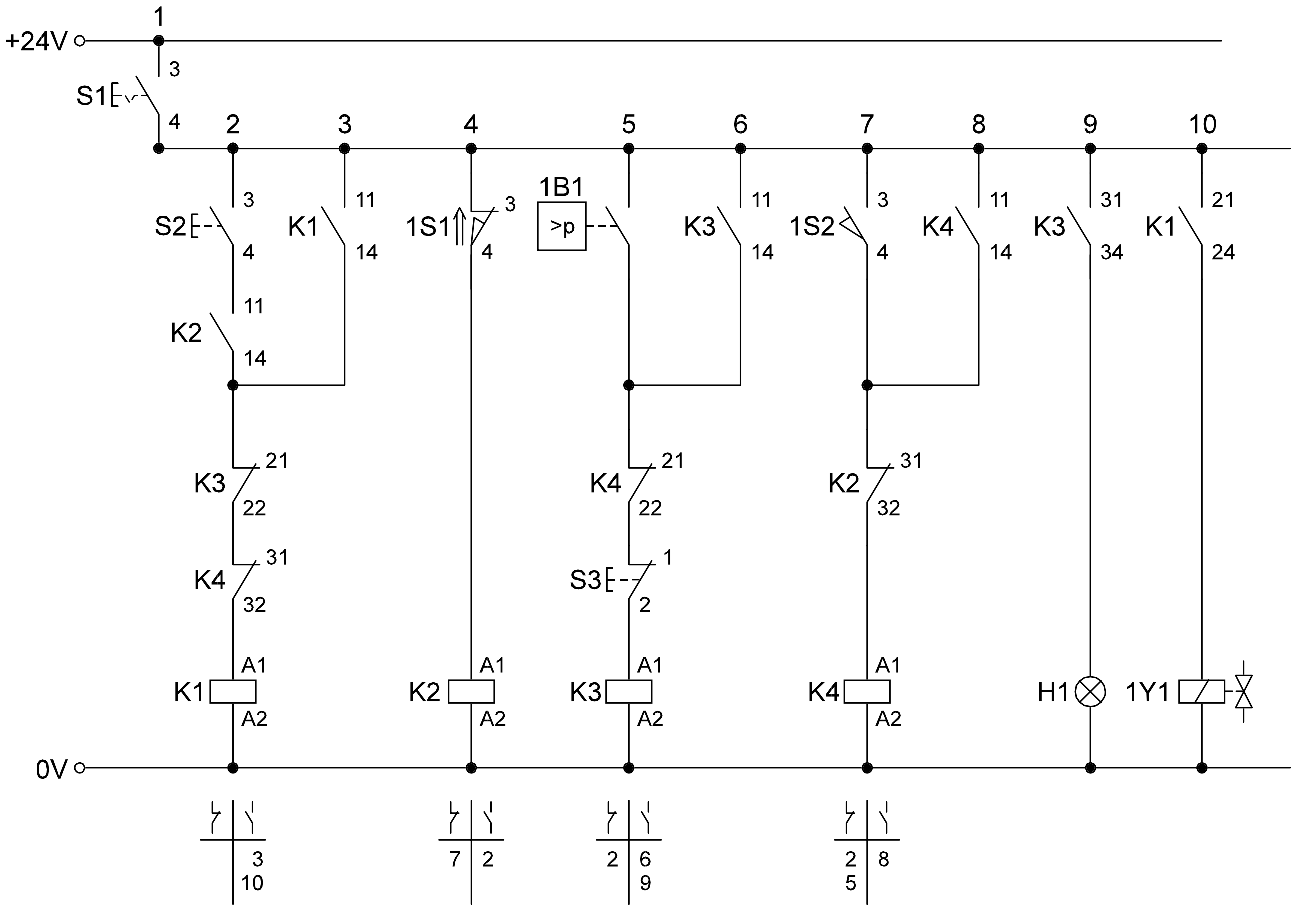
Other measures to ensure that a circuit diagram is easy to read include:

- Division into individual current paths
- Identification of devices and contacts by letters and numbers
- Subdivision into a control circuit and main circuit
- Preparation of tables of contact elements

Current paths

The individual current paths of an electropneumatic control system are drawn alongside each other in the circuit diagram and numbered consecutively. The circuit diagram of an electropneumatic control system shown in Fig. 6.28 has 10 current paths. Current paths 1 to 8 belong to the control circuit, current paths 9 and 10 to the main circuit.

Fig. 6.28:
Electrical circuit diagram
of an electropneumatic
control system



S1 = Main switch
S2 = Start switch
S3 = Acknowledgement switch

1S1/1S2 = Limit switch
1B1 = Pressure switch

All relay contacts are changeover contacts.

Identification of components

The components in the circuit diagram of a control system are identified by a letter in accordance with Table 6.4. Components with identical identifying letters are assigned consecutive numbers (for example 1S1, 1S2 etc.).

Sensors and valve coils must be represented both in the pneumatic circuit diagram and the electrical circuit diagram. In order to ensure that there is no ambiguity and that the diagrams are easy to read, the symbols in both types of diagram should be identified and numbered in the same way. For example, if a certain limit switch is designated 1S1 in the pneumatic circuit diagram, the same identification should also be used in the electrical circuit diagram.

Component type	*Identification*
Limit switch	S
Manually operated pushbutton, input elements	S
Reed switch	B
Electronic proximity switch	B
Pressure switch	B
Indicator	H
Relay	K
Contactor	K
Solenoid coil of a valve	Y

Table 6.4:
Designation of components in an electrical circuit diagram
(DIN 40719, Part 2)

Example of identification of components

The components shown in the circuit diagram (Fig. 6.28) are identified as follows:

- Manually operated switches S1, S2 and S3
- Limit switches 1S1 and 1S2
- Pressure switch 1B1
- Relays K1, K2, K3 and K4
- Solenoid coil 1Y1
- Lamp H1

Terminal designations of contacts and relays

In order to ensure error-free wiring of contacts, all connections on a component and in the circuit diagram are identified in the same way. Each connection of a contact is assigned a function number. The function numbers for different types of contact are listed in Table 6.5. If a switch, relay or contactor has more than one contact, they are numbered by means of sequence numbers prefixed to the function number (Fig. 6.29).

Fig. 6.30 shows a sectional view of a relay with its associated terminal designations. The terminals of a relay coil are designated A1 and A2.

Table 6.5: Function numbers for contacts

Type of contact	*Function number*
Normally closed contact	1, 2
Normally open contact	3, 4
Normally closed contact, delayed	5, 6
Normally open contact, delayed	7, 8
Changeover contact	1, 2, 4
Changeover contact, delayed	5, 6, 8

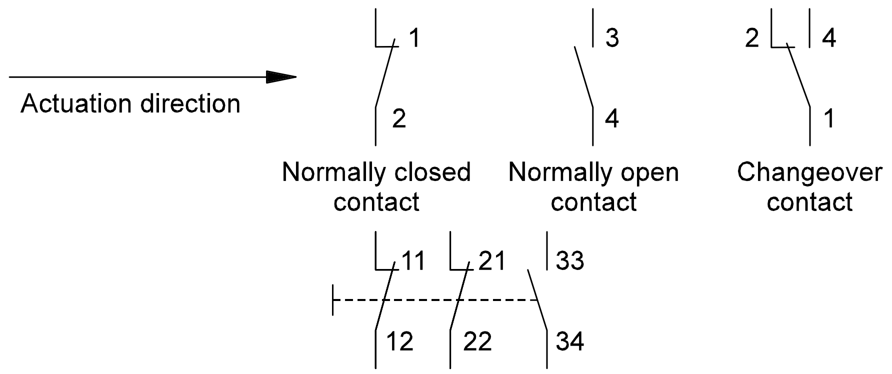


Fig. 6.29: Contact designation by means of function numbers and sequence numbers

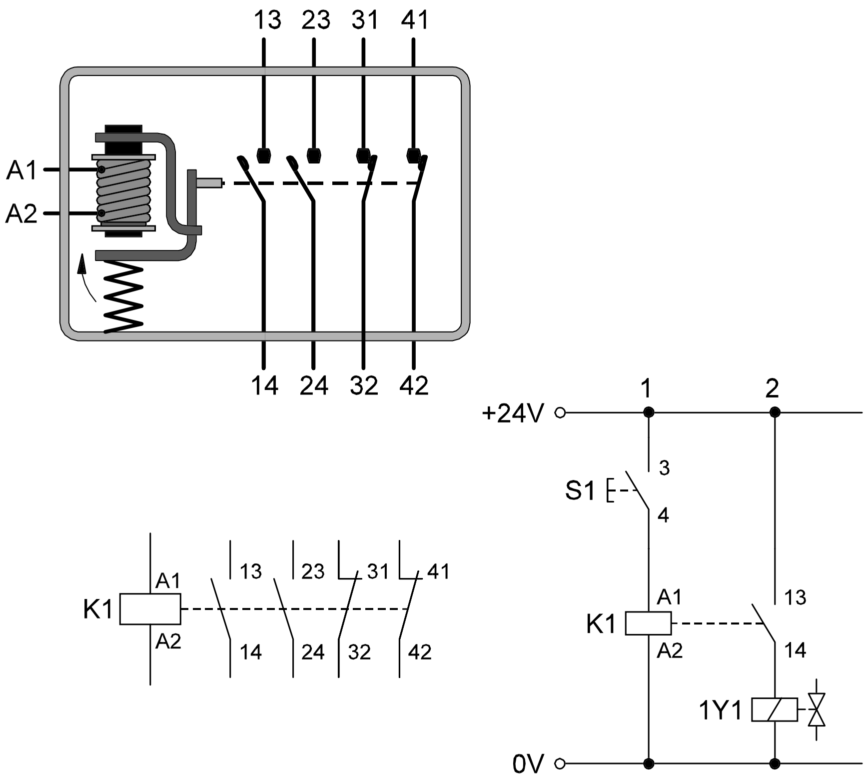


Fig. 6.30: Graphical symbols and terminal designations for a relay

Example of terminal designations for a relay

In the circuit diagram in Fig. 6.28, the terminals of relay K1 are identified as follows:

- Coil (current path 2): A1, A2
- Normally open contact (current path 3): 11, 14
- Normally open contact (current path 10): 21, 24

Contact element table

All contacts actuated by a relay coil or contactor coil are listed in a contact element table. The contact element table is placed beneath the current path containing the relay coil. Contact element tables may be shown in either simplified or detailed form (Fig. 6.31).

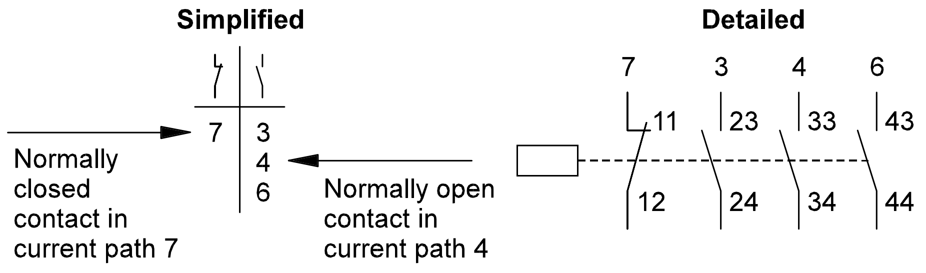


Fig. 6.31: Contact element table for a relay in simplified and detailed form

Examples of contact element tables

There are a total of 4 contact element tables in the circuit diagram in Fig. 6.28:

- Current path 2: contact element table for relay K1
- Current path 4: contact element table for relay K2
- Current path 5: contact element table for relay K3
- Current path 8: contact element table for relay K4

Actuated contacts and sensors

The electrical circuit diagram is shown in the de-energized state (electric power supply switched off). If limit switches are actuated in this position, they are identified by an arrow (Fig. 6.32). The associated contacts are also shown in the actuated position.

Symbol

Actuated normally closed contact

Actuated normally open contact

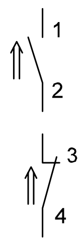


Fig. 6.32:
Representation of actuated contacts in a circuit diagram

6.5 Terminal connection diagram

In an electropneumatic control system, sensors, control elements, signal processing units and solenoid coils have to be wired up to each other. Particular attention needs to be paid to the arrangement of the control components:

- Sensors are frequently mounted in parts of an installation that are difficult to access.
- Signal processing equipment (relays, programmable logic controllers) are usually located in a control cabinet. To an increasing extent, however, PLCs are also now being integrated into valve terminals.
- Control elements are either mounted directly in the front of the control cabinet or the system is operated via a separate control console.
- Electrically actuated directional control valves are mounted in blocks in the control cabinet, in blocks on valve terminals or individually in the vicinity of the drive units.

The large number of components and the distances between them make wiring a significant cost factor in an electropneumatic control system.

Wiring requirements

The wiring of an electropneumatic control system must satisfy the following requirements:

- Cost-effective design (use of components which allow speedy wiring while maintaining a good price/performance ratio, optimization of the circuit diagram in terms of wiring expense, use of components with reduced number of terminals)
- Simple troubleshooting (clear wiring which is accurately documented and is easy to follow)
- Swift repair (simple replacement of components by means of terminal or plug-in connections, no soldered-on components)

Fieldbus systems

In electropneumatics, increasing use is being made of fieldbus systems for the transmission of signals. These systems exhibit the following characteristics:

- Particularly clear, easy to maintain layout of the control circuit
- Effort and cost of wiring reduced to a fraction (plug-in connections)
- Amount and cost of hardware increased (more complex electronics)

The decision as to whether a fieldbus system should be used or the control system should be set up using individual wiring is dependent on the particular application (see Chapter 9).

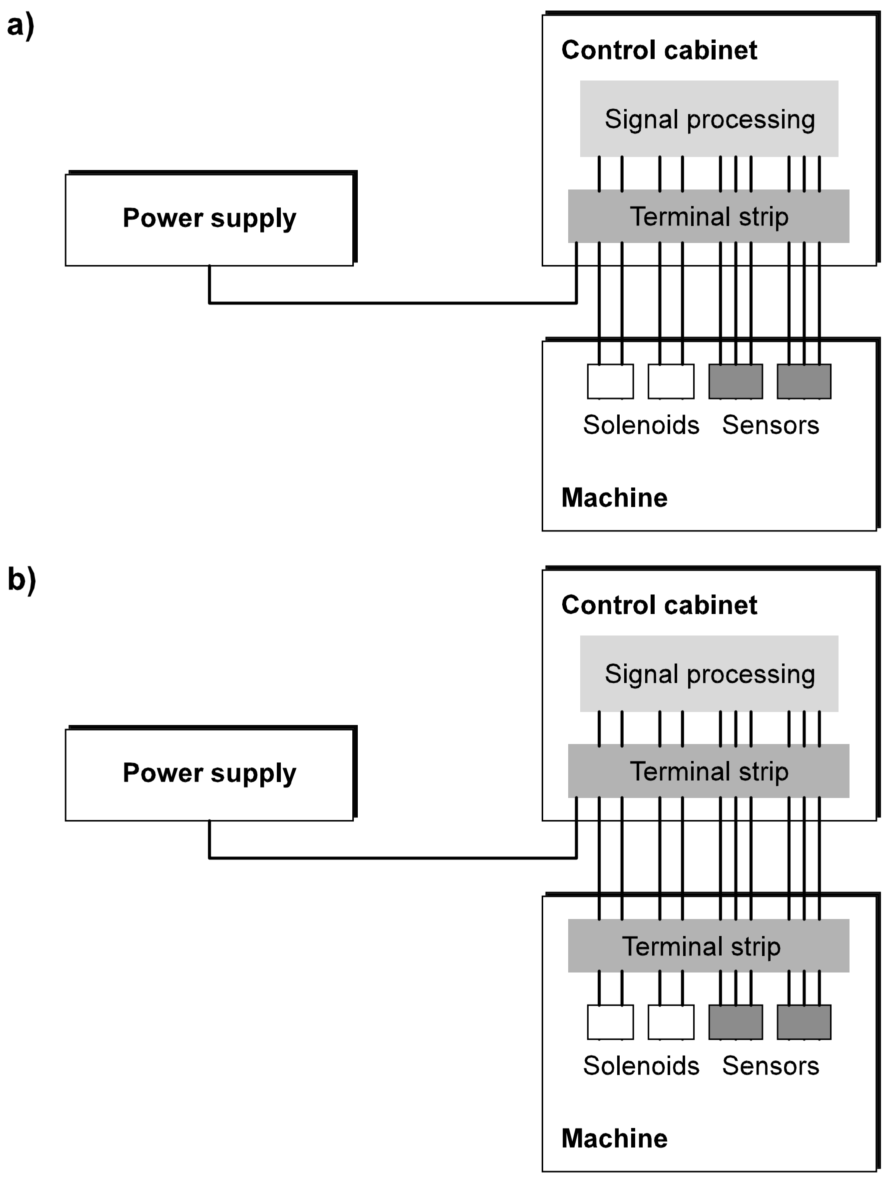


Fig. 6.33:
Structure of an electropneumatic control system using terminal strips

Wiring with terminal strips

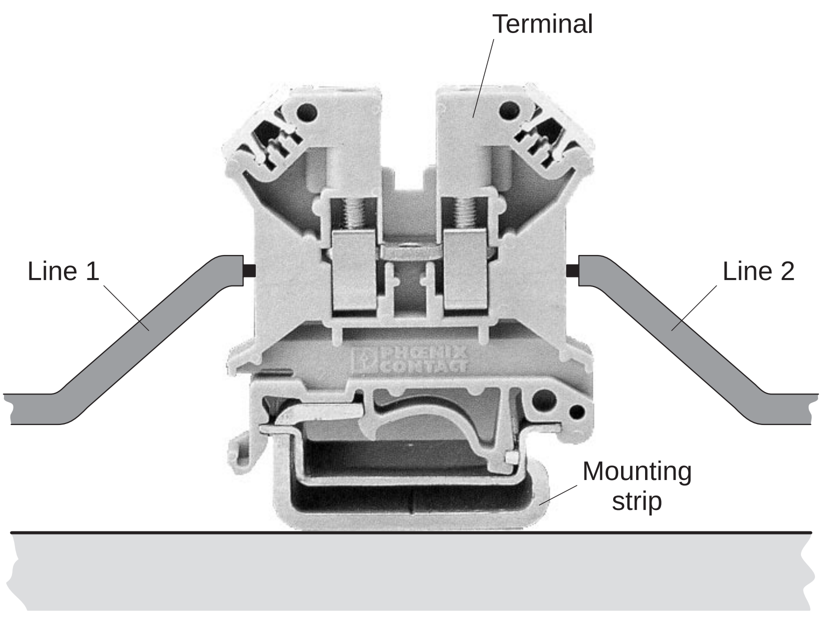
In control systems where components are wired individually, terminal strips are used in order to satisfy the requirements regarding low wiring costs, simple troubleshooting and repair-friendly layout. All lines leading into or out of the control cabinet are run via a terminal strip (Fig. 6.33a). Faulty components can easily be disconnected from the strip and then replaced.

If additional terminal strips are mounted directly on the installation or machine, the supply lines used to connect the components situated outside the control cabinet can be considerably shorter (Fig. 6.33b). This makes installing and replacing the components even easier. Each additional terminal strip is fitted inside a terminal box in order to protect it from environmental effects.

Design of terminals and terminal strips

A terminal has two receptacles for electrical lines; these are arranged one beneath the other and have an electrically conductive connection (Fig. 6.34). All terminals are attached to a strip, alongside each other. Electrically conductive connections between adjacent terminals can be established with straps or jumpers.

Fig. 6.34: Terminal



Terminal allocation

The twin goals of wiring a control system as inexpensively as possible while keeping the structure clear are impossible to achieve at the same time. For the purpose of maintaining a control system it is preferable if the terminals of a terminal strip are assigned in such a way that the wiring layout is easy to follow (Table 6.6). In practice the following types are encountered:

- Control circuits with systematic terminal allocations, helpful to maintenance
- Control circuits in which the number of terminals has been minimized at the expense of clarity
- Hybrids of the two other variants

Under no circumstances must several wires be assigned to one terminal connection.

	Clear terminal allocation	*Minimum number of terminals*
Advantages	- Fast troubleshooting - Easy to follow - Easy repair	- Savings (space in control cabinet, terminals) - Less wiring effort - Fewer sources of error when wiring
Disadvantages	- Material expense - Time-consuming wiring	- Lack of clarity, time-consuming especially for newcomers to the system

Table 6.6: Approaches to terminal allocation

Structure of a terminal connection diagram

Terminal allocations are documented in a terminal connection diagram. This consists of two parts: a circuit diagram and a terminal allocation list.

In the circuit diagram, each terminal is represented by a circle (Fig. 6.37). The terminals are identified by the letter X, and are numbered consecutively in sequence within the terminal strip (terminal designation X1, X2 etc. for example). If there is more than one terminal strip, each strip is also assigned a sequence number (terminal designation X2.6, for example, for the 6th terminal of terminal strip 2).

The terminal allocation list itemizes the allocations of all terminals of one strip in order. If the control system has more than one terminal strip, a separate list is produced for each strip. Terminal allocation lists are used as aids for control system installation, troubleshooting (measuring signals at the terminals) and repair.

Preparation of a terminal connection diagram

The basis on which to produce the terminal connection diagram is the circuit diagram with no terminal allocations shown. The terminal connection diagram is drawn up in two stages:

1. Allocation of terminal numbers and drawing the terminals in the circuit diagram.
2. Compilation of the terminal allocation list(s).

Application example

In the following an explanation is given of a terminal allocation procedure with which to obtain clear, easy-to-follow wiring. The starting point for preparing the terminal connection diagram is given by:

- The circuit diagram of a control system without the terminal markings (Fig. 6.35)
- A printed form for a terminal allocation list (Fig. 6.36)

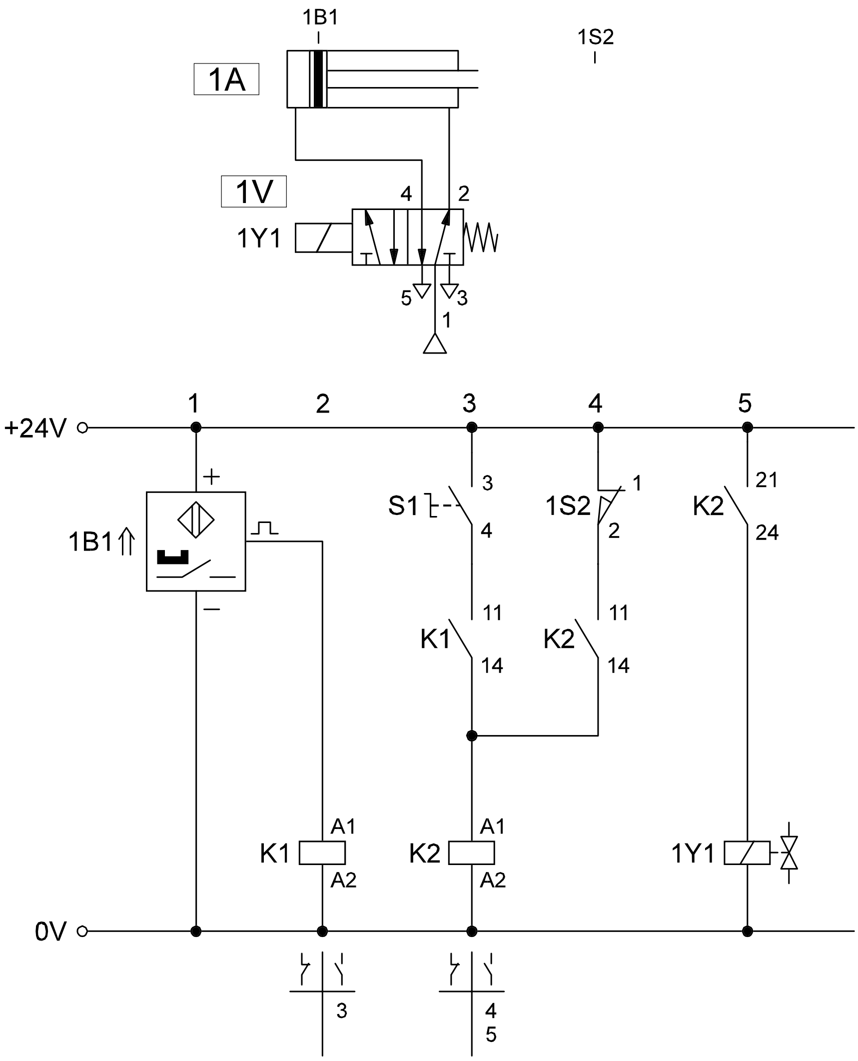


Fig. 6.35:
Pneumatic circuit diagram and electrical circuit diagram of an electro-pneumatic control system

Fig. 6.36: Printed form for a terminal allocation list

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

Allocation of terminal numbers

The terminal numbers are allocated in ascending order and marked on the circuit diagram. The allocation procedure between the circuit diagram and terminals comprises three stages:

1. Power supply for all current paths (terminals X1-1 to X1-4 in the circuit diagram in Fig. 6.37)
2. Ground connection for all current paths (terminals X1-5 to X1-8 in the circuit diagram in Fig. 6.37)
3. Connection of all components situated outside the control cabinet, according to the following system:
   - In the order of the current paths
   - From top to bottom within each current path
   - In the case of contacts, in the order of the function numbers
   - In the case of electronic components, in the order of supply voltage connection, signal connection (if applicable), ground connection

In the circuit diagram in Fig. 6.37, the components are allocated to terminals X1-9 to X1-17.

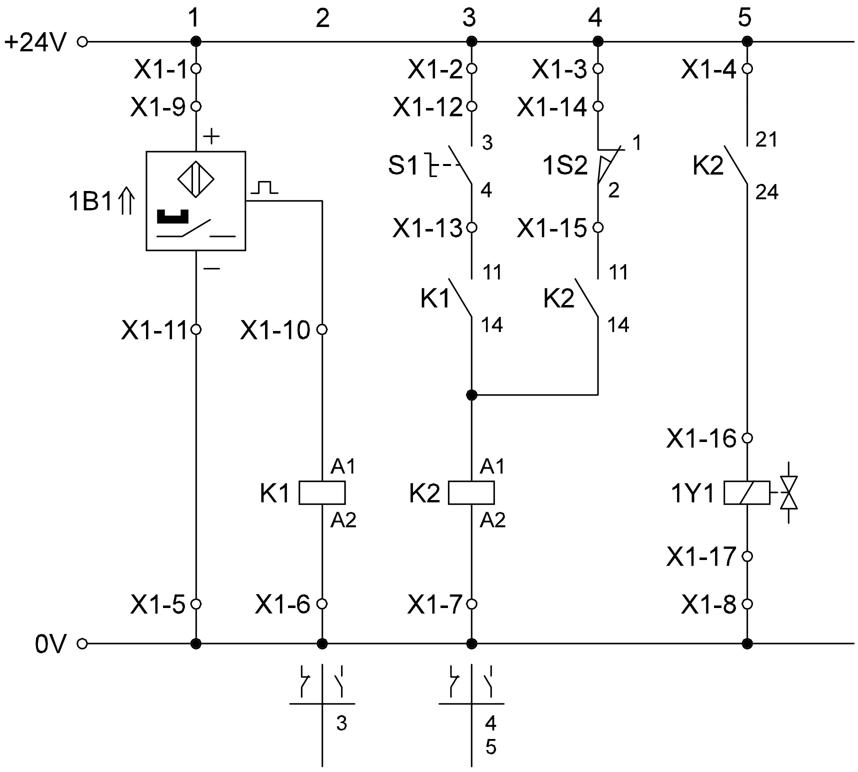


Fig. 6.37: Circuit diagram with terminals entered

Completing the terminal allocation list

Entries are made in the terminal allocation list in the following steps:

1. Enter the component and connection designations of the components outside the control cabinet (on the left-hand side of the terminal allocation list).
2. Enter the component and connection designations of the components inside the control cabinet (on the right-hand side of the terminal allocation list).
3. Draw any required jumpers (in the example: terminals X1-1 to X1-4 for 24 V supply voltage, X1-5 to X1-8 for supply ground).
4. Enter the terminal-terminal connections that cannot be implemented with jumpers.

Fig. 6.38: Terminal allocation list for the example control system

Machine: Destination		Connection brigde	Terminal no. X1	Control cabinet: Destination	
Component designation	Connection designation			Component designation	Connection designation
	+24V	○	1	X1	9
		○	2	X1	12
		○	3	X1	14
		○	4	K2	21
	0V	○	5	X1	11
		○	6	K1	A2
		○	7	K2	A2
		○	8	X1	17
1B1	+	○	9	X1	1
1B1	⎍	○	10	K1	A1
1B1	–	○	11	X1	5
S1	3	○	12	X1	2
S1	4	○	13	K1	11
1S2	1	○	14	X1	3
1S2	2	○	15	K2	11
1Y1		○	16	K2	24
1Y1		○	17	X1	8
		○	18		
		○	19		
		○	20		

Wiring an electropneumatic control system

The structure of a terminal allocation list is based on the design of the terminal strip. Accordingly, an electropneumatic control system can largely be wired up on the basis of the terminal allocation list (Fig. 6.38):

- All lines running to components outside the control cabinet are connected in accordance with the list on the left-hand side of the terminal strip.
- All lines running to components inside the control cabinet are connected in accordance with the list on the right-hand side of the terminal strip.
- Adjacent terminals on which a bridge has been drawn in the terminal allocation list are connected to each other.

Lines linking two components inside the control cabinet are not routed via the terminal strip. They are therefore not included in the terminal allocation list and have to be wired up according to the circuit diagram.

Chapter 7

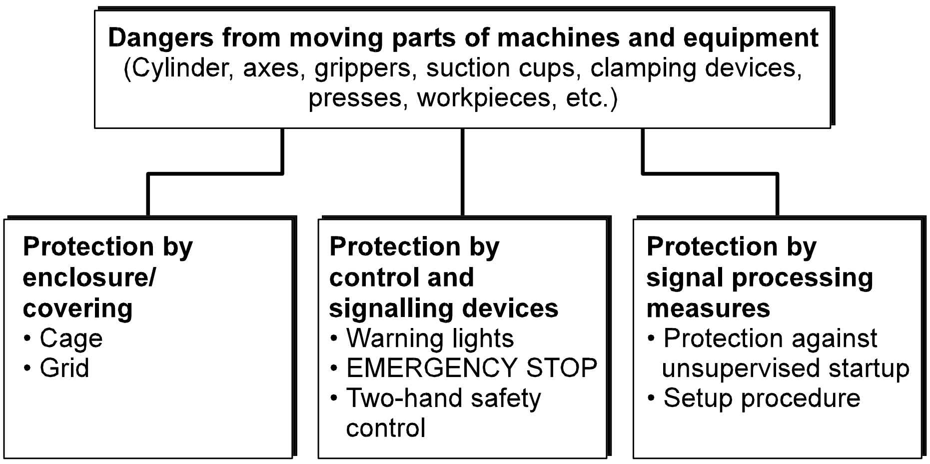
Safety measures for electropneumatic control systems

7.1 Dangers and protective measures

Numerous protective measures are necessary in order to ensure that electropneumatic control systems can be safely operated.

One source of danger is moving parts of machines and equipment. On a pneumatic press, for example, care must be taken to prevent the operator's fingers or hands from being trapped. Fig. 7.1 provides an overview of sources of danger and suitable protective measures.

Fig. 7.1: Moving parts of machines and equipment: sources of danger and protective measures



Electric current is another source of danger. The dangers and protective measures relating to electric current are summarized in Fig. 7.2.

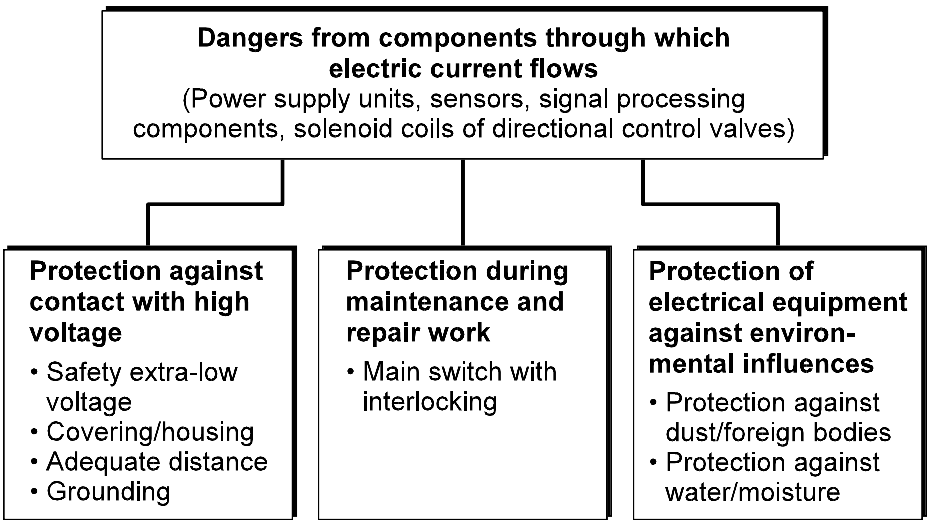


Fig. 7.2: Electric current: sources of danger and protective measures

Safety rules

In order to provide the best possible safeguards for operating personnel, various safety rules and standards must be observed when designing electropneumatic control systems. The key standards dealing with protection against the dangers of electric current are listed below:

- Protective Measures for Electrical Power Installations up to 1000 V (DIN VDE 0100)
- Specifications for Electrical Equipment and Safety of Machines (DIN/EN 60204)
- Degrees of Protection of Electrical Equipment (DIN-VDE 470-1)

7.2 Effect of electric current on the human body

When a person touches a live part, an electric circuit is completed (Fig. 7.3a). An electric current I flows through the person's body.

Effect of electric current

The effect of electric current on the human body increases with the intensity of the current and with the length of time in contact with the current. The effects are grouped according to the following threshold values:

- Below the threshold of perception, electric current has no effect on the human body.
- Up to the let-go threshold, electric current is perceived but there is no danger to human health.
- Above the let-go threshold, muscles become cramped and functioning of the heart is impaired.
- Above the threshold of non-fibrillation, the effects are cardiac arrest or ventricular fibrillation, cessation of breathing and unconsciousness. There is an acute risk to life.

The threshold of perception, let-go threshold and non-fibrillation threshold are plotted in Fig. 7.4 for alternating current with a frequency of 50 Hz. This corresponds to the frequency of the electrical supply network. For direct current, the threshold values for endangering human beings are slightly higher.

Electrical resistance of the human body

The human body offers resistance to the flow of current. Electric current may enter the body through the hand, for example; it then flows through the body to re-emerge at another point (such as the feet - see Fig. 7.3a). Accordingly, the electrical resistance R_M of the human body (Fig. 7.3c) is formed by a series circuit comprising the entry resistance $R_{Ü1}$, the internal resistance R_I and the exit resistance $R_{Ü2}$ (Fig. 7.3b). It is calculated using the following formula:

$$R_M = R_{Ü1} + R_I + R_{Ü2}$$

The contact resistances $R_{Ü1}$ and $R_{Ü2}$ vary greatly depending on the contact surface and the moistness and thickness of the skin. This affects the total resistance R_M. It may range between the following extremes:

- Less than 1000 ohms (large contact surfaces, wet, sweaty skin)
- Several million ohms (point contact, very dry, thick skin)

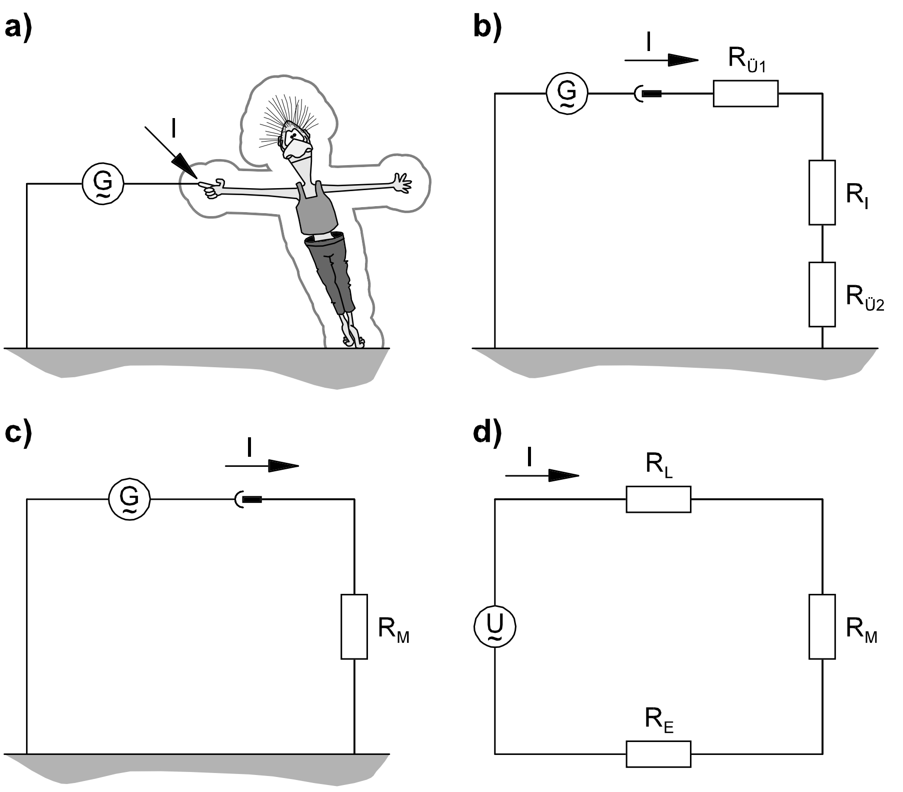


Fig. 7.3:
Touching live parts

Variables influencing the risk of accident

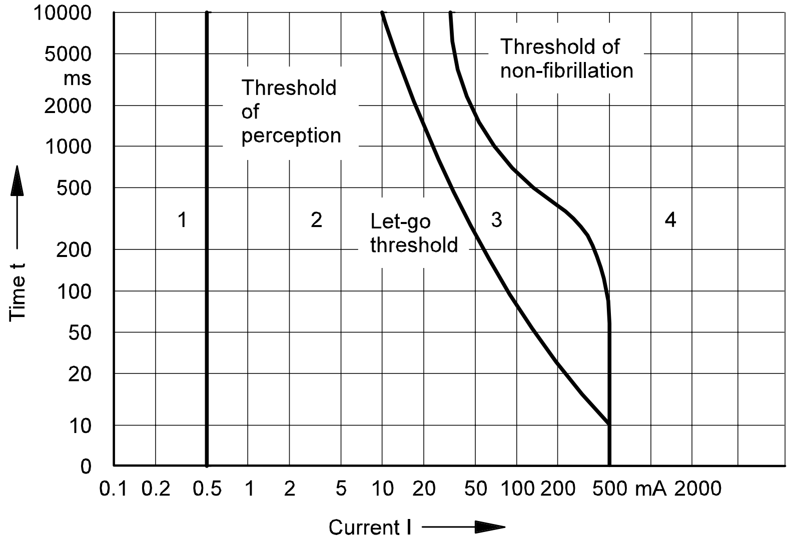
The current I through the human body is dependent on the source voltage V, the resistance R_L of the electric line, the resistance R_M of the person and the resistance R_E of the ground (Fig. 7.3d). It is calculated as follows:

$$I = \frac{V}{R_L + R_M + R_E}$$

According to this formula, a high current, i.e. a high level of danger, is obtained in the following circumstances:

- When touching an electrical conductor carrying a high voltage U (such as a conductor in the electrical supply network, 230 V AC)
- When touching a conductor at a low contact resistance RÜ and consequently low resistance RM (such as with large contact surfaces, sweaty skin, wet clothing)

Fig. 7.4: Danger zones with AC voltage (frequency 50 Hz / 60 Hz)



7.3 Measures to protect against accidents with electric current

There are a wide variety of protective measures which prevent the operator of an electropneumatic control system from being put at risk from electric current.

Protection against direct contact

Protection against touching live parts is prescribed for both high and low voltages. Such protection can be ensured in the following ways:

- Insulation
- Covering
- Sufficient clearance

Grounding

Components which are liable to be touched by anyone must be grounded. If a grounded housing becomes live, the result is a short circuit and the overcurrent protective devices are tripped, interrupting the voltage supply. Various devices are used for overcurrent protection:

- Fuses
- Power circuit-breakers
- Fault-current-operated circuit-breakers
- Fault-voltage-operated circuit-breakers

Safety extra-low voltage

There is no risk to life when touching an electric conductor carrying a voltage of less than approximately 30 V because only a small current flows through the body.

For this reason, electropneumatic control systems are not normally operated at the voltage of the electrical supply network (such as 230 V AC) but at 24 V DC. The supply voltage is reduced by a power supply unit with an isolating transformer (see Section 3.1).

Warning: Despite this precaution, the electrical wiring at the inputs to the power supply unit carry high voltage.

7.4 Control panel and indicating elements

Control elements and indicating elements must be designed in such a way as to ensure safe and fast operation of the control system. The functions, arrangement and colour coding of control elements and indicator lamps are standardized. This allows the use of uniform operating procedures for different control systems, and operating errors are prevented as far as possible.

Main switch

Every machine and installation must have a main switch. This switch is used to switch off the supply of electric power for the duration of cleaning, maintenance or repair work and for lengthy shut down periods. The main switch must be manually operated and must have only two switch positions: "0" (Off) and "1" (On). The Off position must be lockable in order to prevent manual starting or remote starting. If there is more than one incoming supply, the main switches must be interlocked such that no danger can arise for the maintenance personnel.

EMERGENCY STOP

The EMERGENCY STOP control switch is actuated by the operator in dangerous situations.

The EMERGENCY STOP operating device must have a mushroom button if it is operated directly by hand. Indirect operation by pull-wire or foot pedal is permissible. If there is more than one workstation or operating panel, each one must have its own EMERGENCY STOP operating device. The colour of the EMERGENCY STOP actuation element is a conspicuous red. The area beneath the control switch must be marked in contrasting yellow.

Once the EMERGENCY STOP device has been actuated the drives must be shut down as quickly as possible and the control system should be isolated from the electrical and pneumatic power supplies where feasible. The following limitations have to be observed, however:

- If illumination is necessary, this must not be switched off.
- Auxiliary units and brake devices provided to aid rapid shutdown must not be rendered ineffective.
- Clamped workpieces must not be released.
- Retraction movements must be initiated by actuation of the EMERGENCY STOP device where necessary. Such movements may however only be initiated if this can be done without danger.

Control elements of an electropneumatic control system

An electropneumatic control system has other control elements in addition to the main and EMERGENCY STOP switch. An example of a control panel is shown in Fig. 7.5.

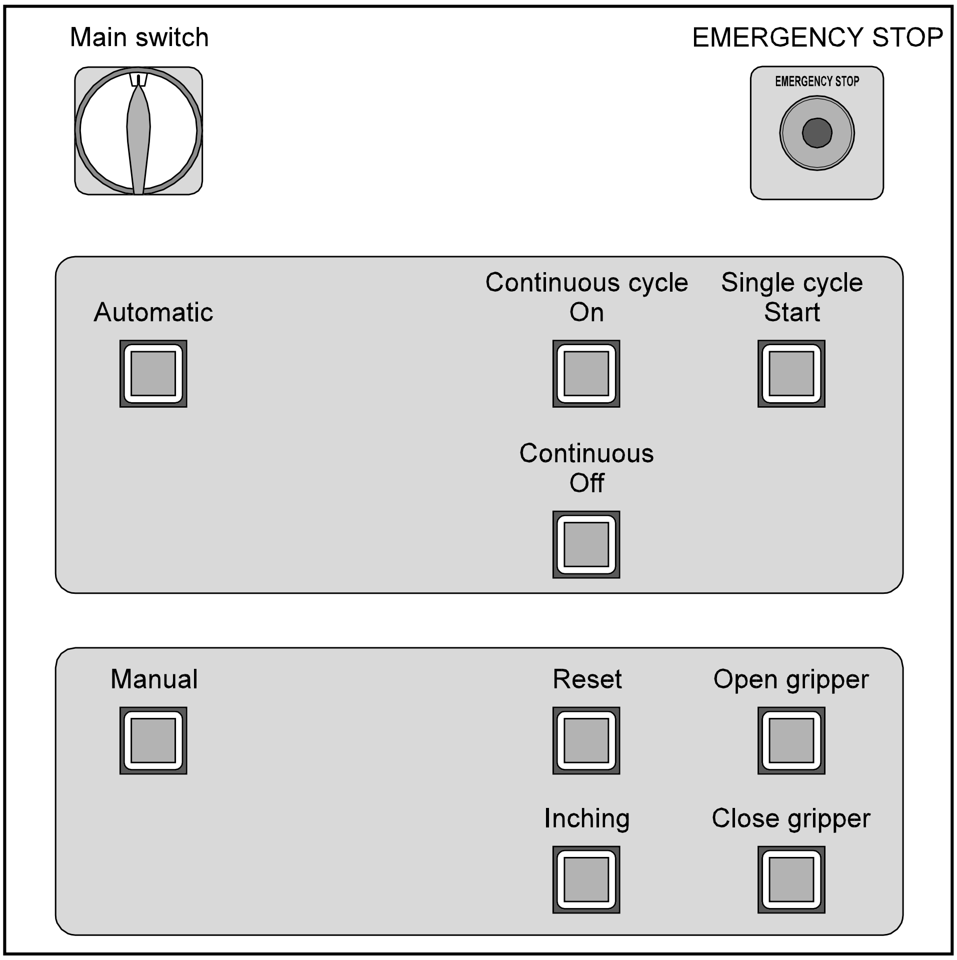


Fig. 7.5:
Control panel of an electropneumatic control system (example)

A distinction is drawn between two different types of operation for electropneumatic control systems:

- Manual operation
- Automatic, i.e. program-controlled operation

Manual operation

The following control elements have an effect in manual operation:

- "Reset": The system is moved to the initial position.
- "Inching": Each time that this pushbutton is pressed, the sequence is extended by one step.
- Individual movements: A drive is actuated when the corresponding pushbutton or control switch is pressed (example in Fig. 7.5: "Open gripper" or "Close gripper").

Automatic operation

The following operating modes are possible only in automatic operation:

- Single cycle: The sequence is executed once.
- Continuous cycle: The sequence is executed continuously.

Pressing the "Continuous cycle OFF" pushbutton (or a "Stop" button) interrupts the sequence. The interruption occurs either after the next step or after completion of the entire sequence.

The main switch and EMERGENCY STOP switch are effective in all operating modes. They must be available on every electropneumatic control system together with control elements for "Manual" and "Automatic", "Start", "Stop" and "Reset". Which control elements are necessary in addition to these is dependent on each individual application.

Colour coding of control elements

Table 7.1 provides an overview of the colours of control elements and what these colours mean, in line with EN 60204.

Table 7.1: Colour coding of control elements of machine control systems

Colour	*Command*	*Required operating status*
Red	Stop, Off	Shut down one or more motors. Shut down units of a machine. Switch off magnetic clamping devices.
		Stop the cycle (if the operator presses the pushbutton during a cycle, the machine stops once the current cycle has been completed).
	EMERGENCY STOP	Stop in the event of danger (e. g. shutdown because of dangerous overheating).
Green or black	Start, On, Inching	Energize control circuits (ready for operation). Start one or more motors for auxiliary functions. Start units of the machine. Switch on magnetic clamping devices. Inching operation (inching when switched on).
Yellow	Start a return movement outside the normal work sequence, or start a movement to counteract dangerous conditions.	Return machine units to the starting point of the cycle, if the cycle is not yet completed. Actuation of the yellow pushbutton may deactivate other, previously selected functions.
White or black	Any function for which none of the above colours is used.	Control auxiliary functions which are not directly linked to the operation cycle.

Colour coding of indicator lamps

To enable operating staff to immediately identify the operating status of a system, especially malfunctions and dangerous situations, indicator lamps are colour-coded in accordance with EN 60204. The meanings of the various colours are shown in Table 7.2.

Table 7.2: Colour coding of indicator lamps on machine control systems

Colour	*Operating status*	*Examples of application*
Red	Abnormal status	Indication that the machine has been stopped by a protective device (e. g. due to overload, overtravel or some other fault). Prompt to shut down the machine (e. g. because of overload).
Yellow	Attention or caution	A value (current, temperature) is approaching its permissible limit or Signal for automatic cycle.
Green	Machine ready to start	Machine ready to start: Auxiliaries operational. The (various) units are at their initial positions and the pneumatic pressure or the voltage of a transformer have reached the prescribed values. The operation cycle is completed and the machine is ready for restarting.
White (colourless)	Electric circuits energized Normal status in operation	Master switch in On position. Selection of speed or direction of rotation. Individual drives and auxiliary devices in operation. Machine running.
Blue	Any function for which none of the above colours is used	

7.5 Protecting electrical equipment against environmental influences

Electrical equipment such as sensors or programmable logic controllers may be exposed to a variety of environmental influences. The factors which may impair operation of such equipment include dust, moisture and foreign matter.

Depending on the circumstances of installation and the environmental conditions, electrical equipment may be protected by housings and seals. Such measures also prevent danger to personnel handling the equipment.

Identification of the degree of protection

The identifier for the degree of protection in accordance with DIN-VDE 470-1 consists of the two letters IP (standing for "International Protection") and two digits. The first digit indicates the scope of protection against the ingress of dust and foreign bodies, and the second digit the scope of protection against the ingress of moisture and water. Tables 7.3 and 7.4 show the assignment between the class of protection and the scope of protection.

Table 7.3: Protection against contact, dust and foreign bodies

First digit	*Scope of protection* *Designation*	*Explanation*
0	No protection	No particular protection of persons against accidental touching of energized or moving parts. No protection of the equipment against the ingress of solid foreign bodies.
1	Protection against large foreign particles	Protection against accidental large-area touching of energized or moving internal parts, such as touching with the hand, but no protection against intentional access to these parts. Protection against the ingress of solid foreign bodies with a diameter of greater than 50 mm.
2	Protection against medium foreign particles	Protection against touching with fingers of energized or moving internal parts. Protection against the ingress of solid foreign bodies with a diameter of greater than 12 mm.
3	Protection against small foreign particles	Protection against touching of energized or moving internal parts with tools, wires or similar objects with a thickness greater than 2.5 mm. Protection against the ingress of solid foreign bodies with a diameter of greater than 2.5 mm.
4	Protection against granular foreign particles	Protection against the ingress of solid foreign bodies with a diameter of greater than 1 mm.
5	Protection against dust accumulation	Complete protection against touching of energized or moving internal parts. Protection against detrimental accumulation of dust. The ingress of dust is not entirely prevented, but dust must not be allowed to ingress in sufficient quantities to impair operation.
6	Protection against dust ingress	Complete protection against touching of energized or moving internal parts. Protection against the ingress of dust.

Second Code no.	Scope of protection Designation	Explanation
0	No protection	No specific protection.
1	Dripping water	Drops falling vertically must not have any harmful effects
2	Water drops at 15° angle	Vertically falling drops of water must not have any harmful effects if the housing is tilted by angle of up to 15° on either side of the vertical.
3	Spraying water	Water sprayed at an angle of up to 60° on either side of the vertical must not have any harmful effects.
4	Splashing water	Water that is directed towards the housing from any direction must not have any harmful effects.
5	Jets of water	Jets of water from a nozzle directed at the housing from any direction must not have any harmful effects.
6	Strong jets of water	Strong jets of water from a nozzle directed at the housing from any direction must not have any harmful effects.
7	Periodic immersion	Water must not penetrate in harmful amounts if the housing is immersed in water periodically under specified conditions of pressure and time.
8	Prolonged submersion	Water must not penetrate in harmful amounts if the housing is continually submersed under water in conditions which must be agreed between the manufacturer and the user. However, the conditions must be more extreme than those for code no. 7.

Table 7.4: Protection against moisture and water

Example 1: PLC

A programmable logic controller is accommodated in a metal housing which has slits for cooling. IP 20 is specified as the degree of protection. This means:

- First digit 2: protection against the ingress of foreign bodies with a diameter greater than 12 mm, live parts protected against touching with fingers
- Second digit 0: no protection against the ingress of water or moisture

Example 2: Inductive proximity switch

The electronics for an inductive proximity switch are accommodated in an enclosed housing and the cable connection is sealed. The degree of protection of the sensor is IP 65. This means:

- First digit 6: Dust-proof
- Second digit 5: Deckwater-tight

Chapter 8

Relay control systems

8.1 Applications of relay control systems in electropneumatics

The entire signal processing needs of an electropneumatic control system can be implemented with relays. Relay control systems used to be made in large numbers. Many of these control systems are still in use in industry today.

Nowadays programmable logic controllers are commonly used for signal processing instead of relay control systems. Relays are still used in modern control systems however, for example in an EMERGENCY STOP switching device.

The principal advantages of relay control systems are the clarity of their design and the ease of understanding their mode of operation.

8.2 Direct and indirect control

The piston rod of a single-acting cylinder is to be extended when pushbutton S1 is pressed and retracted when the pushbutton is released.

Fig. 8.1a shows the associated pneumatic circuit diagram.

Direct control of a single-acting cylinder

The electrical circuit diagram for direct control of a single-acting cylinder is shown in Fig. 8.1b. When the pushbutton is pressed, current flows through the solenoid coil 1Y1 of the 3/2-way valve. The solenoid is energized, the valve switches to the actuated position and the piston rod advances.

Releasing the pushbutton results in interruption of the flow of current. The solenoid is de-energized, the directional control valve switches to the normal position and the piston rod is retracted.

Indirect control of a single-acting cylinder

If the pushbutton is pressed in an indirect control system (Fig. 8.1c), current flows through the relay coil. Contact K1 of the relay closes, and the directional control valve switches. The piston rod advances.

When the pushbutton is released, the flow of current through the relay coil is interrupted. The relay is deenergised, and the directional control valve switches to the normal position. The piston rod is retracted.

The more complex indirect type of control is used whenever the following conditions apply:

- The control circuit and main circuit operate with different voltages (such as 24 V and 230 V).
- The current through the coil of the directional control valve exceeds the permissible current for the pushbutton (such as current through the coil: 0.5 A; permissible current through the pushbutton: 0.1 A).
- Several valves are operated with one pushbutton or one control switch.
- Complex links are necessary between the signals of the various pushbuttons.

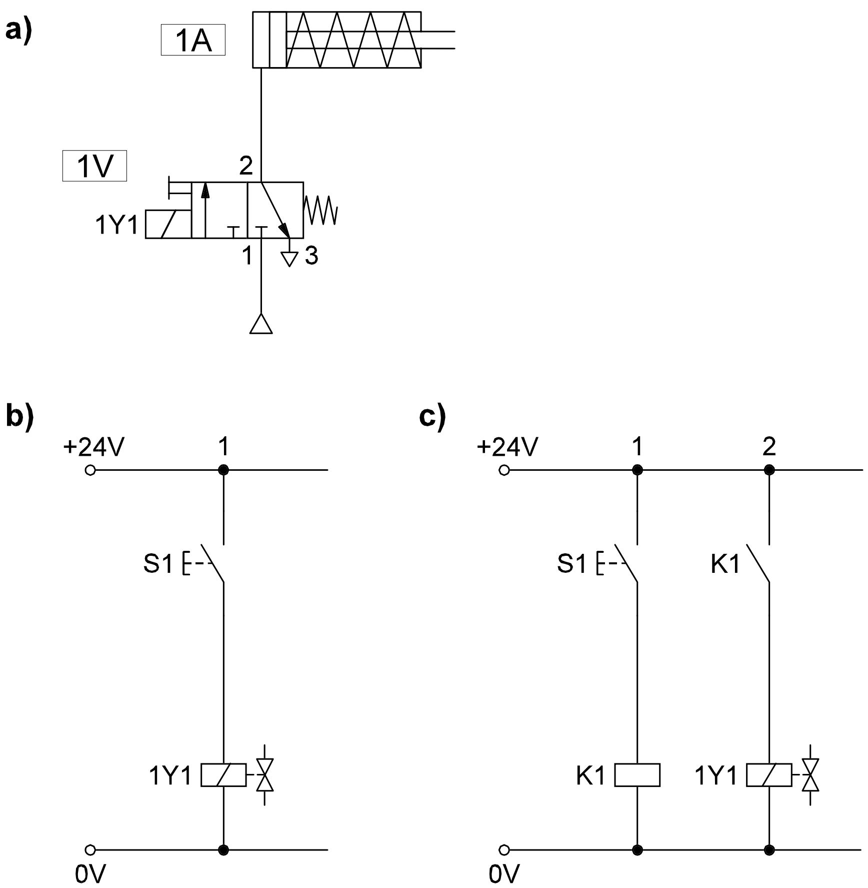


Fig. 8.1:
Circuit diagrams for control of a single-acting cylinder

a) Pneumatic circuit diagram

b) Electrical circuit diagram for direct control

c) Electrical circuit diagram for indirect control

Control of a double-acting cylinder

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

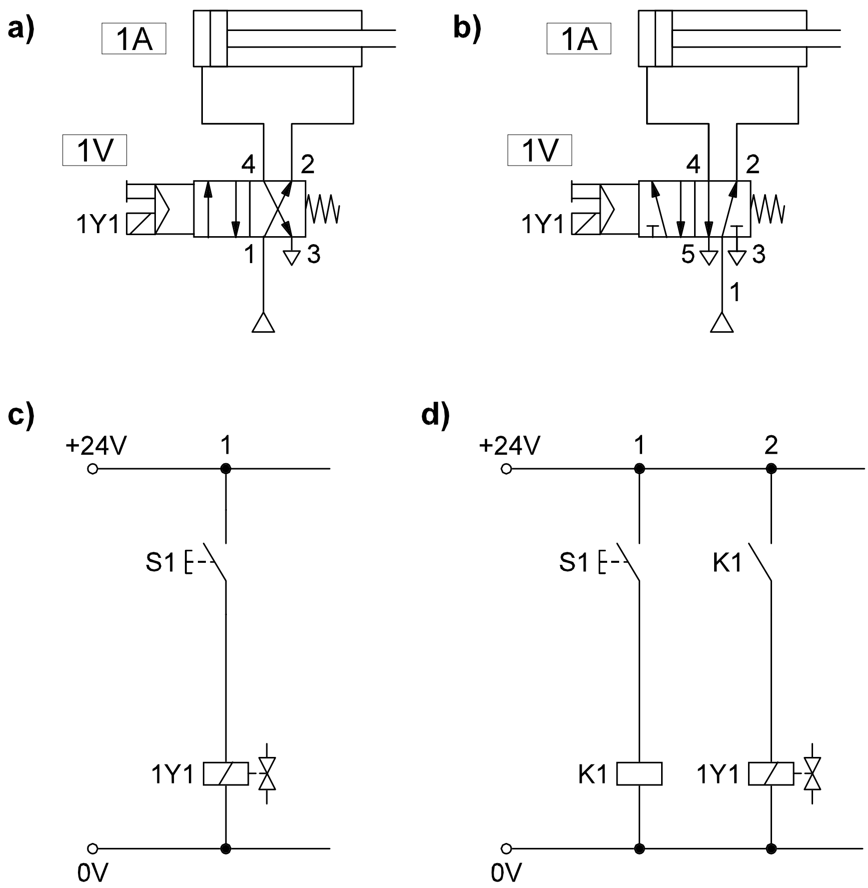
Fig. 8.2:
Circuit diagrams for control of a double-acting cylinder

a) Pneumatic circuit diagram with 4/2-way valve

b) Pneumatic circuit diagram with 5/2-way valve

c) Electrical circuit diagram with direct control

d) Electrical circuit diagram with indirect control



The electrical signal control section is unchanged from the control system for a single-acting cylinder. As there are two cylinder chambers which have to be vented or pressurized, either a 4/2 or 5/2-way valve is used (Fig. 8.2a and 8.2b respectively).

8.3 Logic operations

In order to produce the required movements by pneumatic cylinders, it is often necessary to combine signals from several control elements through logic operations.

Parallel connection (OR circuit)

The aim is to be able to trigger extend of the piston rod of a cylinder with two different input elements, pushbuttons S1 and S2.

The contacts of the two pushbuttons S1 and S2 are arranged in parallel in the circuit diagram (Figs. 8.3c and 8.3d).

- As long as no pushbutton is pressed, the directional control valve remains in the normal position. The piston rod is retracted.
- If at least one of the two pushbuttons is pressed, the directional control valve switches to the actuated position. The piston rod advances.
- When both pushbuttons are released, the valve switches to the normal position. The piston rod is retracted.

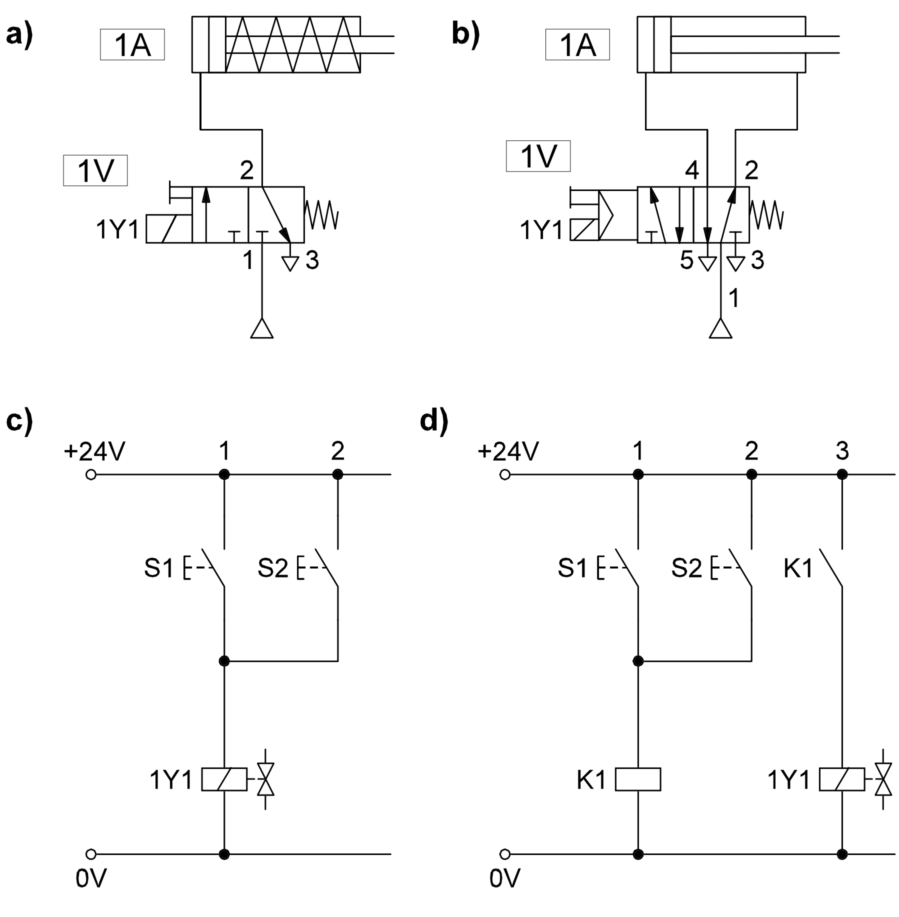


Fig. 8.3: Parallel connection of two contacts (OR circuit)

a) Pneumatic circuit diagram with single-acting cylinder

b) Pneumatic circuit diagram with double-acting cylinder

c) Electrical circuit diagram with direct control

d) Electrical circuit diagram with indirect control

Series connection (AND circuit)

In this case the piston rod of a cylinder is to be advanced only if both pushbuttons, S1 and S2, are pressed.

The contacts of the two pushbuttons are arranged in series in the circuit diagram (Figs. 8.4c and 8.4d).

- As long as neither or only one of the two pushbuttons is pressed, the directional control valve remains in the normal position. The piston rod is retracted.
- If both pushbuttons are pressed at the same time, the directional control valve switches. The piston rod advances.
- When at least one of the two pushbuttons is released, the valve switches to the normal position. The piston rod is retracted.

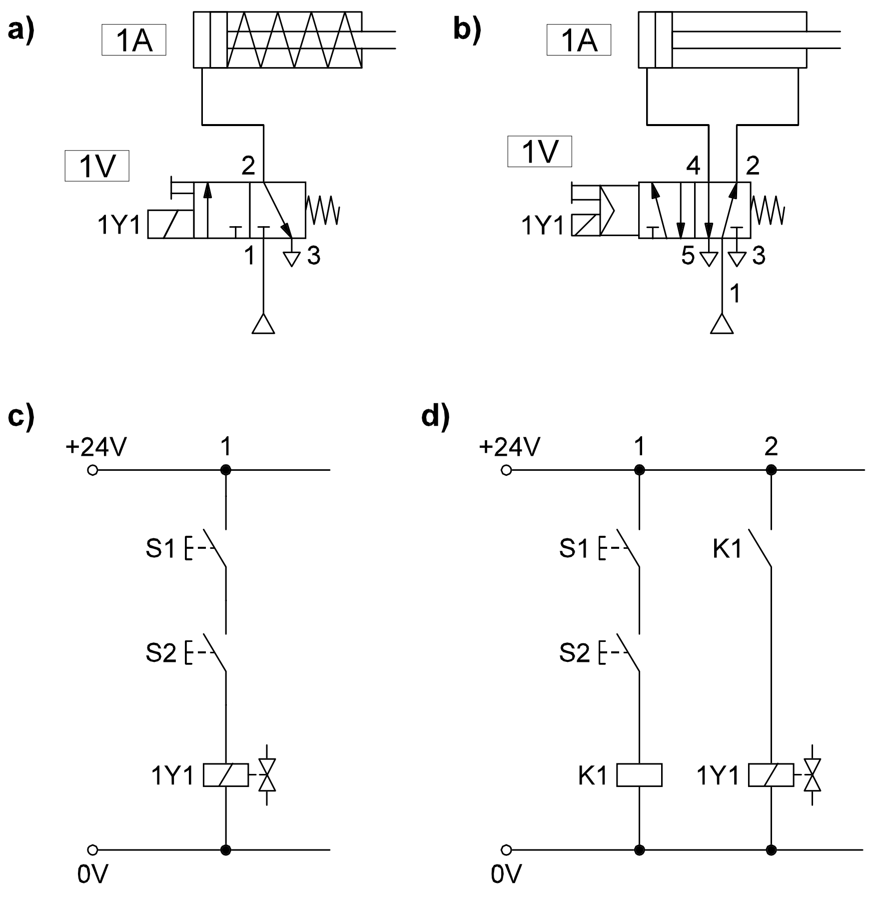


Fig. 8.4:
Series connection of two contacts (AND circuit)

a) Pneumatic circuit diagram with single-acting cylinder

b) Pneumatic circuit diagram with double-acting cylinder

c) Electrical circuit diagram with direct control

d) Electrical circuit diagram with indirect control

Representation of logic operations in tabular form

The OR and AND operations are shown in summarized form in Tables 8.1. and 8.2. The following values are assigned to the signals in the three right-hand columns:

– 0: Pushbutton not pressed or piston rod does not advance

– 1: Pushbutton pressed or piston rod advances

Pushbutton S1 pressed	*Pushbutton S2 pressed*	*Piston rod advances*	*S1*	*S2*	*1Y1*
No	No	No	0	0	0
Yes	No	Yes	1	0	1
No	Yes	Yes	0	1	1
Yes	Yes	Yes	1	1	1

Table 8.1: OR operation

Pushbutton S1 pressed	*Pushbutton S2 pressed*	*Piston rod advances*	*S1*	*S2*	*1Y1*
No	No	No	0	0	0
Yes	No	No	1	0	0
No	Yes	No	0	1	0
Yes	Yes	Yes	1	1	1

Table 8.1: AND operation

8.4 Signal storage

In the circuits that we have looked at so far, the piston rod only advances as long as the input pushbutton is actuated. If the pushbutton is released during the advancing movement, the piston rod is retracted without having reached the forward end position.

In practice it is usually necessary for the piston rod to be fully advanced even if the pushbutton is pressed only briefly. To achieve this, the directional control valve must remain in the actuated position when the pushbutton is released; in other words, actuation of the pushbutton must be stored.

Signal storage with double solenoid valve

A double solenoid valve maintains its switching position even when the associated solenoid coil is no longer energized. It is used as a storage element.

Manual forward and return stroke control with double solenoid valve

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

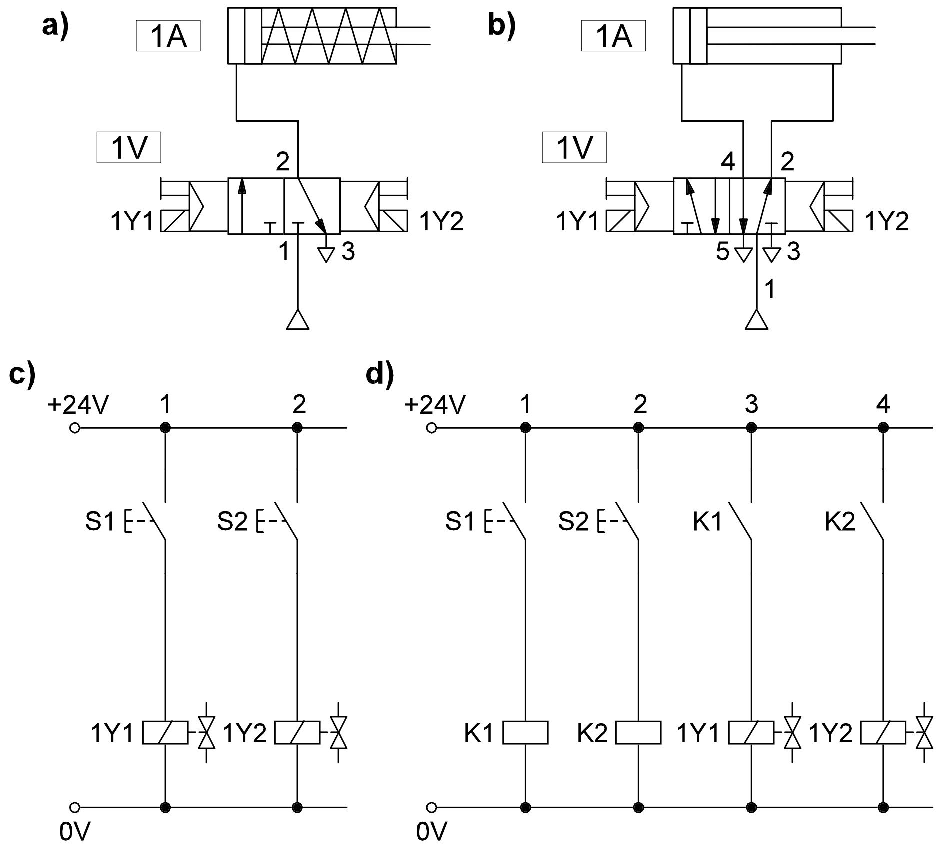


Fig. 8.5: Manual forward and return stroke control with signal storage by double solenoid valve

a) Pneumatic circuit diagram with single-acting cylinder

b) Pneumatic circuit diagram with double-acting cylinder

c) Electrical circuit diagram with direct control

d) Electrical circuit diagram with indirect control

The two pushbuttons act directly and indirectly on the coils of a double solenoid valve (Figs. 8.5c and 8.5d).

When pushbutton S1 is pressed, solenoid coil 1Y1 is energized. The double solenoid valve switches and the piston rod advances. If the pushbutton is released during the advancing movement, the piston rod continues extending to the forward end position because the valve retains its switching position.

When pushbutton S2 is pressed, solenoid coil 1Y2 is energized. The double solenoid valve switches again, and the piston rod returns. Releasing pushbutton S2 has no effect on the return movement.

Automatic return stroke control with double solenoid valve

The aim is for the piston rod of a double-acting cylinder to be advanced when pushbutton S1 is actuated. When the forward end position is reached, the piston rod is to return automatically.

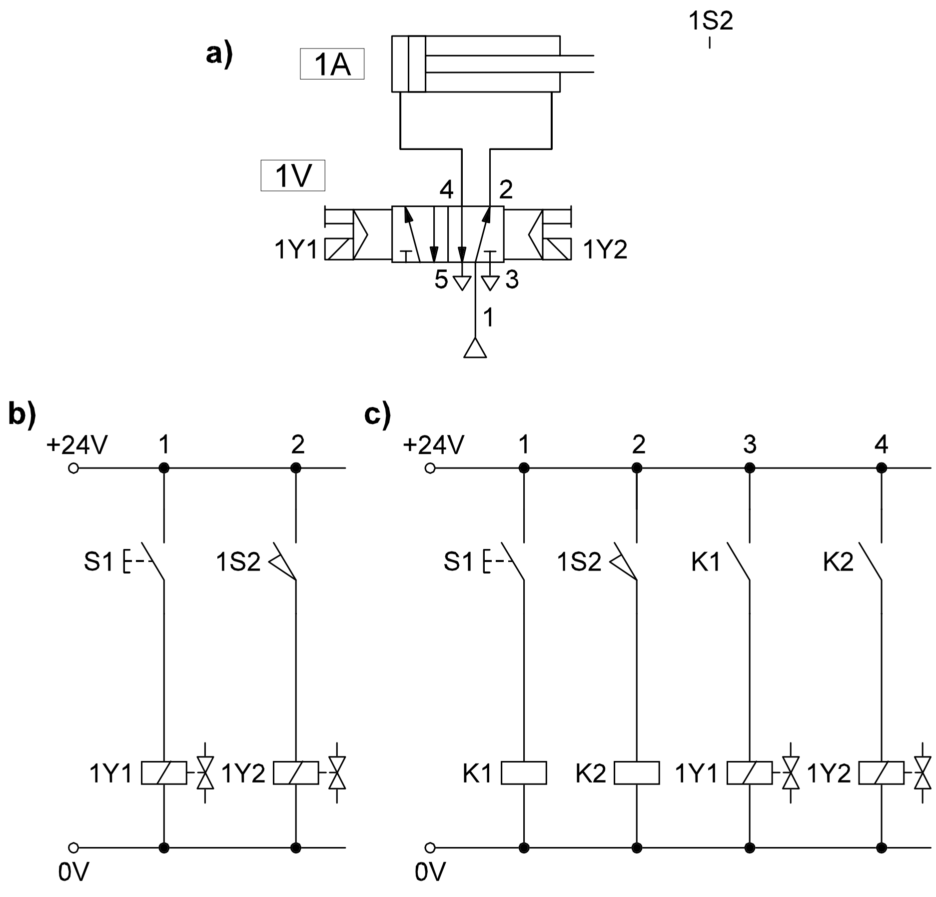


Fig. 8.6: Automatic return stroke control with signal storage by double solenoid valve

a) Pneumatic circuit diagram

b) Electrical circuit diagram with direct control

c) Electrical circuit diagram with indirect control

The circuit diagram for return stroke control is shown in Figs. 8.6b and 8.6c. When pushbutton S1 is pressed, the piston rod advances (see previous example). When the piston rod reaches the forward end position, current is applied to solenoid coil 1Y2 via limit switch 1S2, and the piston rod retracts.

The prerequisite for the return movement is that pushbutton S1 must first have been released.

Oscillating movement with double solenoid valve

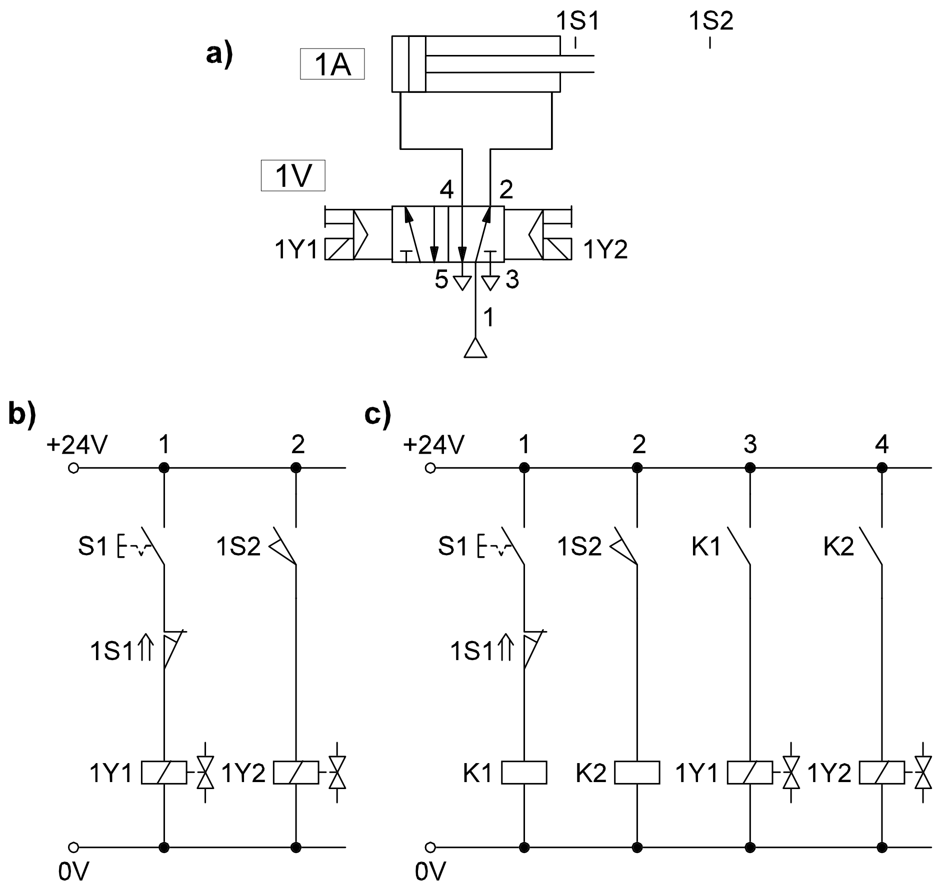
The piston rod of a cylinder is to advance and retract automatically as soon as control switch S1 is actuated. When the control switch is reset, the piston rod is to occupy the retracted end position.

Fig. 8.7: Automatic forward and return stroke control with signal storage by double solenoid valve

a) Pneumatic circuit diagram

b) Electrical circuit diagram with direct control

c) Electrical circuit diagram with indirect control



Initially the control system is in the normal position. The piston rod is in the retracted position and limit switch S1 is actuated (Figs. 8.7b and 8.7c). When contact S1 is closed, the piston rod advances. When the forward end position is reached, limit switch 1S2 is actuated and the piston rod is retracted. Provided the contact of S1 remains closed, another movement cycle begins when the piston rod reaches the retracted end position. If the contact of S1 has been opened in the meantime, the piston rod remains at the retracted end position.

Relay circuit with latching

When the "ON" pushbutton is actuated in the circuit in Fig. 8.8a, the relay coil is energized. The relay is energised, and contact K1 closes. After the "ON" pushbutton is released, current continues to flow via contact K1 through the coil, and the relay remains in the actuated position. The "ON" signal is stored. This is therefore a relay circuit with latching function.

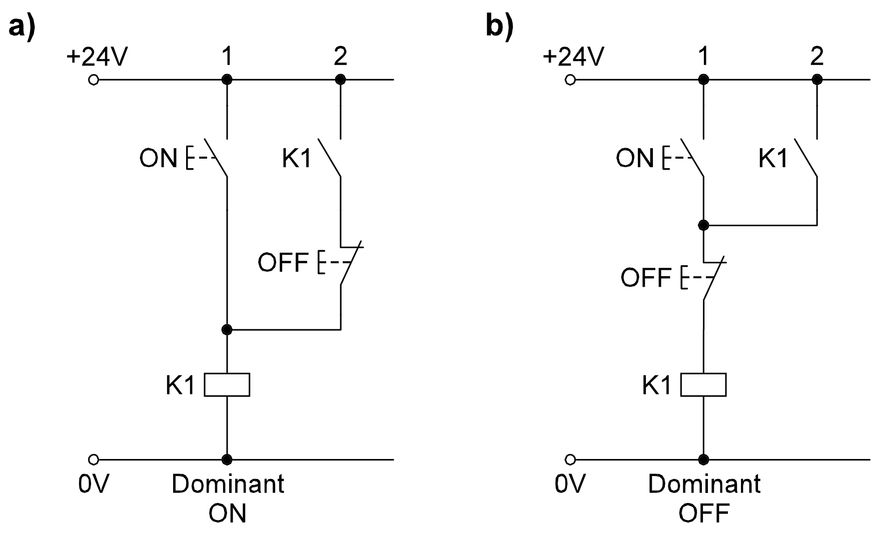


Fig. 8.8:
Latching circuit

a) Dominant ON

b) Dominant OFF

When the "OFF" pushbutton is pressed the flow of current is interrupted and the relay becomes deenergised. If the "ON" and "OFF" pushbuttons are both pressed at the same time, the relay coil is energized. This circuit is referred to as a dominant ON latching circuit.

The circuit in Fig. 8.8b exhibits the same behavior as the circuit in Fig. 8.8a provided that either only the "ON" pushbutton or only the "OFF" pushbutton is pressed. The behavior is different when both pushbuttons are pressed: The relay coil is not energized. This circuit is referred to as a dominant OFF latching circuit.

Manual forward and return stroke control via relay with latching function

In this case the piston rod of a cylinder is to advance when pushbutton S1 is pressed and retract when pushbutton S2 is pressed. A relay with latching function is to be used for signal storage.

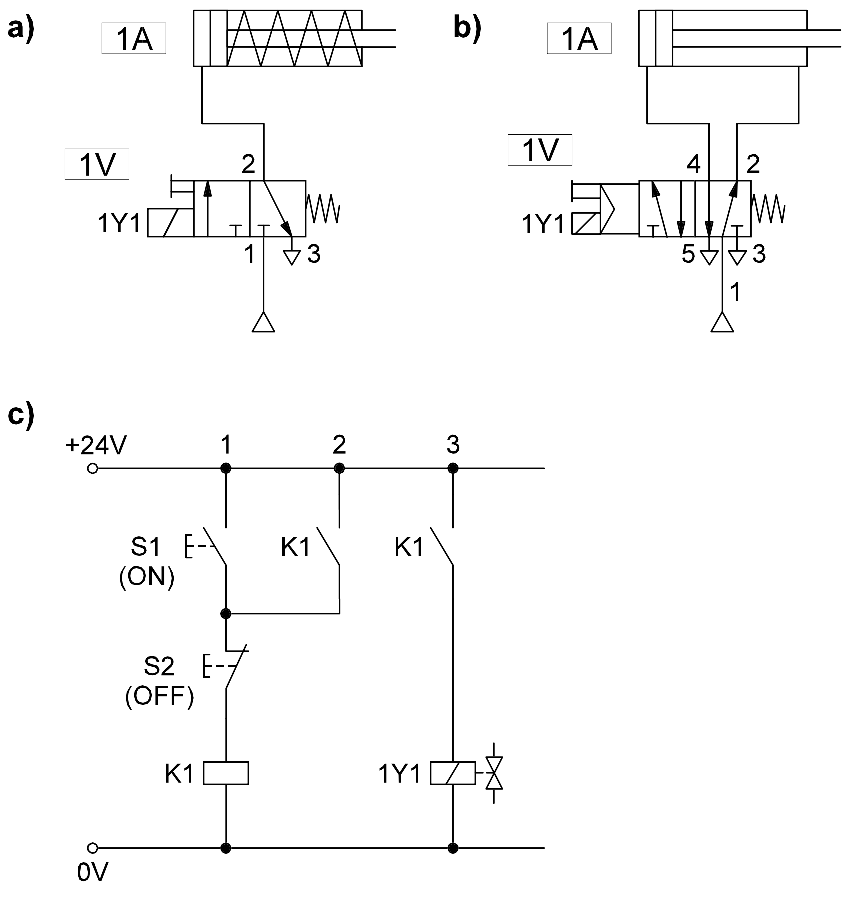


Fig. 8.9:
Manual forward and return stroke control with signal storage by latching relay

a) Pneumatic circuit diagram with single-acting cylinder

b) Pneumatic circuit diagram with double-acting cylinder

c) Electrical circuit diagram

When pushbutton S1 is pressed, the relay is latched (Fig. 8.9c). The directional control valve is actuated via another relay contact. When the latching is released by actuation of pushbutton S2, the piston rod retracts.

As this is a dominant OFF relay circuit, actuation of both pushbuttons together results in the piston rod being retracted or in it remaining in the retracted end position.

Comparison of signal storage by double solenoid valve and latching relay

Signal storage can be effected in the power section by means of a double solenoid valve, or alternatively in the signal control section by means of a relay with latching function. The various circuits behave differently in response to the simultaneous presence of a setting and resetting signal, and in the event of failure of the electrical power supply or a wire break (Table 8.3; see Section 4.3).

Table 8.3: Comparison of signal storage by latching circuit and double solenoid valve

Situation	*Signal storage by double solenoid valve*	*Signal storage by electrical latching circuit combined with spring-return valve*	
		Dominant ON	*Dominant OFF*
Setting and resetting signal together	Valve position unchanged	Valve actuated	Valve moves to neutral position
Failure of electrical power supply	Valve position unchanged	Valve moves to neutral position	Valve moves to neutral position

8.5 Delay

In many applications it is necessary for the piston rod of a pneumatic cylinder to remain at a certain position for a set length of time. This is the case for the drive of a pressing device, for example, which presses two workpieces together until the adhesive has set.

Time relays with delayed switch-on or switch-off are used for tasks such as these.

Control of a cylinder with timing

When pushbutton S1 is pressed momentarily, the piston rod of a cylinder is to advance, subsequently remain at the forward end position for ten seconds and then automatically return.

Fig. 8.10: Delayed return (delayed switch-on relay, storage by double solenoid valve)

a) Pneumatic circuit diagram

b) Electrical circuit diagram

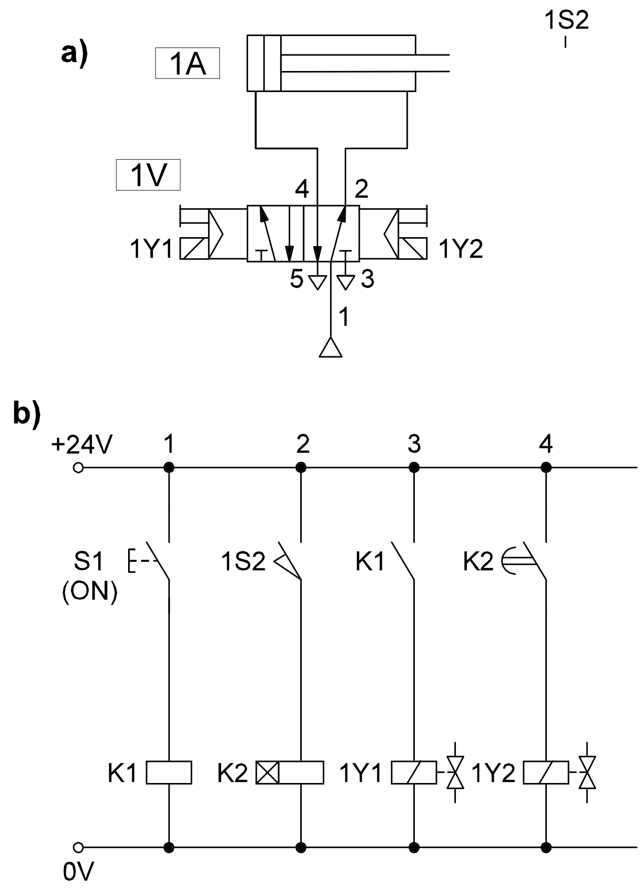


Fig. 8.10b shows the electrical circuit diagram for delayed retraction. When pushbutton S1 is actuated, the piston rod advances. When it reaches the forward end position, limit switch 1S2 closes. Current flows through coil K2. Contact K2 remains open until the variable time delay (in this case: 10 seconds) has elapsed. The contact is then closed, and the piston rod retracts.

8.6 Sequence control with signal storage by double solenoid valves

In sequence control systems, the storage of signals is an essential feature. It can be accomplished by means of either latching relays or double solenoid valves. The design of a circuit with signal storage by double solenoid valves is explained in the following.

Application example:Feeding device

The positional sketch of a feeding device is shown in Fig. 8.11. The end positions of the two cylinder drives 1A and 2A are detected by the positive switching inductive proximity switches 1B1 and 2B2.

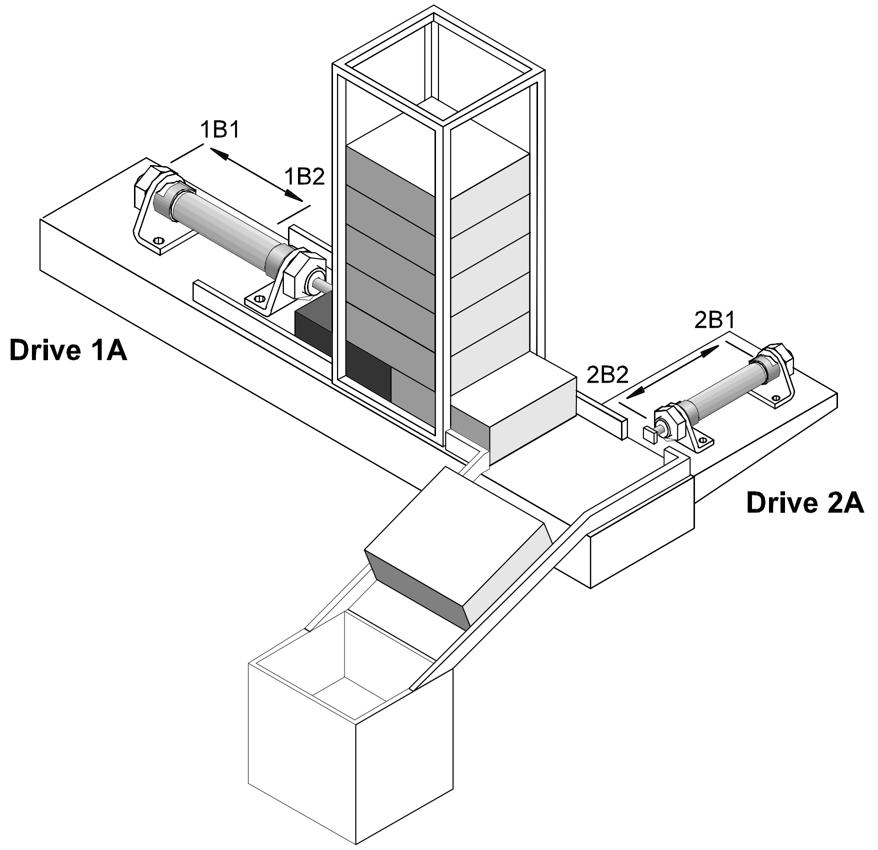


Fig. 8.11: Positional sketch of feeding device

Displacement-step diagram for the feeding device

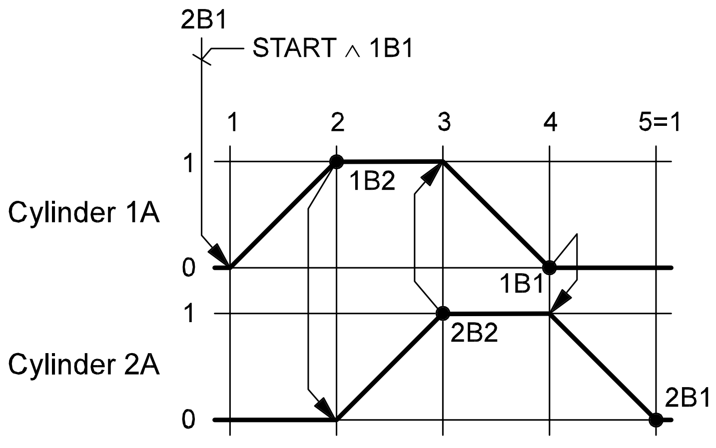
The program-controlled sequence is triggered when the operator presses the "START" pushbutton. The sequence comprises the following steps:

- Step 1: The piston rod of cylinder 1A advances.
  The workpiece is pushed out of the magazine.
- Step 2: The piston rod of cylinder 2A advances.
  The workpiece is fed to the machining station.
- Step 3: The piston rod of cylinder 1A retracts.
- Step 4: The piston rod of cylinder 2A retracts.

The "START" button must be pressed again to trigger another feed operation.

The program-controlled sequence of motions of the feeding device is shown in the displacement-step diagram (Fig. 8.12).

Fig. 8.12: Displacement-step diagram for the feeding device



Pneumatic circuit diagram of the feeding device

The control system is implemented using double-acting cylinders and 5/2-way double solenoid valves. The pneumatic circuit diagram is shown in Fig. 8.13.

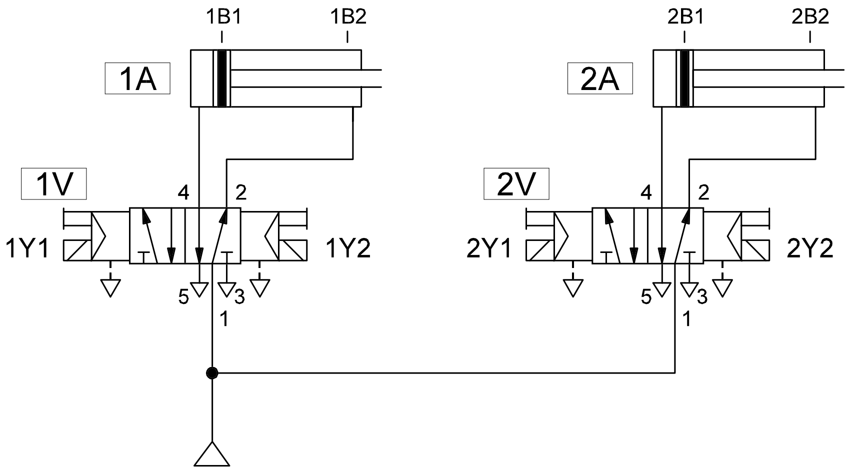
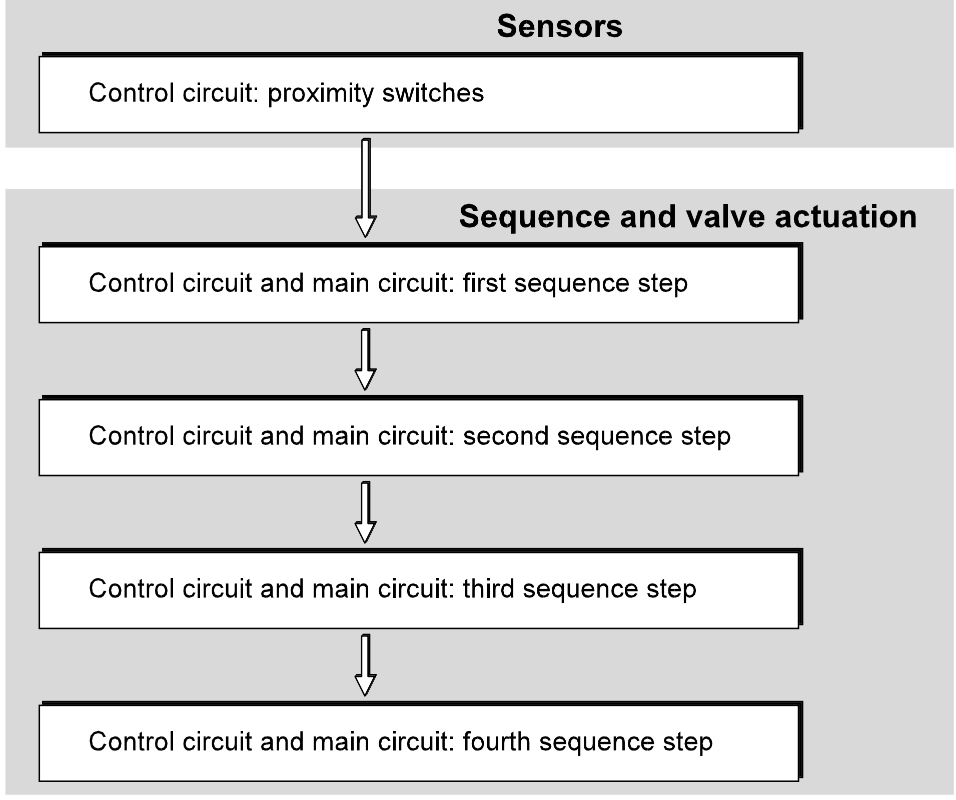


Fig. 8.13:
Pneumatic circuit diagram of the feeding device

Design of the relay circuit diagram

A systematic approach should be used when designing the relay circuit diagram. It makes sense to plan the circuit diagram for sensor evaluation and the "START" pushbutton first. The individual steps in the sequence can then be added to the diagram. The design stages are shown in Fig. 8.14.

Fig. 8.14: Procedure for designing the relay circuit diagram for the feeding device



Sensor evaluation

In a relay circuit the signals are combined with each other by the contacts of control switches, pushbuttons and relays. The electronic proximity switches used here do not have contacts; instead they generate an output signal by means of an electronic circuit. Each sensor output signal therefore acts on the coil of a relay, which in turn switches the necessary contact or contacts (Fig. 8.15). If proximity switch 1B1 is tripped, for example, current flows through the coil of relay K1. The related contacts switch to the actuated position.

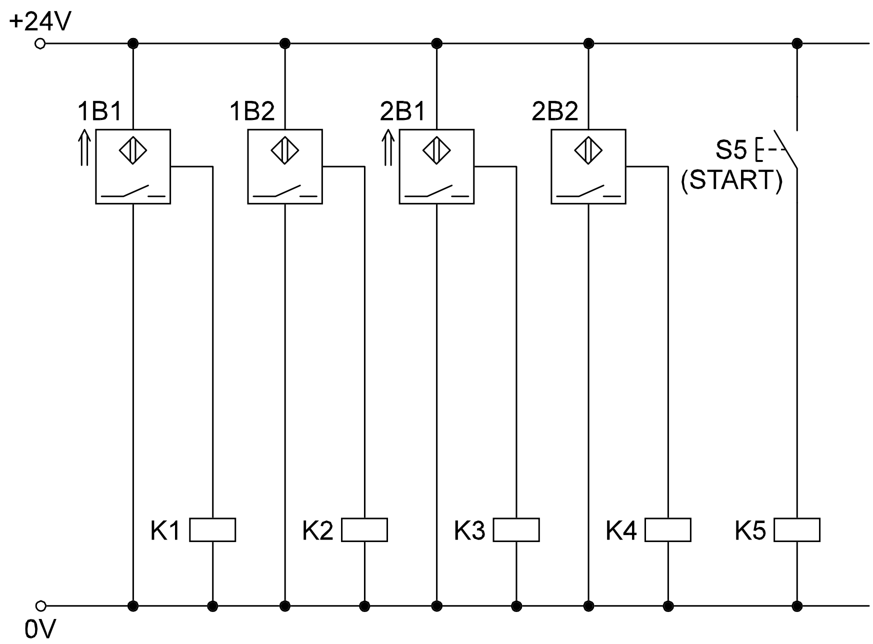


Fig. 8.15: Electrical circuit diagram with sensor evaluation

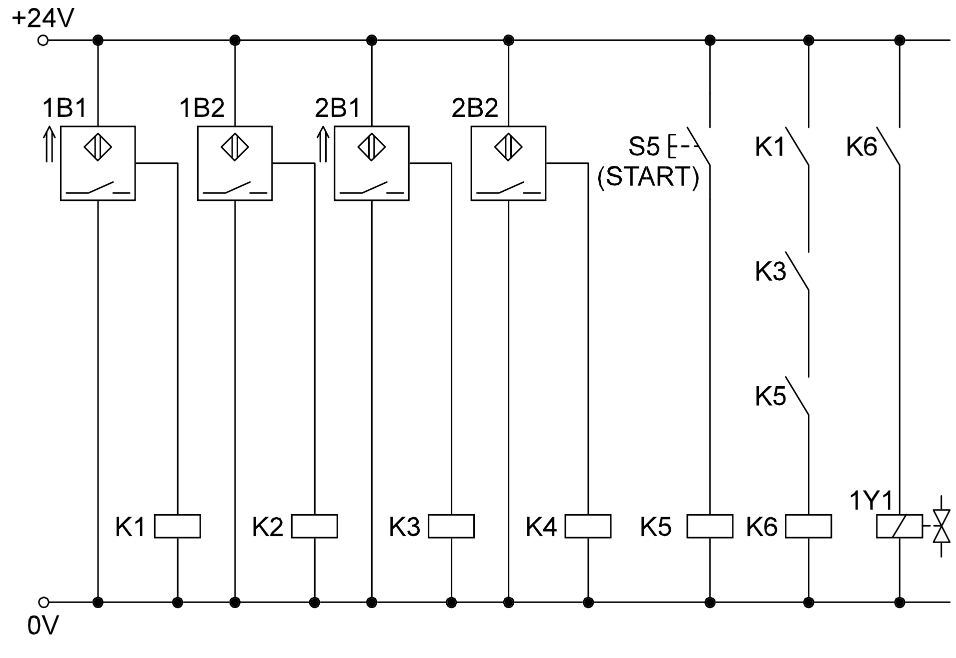
First sequence step

The following preconditions must be satisfied before the sequence is started:

- Piston rod of cylinder 1A in retracted end position (proximity switch 1B1 and relay K1 actuated)
- Piston rod of cylinder 2A in retracted end position (proximity switch 2B1 and relay K3 actuated)
- START pushbutton (S5) actuated

If all of these conditions are met, relay coil K6 is energised. Solenoid coil 1Y1 is actuated, and the piston rod of cylinder 1A advances.

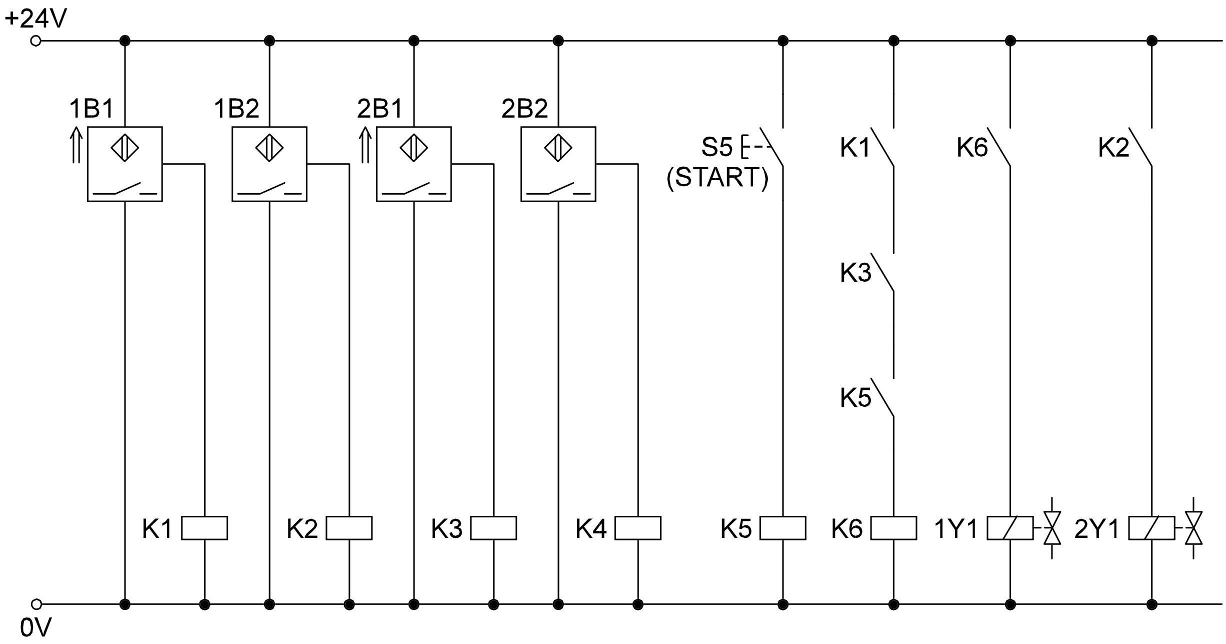
Fig. 8.16:
Electrical circuit diagram with sensor evaluation and first sequence step



Second sequence step

When the piston rod of cylinder 1A reaches the forward end position, sensor 1B2 responds. The second step of the sequence is activated. Solenoid coil 2Y1 is actuated, and the piston rod of drive 2A advances.

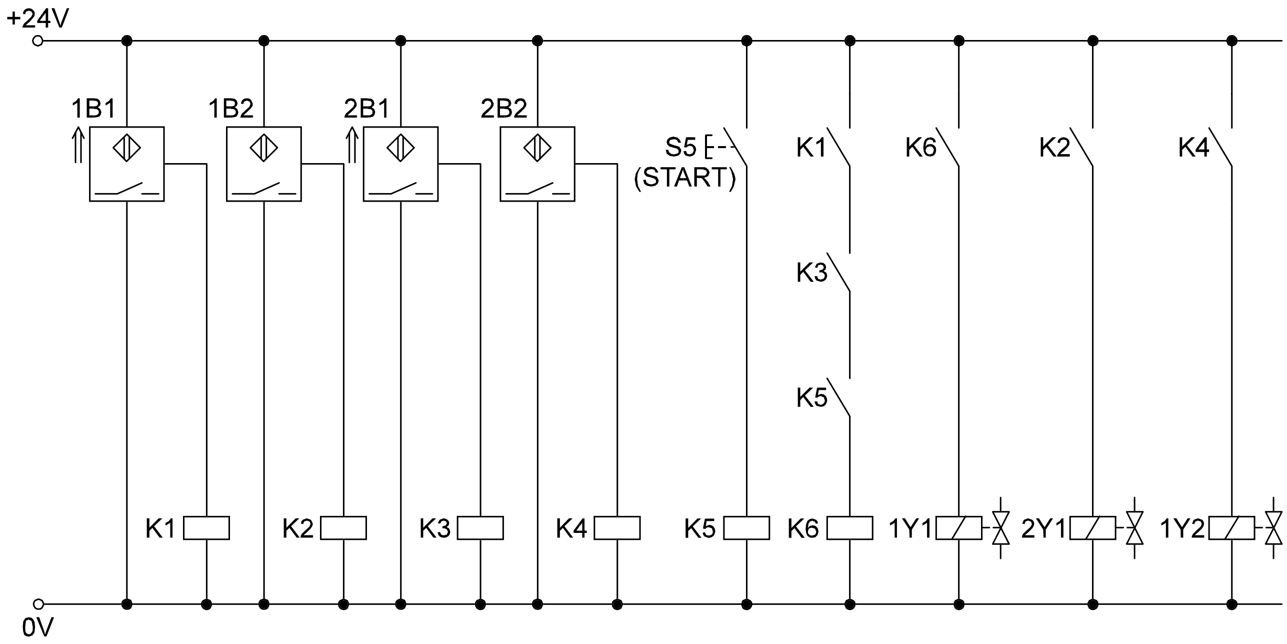
Fig. 8.17:
Electrical circuit diagram with sensor evaluation and first and second steps of the sequence



Third sequence step

When the piston rod of cylinder 2A reaches the forward end position, sensor 2B2 responds. The third step of the sequence is activated. Solenoid coil 1Y2 is actuated, and the piston rod of drive 1A retracts.

Fig. 8.18:
Electrical circuit diagram with sensor evaluation and first, second and third steps of the sequence

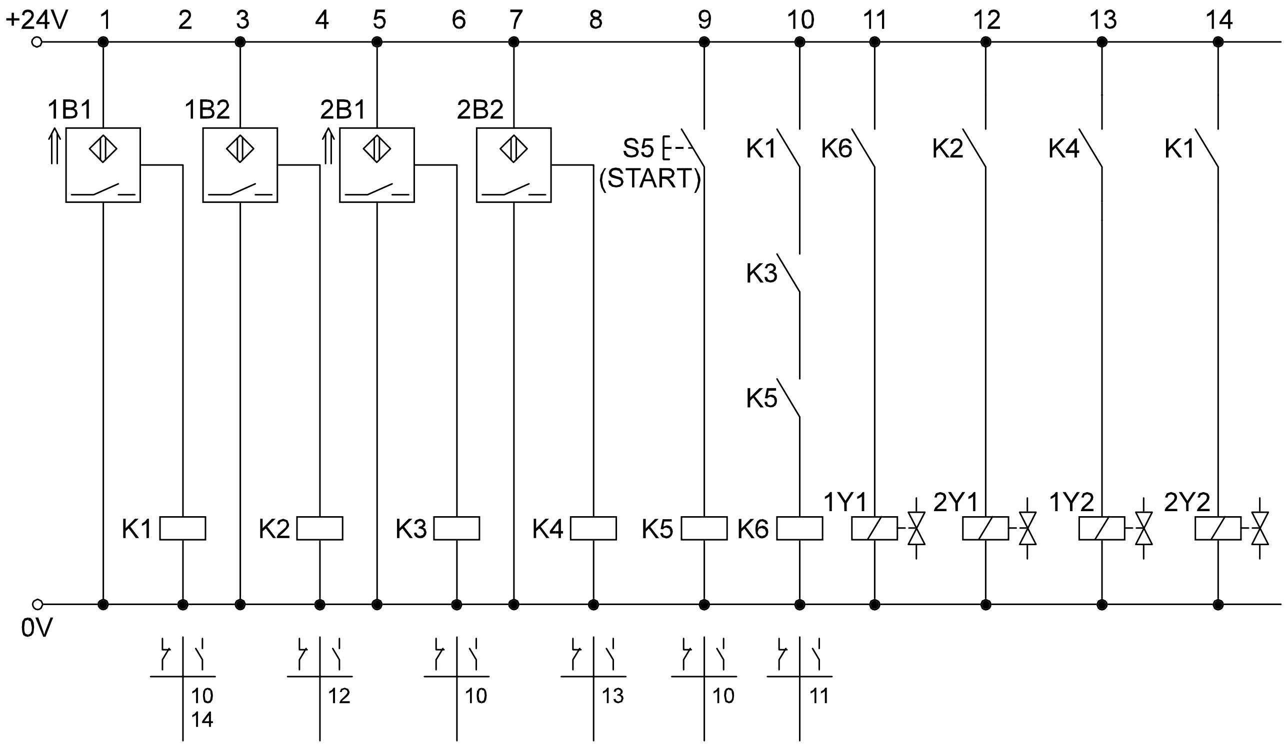


Fourth sequence step

When the piston rod of cylinder 1A reaches the retracted end position, sensor 1B1 responds. The fourth step of the sequence is activated. Solenoid coil 2Y2 is actuated, and the piston rod of drive 2A retracts.

Fig. 8.19 shows the complete electrical circuit diagram of the feeding device, including contact element tables and current path designations.

Fig. 8.19:
Electrical circuit diagram of the feeding device



8.7 Circuit for evaluating control elements

The electropneumatic control systems explained in Sections 8.2 to 8.6 accomplish the functions they are required to perform. Important control elements such as a main switch and EMERGENCY STOP switch are missing (see Section 7.4).

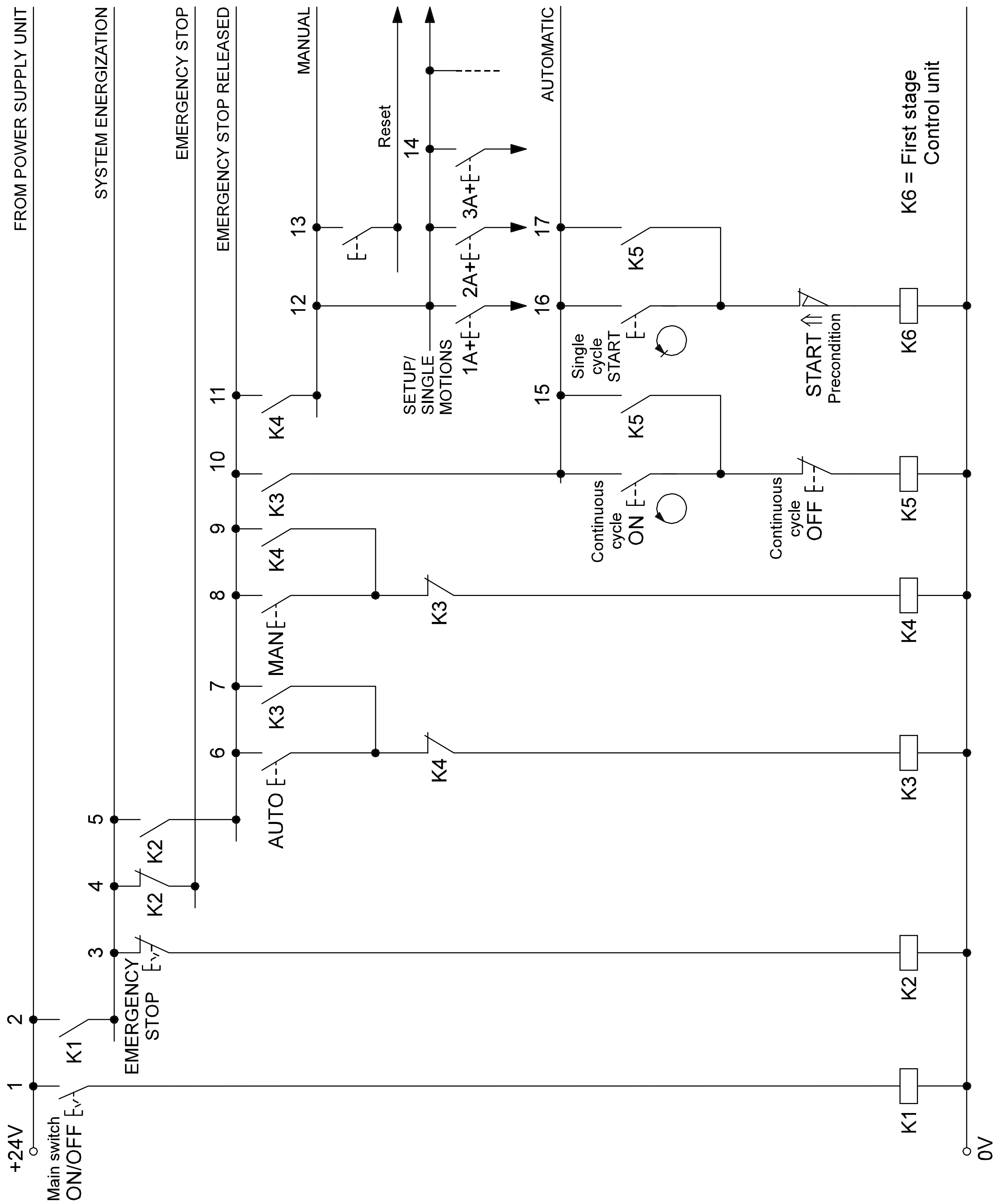
Procedure for designing a control circuit

A standard circuit for evaluation of the control elements usually provides the basis for the design of a relay circuit. The standard circuit is then extended with control-specific functions, such as sequence control and logic operations.

Relay circuit for evaluating control elements

It is stipulated that control switches (latching-type switches) must be used for switching on electrical power and for the EMERGENCY STOP function. All other control elements may take the form of either pushbuttons (momentary-contact switches) or control switches. In the circuit shown in Fig. 8.20, the control elements for "Manual", "Reset", "Automatic", "Continuous cycle ON", "Continuous cycle OFF" and "Single cycle Start" are implemented as pushbuttons, as are the elements for individual movements.

Fig. 8.20:
Design of a relay control system with selection of operating modes by pushbutton



Main switch

When the main switch is closed, relay K1 is energised. Voltage is supplied to the signal control section and the entire system via contact K1.

EMERGENCY STOP

If the EMERGENCY STOP switch is actuated, relay K2 is de-energised and the associated contacts switch to the normal position.

The EMERGENCY STOP line is connected to the supply voltage via the normally closed contact of K2. Warning lamps can be actuated via this line, for example.

The "EMERGENCY STOP released" line is de-energized, causing the voltage supply to the signal control section to be interrupted. As long as EMERGENCY STOP applies, all control elements except the main switch are rendered inoperative.

Manual operation

When the "Manual" pushbutton is actuated, relay K4 picks up and latches. The line marked "Manual" in the circuit diagram is connected to the supply voltage. If relay K3 is latched, the latching is released. The line marked "Automatic" is disconnected from the supply voltage.

Reset, setup, individual movements

These functions can only be executed in manual mode. Power is therefore supplied to the associated contacts and relays via the line marked "Manual".

Automatic operation

When the "Automatic" pushbutton is actuated, relay K3 is energised and latches. The line marked "Automatic" in the circuit diagram is connected to the supply voltage. If relay K4 is latched, the latching is released, and the line marked "Manual" is disconnected from the supply voltage

Continuous cycle ON, Continuous cycle OFF, Single cycle Start

These functions are only possible in automatic mode. Electrical power is therefore supplied to the associated contacts and relays via the line marked "Automatic".

If "Automatic" mode is selected (relay K3 latched) and "Continuous cycle ON" is active (relay K5 latched), the control system runs in continuous operation. This means that when one movement cycle is completed, the next one follows automatically.

Actuating the "Continuous cycle OFF" pushbutton releases the latching of relay K5. The program-controlled sequence stops as soon as the last step in the sequence is completed.

When the "Single cycle Start" pushbutton is actuated, the sequence (movement cycle) is executed once only.

8.8 Sample application: Sequence control for a lifting device

This section explains the design of a relay control system with clearly defined requirements as to operator control, operational performance and behavior in the event of a fault. The control system for a lifting device is used as an example. All requirements to be met by this control system are described in Section 5.3.

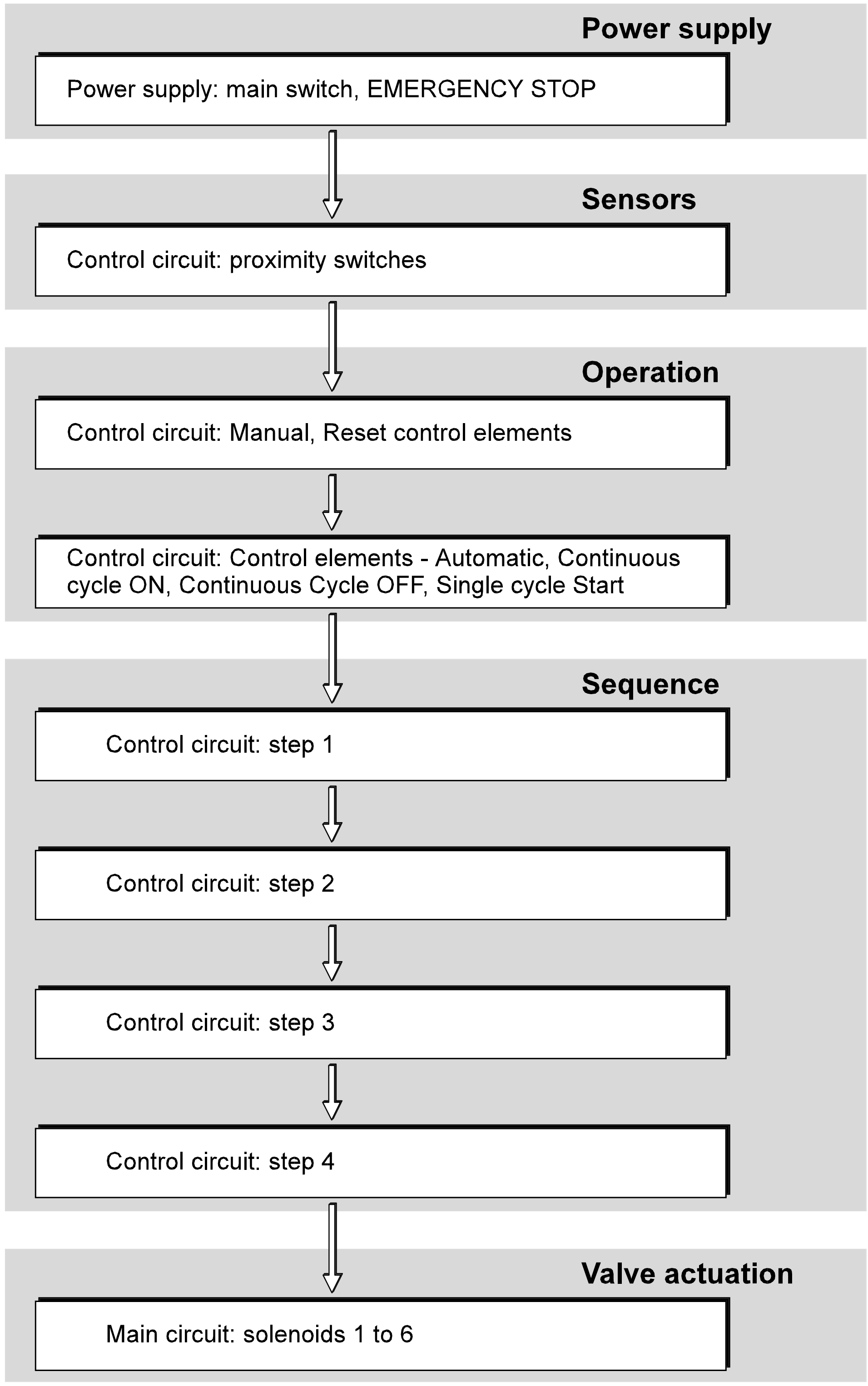
The relay control system is designed in the following order:

- Power supply
- Sensor evaluation
- Operator control
- Program-controlled sequence
- Wiring of solenoids

The flow chart (Fig. 8.21) illustrates the various steps involved in designing the circuit diagram.

Because of the large size of the circuit, it is shown in a total of 6 partial circuit diagrams (Figs. 8.22, 8.25 to 8.27, 8.29 and 8.30).

Fig. 8.21:
Procedure for designing the relay circuit diagram for a lifting device



Main switch (S1) and EMERGENCY STOP (S2) control elements

In comparison with the standard circuit in Fig. 8.20, evaluation of the main switch and EMERGENCY STOP control elements can be simplified because the EMERGENCY STOP signal is required in inverted form only. The associated circuit diagram is shown in Fig. 8.22.

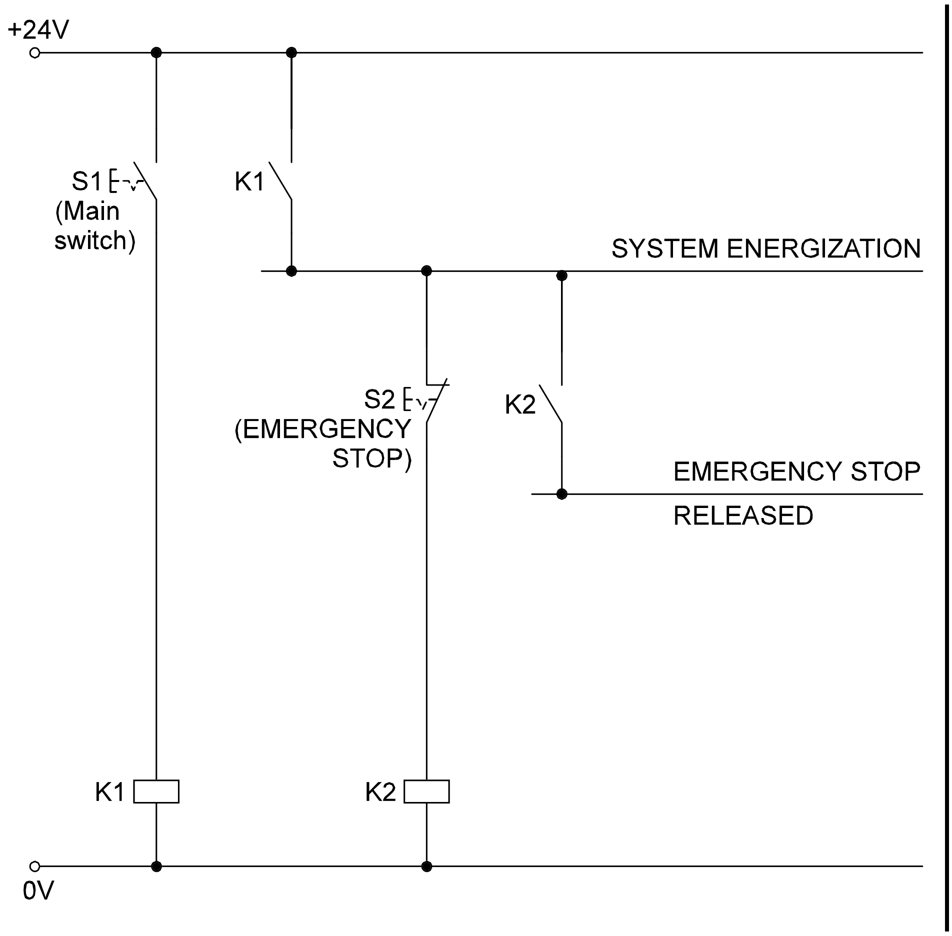


Fig. 8.22:
Relay circuit for the main switch and EMERGENCY STOP control elements

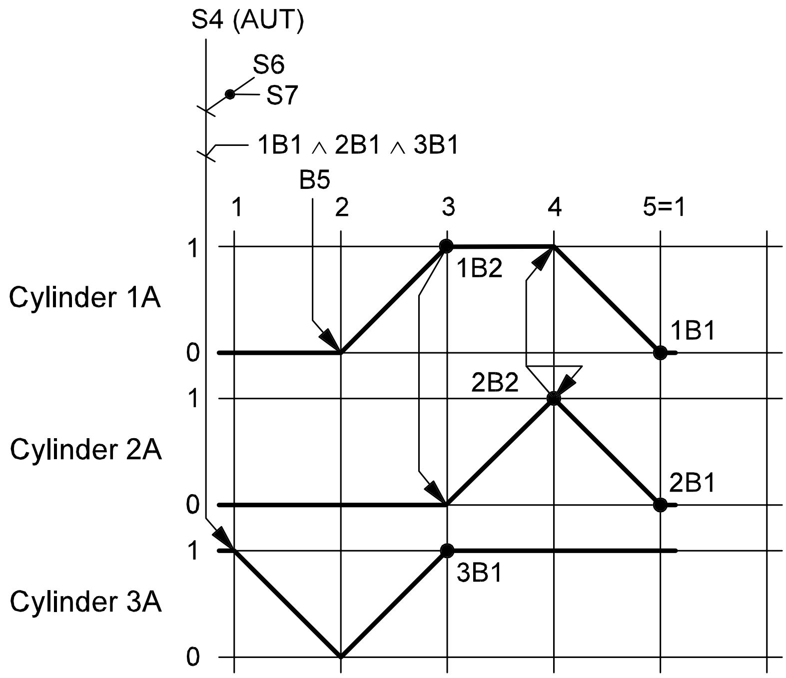


Fig. 8.23: Displacement-step diagram of the lifting device

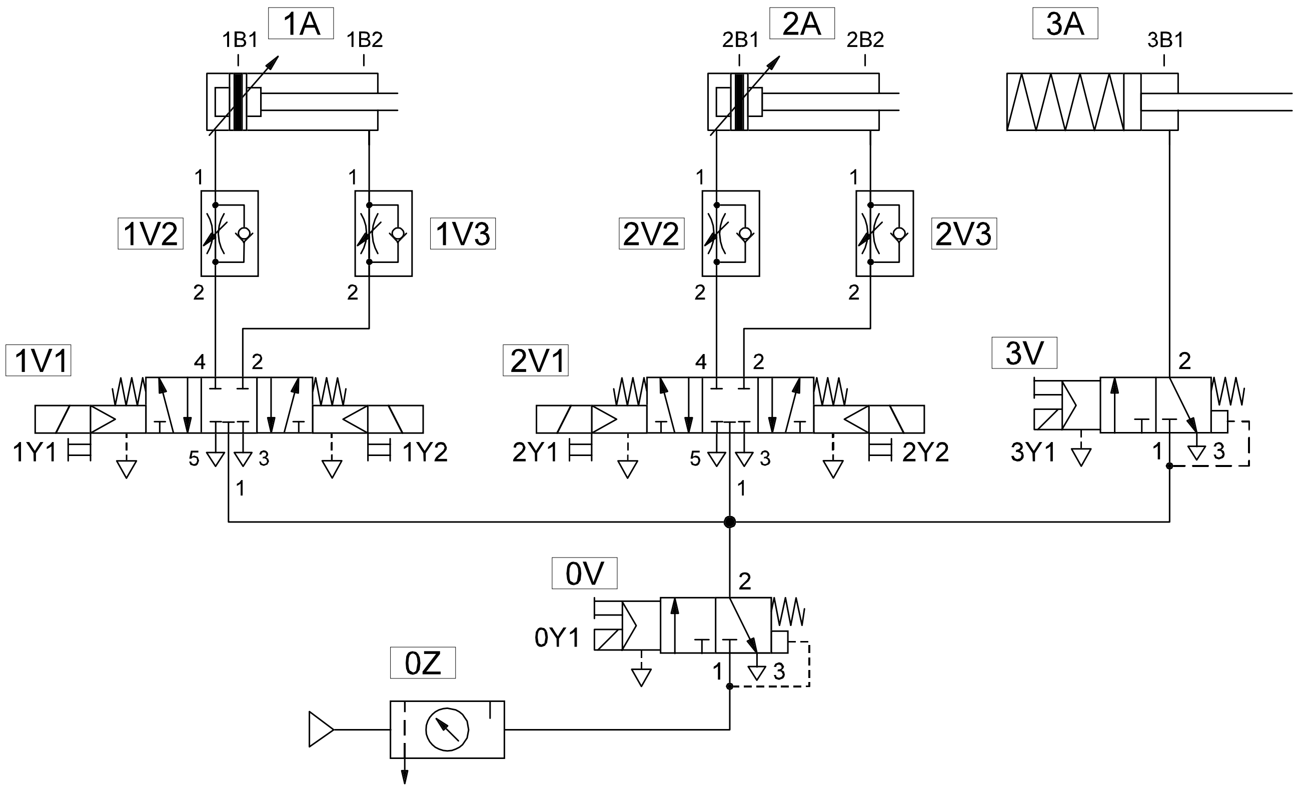


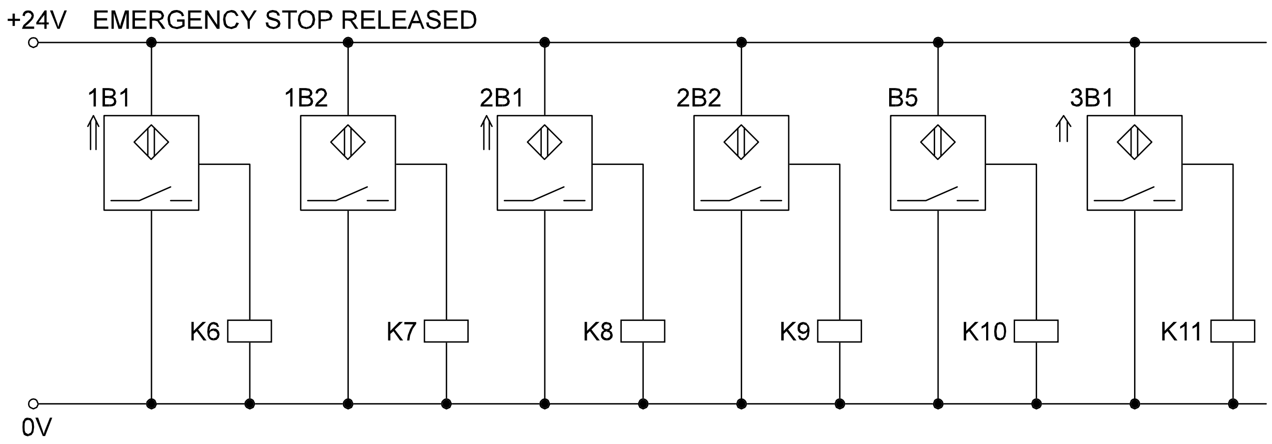
Fig. 8.24: Pneumatic circuit diagram of the lifting device

Sensor evaluation

Electrical power is supplied to the sensors as long as the EMERGENCY STOP device is not actuated. Relays K6 to K11 are assigned to sensors 1B1 to 3B1 and B5 (Fig. 8.25).

EMERGENCY STOP RELEASED

Fig. 8.25: Relay circuit diagram for sensor evaluation



Manual (S3) and Reset (S5) control elements

The circuit diagram for evaluation of the Manual and Reset control elements is shown in Fig. 8.26. Evaluation of the "Manual" pushbutton is carried out in accordance with the standard circuit (Fig. 8.20). When pushbutton S3 is pressed, relay K4 is latched (Fig. 8.26).

When the EMERGENCY STOP pushbutton is pressed, the piston rods of cylinders 1A and 2A remain at whatever intermediate position they happen to be in. In order to restore the control system to a known status, the drives have to be returned to their initial positions. This is the purpose of the reset process.

If "Manual" mode is selected (relay K4 latched) and the "Reset" pushbutton (S5) is pressed, relay K12 is then latched. The reset process is ended when the piston rods of the cylinders assume the following positions:

- Cylinder 1A: retracted end position
  (sensor 1B1 responds, relay K6 actuated)
- Cylinder 2A: retracted end position
  (sensor 2B1 responds, relay K8 actuated)
- Cylinder 3A: forward end position
  (sensor 3B1 responds, relay K11 actuated)

When all three of these conditions are met, the latching of relay K12 is released via normally closed contacts K6, K8 and K11.

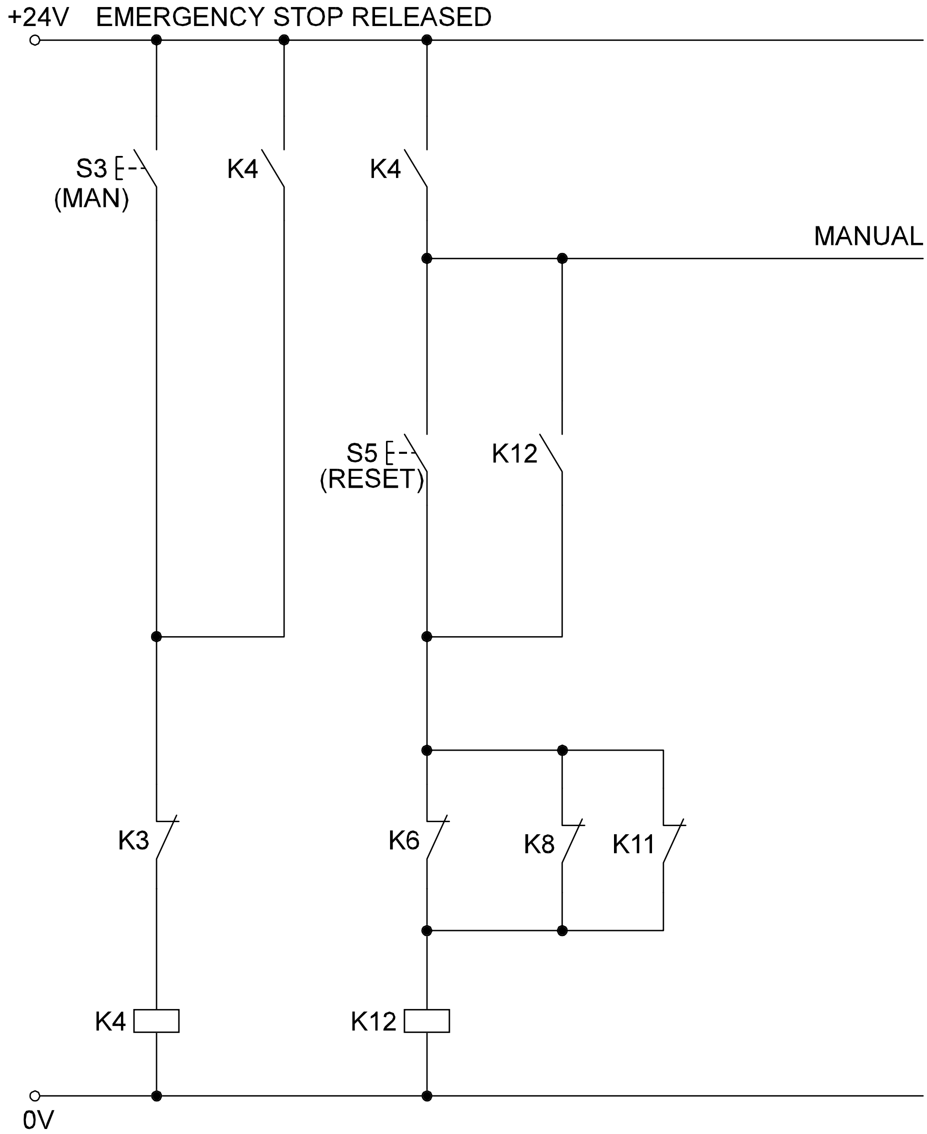
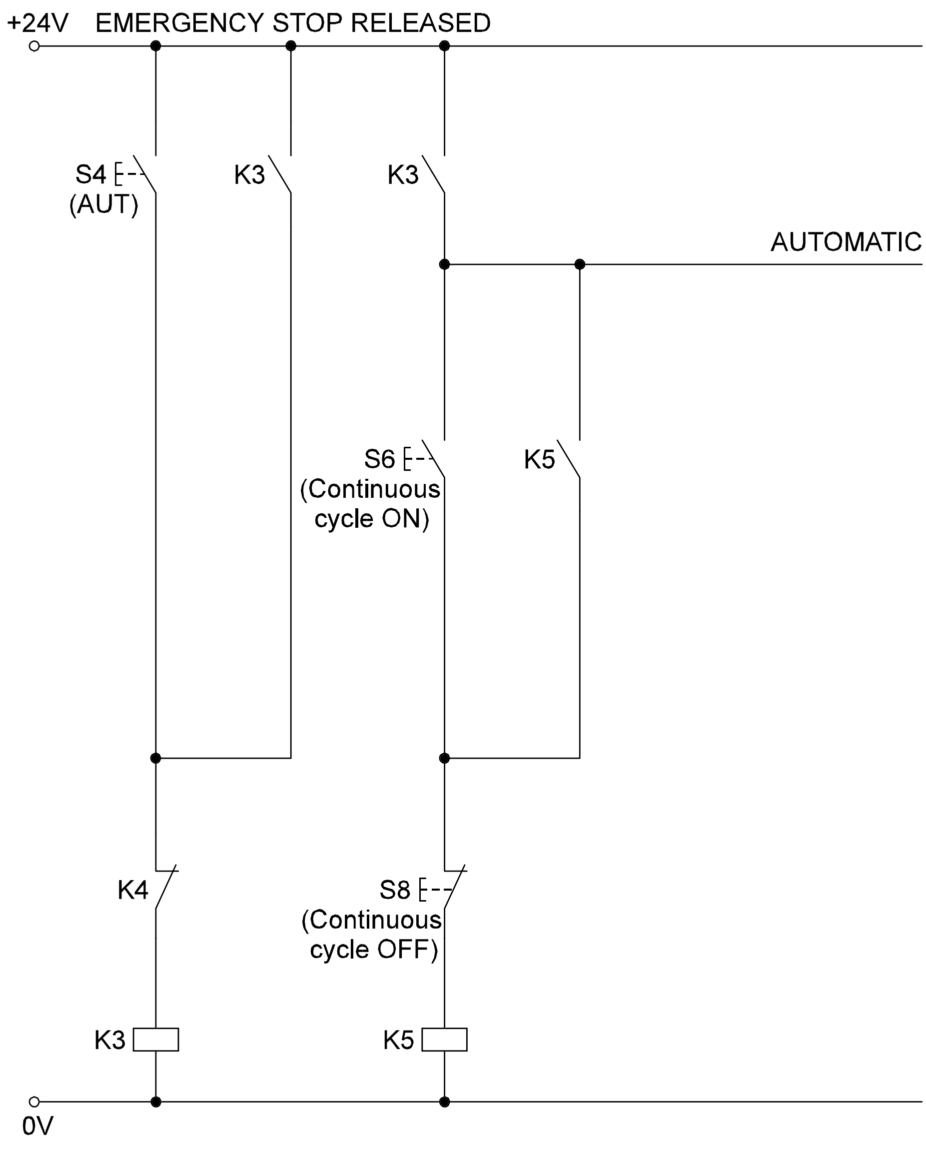


Fig. 8.26:
Relay circuit diagram for the "Manual" and "Reset" control elements

Automatic (S4), Continuous cycle ON (S6) and Continuous cycle OFF (S8) control elements

Evaluation of the "Automatic", "Continuous cycle ON" and "Continuous cycle OFF" pushbuttons is carried out in accordance with the standard circuit (Fig. 8.20). "Continuous cycle ON" is stored by latching of relay K5 (Fig. 8.27)

*Fig. 8.26:
Relay circuit diagram for the "Automatic", "Continuous cycle ON" and "Continuous cycle OFF" control elements*



Reset sequencer with latching relays

There are different ways of implementing a stepped sequence with a relay control system. In this case a reset sequencer is used.

The movement process is made up of four steps (see Table 8.4). Relays K13 (step 1) to K16 (step 4) are assigned to these four steps.

The schematic design of the reset sequencer with signal storage by latching relays is shown in Fig. 8.28.

Table 8.4: Movement process for the lifting device

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

Interlocking of steps

The way in which the reset sequencer works can be explained using the example of the second step in the sequence.

If the preceding step is set (in this case: step 1, normally open contact of relay K13 closed) and the other setting conditions for step 2 are satisfied, relay K14 switches to the latched position. The latching of relay K13 is released via the normally closed contact of relay K14. The second step in the sequence is now set, and the first step deactivated.

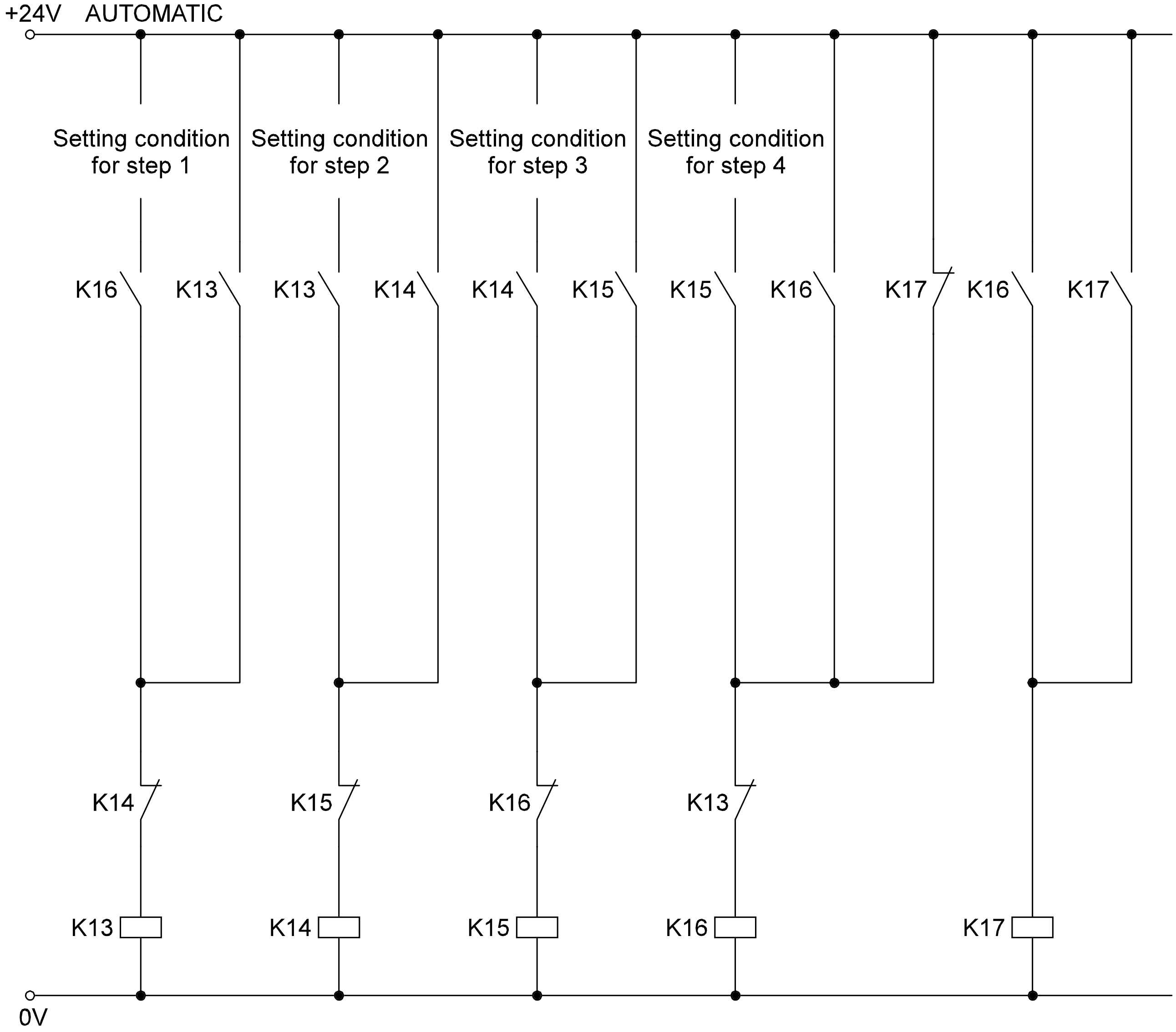
As step 4 is followed by step 1 in continuous operation, normally closed contact K13 is used to release the latching for relay K16.

Start condition for a reset sequencer

To enable the sequence to be started, the fourth step of the sequence (relay K16) must be activated. When the system is switched to automatic mode, therefore, relay coil K16 is actuated via the "Automatic" line and normally closed contact K17. Relay K16 is latched. Current flows through the coil of relay K17 via a normally open contact of K16, and relay K17 is also latched. No more current flows through the normally closed contact of K17.

Relays K1 to K12 are already used for the control elements and sensor evaluation.

Fig. 8.28:
Schematic design
of a reset sequencer
for the lifting device



Step enabling conditions

The step enabling conditions for all 4 sequence steps are shown in table 8.5. In order to ensure that the required sequence is obtained, none of the steps can be set unless the relay in the preceding step has been actuated.

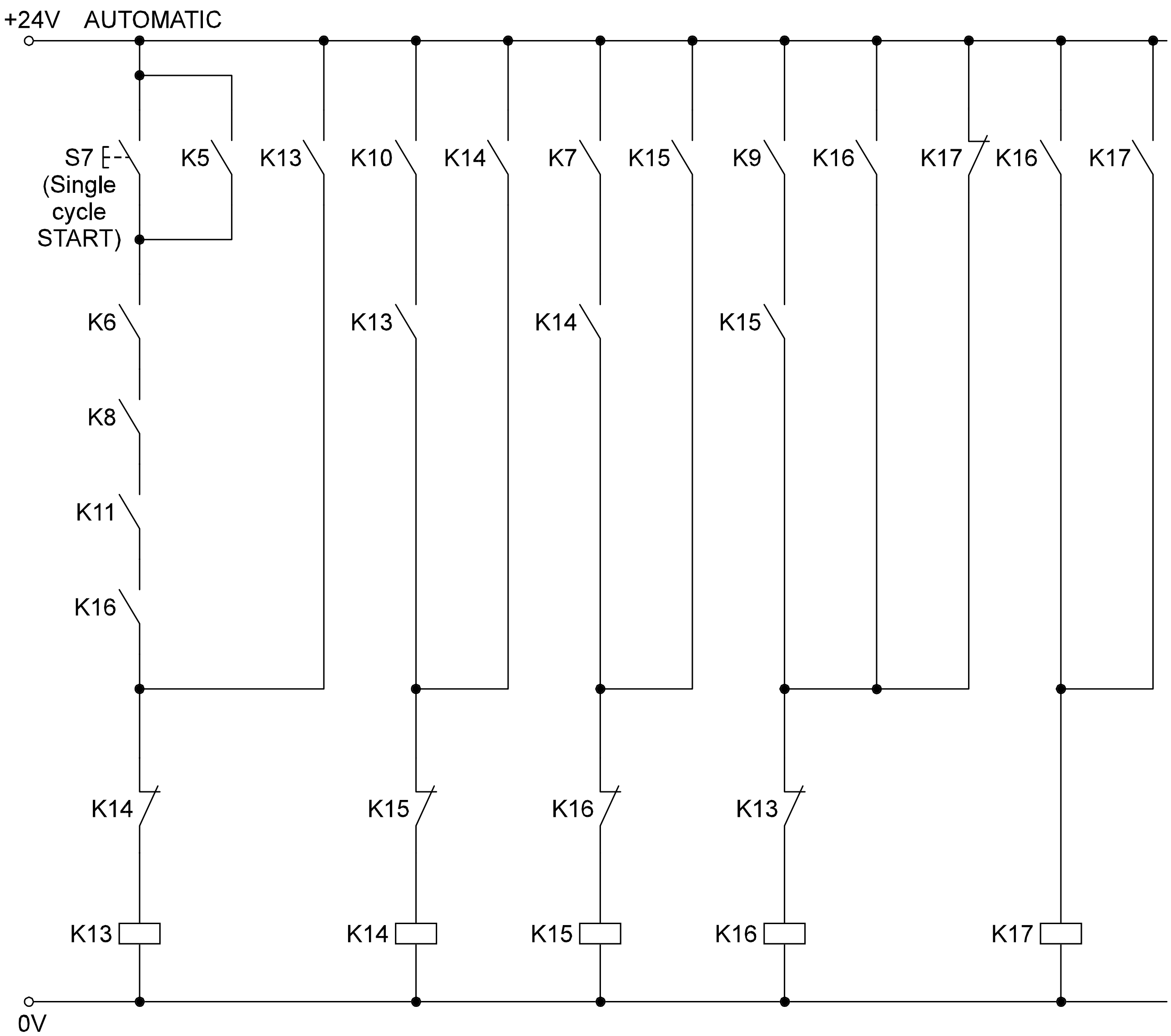
Table 8.5: Step enabling conditions for the four sequence steps

Progression	*Operating mode, control element*	*Actuated sensor(s) with associated relay*	*Active step with associated relay*
Start of first step	S7 or K5	1B1 (K6) and 2B1 (K8) and 3B1 (K11)	4 (K16)
Step 1 to step 2	No condition	B5 (K10)	1 (K13)
Step 2 to step 3	No condition	1B2 (K7)	2 (K14)
Step 3 to step 4	No condition	2B2 (K9)	3 (K15)

Relay circuit diagram for the program-controlled sequence

The relay circuit for implementing the four steps of the sequence (Fig. 8.29) is obtained by transferring the step enabling conditions to the reset sequencer (Fig. 8.28). The way in which this relay circuit works is explained in the following.

Fig. 8.29:
Relay circuit diagram for the four sequence steps



Start of first step

To allow the first movement step to be activated, the following conditions must be satisfied:

- Piston rod of cylinder 1A in retracted end position
(relay K6 actuated)
- Piston rod of cylinder 2A in retracted end position
(relay K8 actuated)
- Piston rod of cylinder 3A in forward end position
(relay K11 actuated)
- Step 4 active
(relay K16 actuated)
- Either continuous cycle active
(relay K5 latched) or "Single cycle Start" (pushbutton S7) actuated

If all of these conditions are satisfied, relay K13 is latched and the first step is active.

Progression from first to second step

If optical sensor B5 responds while the first step is active, the setting condition for the second step is satisfied. The step is activated by actuation of relay K14. Relay K14 is latched, and the latching of relay K13 is released by the normally closed contact K14.

Progression from second to third step

If proximity switch 1B2 responds while the second step is active, relay K15 is latched. The latching of relay K14 is released.

Progression from third to fourth step

If proximity switch 2B2 responds while the third step is active, relay K16 is latched. The latching of relay K15 is released.

Progression from fourth to first step

The same conditions apply to progression from the fourth to the first step as to starting of the first step.

Main circuits

The solenoid coils of the directional control valves are actuated with the main circuits. There are 6 coils altogether. To allow power to be supplied to the coils, the main switch must be in position 1 and the EMERGENCY STOP device must not have been actuated. The other conditions for actuation of the solenoid coils are summarized in table 8.6.

Table 8.6: Conditions for actuation of the solenoid coils

Solenoid coil	*Effect*	*Condition (with actuated relay)*	*Comments*
1Y1	Cylinder 1A: advance	Step 2 (K14)	
1Y2	Cylinder 1A: retract	Step 4 (K16) or Reset (K12)	
2Y1	Cylinder 2A: advance	Step 3 (K15)	
2Y2	Cylinder 2A: retract	Step 4 (K16) or Reset (K12)	
3Y1	Cylinder 3A: retract	Step 1 (K13)	
0Y1	Compressed air supply	K18	Connect compressed air

The compressed air is connected via relay K18 in order to prevent the pneumatic drives from moving before the relays have assumed a defined position.

The wiring for the solenoids is shown in Fig. 8.30.

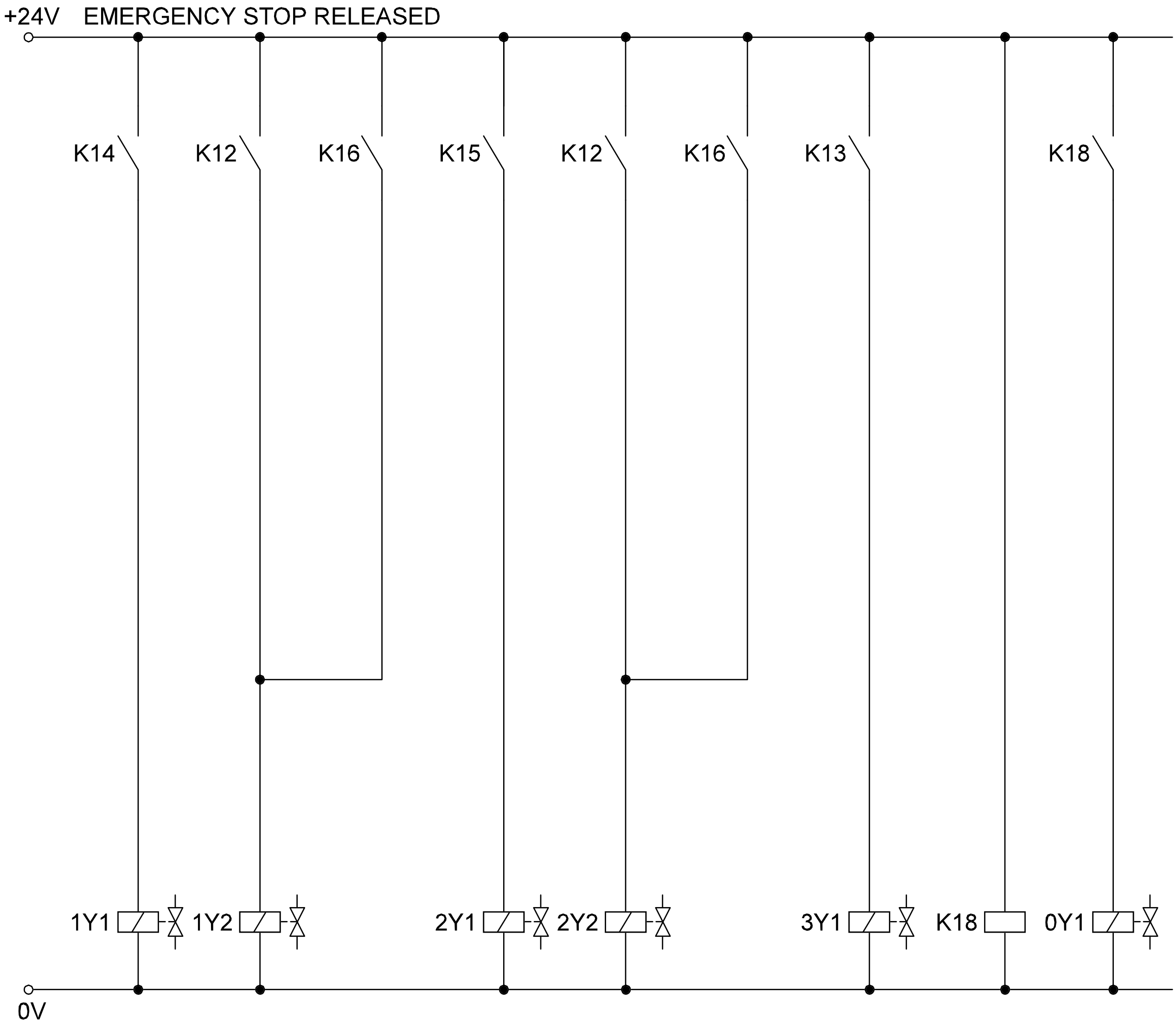


Fig. 8.30:
Wiring of the directional control valve solenoid coils

List of relays

All of the relays used for controlling the lifting device are listed in table 8.7, with their associated functions.

Table 8.7:
Functions of the relays

Relay number in circuit diagram	*Relay type/ circuit type*	*Function*
K1	Standard	Electrical power circuit (main switch, S1)
K2	Standard	EMERGENCY STOP, S2
K3	Self-latching	Automatic operation, S4
K4	Self-latching	Manual operation, S3
K5	Self-latching	Continuous cycle, S6
K6	Standard	Proximity switch 1B1
K7	Standard	Proximity switch 1B2
K8	Standard	Proximity switch 2B1
K9	Standard	Proximity switch 2B2
K10	Standard	Proximity switch B5
K11	Standard	Proximity switch 3B1
K12	Self-latching	Reset, S5
K13	Self-latching	Step 1
K14	Self-latching	Step 2
K15	Self-latching	Step 3
K16	Self-latching	Step 4
K17	Self-latching	Start condition, sequencer
K18	Delayed	Connect compressed air

List of control elements

All switches and pushbuttons used for controlling the lifting device are listed in Table 8.8.

Table 8.8: Functions of the control elements

Switch number	*Type*	*Comments*
S1	Switch	Main switch
S2	Switch	EMERGENCY STOP (normally closed contact)
S3	Pushbutton	Manual (MAN)
S4	Pushbutton	Automatic (AUT)
S5	Pushbutton	RESET
S6	Pushbutton	Continuous cycle ON
S7	Pushbutton	Single cycle START
S8	Pushbutton	Continuous cycle OFF

The complete electrical circuit diagram for the lifting device is shown in Figs. 8.31a to 8.31d.

*Fig. 8.31a:
Electrical circuit diagram of lifting device - control elements*

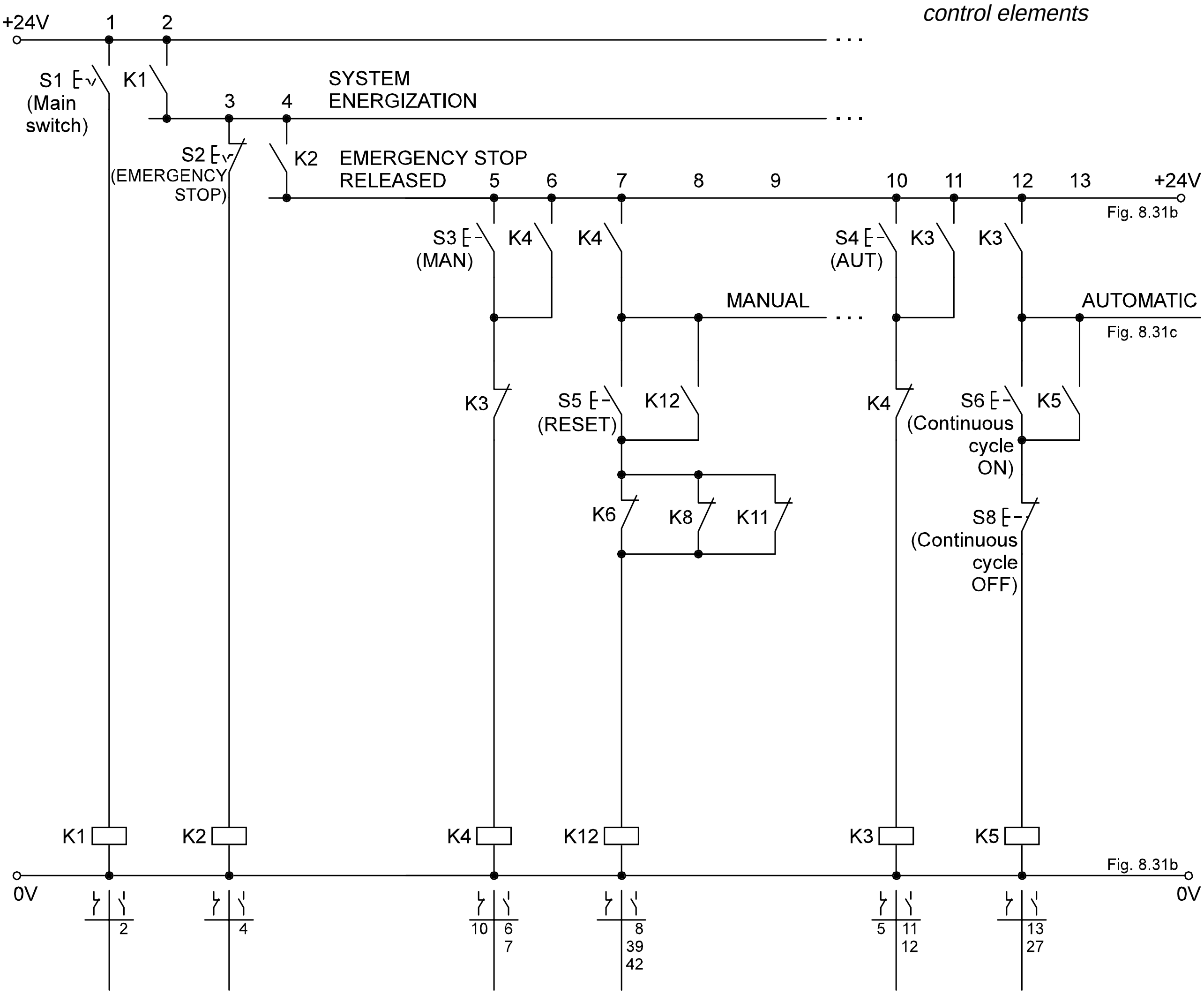


Fig. 8.31b:
Electrical circuit diagram
of lifting device
- sensor evaluation

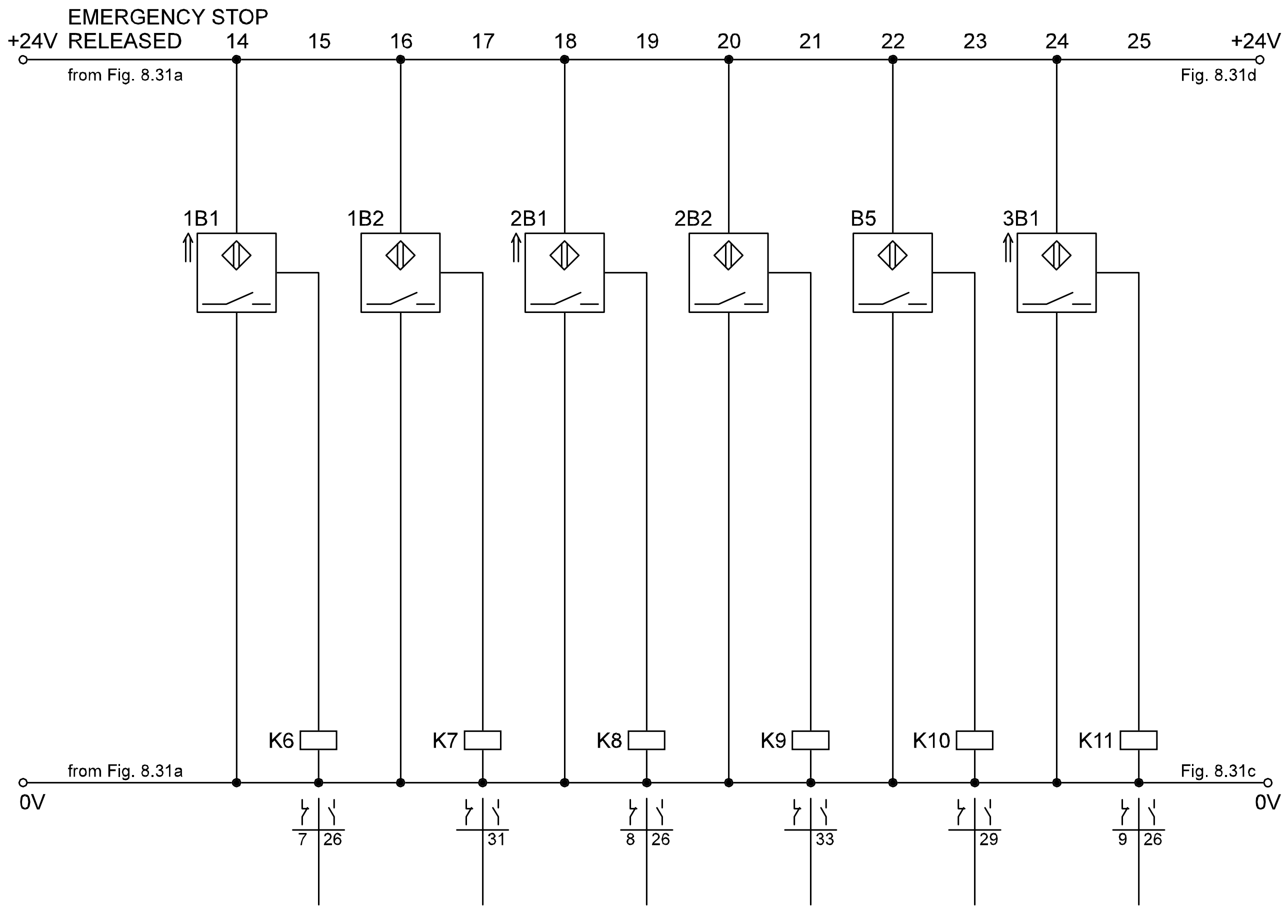


Fig. 8.31c:
Electrical circuit diagram of lifting device - switching of sequence steps

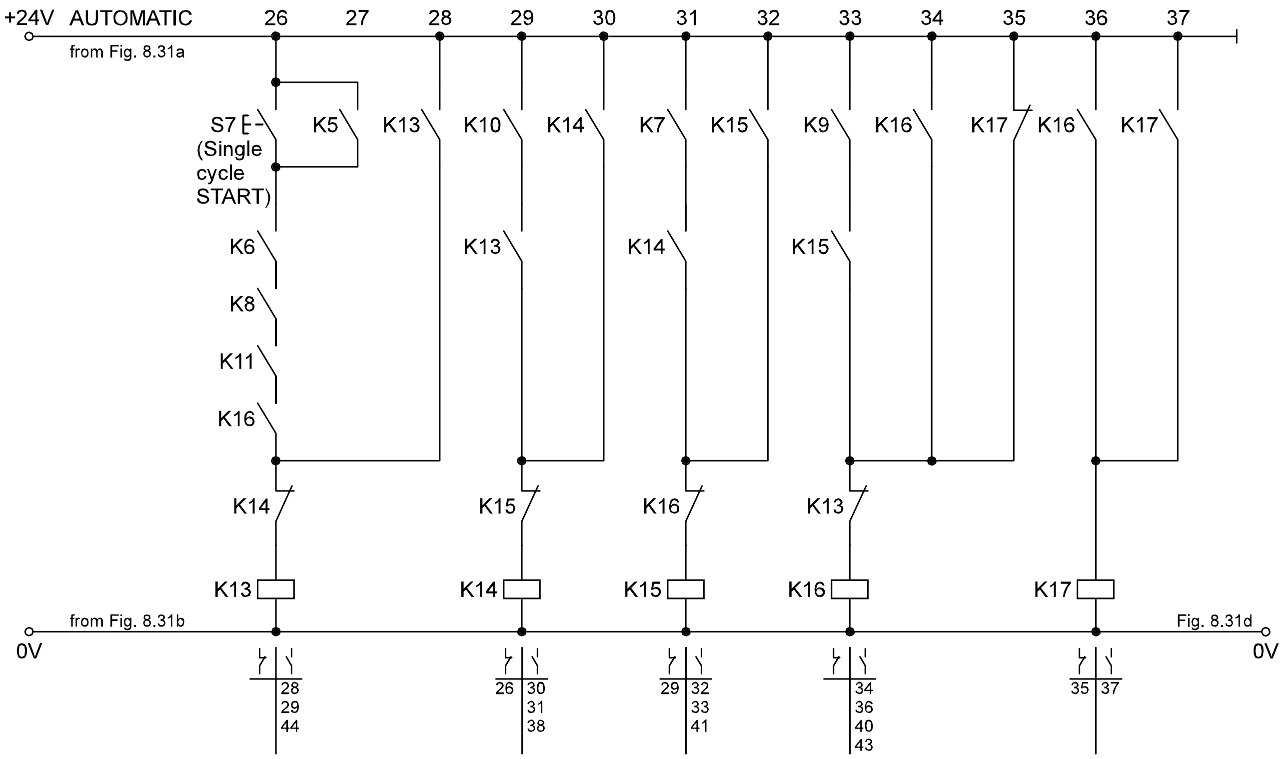
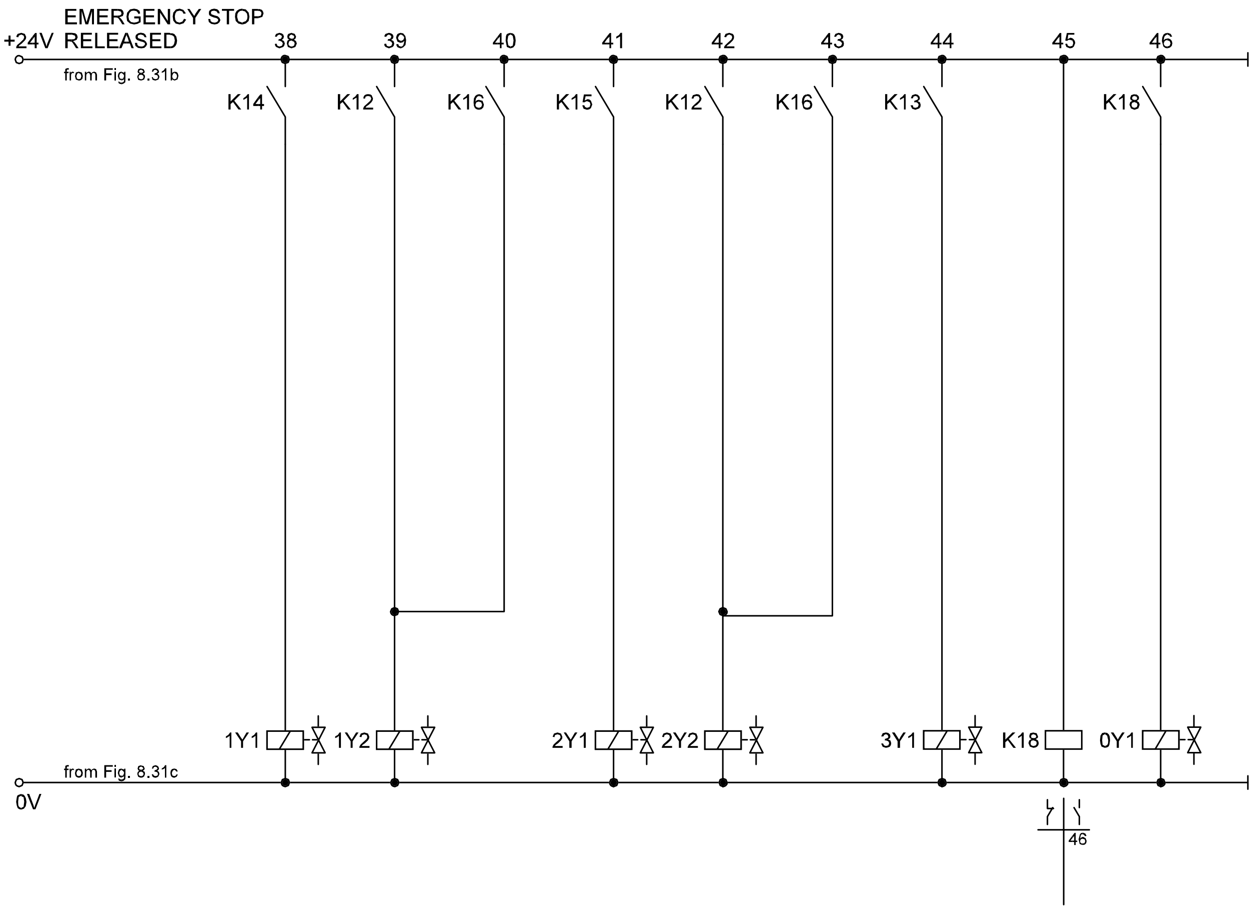


Fig. 8.31d:
Electrical circuit diagram
of lifting device
- circuitry of solenoid coils



Measures to reduce costs of equipment and installation

There are various measures which can be taken to reduce the number of relays and contacts in comparison with the above example (Table 8.9). This reduces investment costs and the cost of installation. Undesirable consequences do occur, however, particularly with regard to behavior in the event of a fault. It is greatly dependent on the individual application whether measures to reduce the number of relays are advisable, and if so, which ones.

Table 8.9: Possibilities for saving components in relay control systems

Measures	*Advantages*	*Disadvantages*
Signal storage by double solenoid valves	Fewer relays	Frequently undesirable behavior in event of fault
		Limited scope for use in many control systems
		More difficult troubleshooting
Simplification of setting conditions	Fewer contacts and connections	Unfavorable behavior in event of faults
Reed switches instead of electronic proximity switches	Fewer relays Sensors more affordable	Shorter service life of sensors

Chapter 9

Design of modern electropneumatic control systems

9.1 Trends and developments in electropneumatics

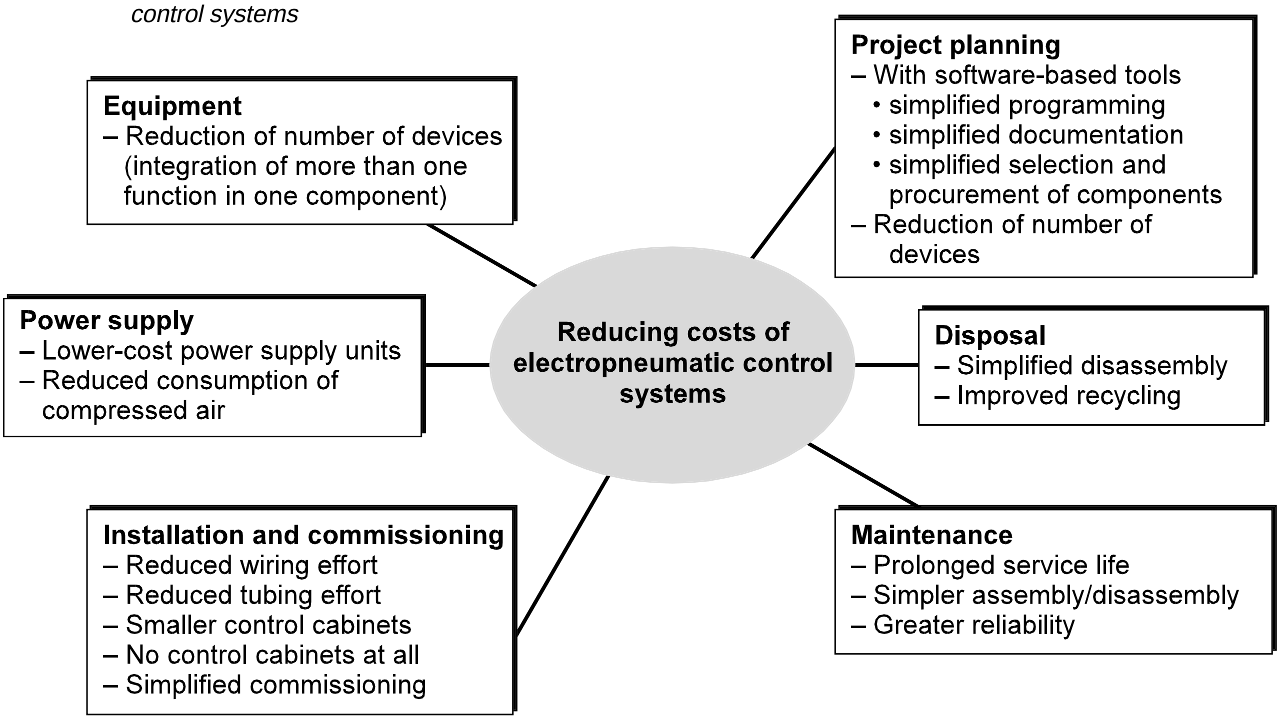
The components of electropneumatic control systems have been constantly improved in recent years. A great many new products, such as valve terminals, have appeared on the market. This trend will also continue into the future. The most important objectives in all developments in electropneumatics, whether of new or existing products, are these:

- Reduction of overall costs of an electropneumatic control system
- Improvement of the system's performance data
- Opening up of new fields of application

Cost reduction

The overall costs of an electropneumatic control system are affected by many factors. Accordingly, the opportunities for reducing cost are also highly diverse (Fig. 9.1). The design of present-day electropneumatic control systems is primarily aimed at reducing the cost of project planning, installation, commissioning and maintenance.

Fig. 9.1: Reducing costs of electropneumatic control systems



Improving performance data

Examples of how the performance data of pneumatic components can be improved include:

- Reducing cycle times by increasing motion speeds
- Reducing mounting space and weight
- Integration of additional functions, such as linear guides

Opening up new fields of application for pneumatics

Applications in which speeds, positions and forces are continuously set and monitored by an electrical control system have so far been the preserve of electrical and hydraulic drives. The development of low-cost proportional valves and pressure sensors makes it feasible today to use pneumatic drives in many applications. A new market for pneumatics is emerging as a result. Although this market is small in comparison with the market for classical electropneumatic controls, it is characterized by strong growth.

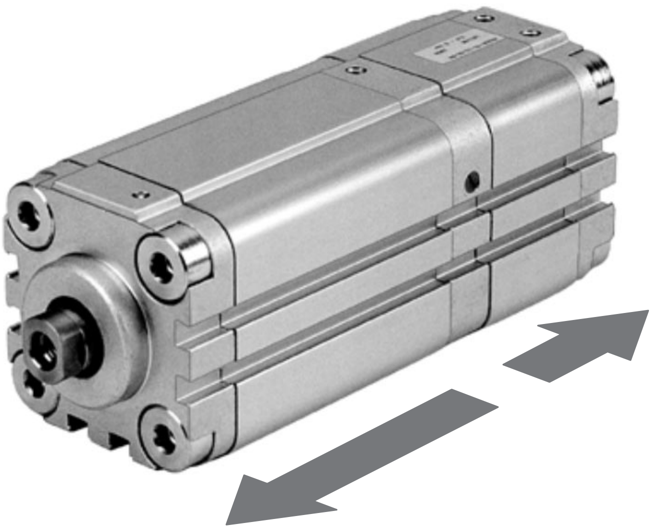
9.2 Pneumatic drives

Alongside standard cylinders, which are retaining their importance as cost-effective, versatile drive elements, special-purpose cylinders are increasingly growing in significance. When these drives are used, additional components such as guides and supports are frequently mounted directly on the cylinder housing. This offers advantages such as smaller installation space and reduced displaced masses. The reduction in outlay for materials, project planning and assembly results in a noticeable lowering of costs.

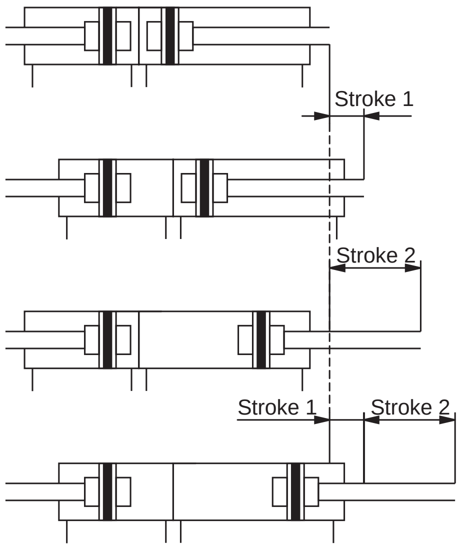
Multi-position cylinders

Multi-position cylinders are used for applications in which more than two positions are needed. Fig. 9.2 illustrates the mode of operation of a double-acting multi-position cylinder. One piston rod is attached to the frame, the other is connected to the load. Four different positions can be approached precisely to a stop.

Fig. 9.2: Multi-position cylinder with four different positions



Cylinder positions



Robotics

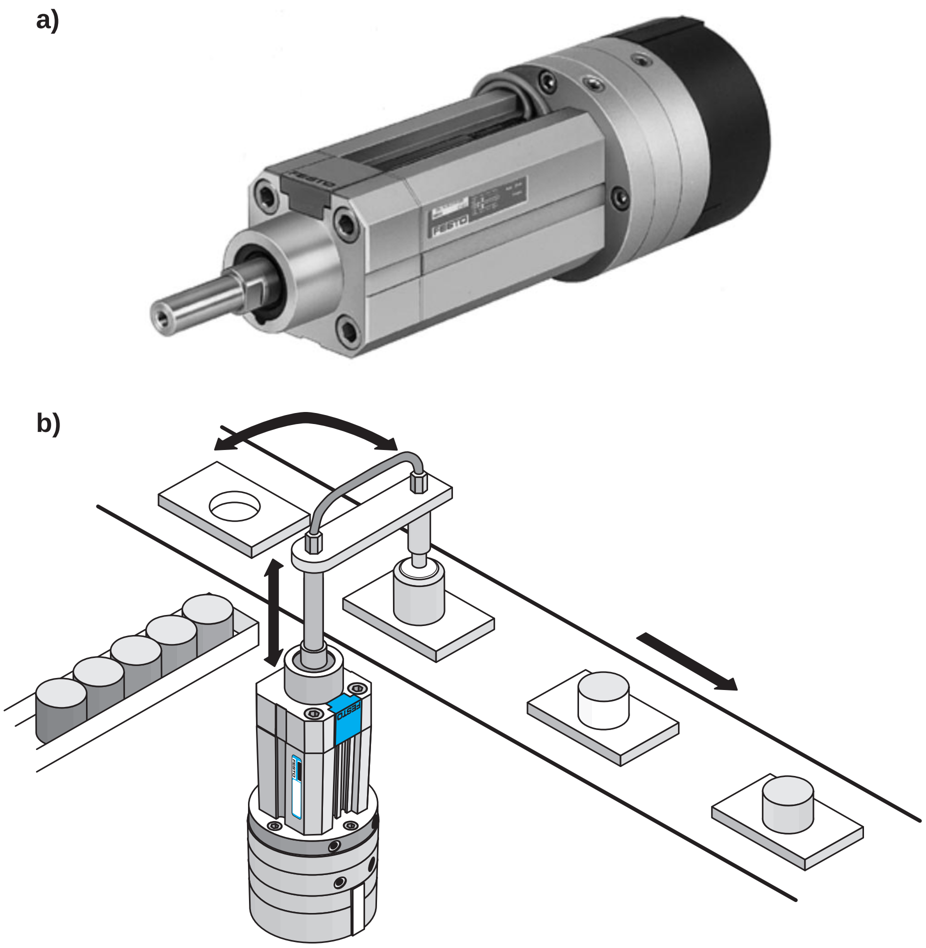
For handling and assembly operations it is often necessary to use components which are capable of executing movements in two or three different directions. This field used to be dominated by special-purpose designs. Nowadays increasing use is being made of standard, commercially available handling modules which can be combined to suit the application. The modular approach has the following advantages:

- Simple assembly
- Matching drive units and mechanical guides
- Integrated power supply line, such as for grippers or suction cups

Rotary/linear drive

The rotary/linear drive (Fig. 9.3a) can be used to reposition workpieces, for example (Fig. 9.3b). The bearing assembly of the piston rod is designed to cope with high transverse loads. The drive can be mounted in different ways, for example with a flange on the end face or with slot nuts which are inserted into the linear profile. If necessary, the power for the gripper or suction cup can be supplied through the hollow piston rod.

Fig. 9.3: Rotary/linear drive (Festo)



Pneumatic grippers

Pneumatically driven grippers are used for manipulating workpieces. Various types of gripper are shown in Fig. 9.4.

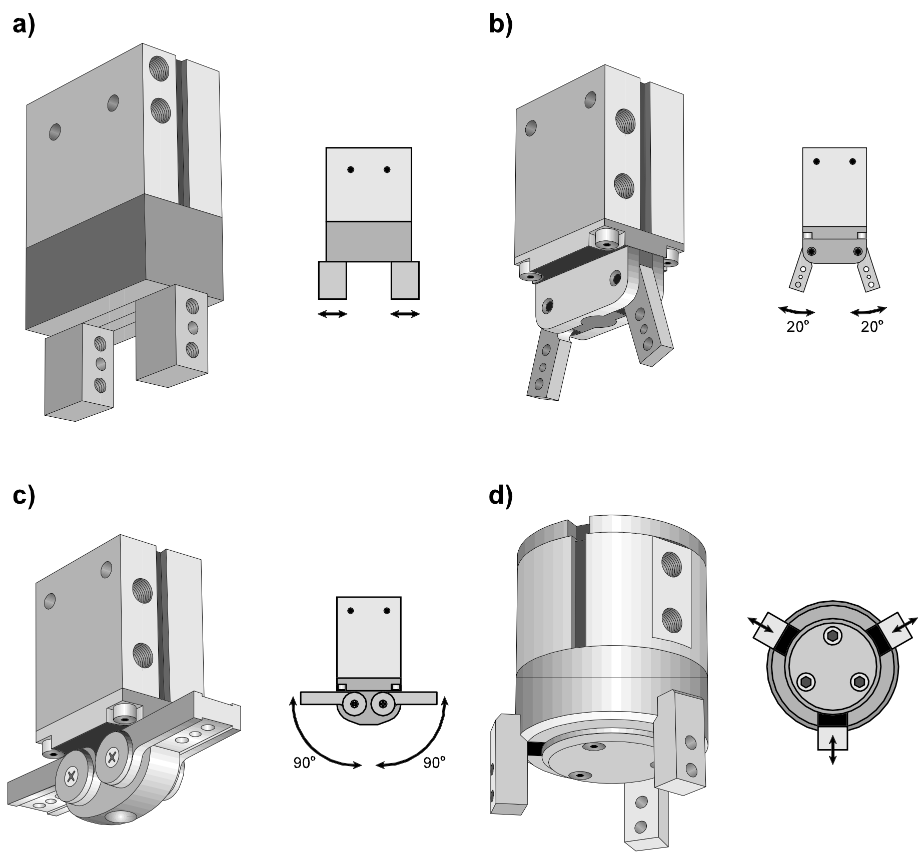


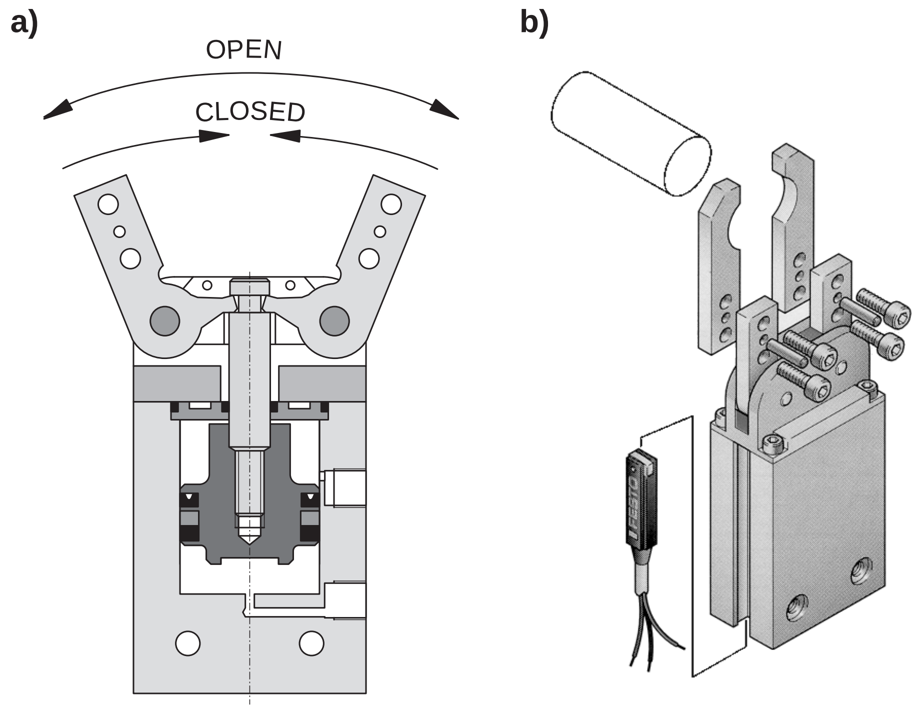
Fig. 9.4: Pneumatic grippers

a) Parallel gripper
b) Angular gripper
c) Radial gripper
d) 3-point gripper

Fig. 9.5a shows a section through the angular gripper shown in Fig. 9.4b. It is driven by a double-acting cylinder. Fig. 9.5b illustrates how gripper jaws (in this case: for cylindrical workpieces) and proximity switches are attached to the gripper.

The choice of gripper type, size and jaws is dependent on the shape and weight of the workpieces.

Fig. 9.5: Angular gripper: drive principle, gripper jaws and proximity switch



Vacuum suction cup

Vacuum suction cups are used for handling large workpieces (such as packages), flexible parts (such as foils) or parts with sensitive surfaces (such as optical lenses).

Fig. 9.6a illustrates the principle of vacuum generation using an ejector. The compressed air flows through a jet nozzle, in which it is accelerated to high speed. Downstream of the jet nozzle the pressure is lower than the ambient pressure. As a result, air is sucked in from connection U, causing a partial vacuum here also. The vacuum suction cup is attached at connection U.

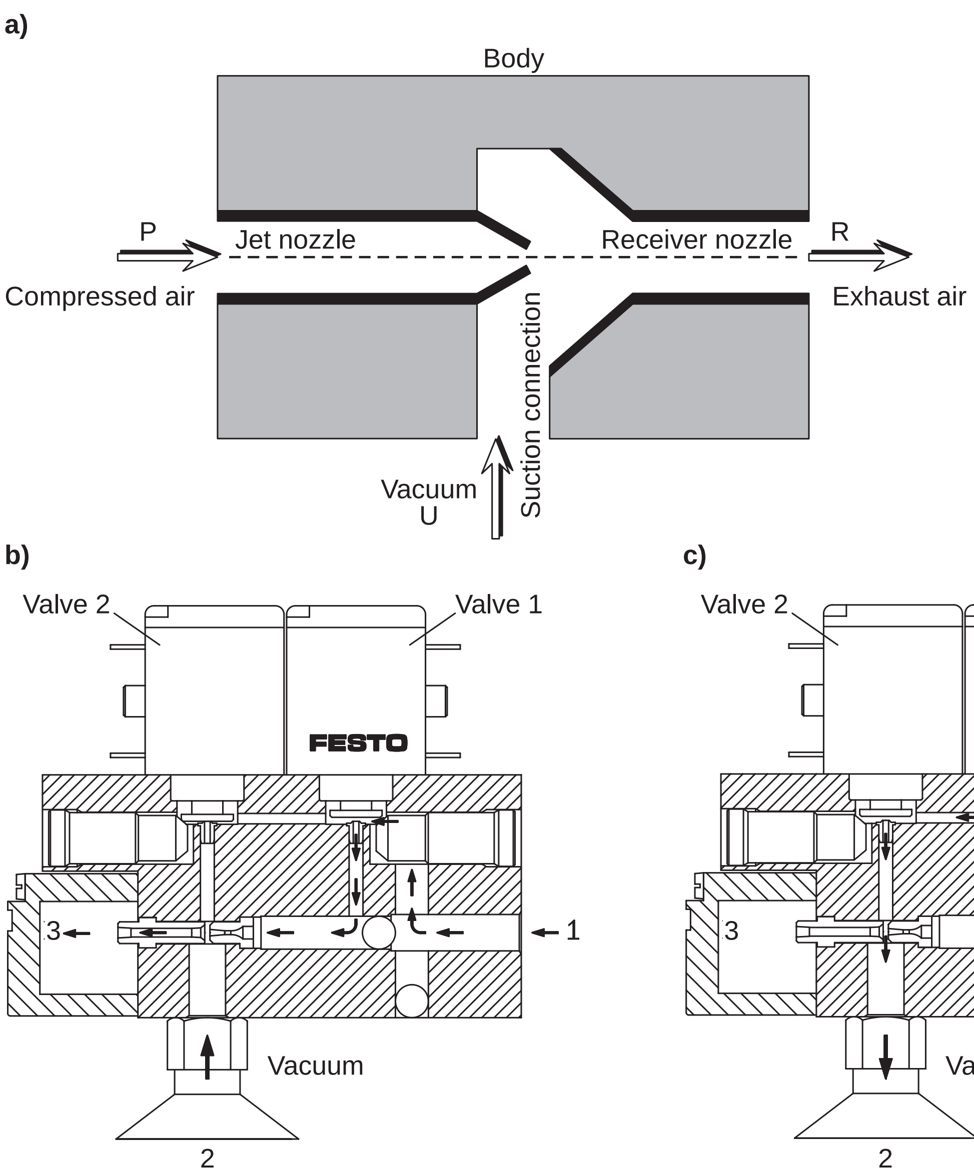


Fig. 9.6:
Mode of operation of an electropneumatic vacuum generator

a) Ejector principle
b) "Suction" mode
c) "Release" mode

Vacuum generator

The mode of operation of a vacuum generator based on the ejector principle is illustrated in Figs. 9.6b and 9.6c. Fig. 9.6b shows the "Suction" mode. The electrically operated 2/2-way valve 1 is open. Compressed air flows from connection 1 through the jet nozzle to the silencer 3. As a result, a partial vacuum is generated at the suction cup 2 and the workpiece is taken up.

Fig. 9.6c shows the "Release" mode. The directional control valve 2 is open, and the compressed air is fed directly to the suction cup. The parts picked up by the unit are rapidly ejected from the suction cup via a pressure surge from connection 1 via valve 2.

9.3 Sensors

Increasing use is now being made of electronically operating binary sensors in electropneumatics. Such sensors include:

- Inductive proximity sensors instead of reed switches
- Pneumatic-electronic converters instead of pressure switches

The absence of moving parts means that these sensors offer a longer service life and greater reliability. Moreover, the switching point can often be set more precisely and easily.

Position detection

Table 9.1 provides an overview of binary sensors that are used to detect positions. Limit valves are still widely used on account of their rugged design.

Table 9.1: Proximity switches, sensors and limit valves

Sensor type	*Triggering*	*Switching*
Limit valve	Contacting	Moving contact
Reed switch	Non-contact	Moving contact
Inductive proximity sensor	Non-contact	Electronic
Capacitive proximity sensor	Non-contact	Electronic
Ultrasonic proximity sensor	Non-contact	Electronic
Optical proximity sensor (Light barrier, optical sensor)	Non-contact	Electronic

9.4 Signal processing

The signal control section of an electropneumatic control system can be designed in two ways: hard-wire programmed (for example using relays) or memory-programmed (via PLC).

Advantages of programmable logic controllers

Compared to a relay control system, a programmable logic controller offers a whole series of inherent advantages:

- Greater reliability and longer service life because it operates without moving contacts
- Less project planning work as tested programs and subprograms can be used for a number of different control setups, whereas each relay control circuit has to be wired and tested from scratch
- Faster control development because programming and wiring can be carried out in parallel
- Simpler monitoring of stations by a higher-level host computer because a programmable logic controller can easily exchange data with the host computer

If one considers not merely the hardware costs but also the expenditure on project planning, setting up, commissioning and maintenance, a PLC is nowadays usually the most cost-effective solution for implementation of a signal processing system. Today's electropneumatic control systems are therefore almost always equipped with a PLC.

9.5 Directional control valves

The further development of electrically actuated directional control valves is relevant to individually mounted valve units and to valve combinations such as valve blocks or valve terminals.

Measures to optimize individual valve units

The objectives for further development of individual valve units are minimization of size and weight, shortening of response times and reduction of electrical power consumption. These objectives are achieved in the following ways:

- The solenoid coils are provided with a different winding with reduced inductance. As a result, the current through the coil increases faster when the valve is actuated, and the force for switching the preliminary stage is built up more quickly. After switchover, the current through the coil is reduced electronically to the extent that the preliminary stage is just held in the actuated position against the force of the reset spring. In this way, electrical power consumption is noticeably reduced in this phase. As the holding phase lasts for considerably longer than the changeover phase, notably less electrical power is required for operation of the coil overall.
- Directional control valves are optimized with regard to dead volume, actuating force and displaced masses, thus achieving faster switching of the valve.
- In order to achieve a high flow rate, the interior of the housing is redesigned to improve flow.
- The wall thickness of the housing is reduced as much as possible in order to minimize size and weight.

Advantages of optimized individual valve units

An optimized electrically actuated directional control valve offers the following advantages:

- Improved dynamic response (through short switching times and high flow rate)
- Reduced compressed air consumption (thanks to reduced volume of air between valve and drive unit)
- Reduced cost of the power supply unit (due to lower electrical power consumption)
- Less mounting space and minimized weight

Optimized valves for block mounting

The valve blocks of modular design shown in Figs. 9.7b and 9.7c feature particularly low-loss air ducting, very compact dimensions and good price-performance. A block may consist of the following:

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

Fig. 9.7a shows a directional control valve module optimized for block mounting. Several of these modules are mounted between two end plates. Compressed air is supplied either via one of the two end plates (Fig. 9.7b) or via a connection module on the underside (Fig. 9.7c).

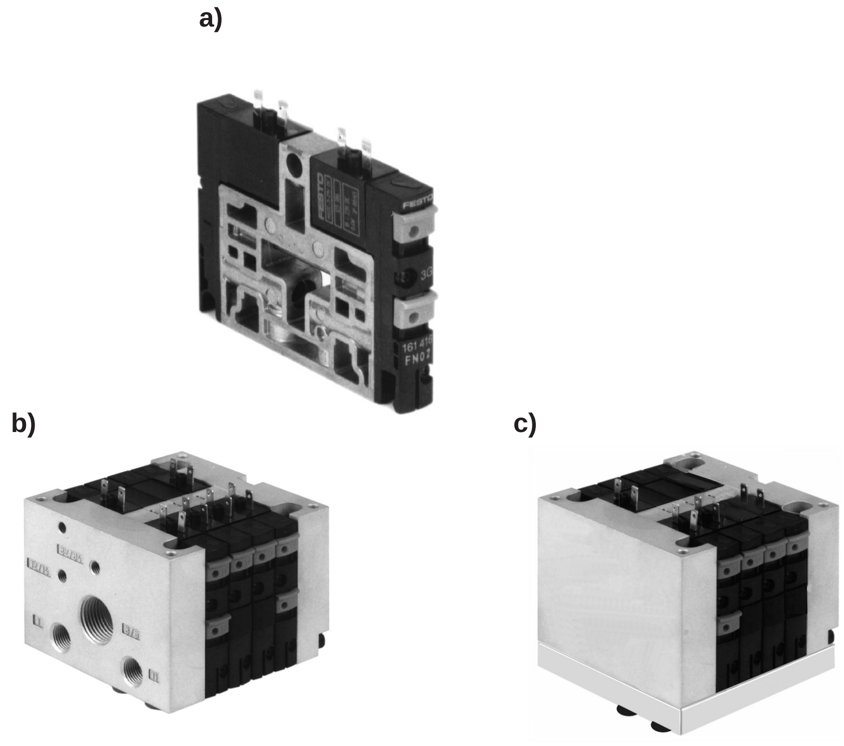


Fig. 9.7: Modular design of a valve block

a) Valve module

b) Air supply and silencer mounting on an end face

c) Air supply and silencer mounting on underside

Electrical connection of valve blocks

The electrical contacts of the valve blocks in Fig. 9.7 are brought out at the top. This allows the solenoid coils to be wired differently by using the relevant electrical connection modules (Fig. 9.7):

1. With no additional connection module, each coil is connected individually via a separate cable socket (Fig. 9.8a).

2. Module for multi-pin connection: all solenoid coils are connected to a single multi-pin plug within the valve terminal (Fig. 9.8b, see Section 9.6).

3. Module for fieldbus connection: all solenoid coils are connected to a fieldbus interface within the valve terminal (Fig. 9.8c, see Section 9.6).

4. Module for AS i connection (actuator-sensor interface): all solenoid coils are connected to the two interfaces for connection of the actuator-sensor bus within the valve terminal (Fig. 9.8d, see Section 9.6).

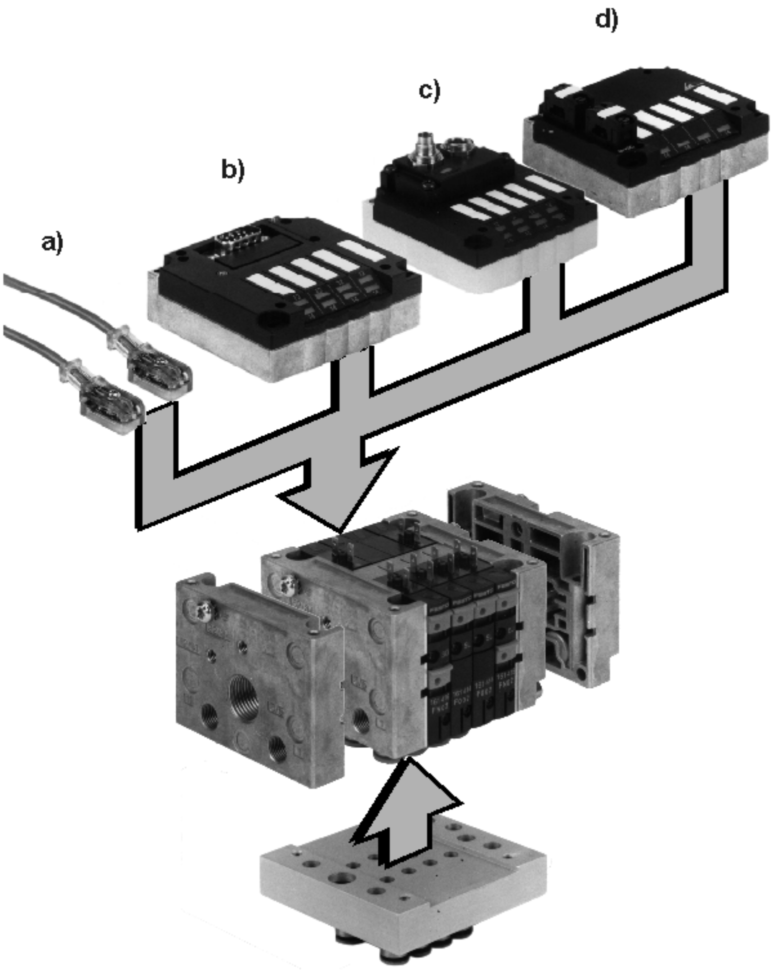


Fig. 9.8: Electrical connection of valve blocks and valve terminals

a) Individual connection with separate connector for each solenoid coil

b) Multi-pin plug connection

c) Fieldbus connection

d) Actuator-sensor interface

Valve terminals

Valve blocks in which the electrical supply lines are also brought together (by multi-pin plug, fieldbus or ASi connection) are referred to as valve terminals.

9.6 Modern installation concepts

Conventional wiring techniques involve connecting all components of an electropneumatic control setup via terminal strips. A separate terminal box is required for connection of the solenoids and sensors (Fig. 9.15a). Electrical installation is correspondingly complex.

Advantages of modern installation concepts

The use of advanced components in electropneumatics allows valves to be combined in valve terminals. The contacts of the solenoid coils engage directly into the corresponding connection sockets on the valve terminals (Fig. 9.8). The sensors are connected to the input module via plugs; the input module may be set up separately or integrated in a valve terminal. The advantages are as follows:

- No need for terminal boxes and associated terminals strips (Figs. 9.15b and 9.15c).
- Faulty directional control valves and sensors can be replaced without having to be disconnected from and reconnected to terminals.
- Wiring effort is reduced.

Control components for reduced installation effort

Two examples of modern control components are shown in Fig. 9.9.

- Fig. 9.9a shows a valve terminal and an input module to which the sensors are connected via plugs. The two components are connected to each other via a fieldbus line.
- Fig. 9.9b shows a valve terminal on which valves, sensor connections and a PLC are combined.

Valve/sensor terminal

A valve terminal with additional functions (such as an integrated PLC or integrated sensor connection module) is also referred to as a valve/ sensor terminal. In the following the more common term "valve terminal" is always used to cover all types.

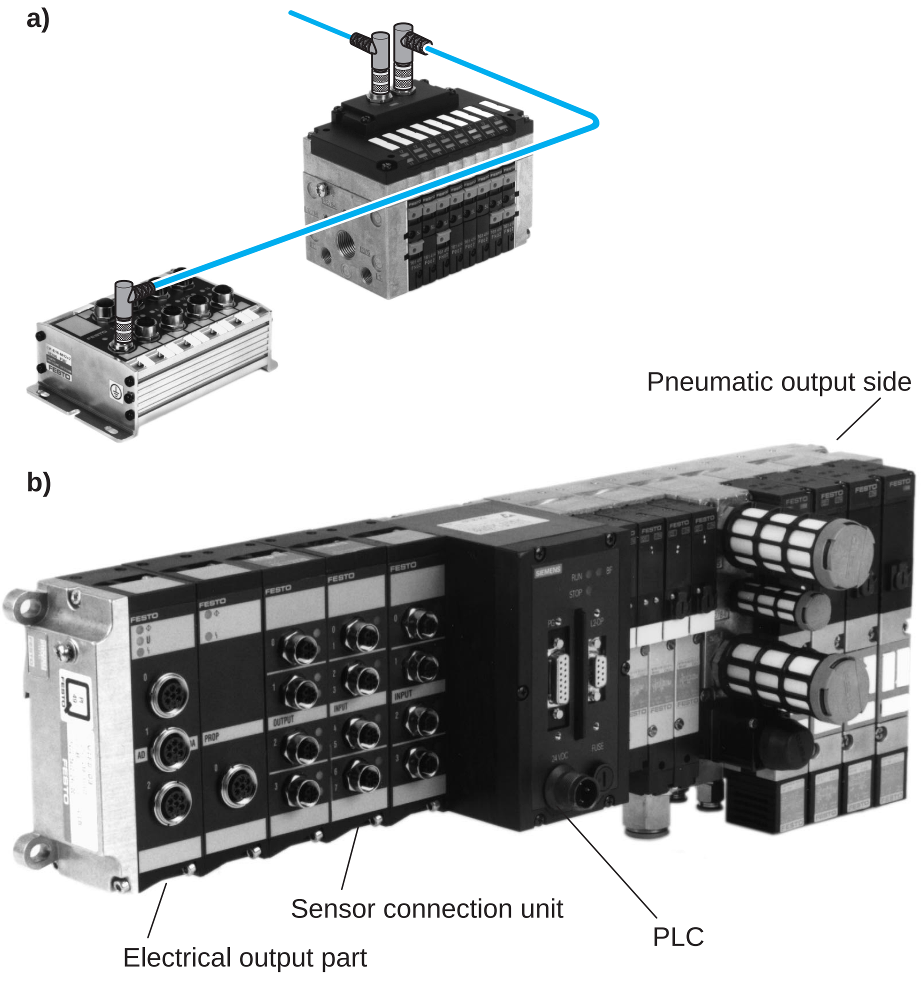


Fig. 9.9:
Control components for reduced installation effort

a) Valve terminal and separate sensor connection unit

b) Valve terminal with integrated sensor connection unit and integrated PLC

Wiring with multi-pin connection

On a valve terminal with multiple connections, all electrical connections are consolidated within the terminal on a multi-pin plug (Fig. 9.8b). A mating socket is used to connect the cable that runs to the terminal strip in the control cabinet (Fig. 9.15b). Several valve terminals with multipin connections can be connected to the terminal strip in the control cabinet (Fig. 9.15b).

Layout of a fieldbus system

Fig. 9.10 illustrates the layout of a fieldbus system in electropneumatics.

- The programmable logic controller and the valve terminals each have an interface by means of which they are connected to the fieldbus. Each interface consists of a transmitter circuit and a receiver circuit.
- The fieldbus transfers information between the PLC and the valve terminals.

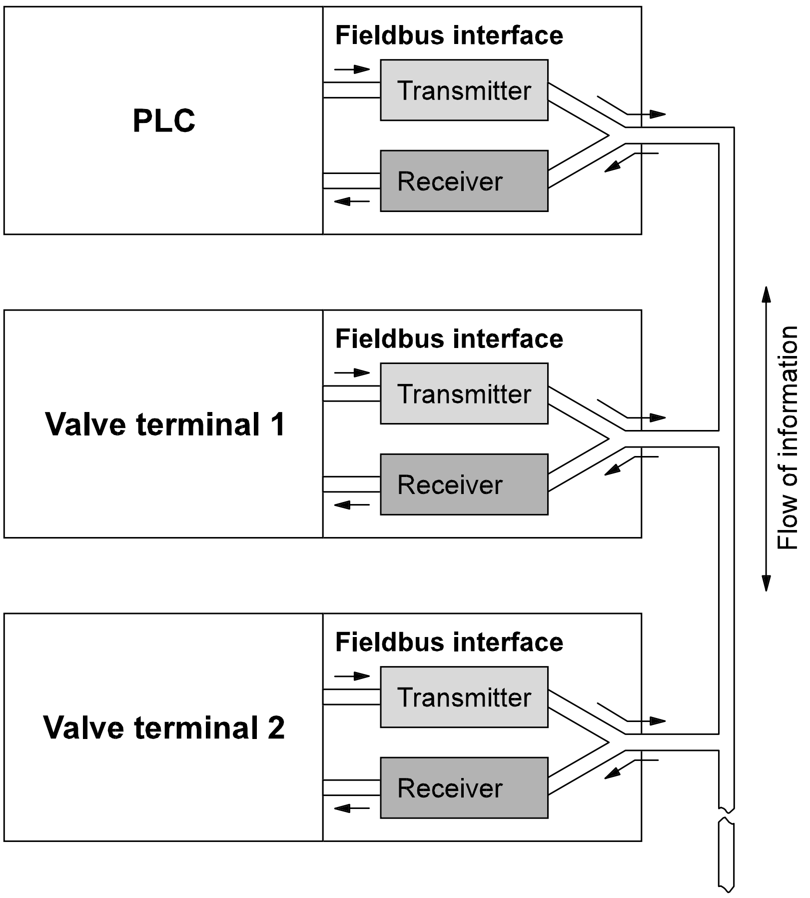


Fig. 9.10: Layout of a fieldbus system in electropneumatics

The power for operating the valves and sensor is transmitted via the same cable.

Mode of operation of a fieldbus system

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

- If the solenoid coil of a valve is to be actuated, for example, the PLC sends a sequence of binary signals over the fieldbus. From this signal sequence the valve terminal detects which solenoid coil is to be actuated and executes the command.
- If the signal status of a proximity switch changes, the valve terminal or the sensor connection module sends a signal sequence to the programmable logic controller. The PLC recognizes the change and takes account of it when processing the program.

Apart from the input/output statuses, other information is exchanged over the fieldbus, for example preventing the PLC and a valve terminal or two valve terminals from transmitting at the same time.

It is likewise possible to network the PLCs of two electropneumatic controls via a fieldbus system so that the two PLCs are able to exchange information.

Types of fieldbus

There are numerous types of fieldbus. They differ in terms of the following features:

- Encoding and decoding the information
- Electrical connection
- Transmission rate

Fieldbus systems can be divided into company-specific (proprietary) bus systems and open bus systems which are used by various PLC manufacturers (for example Profibus). Valve terminals and sensor connection modules are available for a great many fieldbus systems. Only controllers and valve terminals that are designed for the same fieldbus may be combined with each other.

Wiring of a fieldbus system

The work involved in electrical installation of a fieldbus system is limited to plugging in a connecting cable between two components of an electropneumatic control system. If there are more than two fieldbus stations, all devices are connected to each other in the form of a chain.

- A connection between a valve terminal and a sensor connection module is shown in Fig. 9.9a. The cable from the PLC to the valve terminal is only partly shown.

When using a fieldbus, there is no need for a terminal box or any terminal strips (see Fig. 9.15c).

Wiring with the actuator-sensor interface (AS-i)

The actuator-sensor interface is a special fieldbus system that was developed to facilitate the wiring up of valves with electrical actuation, sensors and low-power electrical drive units.

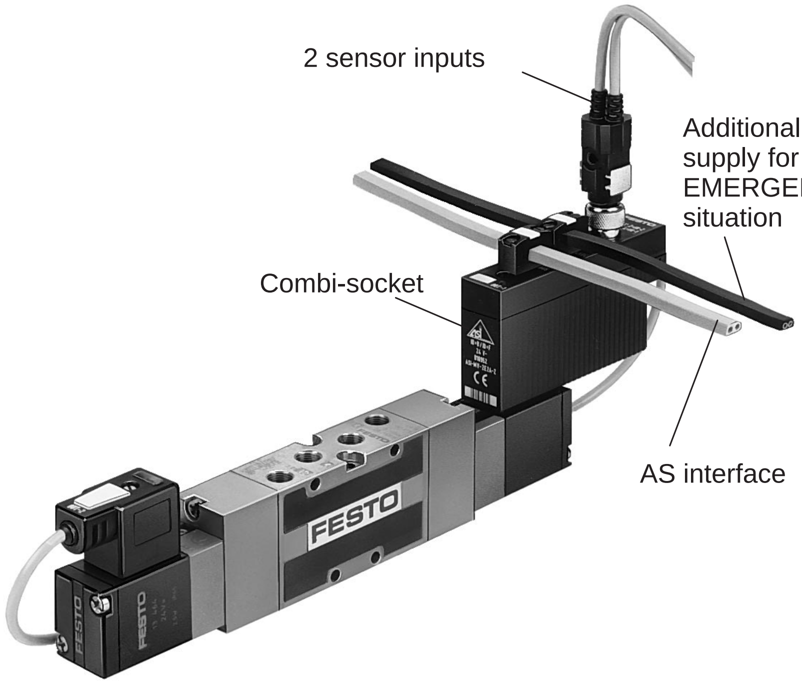
Fig. 9.11 shows a directional control valve that is connected to the AS interface via a combi-socket. The two solenoid coils of the valve are actuated via the interface. In addition, two binary sensors can be supplied with power and evaluated via the same interface.

An electropneumatic control system with AS interface is designed as follows:

- A continuous two-wire cable (yellow, i.e. light-coloured flat cable in Fig. 9.11) connects the PLC to all sensors and valves. This two-wire cable supplies power to the stations on the bus and at the same time serves to transmit signals.
- The stations are clamped directly to the two-wire cable; no connectors are needed (Fig. 9.11).

If the stations on the bus still need to be supplied with electrical power after an EMERGENCY STOP has been triggered or if valves with a high electrical power consumption are connected to the bus, an additional power supply is required. This is provided via the black flat cable shown in Fig. 9.11. The power supply carried on the yellow cable is disconnected in the event of an EMERGENCY STOP.

Fig. 9.11: Directional control valve with AS interface



The AS interface is designed to allow only small units to be connected. There can be up to four input or output signals per AS-i connection. Various types of valve terminals, combi-sockets and input/output modules with AS-i connections are listed in Table 9.2.

Table 9.2: Examples of valve terminals, combi-sockets and input/output modules with AS-i connections

Valve terminals with AS-i connection	a) 4 valves, each with 1 solenoid coil (such as spring-return 3/2-way or 5/2-way valves)
	b) 2 valves, each with 2 solenoid coils (such as double solenoid valves or 5/3-way valves)
	c) 1 directional control valve with 2 solenoid coils + 2 directional control valves each with 1 solenoid coil and spring return
Combi-sockets with AS-i connection	a) 1 coil connection, 2 sensor connections
	b) 2 coil connections, 2 sensor connections
	c) 4 coil connections
Input/output modules with AS-i connection	a) 2 sensor connections + 2 outputs
	b) 2 sensor connections

Advantages of the actuator-sensor interface

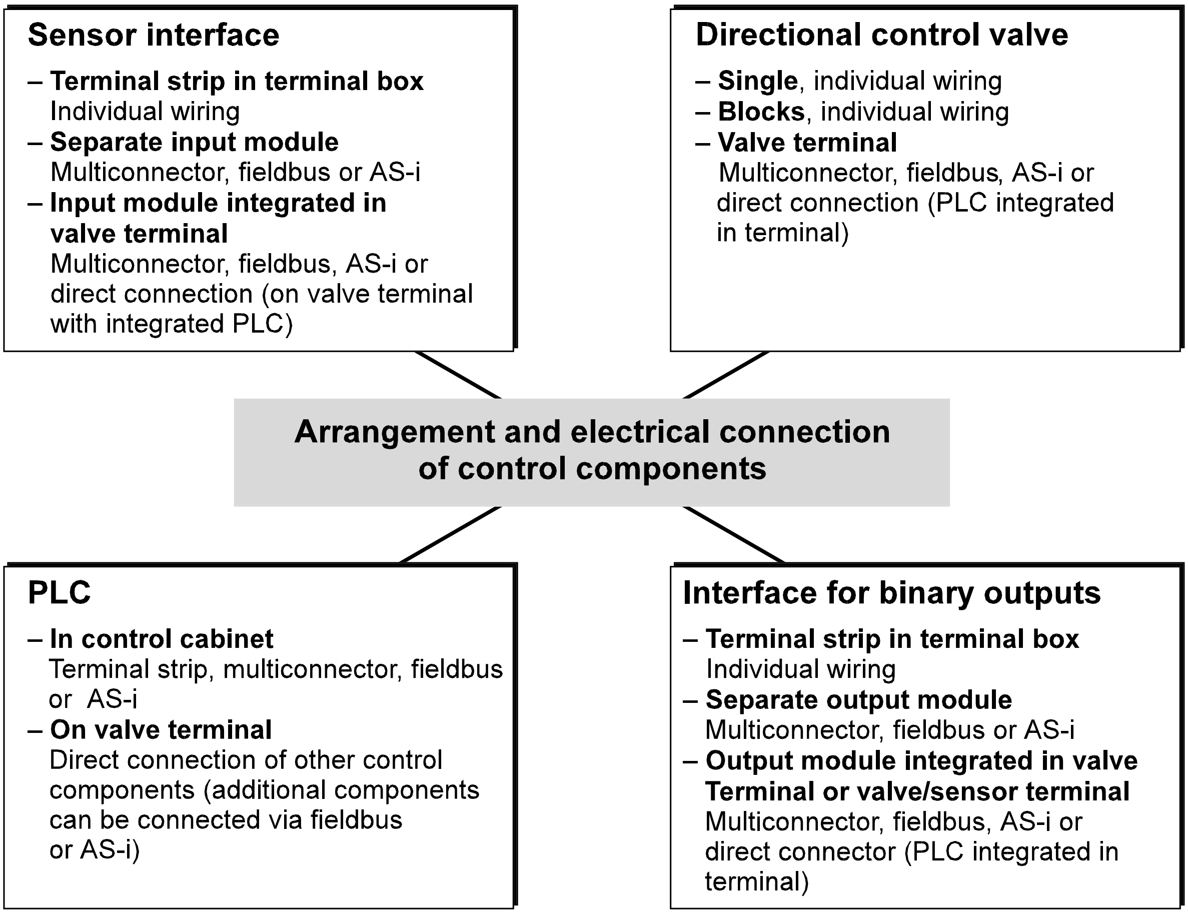
The AS interface has a number of advantages over other fieldbus systems, namely:

- Information can be transmitted very quickly, such that the bus is not overloaded even when there are a large number of stations on the bus.
- The electronics for signal conversion, the bus cable and the connection between the bus cable and the connected components are overall more cost-effective.

Arrangement and connection of control components

Thanks to extensive development work in the field of valve terminals and bus systems there are numerous different ways of arranging and connecting the components of an electropneumatic control system. A summary of the options is shown in Fig. 9.12.

Fig. 9.12: Options for arranging and connecting control components



Selection of components and installation concept

The components of an electropneumatic control system must be selected in such a way as to keep the total costs of equipment, installation and maintenance to a minimum (Fig. 9.13). The component arrangement, tube connection and wiring that is chosen is dependent on many influencing factors (Fig. 9.14). As electropneumatic control systems differ greatly in terms of their layout and number of drive units, it is not possible to offer a general recommendation; the decisions have to be taken for each control system on a case by case basis.

Fig. 9.13: Factors influencing the cost of equipment, installation and maintenance of an electropneumatic control system

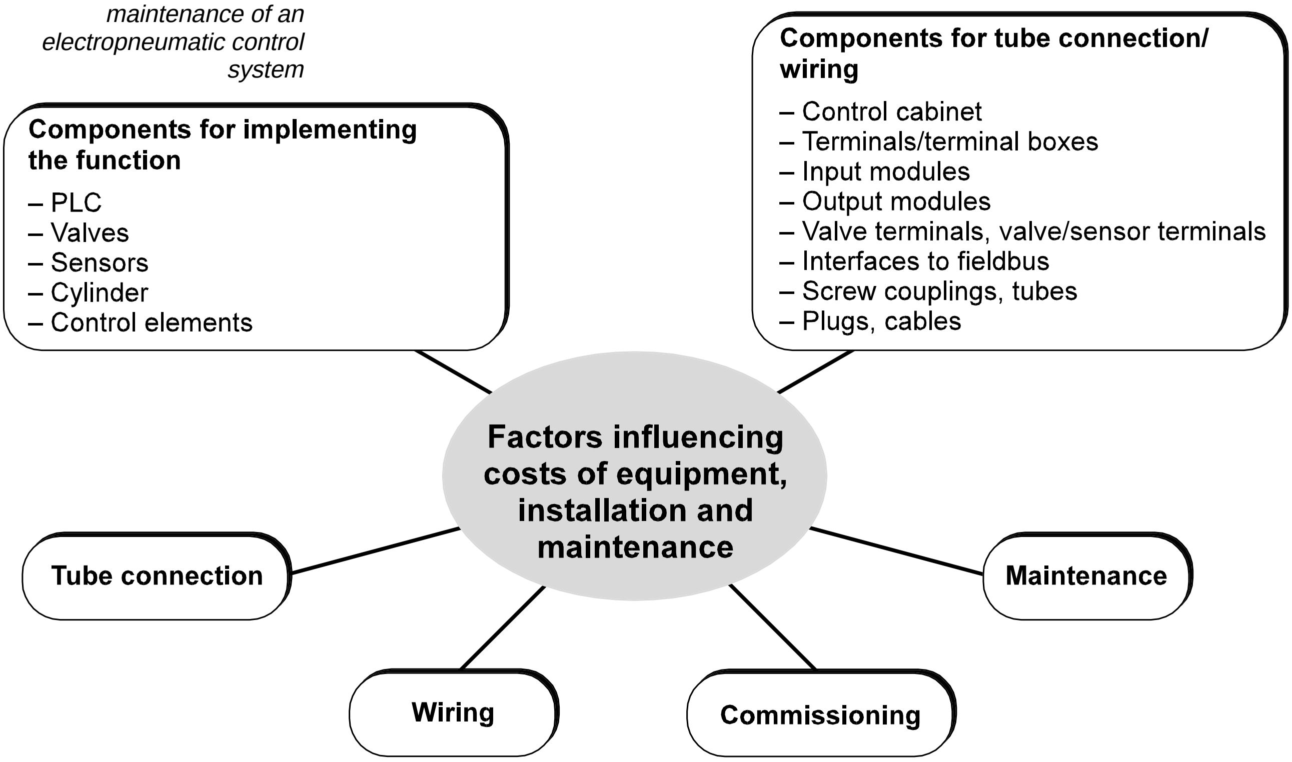
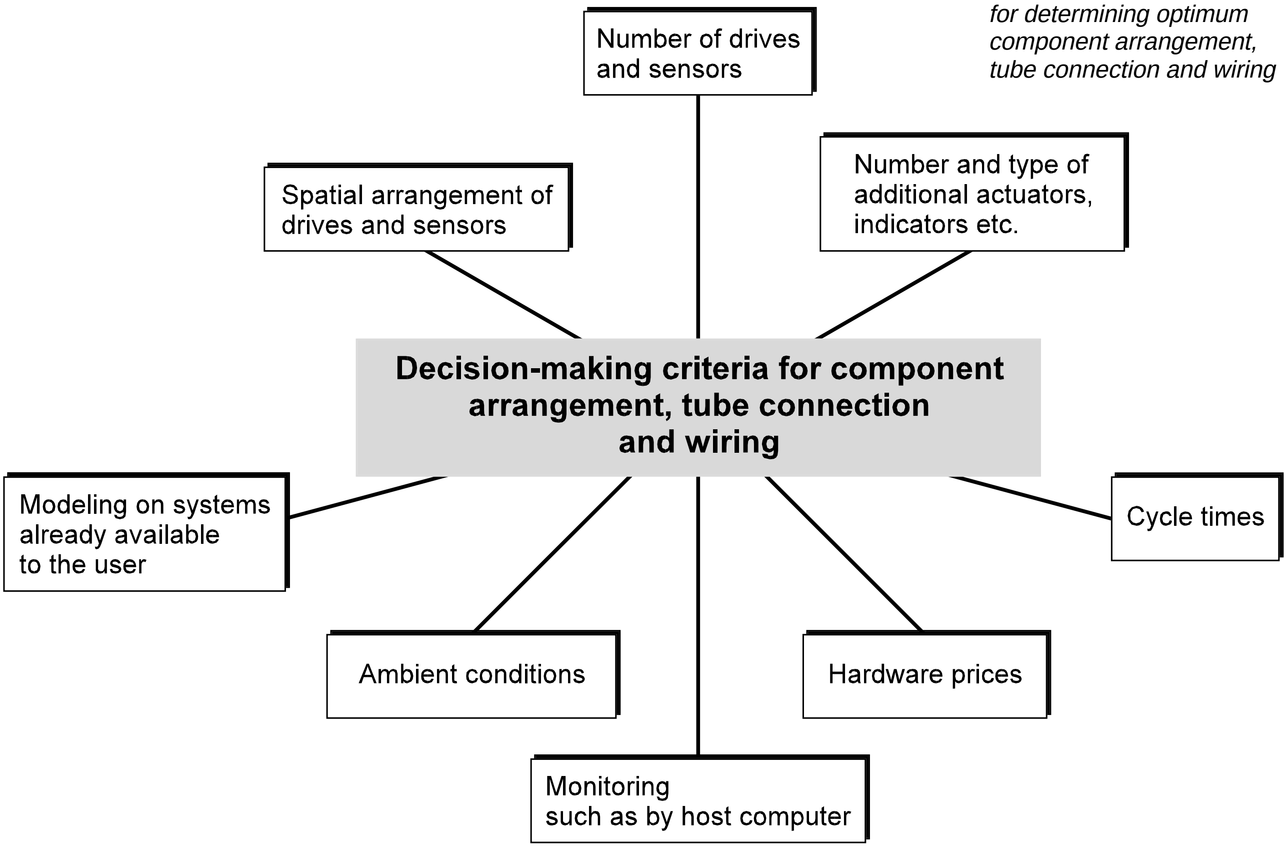


Fig. 9.14:
Decision-making criteria for determining optimum component arrangement, tube connection and wiring



Control example

In order to illustrate the advantages of advanced installation techniques and the procedure for selecting components, various concepts are compared to each other on the following pages using the control of a palletizing device as an example. The control arrangement comprises a total of 12 pneumatic control chains, 10 of which are double-acting cylinders and 2 single-acting cylinders. The components of the example control system are listed in Table 9.3.

Table 9.3: Components of the example control system

Components		*Number*
Cylinders	Double-acting	10
	Single-acting	2
Electropneumatic directional control valves	Spring-return 3/2-way valve for compressed air supply (on-off valve)	1
	Spring-return 5/2-way valves (for double-acting cylinders)	5
	5/2-way double solenoid valves (for double-acting cylinders)	5
	Spring-returned 3/2-way valves (for single-acting cylinders)	2
Electrical components	Proximity switches	24
	PLC	1

9.7 Reducing tubing effort

If the directional control valves of all control chains are mounted together on one manifold or one valve terminal, it is sufficient to have one tube to supply compressed air to all control chains, and two silencers take over channeling all exhaust air. As a consequence, numerous tube connectors and silencers as well as a compressed air distributor are saved in comparison with individual mounting. The amount of work needed for tube connection is also reduced accordingly.

Table 9.4 indicates how many components are saved in the example control system by using block-type valve assembly.

Table 9.4: Reducing tubing effort in the example control system by using block-type valve assembly

Components	*Individual mounting of directional control valves*	*Block mounting of directional control valves (manifold or valve terminal)*	*Saving with block-type mounting*
Tubing			
Number of tubes for supplying compressed air to on-off valve	1	1	–
Number of compressed air distributors	1	0	1
Number of tubes for supplying compressed air distributor	1	0	1
Number of tubes for supplying compressed air to control chains	12	1	11
Number of tubes between directional control valves and cylinders	22	22	–
Silencers			
Number of silencers for start-up valve	1	1	–
Number of silencers for control chains	22	2	20

Tubing for spatially dispersed control systems

Despite its undisputed advantages, block-type valve assembly gives rise to undesirable side-effects when cylinder drives are arranged some considerable distance apart.

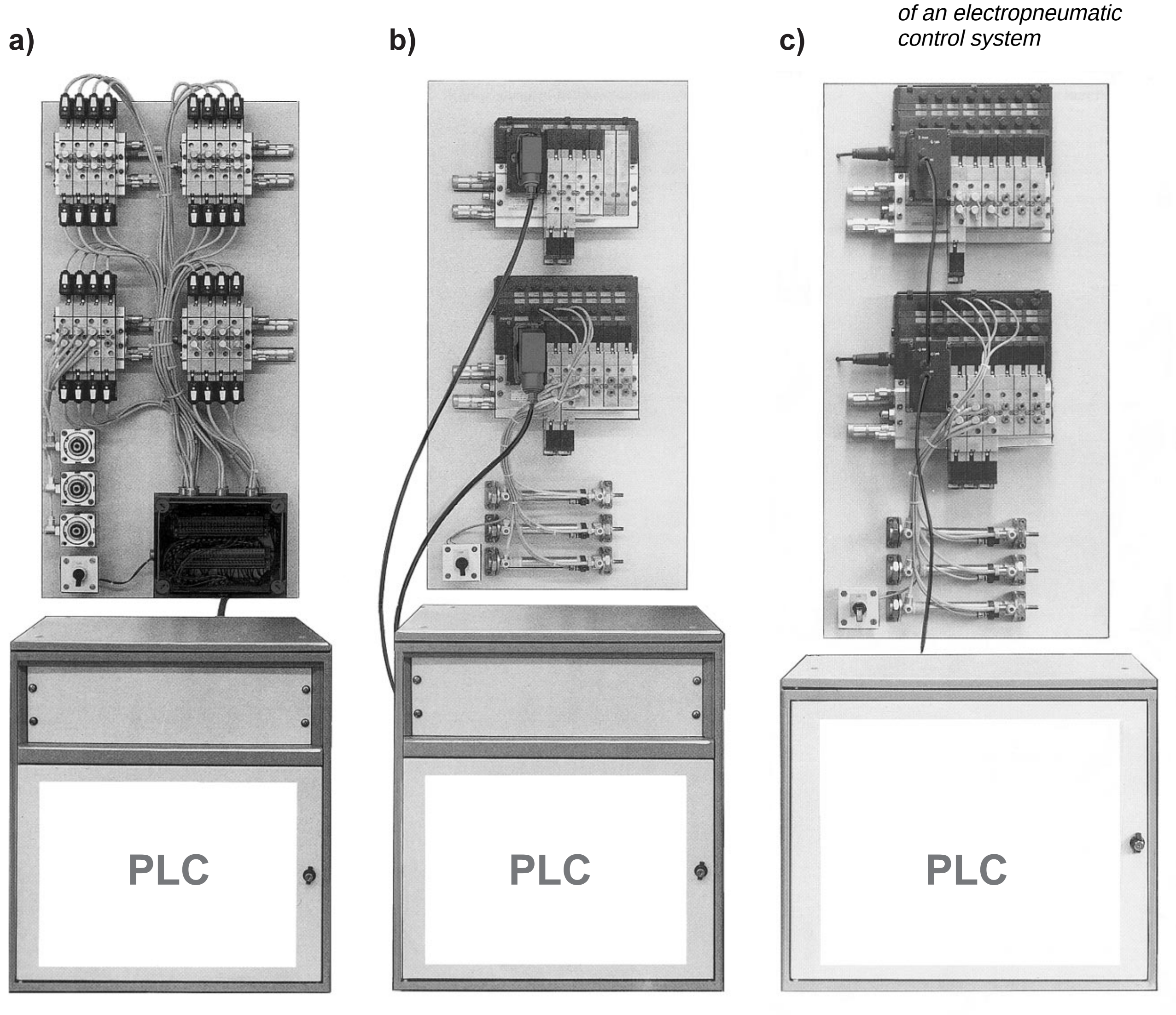
- Lenthy tubing is required between directional control valves and cylinders. This results in long signal propagation times (with a tube length of 10 m, for example, approximately 30 ms). The cylinder response is delayed. The electropneumatic control system response is correspondingly slow.
- The large tube volume between the valves and cylinders results in greater consumption of compressed air.
- The presence of numerous long tubes makes the overall layout very unclear. In the event of a defect, replacing the tubes is costly.

Directional control valves should therefore only be mounted in blocks if the associated cylinder drives are situated relatively close together, or if the disadvantages listed above can be tolerated.

9.3 Reducing wiring effort

When using classical wiring techniques, the components of an electropneumatic control system are wired via terminal strips (Fig. 9.15a). Table 9.5 shows the amount of wiring needed for the example control system using conventional wiring technology.

Fig. 9.15: System structure of an electropneumatic control system



a) Valve blocks with conventional wiring (wiring concept 1)

b) Valve terminal with multi-pin plug connection (wiring concept 2)

c) Valve terminal with fieldbus connection (wiring concept 3)

Control cabinet wiring

The voltage supply and the inputs and outputs of the PLC are connected on one side of terminal strip 1 (= terminal strip in the control cabinet). The connecting cable to the terminal box is connected on the other side.

Connection between control cabinet and terminal box

The following lines are run from the control cabinet to the terminal box:

- One line for each PLC input signal (sensor evaluation)
- One line for each PLC output signal (valve actuation)
- One grounding cable
- One line to supply electrical power to the proximity switches

Wiring the terminal box

The lines coming from the terminal strip in the control cabinet are connected on one side of terminal strip 2 (= terminal strip in the terminal box). The cables to the solenoid coils, proximity switches and additional outputs are connected on the other side. 3 terminals are required for each sensor and 2 terminals for each solenoid coil.

Table 9.5:
Amount of wiring needed for the example control system (conventional wiring)

Terminal strip 1 (in control cabinet)	Grounding cable	1 terminal
	Supply voltage (24 V)	1 terminal
	18 PLC outputs (actuation of solenoid coils)	18 terminals
	24 PLC inputs (evaluation of proximity switches)	24 terminals
Terminal strip 1, total		44 terminals
Cable from control cabinet to terminal box	Cable between terminal strips 1 and 2	1 cable or 1 cable harness with 44 wires
Terminal strip 2 (in control cabinet)	24 proximity switches x 3 wires per proximity switch	72 terminals
	18 solenoids x 2 wires per solenoid	36 terminals
Terminal strip 2, total		108 terminals
Cable to directional control valves and sensors	Connection of solenoid coils	18 cables, each 2 wires
	Connection of sensors	24 cables, each 3 wires

Modern wiring concepts

We shall compare 5 different wiring concepts for the example control system (Table 9.4):

- Wiring concept 1: Conventional wiring
  (Fig. 9.15a)
- Wiring concept 2: Valve terminal with multi-pin plug connection
  (Fig. 9.15b)
- Wiring concept 3: Valve terminal with fieldbus connection
  (Fig. 9.15c)
- Wiring concept 4: Valve terminal with integrated PLC
- Wiring concept 5: Wiring with AS-i bus
  (Actuator-sensor interface)

The amount of wiring needed for the 5 different concepts is shown in Table 9.6.

Table 9.6: Comparison of amount of wiring needed for the example control system

** tm = terminals; wr = wires*

Components	*Concept 1*	*Concept 2*	*Concept 3*	*Concept 4*	*Concept 5*
Control cabinet	1	1	1	–	1
Terminal strip 1	1 (44 tm*)	1 (44 tm*)	–	–	–
Terminal box	1	–	–	–	–
Terminal strip 2	1 (108 tm*)	–	–	–	–
Cables to solenoids	17 (34 wr*)	–	–	–	–
Cables to sensors	24 (72 wr*)	24 (72 wr*)	24 (72 wr*)	24 (72 wr*)	24 (72 wr*)

Wiring concept 2: Multi-pin plug connection

All valves and sensor connections in the control system are arranged on one valve terminal. If the valve terminal is connected via a multi-pin connector, the equipment not needed in comparison with the conventional wiring concept is the terminal box, terminal strip 2 and the cables to the solenoid coils (Table 9.6).

Wiring concept 3: Fieldbus

If a fieldbus system is used, the effort for wiring is considerably reduced in comparison with the multi-pin plug connection method (Table 9.6). The terminal strip in the control cabinet is not necessary.

Wiring concept 4: Valve terminal with integrated PLC

When using a valve terminal with integrated PLC, savings are made by omitting the control cabinet. Expenditure on wiring is very low (Table 9.6). Control systems can be set up very cost-effectively, especially systems in which all valves and sensors are combined on a single valve terminal.

A valve terminal with integrated PLC is also referred to as a programmable valve terminal.

Wiring concept 5: Actuator-sensor interface

If the drive units of an electropneumatic control system are distributed some distance apart, the directional control valves can usually only be combined in small groups on valve terminals, or they may even have to be installed individually. Under such conditions it is often preferred to use the actuator-sensor interface (AS-i) system. In comparison with other fieldbus systems it is easier to work with the cables because all stations are directly clamped to one continuous line.

Fields of application of the various wiring concepts

The characteristics and main areas of application of the various wiring concepts are contrasted with each other in Table 9.7. In order to arrive at an optimum-cost solution for a given application, the total costs of the control system using different wiring concepts need to be worked out and compared with each other.

Table 9.7: Characteristics and main areas of application of various wiring concepts	*Advantages*	*Disadvantages*	*Main areas of application*
Concept 1: Conventional wiring	Low component costs	High wiring effort Costly and time-consuming maintenance	Increasingly being replaced by modern concepts
Concept 2: Valve terminal with multi-pin plug connection	Reduced wiring effort Simplified maintenance	Higher component costs	Tends to be used for control systems with small numbers of valves and sensors
Concept 3: Valve terminal with fieldbus connection	Very low wiring effort Simplified maintenance	Greatly increased component costs	Control systems with numerous valves and sensors, particularly if these can be grouped on a small number of terminals
Concept 4: Valve terminal with integrated PLC	Very low wiring effort Simplified maintenance Omission of control cabinet	If several valve terminals are needed, greatly increased component costs Only available for a few PLC types	Control systems for which a single valve terminal is sufficient: preferable to concept 3; otherwise careful weighing up necessary
Concept 5: Actuator-sensor interface	Very low wiring effort Simplified maintenance Interface to bus system particularly cost-effective	Only a maximum of 4 binary inputs or outputs per bus connection Higher component costs	Control systems with spatially dispersed drive units, suitable for both simple and complex systems

Combination of different wiring concepts

In control arrangements with numerous control chains situated close to each other together with additional components a greater distance away, it may make sense to combine different connection techniques. An example of such a situation is shown in Fig. 9.16. The directional control valves and sensor connections of the control chains arranged close to each other are grouped on a valve terminal. The other components are connected via the AS-interface system.

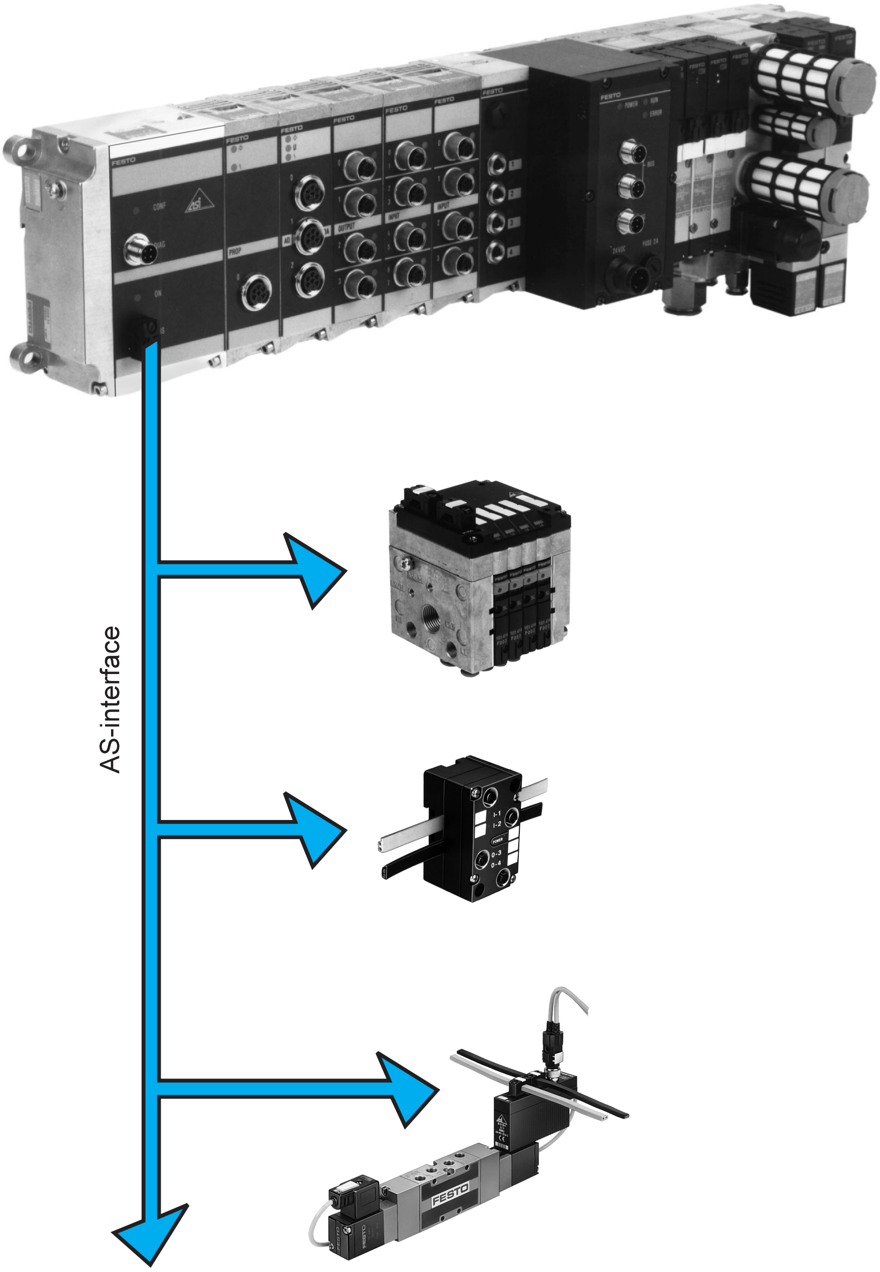


*Fig. 9.16:
Design of an electro-pneumatic control system using the AS-interface*

9.9 Proportional pneumatics

Proportional pneumatics is primarily used in the following fields of application:

- Continuous adjustment of pressures and forces
- Continuous adjustment of flow rates and speeds
- Positioning with numerically controlled drives, such as in robotics

Function of a proportional pressure regulating valve

A proportional pressure valve converts a voltage, its input signal, into a pressure, its output signal. The pressure at the output to a consuming device can be adjusted continuously from 0 bar to a maximum of, for example, 6 bar.

Fig. 9.18a shows proportional pressure regulating valves of various nominal sizes.

Use of a proportional pressure regulating valve

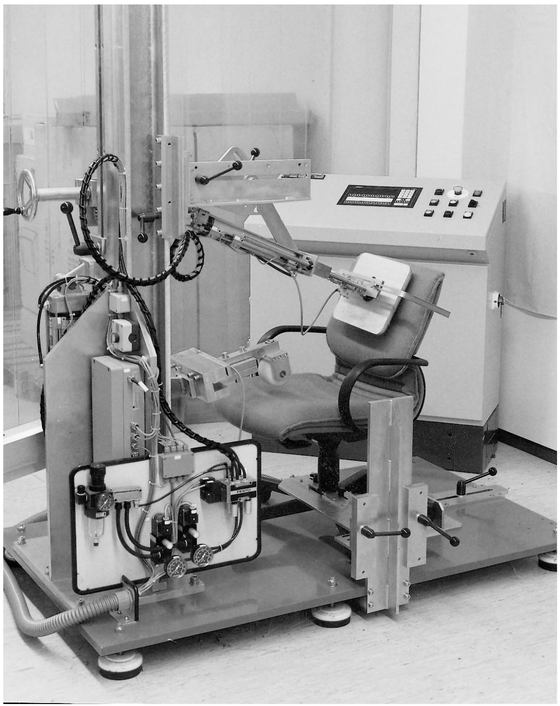
Fig. 9.17a is an illustration of a device for testing office chairs. In order to test the long-term durability of the backrest spring, a periodically changing force is applied to the chair. The maximum force and the characteristics of the force as a function of time can be varied in such a way as to run different test cycles. Two possible characteristics of force as a function of time are shown in Fig. 9.17b.

Fig. 9.17:
Test apparatus for office chairs

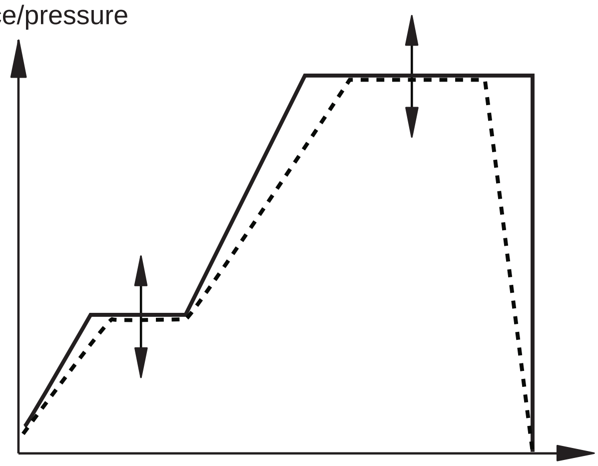
a) Configuration of the test apparatus

b) Characteristic of force as a function of time

a)



b)



Control of the test apparatus

The electropneumatic control system for the test apparatus operates according to the following principle:

- A programmable logic controller which is also capable of processing analogue signals outputs a pressure setpoint in the form of a voltage.
- The proportional pressure regulating valve generates a pressure at its consumer output proportional to the voltage (low voltage = low pressure, high voltage = high pressure).
- The consumer output of the proportional pressure regulating valve is connected to the cylinder chamber. A high pressure at the output of the proportional valve means high cylinder piston force, while low pressure at the valve output means low piston force.

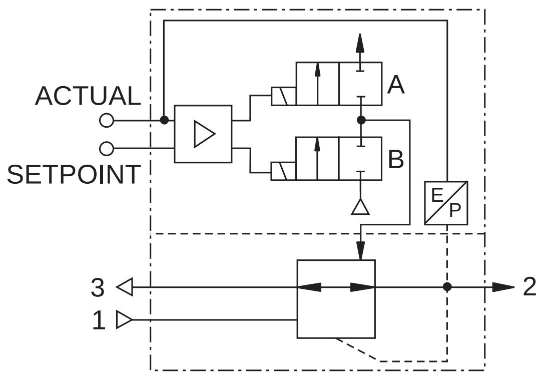
When the voltage at the output of the PLC is increased, the proportional valve raises the pressure in the cylinder chamber. The piston force increases. When the voltage at the output of the PLC is decreased, the proportional valve lowers the pressure in the cylinder chamber. The piston force decreases.

Fig. 9.18: Proportional pressure regulating valves

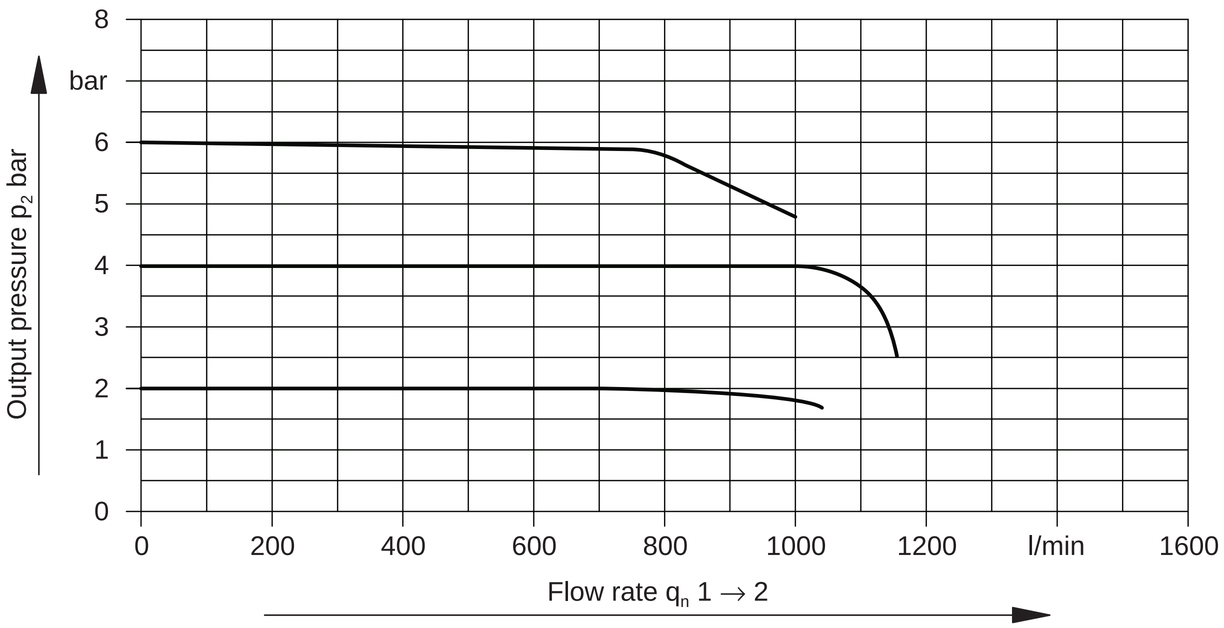
a) Valves of different nominal sizes,
b) Equivalent circuit diagram,
c) Pressure/flow rate characteristics

a)

b)



c)



Equivalent circuit diagram of a proportional pressure regulating valve

Fig. 9.18b shows the equivalent circuit diagram of a proportional pressure regulating valve. The valve has a compressed air supply port, a consumer port and an exhaust port. The two electrical connections have the following functions:

- The signal input on the valve is connected to the analogue output of the electrical control system.
- On the signal output of the valve, the pressure prevailing at the consuming device output can be tapped in the form of an analogue electrical signal. Connection of this output is not essential for operation of the valve.

Mode of operation of a proportional pressure regulating valve

The pressure at the consumer port is measured with a pressure sensor. The measured value is compared to the pressure setpoint.

- If the pressure setpoint is higher than the actual pressure value, switching valve A is opened (Fig. 9.18b). The pressure on the upper side of the pressure balance increases. As a result, the consumer port is connected to the supply port. Compressed air flows to the consumer port. The pressure at the consumer port increases. The pressure on both surfaces of the pressure balance is matched, and the balance moves back to its initial position. When the required pressure is reached, the valve closes.
- If the pressure setpoint is lower than the actual pressure value, switching valve B is opened. The pressure on the upper side of the pressure balance decays. The consumer port is connected to the exhaust side. The pressure at the consumer port falls, and the pressure balance moves to its initial position.

Fig. 9.18c shows the pressure characteristic at the consumer port for three different but constant input voltages. The pressure is kept constant over large ranges, irrespective of the flow rate through the valve. It is only at a very high flow rate that the pressure falls.

Tasks of a proportional directional control valve

A proportional directional control valve combines the properties of an electrically actuated switching directional control valve and an electrically adjustable throttle. The connections between the valve ports can be opened and shut off. The flow rate can be varied between zero and the maximum value.

Fig. 9.19a shows proportional directional control valves of various nominal sizes.

Application of a proportional directional control valve

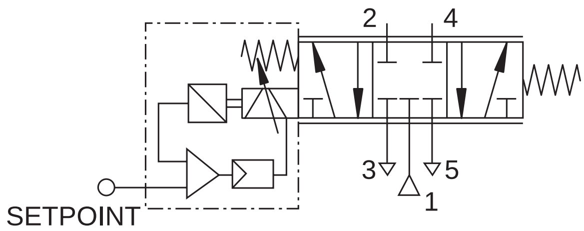
A proportional directional control valve allows continuous adjustment of the valve flow rate and therefore the speed of travel of the piston rod of a pneumatic cylinder. This means that the speed characteristic can be optimized, enabling high speeds to be achieved with gentle acceleration and braking (Fig. 9.19d). Applications are found in conveying sensitive goods (for example in the food industry).

a) Valves of various nominal sizes
b) Equivalent circuit diagram
c) Flow rate characteristic (flow/signal function)
d) Examples of speed characteristics

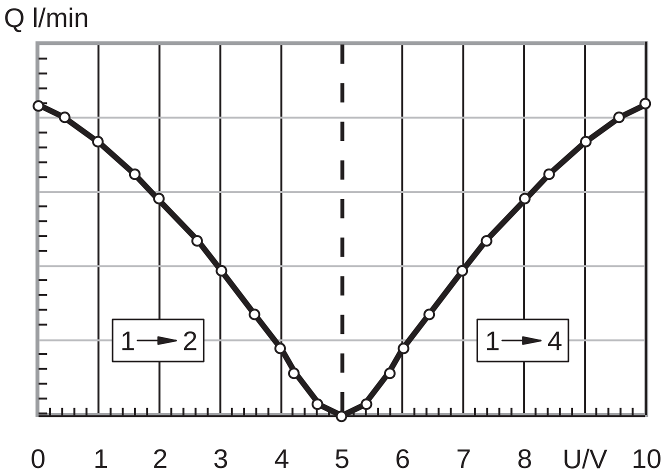
Fig. 9.19:
Proportional directional control valves

a)

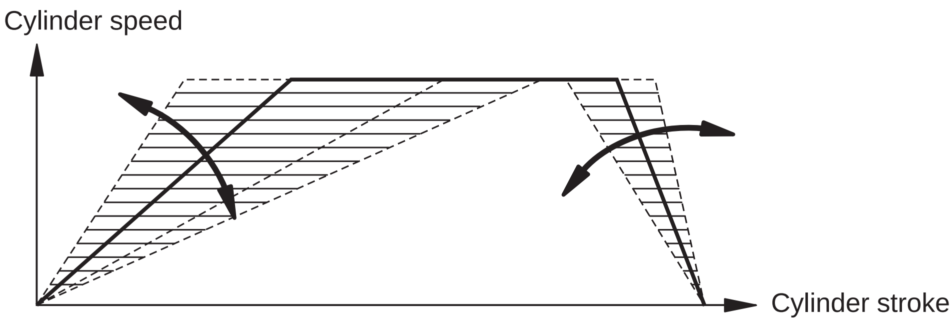
b)



c)



d)



Equivalent circuit diagram of a proportional directional control valve

Fig. 9.19b shows the equivalent circuit diagram of a 5/3-way proportional valve. The valve adopts different switching positions according to the analogue electrical input signal (= manipulated variable):

- Input signal below 5 V: ports 1 and 2 are connected, and ports 4 and 5
- Input signal 5 V: valve closed (mid-position)
- Input signal above 5 V: ports 1 and 4 are connected, and ports 2 and 3

Flow/signal function of a proportional directional control valve

The valve opening is also adjusted as a function of the manipulated variable. The relationship between the manipulated variable and the flow rate is described by the flow/signal function (Fig. 9.19c):

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

Pneumatic positioning drive

A pneumatic positioning drive is used to approach several program-defined positions via a pneumatic cylinder. The piston is clamped between the air columns of the two cylinder chambers by a positional control system. It is therefore possible to position the piston not only at the stops but also at any required position within the stroke range. Depending on the drive unit, a positioning accuracy of 0.1 mm can be achieved. Thanks to the positional control system a position continues to be maintained even when a force acts on the piston.

Application example for a pneumatic positioning drive

Pneumatic positioning drives are used in handling, for example, or for palletizing or assembly. Fig. 9.20 shows a facility in which drink cartons are sorted into packaging with the aid of a pneumatic positioning drive.

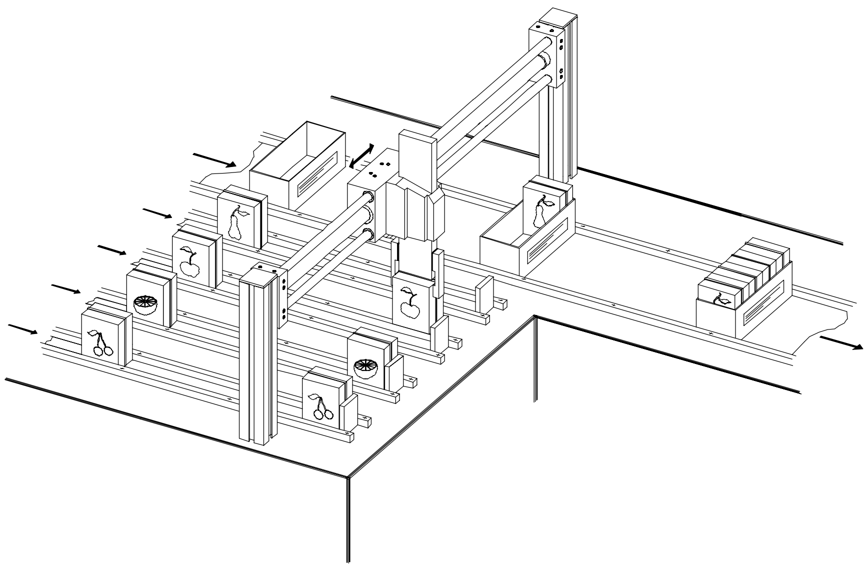


Fig. 9.20: Application of a pneumatic positioning drive

Design of a pneumatic positioning drive

A pneumatic positioning drive consists of the following components:

- A numerical control system
- A proportional directional control valve
- A double-acting pneumatic cylinder
- A positional transducer

Appendix

Index

Standards

Standards	*Description*
DIN/EN 292-1	Safety of machinery; basic terminology, general design guidelines, Part 1: Basic terminology, methodology
DIN/EN 292-2	Safety of machinery; basic terminology, general design guidelines, Part 2: Technical guidelines and specifications
DIN/EN 418	Safety of machinery; EMERGENCY-STOP devices, functional aspects
DIN/VDE 0470 (EN 60 529)	Degrees of protection through housings (IP code)
DIN/VDE 0611-1 (EN 60 947-7-1)	Low voltage switching devices, terminals for copper conductors
DIN/VDE 0660-200	Low voltage switching devices, Part 5-1:Controllers and switching elements; electromechanical controllers
DIN/VDE 0660-210	Low voltage switching devices; safety of machinery; electrical EMERGENCY-STOP devices: safety related construction regulations
DIN/EN 983	Safety requirements for fluid power systems and their components; pneumatics
DIN/ISO 1219-1	Fluid power; graphic symbols and circuit diagrams, Part 1 and Part 2
ISO/DIS 11727	Pneumatic fluid power - Identification of ports and control mechanisms of control valves and other components (port identification for pneumatic devices)
DIN 19226	Open and closed-loop control technology, Part 1 to Part 6
DIN 24558	Pneumatic systems, design fundamentals
DIN 40719	Circuit documentation, Part 2: Identification of electrical equipment
DIN 40719 (IEC 848 modified)	Circuit documentation, Part 6: Standard specifications function charts
DIN/EN 50005	Industrial low voltage switching devices; port identifications and reference codes: General rules

Standards	*Description*
DIN/EN 50011	Industrial low voltage switching devices; port identifications, reference codes and code letters
DIN/EN 50044	Inductive proximity sensors, identification of connections
DIN/EN 60073 (VDE 0199)	Coding of display and operating units by means of colour and ancillary means
DIN/EN 60204 (VDE 0113)	Electrical equipment of machinery, Part 1: General requirements
DIN/EN 60617-2 (IEC 617-2)	Graphic symbols for circuit diagrams, Part 2: Symbol element, designations and other circuit symbols for general use
DIN/EN 60617-4 (IEC 617-4)	Graphic symbols for circuit diagrams, Part 4: Symbols for passive components
DIN/EN 60617-5 (IEC 617-5)	Graphic symbols for circuit diagrams, Part 5: Symbols for semiconductors and electron tubes
DIN/EN 60617-7 (IEC 617-7)	Graphic symbols for circuit diagrams, Part 5: Symbols for circuit and safety devices
DIN/EN 60617-8 (IEC 617-8)	Graphic symbols for circuit diagrams, Part 5: Symbols for measuring and signalling devices
DIN/EN 61082-1 (IEC 1082-1)	Electrical engineering documentation, Part 1: General rules
DIN/EN 61082-2 (IEC 1082-2)	Electrical engineering documentation, Part 2: Function-related circuit diagrams
DIN/EN 61082-3 (IEC 1082)	Electrical engineering documentation, Part 3: Connection diagrams, connection tables and connection lists