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# Mechatronics in Theory and Practice

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# Imprint

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# Mechatronics in Theory and Practice

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# Foreword

"Mechatronics" is an overarching technical field of knowledge that deals with complex systems resulting from the fusion of

- mechanical engineering,
- electrics/electronics and
- computer science.

For optimum project planning, design and maintenance of a complex system, holistic thinking and action are required. This includes safety, environmental protection and EU Directives.

This book "Mechatronics. Theory and Applications" provides the necessary broad knowledge for planning, commissioning and diagnosis of mechatronic systems and addresses the following main aspects:

- Components in mechatronic systems
- Energy generation and transport
- Pneumatic, hydraulic and electric drive technology
- Sensor techolnogy and open-loop control technology
- Programming and documentation
- Safety technology and directives
- Systematic commissioning and error diagnostics
- Industry 4.0

In addition to this book, Bosch Rexroth AG offers tailor-made training and training systems.

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# 1 The field of mechatronics

Mechatronics engineers work in the fields of assembly and maintenance of complex machines, plants and systems in plant and mechanical engineering or with operators of mechatronic systems.

Mechatronics engineers carry out activities independently at various locations, primarily on assembly sites, in workshops or in the service area, observing the relevant regulations and safety provisions in accordance with documents and instructions.

## 1.1 Professional requirements

Mechatronics engineers

- plan and control workflows, check and assess work results and apply quality management systems,
- machine mechanical parts and assemble modules and components into mechatronic systems,
- install electrical assemblies and components,
- measure and test electrical parameters,
- install and test hardware and software components,
- assemble and test electrical, pneumatic and hydraulic controls,
- program mechatronic systems,
- commission and operate mechatronic systems,
- assemble, disassemble, transport and secure machines, systems and plants,
- configure and test the functions of mechatronic systems,
- hand over mechatronic systems and instruct customers,
- carry out maintenance of mechatronic systems.

## 1.2 What is mechatronics?

Mechatronics is an interdisciplinary high-tech field of knowledge.
The made-up word, made up of the root words "mechanics" and "electronics", originated in Japan in the early 1970s and at that time referred to the applications of microprocessor technology for machine control applications.

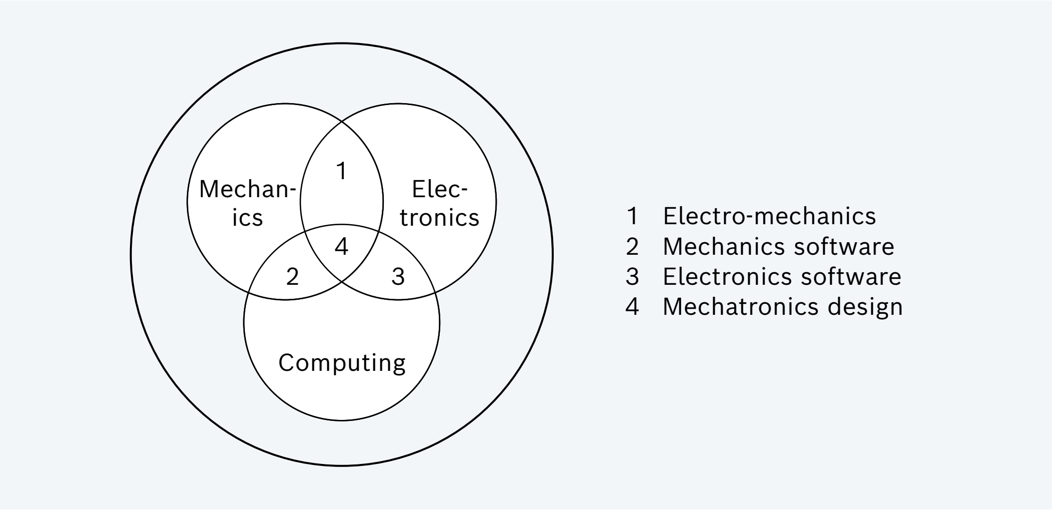

*Fig. 1: Components of mechatronics*

Mechanics, electronics and computing (information technology) are combined and considered holistically throughout the entire product life cycle (modeling, development, manufacturing, use).

The scientific and technological development of recent years has shown that innovations arise particularly at the interfaces of the fields of knowledge. Therefore, the following interdisciplinary fields are considered in mechatronics:

- Electro-mechanics (electro-pneumatics/electro-hydraulics, ECAD electrical design)
- Mechanics software (virtual reality, motion animation)
- Electronics software (NC, PLC, PC, ...)
- Mechatronic systems (system theory, complex automated systems)

# 1.3 Basic structure of mechatronic systems

## 1.3.1 General setup

In general, energy, material and information are converted in a technical system. In mechatronic systems, the focus is on the flow of energy and information. In this case, the energy flow is generated by forces and torques acting on a moving system boundary or by electric currents flowing across system boundaries.

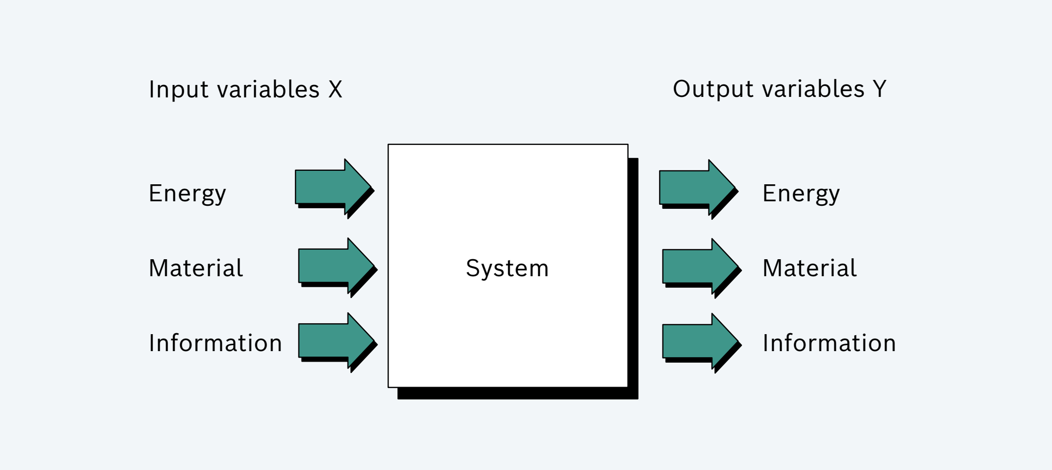

*Fig. 2: General setup of a technical system*

Mechatronic systems consist of:

- a basic mechanical structure that produces a specific load-bearing or motion behavior,
- sensors that capture information about the system or the environment ,
- processors in which the information is evaluated and control variables are generated according to certain rules,
- actuators in which the control variables are converted into forces, motion, electrical voltages or other variables that act on the basic system or its environment.

The general setup of mechatronic systems is illustrated in figure 3. Sensors and actuators represent the links between energy and information.

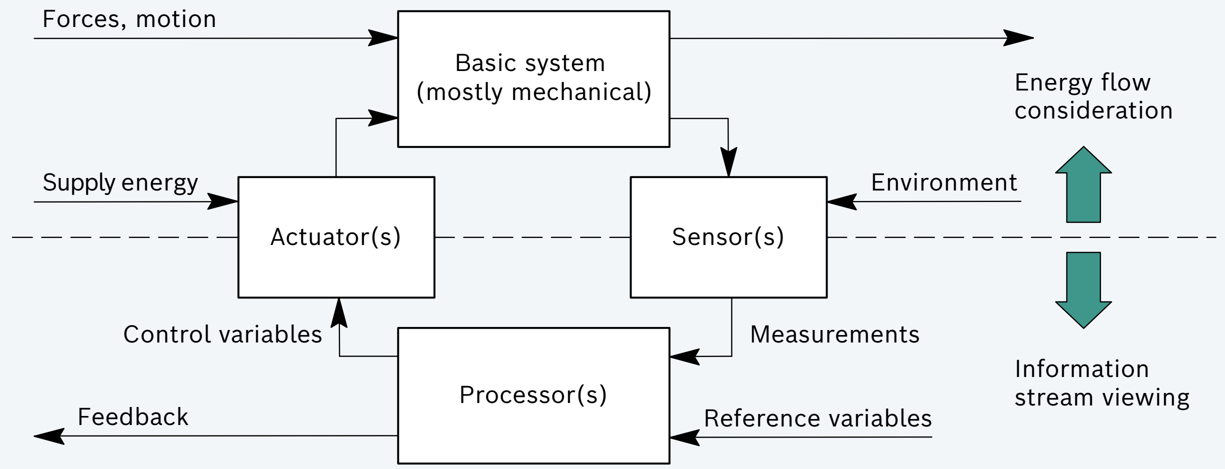

*Fig. 3: Basic structure of mechatronic systems*

## 1.3.2 Development methodology for mechatronic systems

Mechatronic systems are usually characterized by a high degree of complexity.
The main problem in the development of mechatronic products is often mastering this complexity, both in technical and organizational terms.
Development and design are part of the overall creation and use process of the product, which also includes product planning, manufacturing and distribution, as well as use, maintenance and disposal.

The main requirement of the early phases is to define a basic solution path based on the given task by abstracting and setting up functional structures as well as the search for suitable solution principles and their combination. For this purpose, the most important system functions and their interlinking must be recorded and formulated in a solution-neutral way, e.g. by considering the flows of energy, material and signals.
The term "function" is also used in mechatronics according to the usual meaning in the design system of mechanical engineering. According to this, an abstract, solution-neutral and unambiguous form of a task is to be understood. The overall function for description of the overall task of the product or system is more suitably broken down into subtasks which are easy to solve and whose logical or physical interlinking represents the functional structure. These functions are described in natural language.

The sub-functions and the functional structure must be fulfilled by a physical cause-effect relationship, which is accordingly built up from effective principles and their effective structure. As a rule, a function can be fulfilled by several effective principles, which, for example, can be based on physical effects. From these effective principles, the most favorable solution must be selected.

Based on the functional and effective structure obtained in this way, the building structure is then to be completely worked out according to technical and economic aspects. The first step is to look for solutions in principle, which are to be structured in modules depending on the possibilities available for realization. Existing solution elements, such as standard parts or cataloged components, are preferred.
Only then is the detailed design, i.e. the final design of all system parts, started.
While the early phases focus on the function of the system and its parts, the later phases are more oriented towards the shape of the system. Accordingly, these designs are also referred to as "function-oriented" and "design-oriented".

This procedure corresponds to the general design methodology described in VDI Directive 2221 "Development of technical products and systems" (VDI publisher) and introduced in mechanical engineering. In the development of mechatronic products, the main focus is on the cross-disciplinary consideration of system dynamics, especially in the emphatically function-oriented design of the control system.

### 1.3.3 Function concept in mechatronics

A key feature of mechatronic systems is that components from very different areas can be linked together. There is often a whole range of possible alternative solutions that need to be evaluated and compared during development.
At the latest when quantitative evaluation becomes necessary for decision-making, common functional description is no longer sufficient. Further specification of the concept of the function concept becomes necessary.

If we look at the basic structure of mechatronic systems, we notice that this basic structure is suitable both for the description of simple components and subsystems and for the description of complex overall systems. There is always a transformation of input variables to output variables, which, with suitable formalization, can be described mathematically. The state of the system in which this transformation takes place is described by state variables. It is reasonable that the relevant methods of system dynamics are also used for functional description of mechatronic systems.

With increasing complexity and completeness, the functions occurring in mechatronic systems are generally classified as follows:

- Kinematic functions
  → Providing a suitable motion mechanism to find a solution for the task (function)
- Dynamic functions
  → Additional inclusion of acting forces and drive behavior
- Mechatronic functions
  → Inclusion of control algorithms, sensor technology and other components to complete the functional description

The individual components and subsystems are referred to as "functional mechatronic modules".
The behavior of the overall system can now be analyzed in detail.

For mechatronics engineers, functional mechatronic modules represent solution elements for step-by-step buildup of comprehensive systems.
This results in a block-oriented, hierarchical system structure that enables a high degree of reusability of functional modules or even once-generated complex aggregates.

## 1.4 Basic principles of electrical engineering

Electrical engineering covers the full range of technical applications in which the effects of electric current and the properties of electric and magnetic fields are exploited.

### 1.4.1 Electricity

The terms positive and negative electricity were introduced by the American scientist Benjamin Franklin to refer to the type of charge produced on glass and hard rubber rods. He proved that the charges on the rods represent different types of electricity.
Free electrons can move in solid objects. Friction can lead to the transfer of free electrons from one surface to another. The movement of free electrons forms the electric current.
Franklin concluded that the current flow must go via the external current path from the positive terminal of the friction machine to the negative terminal.

The **current** through a metallic conductor with a potential difference between its ends is

- directly proportional to the potential difference and
- indirectly proportional to the electrical resistance of the conductor (Ohm's law).

The **resistance** of a conductor depends on:

- Material
- Length
- Cross-section
- Temperature

The first Kirchhoff's law states that in a node of an electrical network, the sum of input currents is equal to the sum of output currents (node rule). The second Kirchhoff's law states that the sum of all partial voltages (potential differences) of a mesh or a closed circuit system is equal to zero (mesh rule).

Electrical energy can be divided into smallest parts of any size and used without significant losses.
Electrical conductors are not only used to transmit currents to different locations, but also convert electrical energy into other needed forms of energy, such as heat, light, or mechanical energy.

### 1.4.2 Magnetism

Magnetism is generally defined as the ability or force of a material which can attract and hold iron or steel parts.
A magnet is referred to as a body with the polarity properties and thus the ability to attract iron or steel.

Examples of the technical application of magnetism are generators, transformers, relays and others.

The Danish physicist Oerstedt discovered the close connection between electricity and magnetism at the beginning of the 19th century.

The electric current intensity of 1 ampere is defined as

- the electric current through two conductors arranged parallel to each other, 1 meter long and 1 meter apart, which produces an electromagnetic attraction force of $2*10^{-7}$ Newton between these conductors.

Ferromagnetic material has the property that when it is placed in magnetic fields with variable positioning and intensity, the magnetic induction follows the changing magnetic force. This delay in magnetization is referred to as **hysteresis**.
The heat generated by material friction causes power losses.

If ferromagnetic material is used in alternating current devices such as transformers or generators, the material is subject to a cyclic change in direction and intensity.
The energy losses in each cycle are illustrated by a hysteresis loop of the magnetic field strength over the resulting magnetic induction.
Eddy currents are circulating currents generated in a material by variable magnetic fields.

## 1.4.3 Physical and technical terms

| | |
|---|---|
| **DC/AC** | DC: Direct Current<br>AC: Alternating Current |
| **Resistance** | In DC circuits, there is a single "resistance" to the current flow; the "ohmic resistance" $R$ ("resistance" or "active resistance").<br>In AC circuits, the quantities "inductive resistance" $X_L$ and "capacitive resistance" $X_C$ must also be taken into account. Both are combined under the general term "reactance". The effect of resistance and reactance is referred to as "impedance" or "apparent resistance" $Z$. |
| **Inductivity** | Inductivity or inductive resistance is a physical quantity which characterizes the resistance of an AC current flow through an electrical conductor. The inductance causes the current to lag the voltage. |
| **Capacity** | Capacities are mainly used for storage of electric charges. In an electrolytic capacitor, a thin, non-conductive chemical is used on one side of the plate as an insulator.<br>The disadvantages of electrolytic capacitors are that they are not suitable for high voltages (upper limit approximately 600 V) and have a (small) leakage current and thus energy losses.<br>Variable capacitors consist of a series of metal plates which can be moved in and out of one another at a distance from a series of fixed plates.<br>In an alternating current circuit, the capacitor has a capacitive resistance which acts against a changing alternating voltage. Capacitive resistors cause the voltage to lag with respect to the current. |
| **Insulator** | An insulator fulfills various functions in the practical application of electric circuits.<br>It prevents bare conductors from touching each other and thus enables the transmission of high (and possibly dangerous) current intensities. An insulator acts as protection against injury caused by contact with excessive electrical currents. It also prevents high leakage currents (energy losses) and undesired temperature rises as a consequence of high currents. |
| **Semiconductor** | Materials such as silicon, germanium or selenium have the properties of semiconductors with very useful properties for the transmission of electric current.<br>When n-type germanium is connected to p-type germanium, a p-n junction diode is formed at the junction. The main property of a p-n junction is to allow the passage of current in one direction and block it in the opposite direction. |

**Generator**

Rotating machines in electrical engineering basically consist of two physically separate components: stator and rotor. The inner cylindrical surface of the stator acts on the outer surface of the rotor inside it. An air gap between the two allows the rotor to rotate.
The cores of the stator and rotor are made of thin sheets of magnetic material (e.g. silicate steel), minimizing losses due to induced eddy currents and hysteresis.
The material of the cores must have high magnetic permeability to achieve the required intensity of magnetic flux without excessive current. The magnetic flux intensity in the air gap is directly proportional to the magnetic field intensity.

**Switching devices**

Switching devices are used to open or close electric circuits.
As circuit breakers, their main function is to open, i.e. de-energize, electric circuits when required or when an error occurs.
Switching devices must be robust against the currents to be switched and also the mechanical loads that occur during the switching process.
When selecting the switching devices, in addition to economic aspects, compliance with safety provisions must be taken into account.

**Protection relay**

Protective relays constantly measure the current electrical variables in the electric circuit to be monitored and interrupt it as soon as one of these variables deviates from the permitted state for a few milliseconds.
All protection relays have two positions; the normal position with usually open contacts and the error position with closed contacts. The error position is activated if an error is detected within the electric circuit (e.g. by overcurrent).

## 1.4.4 Electrical basic quantities: current intensity, voltage and resistance

The current is one of the seven basic quantities of the international SI system of units, such as length or mass, from which all other quantities of this system and their units can be derived.

| Quantity | Formula | Unit | Fluidically comparable with |
|---|---|---|---|
| Current intensity | $I$ | Ampere (A) | Flow |
| Voltage | $U$ | Volt (V) | Pressure |
| Resistance | $R$ | Ohm (Ω) | Flow resistance due to friction |

*Table 1: Basic quantities of electrical engineering*

**Possible effects of electric current:**

- Thermal effect
  Every conductor through which current flows heats up (example: electric heater).
- Magnetic effect
  Every current-carrying conductor is surrounded by a magnetic field (example: relay).
- Light effect
  Under certain conditions, the electric current excites solid conductors and gases to glow (example: incandescent lamp).
- Chemical effect
  The electric current produces a chemical change on electrolytes (bases and acids in solution) (example: accumulator).
- Harmful effect on living beings
  Humans and animals may suffer an electric shock when touching live conductors (example: electric pasture fence).

## 1.4.5 Ohm's law

Ohm's law states that resistance remains constant as a ratio of voltage to amperage; the higher the voltage, the higher the amperage.

$$R = \frac{U}{I}$$

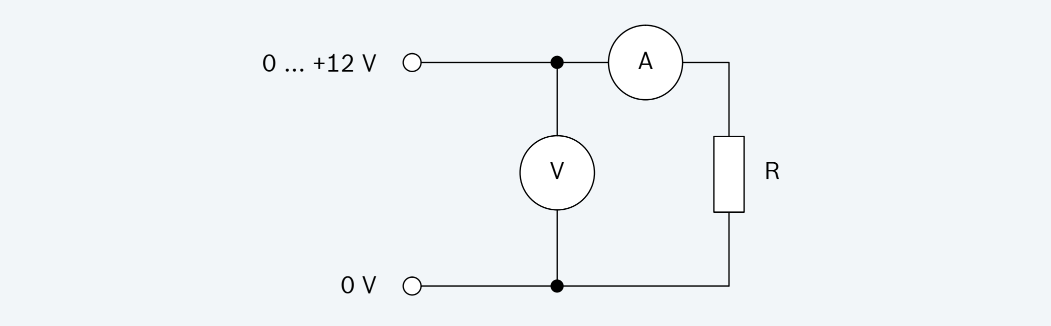

*Fig. 4: Simple circuit*

A distinction is made between the technical direction of current (from positive pole to ground) and the actual direction of movement of the electrons in the conductor (from negative to positive).

The electrical resistance also depends on whether DC voltage or AC voltage is present. The resistance of a normal incandescent lamp, for example, is the same for direct or alternating current, but a solenoid coil has a higher resistance for alternating current than for direct current.
This means that the coils of solenoid valves may be operated with higher values when supplied with AC voltage than with DC current.

**Examples of characteristic resistance values:**

| | |
|---|---|
| Short cable pieces | 1 µΩ – 100 mΩ |
| Longer cable pieces | 0.1 Ω – 10 Ω |
| Resistances of lamps and household appliances | 10 Ω – 1000 Ω |
| Resistors in electronic devices | 0.1 Ω – 1000 MΩ |
| Insulation resistors | 10 MΩ – 1000 GΩ |

### Parallel circuit

A parallel circuit exists when different actuators in an electrical system can be switched on or off independently of each other. This means that each actuator can have a different current flowing through it. What they all have in common, however, is the applied voltage. Examples of parallel circuits are home lighting and devices connected to the electric circuit via sockets.

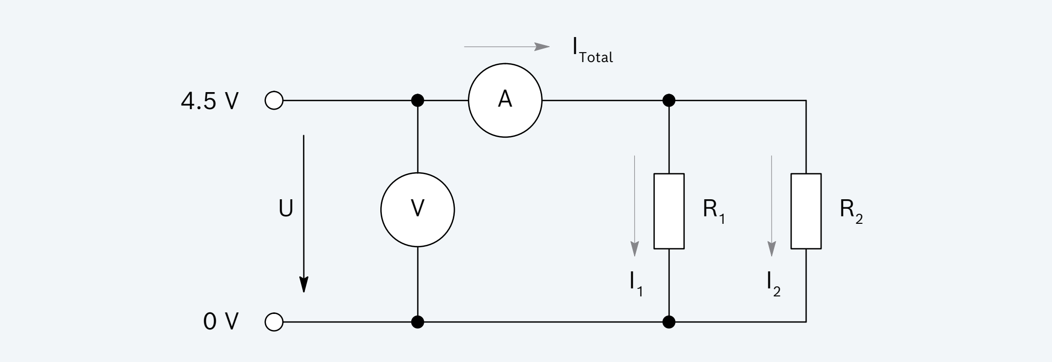

*Fig. 5: Parallel electric circuit*

To calculate the total resistance, first add up the reciprocal values of the individual resistances:

$$\frac{1}{R_{Total}} = \frac{1}{R_1} + \frac{1}{R_2}$$

The total resistance in figure 5 is therefore:

$$\frac{1}{R_{Total}} = \frac{1}{3\ Ohm} + \frac{1}{1\ Ohm} = \frac{1}{0.75\ Ohm} \qquad R_{Total} = 0.75\ Ohm$$

Calculation of the total current:

$$I_{Total} = \frac{U}{R_{Total}} = \frac{4.5\ V}{0.75\ Ohm} = 6\ A$$

Calculation of $I_1$ and $I_2$:

$$I_1 = \frac{4.5\ V}{3\ Ohm} = 1.5\ A \qquad I_2 = \frac{4.5\ V}{1\ Ohm} = 4.5\ A$$

It is shown that the sum of the two partial currents $I_1$ and $I_2$ again gives the total current $I = 6$ A.

**Parallel circuit**

A series circuit exists when the same current flows through the individual actuators (resistors) in series after a voltage is applied.

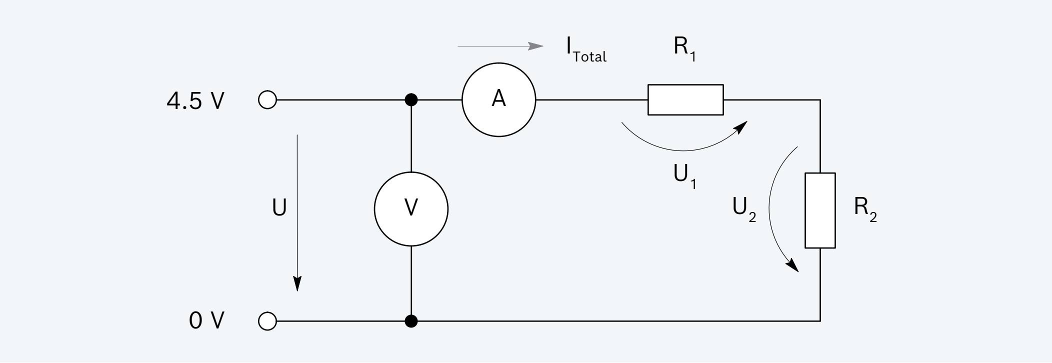

*Fig. 6: Series electric circuit*

To calculate the total resistance, the resistance values of the individual resistors are added:

$$R_{Total} = R_1 + R_2$$

The total resistance of the circuit (figure 6) is therefore:

$$R_{Total} = 3\ Ohm + 1\ Ohm = 4\ Ohm$$

Calculation of the total current:

$$I_{Total} = \frac{U}{R_{Total}} = \frac{4.5\ V}{4\ Ohm} = 1.125\ A$$

Calculation of $U_1$ and $U_2$:

$$U_1 = 1.125\ A \cdot 3\ Ohm = 3.375\ V$$
$$U_2 = 1.125\ A \cdot 1\ Ohm = 1.125\ V$$

From this it can be seen that the sum of the two partial voltages $U_1$ and $U_2$ gives the total voltage $U = 4.5$ V.

## 1.5 Basic principles of electrical drive technology

In drive technology, electric machines are widely used in all sectors of economy. For the selection of an electric drive, its good integrability into technical systems of different kinds plays an essential role.

### 1.5.1 DC motor

The basic principle of a DC motor is that a conductor loop, which is located in a magnetic field, is set into continuous rotary motion by switching the magnetic field. The use of several conductor loops ensures that the motor starts up reliably. In larger motors, the magnetic field is generated with solenoids instead of permanent magnets. A distinction is made between main shunt motors and shunt motors.

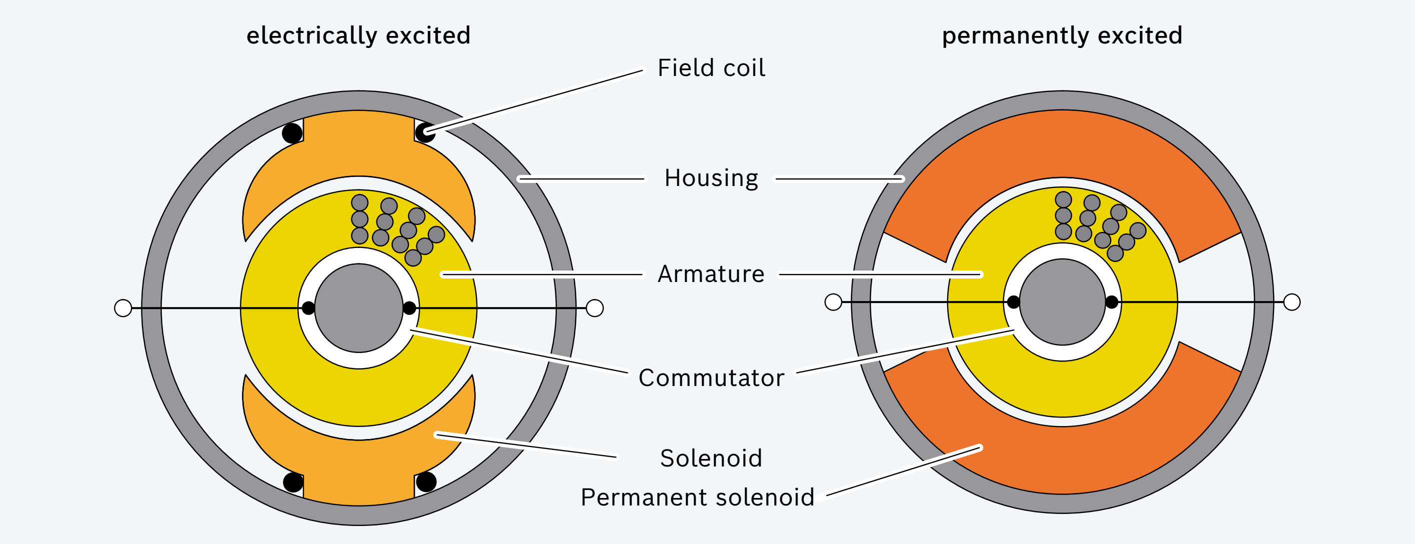

*Fig. 7: DC motor*

### 1.5.2 AC motor/three-phase motor

Three-phase current is generated by linking of 3 alternating voltages, whose phase angles are firmly shifted by 120 degrees. Three-phase current has the same advantages as alternating current.

Additional features of three-phase current:

- Formation of a rotating field for the drive of the motor (rotor).
- Distribution of the load on 3 conductors (reduction of the conductor cross-section possible)
- Voltage between the 3 conductors: 3 x 400 $V_{AC}$.

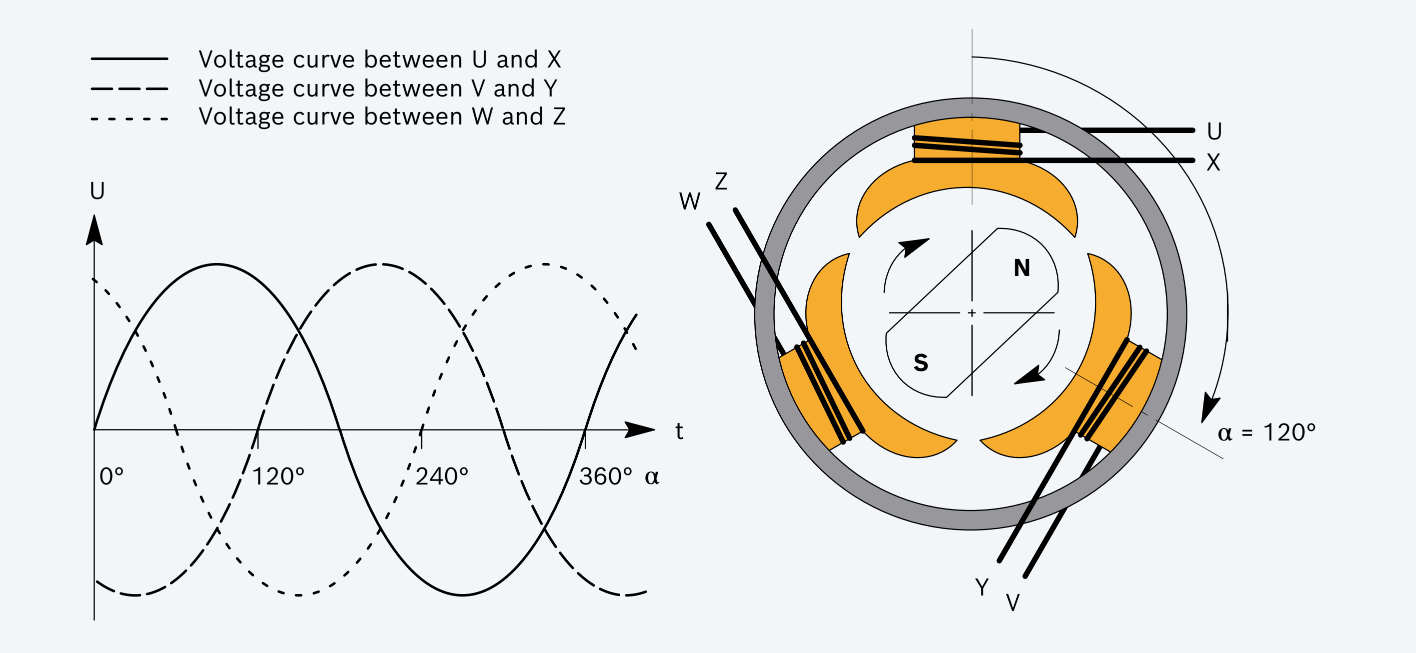

*Fig. 8: Three-phase motor*

For three-phase motors, the direction of rotation can be reversed by swapping two of the three connection lines.

## 1.5.3 Electrical schematics

Circuit symbols and circuit diagrams in electrical engineering are defined in international (IEC) and European standards (EN).

VDE regulations specify the circuit diagram documents that must be included in the scope of delivery of electrical devices and systems.
These include all necessary information for the user about installation, commissioning, maintenance and servicing of the electrical control system.

| **Standard** | **Contents** |
|---|---|
| DIN EN 60617-2 | Graphical symbols for circuit diagrams – Symbol elements, qualifying symbols and other symbols having general application |
| DIN EN 60617-3 | Graphical symbols for circuit diagrams – Conductors and connecting devices |
| DIN EN 60617-7 | Graphical symbols for circuit diagrams – Switchgear, controlgear and protective devices |

*Table 2: Important standards for circuit symbols in electrical engineering*

| Standard | Contents |
|---|---|
| DIN EN 81346-1 | Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Basic rules |
| DIN EN 81346-2 | Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Classification of objects and codes for classes |
| DIN EN 61082-4 | Preparation of documents used in electrotechnology – Location and installation documents |
| DIN EN 61355-1 | Classification and designation of documents for plants, systems and equipment – Rules and classification tables |

*Table 3: Important standards for circuit diagrams in electrical engineering*

## Types of circuit diagrams

Circuit documents are divided according to the purpose and type of illustration.
A distinction is made between:

- Diagrams showing the operation of the control system (e.g. overview circuit diagram, electrical circuit diagram, functional circuit diagram)
- Diagrams showing the connections and spatial location (e.g. construction schematics, arrangement plan, equipment list)

**Overview circuit diagram**

An overview circuit diagram is created according to the specifications of DIN EN 61082-1 as the simplified, abstracted illustration of an electrical circuit. Only the essential elements of the circuit are considered. The overview circuit diagram shows the function and structure of the electrical circuit.

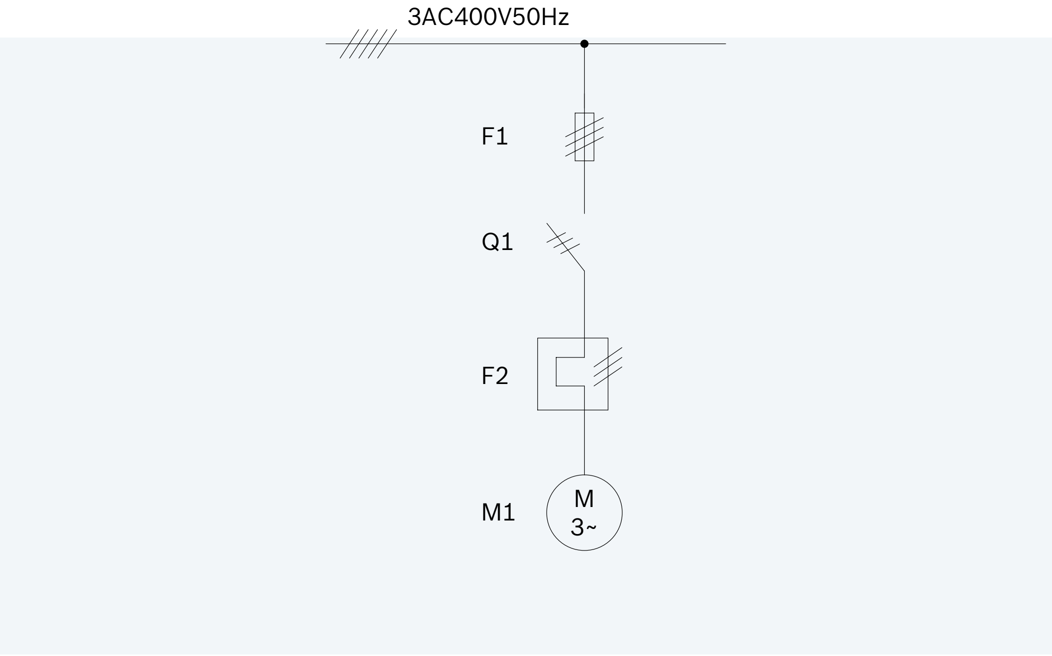

*Fig. 9: Example of an overview circuit diagram*

**Electrical circuit diagram**

An electrical circuit diagram is created according to the specifications of DIN EN 61082-1. It is the detailed, abstracted illustration of an electrical circuit.
The circuit is resolved according to current paths. It is illustrated with all lines and connections. The spatial position of the individual elements of the circuit is not taken into account.
For larger systems, a separate illustration of the electrical circuit diagram is made in the main circuit and control circuit.

The electrical circuit diagram contains horizontally arranged potential lines and vertically running current paths. All switching elements are shown in de-energized state. Automatic contactors, such as limit switches, are illustrated in their basic position with respect to the overall system. If deviating illustrations cannot be avoided, these must be noted in the electrical circuit diagram.
All circuit symbols must be arranged in the direction of the current path (vertical).
The direction of motion of the circuit symbols must always be from left to right.
The circuit symbols are specified in DIN EN 60617-2.
Terminal designations should always be to the left of the symbol and should be readable from below or from the right.

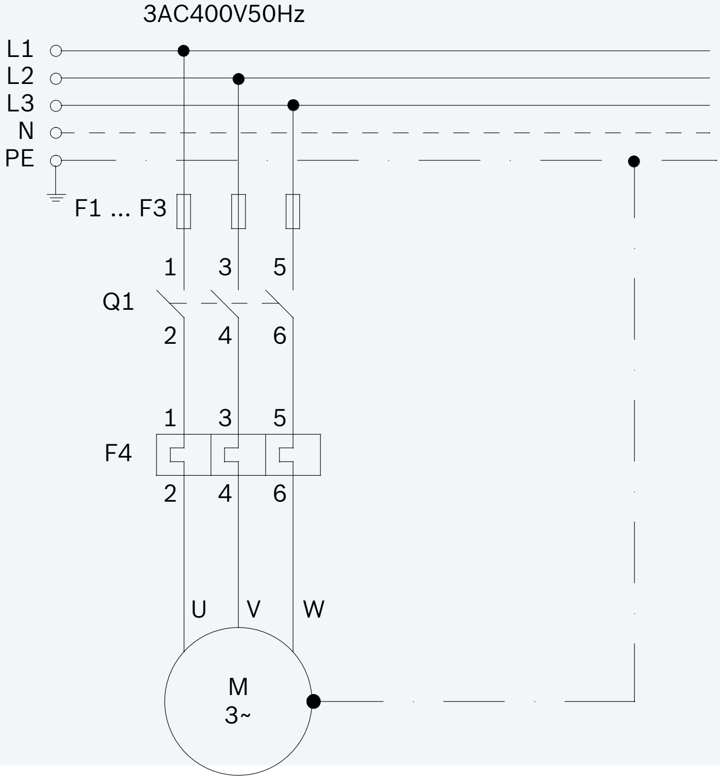

*Fig. 10: Example of an electrical circuit diagram*

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