Actuators

Actuators (final-control elements) form the interface between the electronic signal processor (data processing) and the actual process (mechanical motion). They convert the low-power signals conveying the positioning information into operating signals of an energy level adequate for process control. Signal transducers are combined with amplifier elements to exploit the physical transformation principles governing the interrelationships between various forms of energy (electrical – mechanical – fluid – thermal).

1 Actuator chain

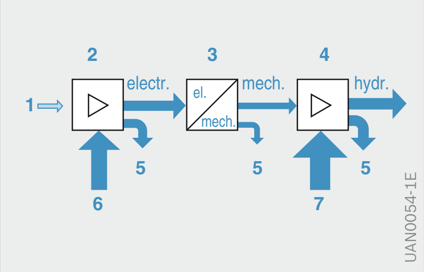


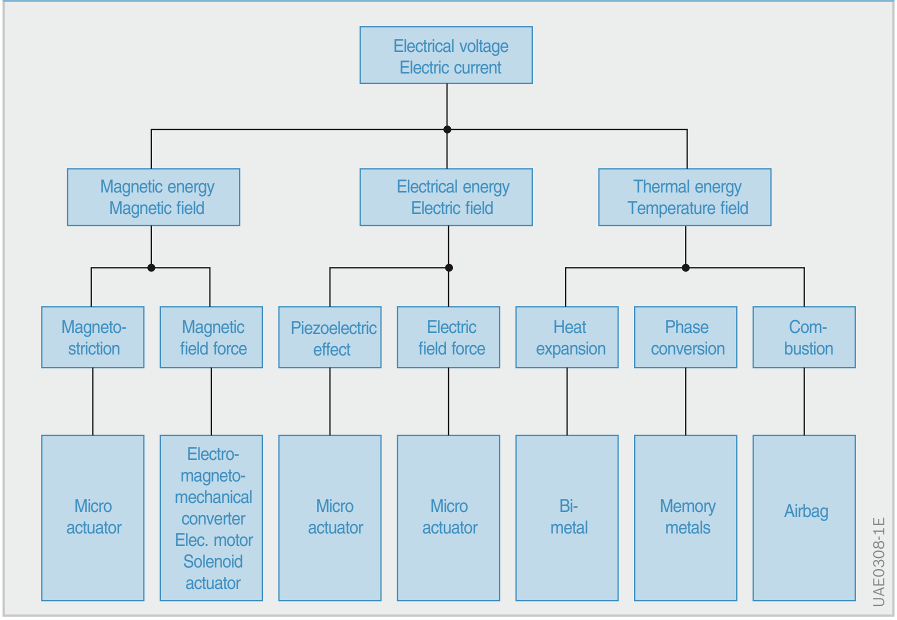
Fig. 1
1 Information
2 Actuator
3 Converter
4 Actuator
5 Losses
6 External electrical energy
7 External hydraulic energy

Electromechanical actuators

This type of energy conversion represents one option for classifying electromechanical actuators. The energy emanating from the source is transformed into magnetic or electrical field energy, or converted to thermal energy. The individual force-generation principle is determined by these forms of energy, and is based on either field forces or certain specific material characteristics. Magnetostrictive materials make it possible to design actuators for applications in the micropositioning range. This category also includes piezoelectric actuators, which are built according to a multilayer design similar to ceramic capacitors, and are actuators for high-speed fuel injectors. Thermal actuators depend exclusively on the exploitation of characteristics of specific materials.

Actuators in a motor vehicle are mostly electromagneto-mechanical converters and, by extension, electrical servomotors, translational, and rotational solenoid actuators.

2 Electromechanical converters (system overview)



Robert Bosch GmbH (ed.), *Bosch Automotive Electrics and Automotive Electronics*,
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An exception is the pyrotechnic airbag system. The solenoid actuators can themselves be the servo element, or they can assume a control function by governing a downstream amplifier (e.g. mechanical-hydraulic).

Force generation in the magnetic field

The distinction between the electrodynamic and the electromagnetic actuator principles stems from the manner in which forces are generated in the magnetic field. Common to both principles is the magnetic circuit with soft-magnetic material and the coil for excitation of the magnetic field. A major difference lies in the force which can be extracted from the unit under technically feasible conditions. Under identical conditions, the force produced by application of the electromagnetic principle is greater by a factor of 40. The electrical time constant for this type of actuator is comparable to the mechanical time constants. Both force-generation principles are applied in linear and rotary drive mechanisms.

Electrodynamic principle

The electrodynamic principle is based on the force exerted on moving charges or charged conductors (Fig. 3a, current *I*) within a magnetic field (Lorentz force). A field coil or a permanent magnet generates a DC magnetic field (magnetic flux density *B*). The electrical energy destined for conversion is applied (current *I*) to the moving armature coil (immersion coil). A high degree of actuator precision is achieved by designing the armature coil with low mass and low inductance. The two energy accumulators (one on the fixed and one on the moving component) produce two active force directions via current-direction reversal in the armature and field coils.

The secondary field produced by the armature current flows in an open magnetic circuit, thereby diminishing the effects of saturation. Approximately speaking, the force (torque) exerted by an electrodynamic actuator over its setting range is proportional to current and independent of travel.

Electromagnetic principle

The electromagnetic principle exploits the mutual attraction displayed by soft iron materials in a magnetic field. The electromagnetic actuator is equipped with only one coil, which generates both the field energy and the energy to be transformed. In accordance with the operating principles, the field coil is equipped with an iron core to provide higher inductance.

3 Electrodynamic and electromagnetic converters

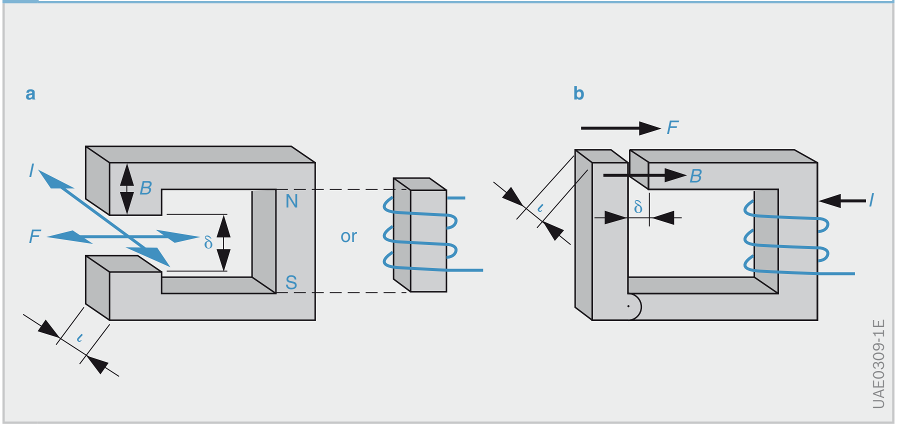


Fig. 3

a Electrodynamic principle: Force on moving charge $F = B \cdot I \cdot l \cdot \sin\alpha$

b Electromagnetic principle: Force between pole faces $F = B^2 \cdot A / 2\mu_0$

However, as the force is proportional to the square of the magnetic flux density *B*, the unit is operative in only a single force-transfer direction. The electromagnetic actuator thus requires a return element (such as a mechanical spring or a magnetic return mechanism).

Dynamic response

The dynamic response of an electromechanical actuator, i.e. the activation and deactivation operations, is defined by the equation of mechanical motion, the differential equation of electrical circuits and Maxwell's equations of dynamics. The current- and position-dependent force follows from Maxwell's equations.

The most basic electrical circuit consists of an inductance with an ohmic resistor. One means of enhancing the dynamic response is through over-excitation at the instant of activation, while deactivation can be accelerated by a Zener diode, for example. In each case, increasing the dynamic response of the electric circuit involves additional expenditure and increased losses in the actuator's triggering electronics.

Field diffusion is a delay effect which is difficult to influence in actuators with high dynamic response. Rapid switching operations are accompanied by high-frequency field fluctuations in the soft-magnetic material of the actuator's magnetic circuit. These fluctuations, in turn, induce eddy currents, which counteract their cause (build-up and decay of the magnetic field). The resultant delay in the build-up or reduction of forces can only be reduced by selecting appropriate materials with low electric conductivity and permeability.

Design

Design selection is essentially determined by operating conditions (i.e. installation space, required force/travel characteristic curve, and dynamic response).

Electromagnetic actuators

A typical form for translational electromagnetic actuators is the switching solenoid (Fig. 4) with a force/travel characteristic curve which falls as a function of the square of positioning travel. The precise shape of the curve (Fig. 5) is determined by the type of working air gap (e.g. conical or solenoid armature).

Rotational electromagnetic actuators are characterized by a defined pole arrangement in stator and rotor. When current is applied to one of the coils, the rotor and stator poles respond with mutual attraction, and in doing so generate a torque.

4 Switching solenoid

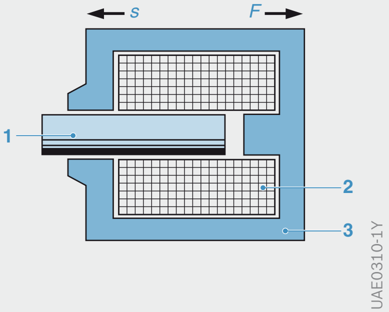


Fig. 4
1 Armature
2 Coil
3 Magnetic yoke

5 Switching solenoid (characteristic curves)

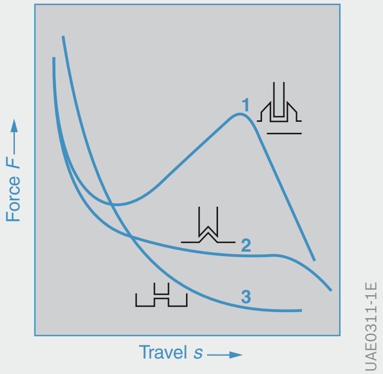


Fig. 5
1 Solenoid plunger
2 Conical armature
3 Cylindrical armature

6 Electromagnetic single-winding rotary actuator

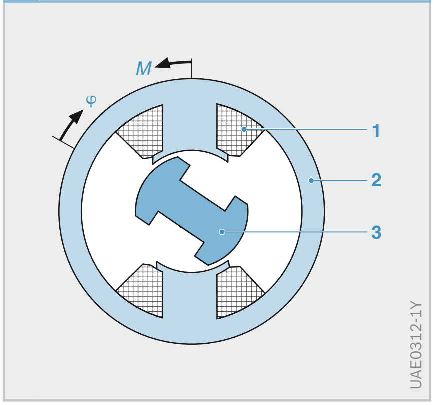


Fig. 6
1 Coil
2 Stator
3 Armature

7 Torque motor

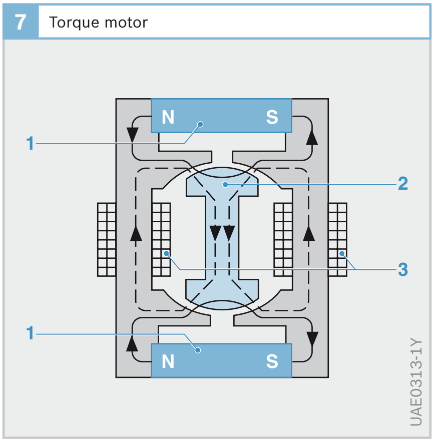


Fig. 7
1 Magnets
2 Armature
3 Control coils

8 Electromagnetic rotary actuators (characteristics)

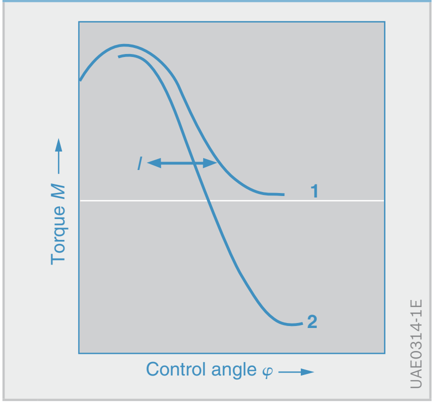


Fig. 8
1 Single-winding rotary actuator
2 Torque motor

The single-winding rotary actuator (Fig. 6) incorporates a pair of poles in each of the two main sections, as well as a coil in the stator. Its maximum adjustment range is approx. 45°.

The torque motor (Fig. 7) is a bidirectional electromagnetic rotary actuator featuring a stable operating point and without counterforces. The rotor is maintained in a stable position by the excitation field of the permanent magnet in the stator. The magnetic field generated by one or two stator windings produces torque and provides unilateral compensation for the excitation field. This type of layout is suitable for applications in which substantial torque is required over small control angles. The relationship between the applied current and the torque motor's force is roughly linear (Fig. 8). The torque-motor principle is also employed in translational actuators.

Electrodynamic actuators

In a pot magnet (immersion-coil actuator, Fig. 9) a cylindrical immersion coil (armature coil) is set in motion in a working air gap. The adjustment range is limited by the axial length of the armature coil and by the air gap.

The short-stroke linear motor (Fig. 10) is an actuator with a virtually round disk coil.

A distinction is made between single-winding and dual-winding rotary actuators (Fig. 11). Both types include a permanent magnet within the rotor and one or two stator windings. The rotor magnet is magnetized at both ends to produce magnetic flux density in the rotary magnet's working air gap, which combines with the armature current to produce a torque. Originating from the position illustrated, the adjustment range is less than ±45°. The setting range of the single-winding rotary actuator also varies according to both the torque requirement and the angle range in which the necessary flux density can be provided.

The dual-winding rotary actuator can be described as a combination of two single-winding rotary actuators with a 90° peripheral offset and designed to produce opposed torque flows. A stable operating point is achieved at the zero transition point on the resulting torque curve without auxiliary counterforces.

Application

Electromechanical actuators are direct-action control elements, and without an intermediate ratio-conversion mechanism, they convert the energy of the electrical control signal into a mechanical positioning factor/work. Typical applications include positioning of flaps, sleeves, and valves. The described actuators are final-control elements without internal return mechanisms, i.e. without a stable operating point. They are only capable of carrying out positioning operations from a stable initial position (operating point) when a counterforce is applied (e.g. return spring and electrical control).

A solenoid armature provides a stable static operating point when its force/travel curve is superimposed on the characteristic response of a return spring. A variation of the coil current in the solenoid shifts the operating point. Simple positioning is achieved by controlling the current. However, particular attention must be paid here to the nonlinearity of the force-current characteristic and the positioning system's sensitivity to interference factors (e.g. mechanical friction, pneumatic, and hydraulic forces). The temperature sensitivity of the coil resistance results in positioning errors, making corrective current control necessary. A high-precision positioning system with good dynamic response must incorporate a position sensor and a controller.

9 Electrodynamic immersion-coil actuator

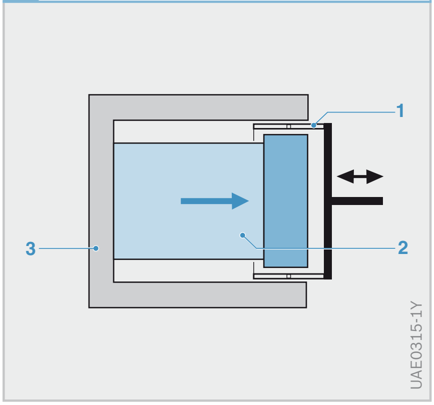


Fig. 9
1 Immersion coil
2 Permanent magnet
3 Magnetic yoke

10 Electrodynamic short-stroke linear motor

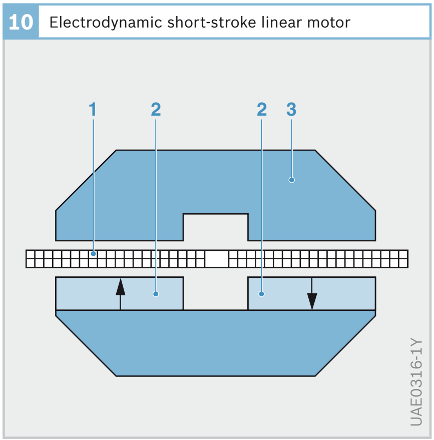


Figure 10
1 Coil
2 Permanent magnet
3 Magnetic yoke

11 Electrodynamic rotary actuator

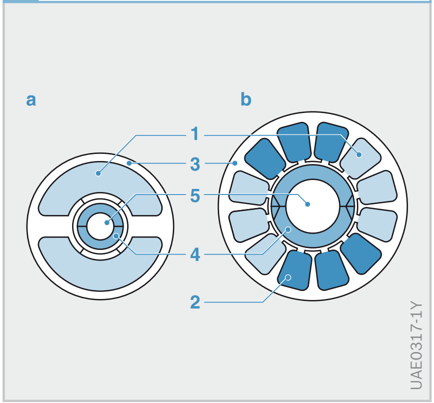


Fig. 11
a Single-winding rotary actuator
b Dual-winding rotary actuator

1 Coil 1
2 Coil 2
3 Stator
4 Permanent magnet
5 Shaft

12 Electrodynamic rotary actuator (characteristic curves)

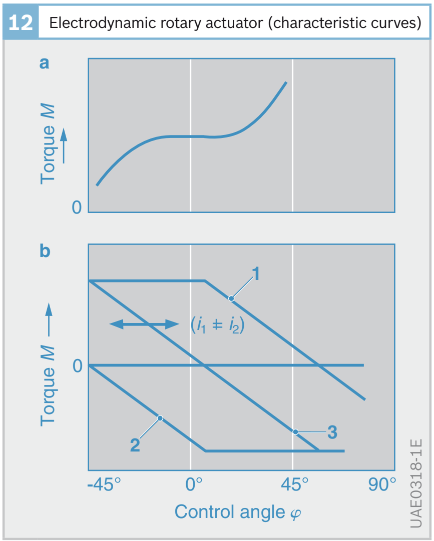


Fig. 12
a Single-winding rotary actuator
b Dual-winding rotary actuator

1 Coil 1
2 Coil 2
3 Coils 1+2

13 Operating points (A) of a linear solenoid

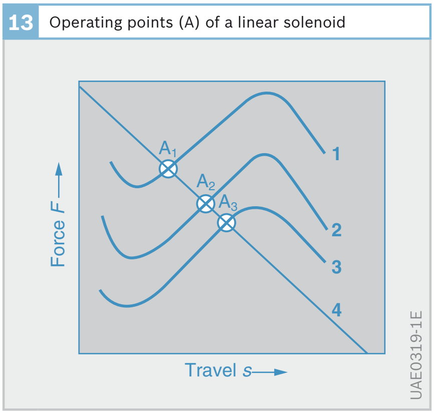


Fig. 13
1, 2, 3 Characteristic curves for various currents
4 Characteristic curve of a return spring

Fluid-mechanical actuators

Hydraulic and pneumatic actuators utilize similar principles for the conversion and regulation of energy. Table 1 shows the differences in characteristics and applications.

In most applications, fluid-mechanical actuator drives are in the form of hydrostatic energy converters. These operate according to the displacement principle, converting the pressure energy of the fluid medium into mechanical work and vice versa (Fig. 14).

In contrast, hydrodynamic transformers operate by converting flow energy (kinetic energy of the moving fluid) into mechanical work (example: hydrodynamic clutch).

Losses during energy conversion stem from leakage and friction. Fluid-thermal losses are caused by flow resistance, in which throttle action transforms the hydraulic energy into heat. A portion of this heat is dissipated into the environment, and some of it is absorbed and carried away by the fluid medium:

$$Q_{\text{heat}} = Q_1 \cdot p_1 - Q_2 \cdot p_2$$

With incompressible fluids:

$$Q_{\text{heat}} = Q_1 \cdot (p_1 - p_2)$$

1 Comparison of hydraulic and pneumatic actuators

	Hydraulic actuators	**Pneumatic actuators**
Medium	– Fluid, mainly oil – Supplied from tank, oil sump – Virtually incompressible – Self-lubricating – Viscosity highly temperature-dependent	– Gas, mainly air – Supplied from ambient air – Compressible – Additional lubrication necessary – Viscosity changes practically irrelevant
Pressure section	– To approx. 30 MPa (200 MPa for diesel-fuel injectors)	– To approx. 1 MPa or greater (approx. 0.05 MPa for vacuum actuators)
Line connections	– Supply and return connection (possible leakage connection)	– Pressure connection only, return directly to environment
Applications	– Positioning applications with high load rigidity, demanding requirements for synchronization and positioning precision in closed-loop control system	– Actuators with low power requirement, positioning by mechanical stops, in open control loop

Table 1

The flow develops into turbulence at restrictions. The flow rate of the fluid is then largely independent of viscosity. On the other hand, viscosity does play a role in the case of laminar flow in narrow pipes and apertures.

Fluid-mechanical amplifiers control the conversion of energy from fluid to mechanical state. The regulating mechanism must be designed for control with only a very small proportion of the energy flow required for the ultimate positioning operation.

Switching valves open and close the orifice governing the flow to and from a fluid-mechanical energy converter (Fig. 15). Provided that the control-element opens sufficiently, the throttling losses remain negligible. Pulse-width-modulated opening and closing can be applied to achieve quasi-continuous control of the fluid-mechanical energy conversion process with virtually no losses. In practice, however, pressure fluctuations and mechanical contact between the valve elements result in undesirable vibration and noise.

Electrical machines

Electrical machines are used to convert electrical and mechanical energy. An electric motor converts electrical energy into mechanical energy, and an alternator converts energy in the opposite direction. Electrical machines (Fig. 16) consist of a stationary component (the stator) and a rotating component (the rotor or armature). There are special designs which depart from this configuration, such as linear machines which produce linear motion.

Permanent magnets or several coils (windings) are used to produce magnetic fields in the stator and rotor. This causes torque to develop between the two machine components. Electrical machines have iron stators and rotors in order to control the magnetic fields. As the magnetic fluxes change over time, stators and rotors must consist of stacks of individual laminations which are insulated with respect to one another (to minimize eddy-current losses).

The spatial arrangement of the coils and the type of current used (direct current, alternating current, or three-phase current) permit a number of different electrical machine designs. They differ from one another in the way they operate, and therefore have different applications.

14 Fluid-mechanical actuators

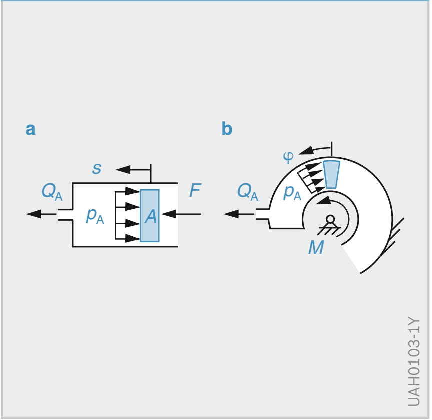


Fig. 14

a Linear actuator

$F = p_A \cdot A$

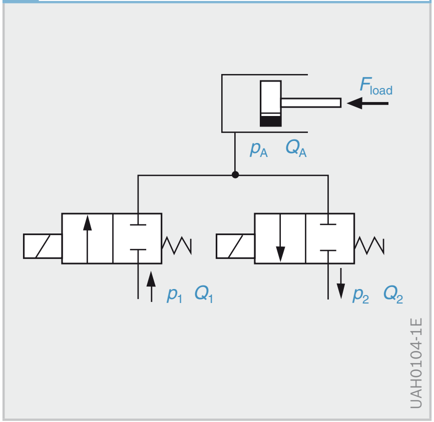
$s = Q_A / A$

b Rotary actuator

$M = (p_A \cdot V_{th}) / 2\pi$

$\varphi = (Q_A / V_{th}) \cdot 2\pi$

15 Energy regulation with 2/2-way switching valves



Direct-current machines

The stator of a direct-current machine contains salient poles which are magnetized by the direct-current excitation windings. In the rotor (here also called the armature), the coils are distributed among slots in the laminated iron core and connected to a commutator. Carbon brushes in the stator housing wipe against the commutator as it rotates, thereby transferring direct current to the armature coils. The rotary motion of the commutator causes a reversal in the direction of current flow in the coils. The different rotational speed vs. torque characteristics result from the method selected for connecting the excitation winding and armature.

Series connection (series characteristics, Fig. 17)

- Clear relationship between speed and load
- High starting torque
- Unacceptably high speed possible at the moment of load reduction, requiring therefore a rigid connection with the load
- Torque reversal (change in direction of rotation) caused by a change in the current direction in the armature or excitation winding
- Application, e.g. as vehicle drive motor or starter for internal-combustion engines

Parallel connection (shunt characteristic, Fig. 18)

- Speed varies only slightly with load
- Change in direction of rotation caused by a change in the current direction in the armature or excitation winding
- Application, e.g. as drive motor for machine tools or direct-current generators

16 Layout of an electrical machine

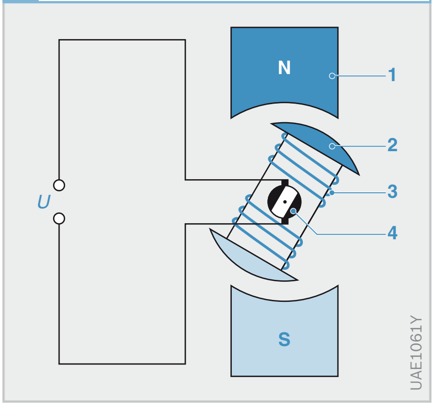
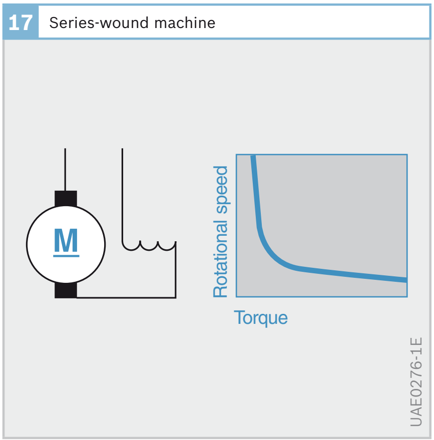


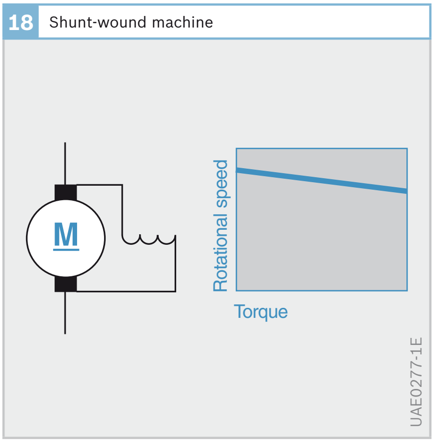
Fig. 16
1 Stator
2 Rotor
3 Rotor coil
4 Commutator

Stator field generated by permanent magnet or electromagnet

17 Series-wound machine



18 Shunt-wound machine



A shunt characteristic can also be obtained by using a separate power supply for the excitation winding (external excitation) or by using permanent-magnet excitation in the stator.

Applications for permanent-field motors in motor vehicles: starter, windshield wiper, and low-power motors for various drives.

If the motor incorporates both series and shunt excitation windings (compound-wound motor), intermediate levels in the rotational speed/torque characteristic can be obtained.

Application: e.g. large starters.

All direct-current machines are easily capable of speed control over a wide range. If the machine incorporates a static converter which allows adjustment of the armature voltage, the torque and therefore the rotational speed are infinitely variable. The rotational speed can be further increased by reducing the excitation current (field weakening) when the rated armature voltage is reached. A disadvantage of direct-current machines is carbon-brush and commutator wear which makes regular maintenance necessary.

Three-phase machines

A three-phase winding is distributed among the stator slots in a three-phase machine. The three phases of current produce a rotating magnetic field. The speed n_0 (in rpm) of this rotating field is calculated as follows:

$$n_0 = 60 \cdot f / p$$

f = frequency (in Hz)
p = number of pole pairs

Three-phase machines are either synchronous or asynchronous, depending on rotor design.

Asynchronous machines

The laminated rotor contains either a three-phase winding, as in the stator, or a rod winding. The three-phase winding is connected to sliprings which are short-circuited either directly or via series resistors (Fig. 19). In the case of the rod winding, the bars are connected to one another by two short-circuiting rings (squirrel-cage rotor). As long as the rotational speed of the rotor deviates from n_0, the rotating stator field induces current in the rotor windings, thereby generating torque. Deviation of the rotational speed of the rotor n from n_0 is termed slip s:
$s = (n_0 - n) / n_0$

Continuous-running operation is only economical in the vicinity of n_0 because losses increase as slip increases (nominal slip ≤ 5%). In this range the asynchronous machine has a shunt characteristic. The machine operates as a motor when $n < n_0$, and as an alternator when $n > n_0$. The direction of rotation is changed by reversing two of the phases.

The asynchronous machine is the most frequently used electric motor in the field of drive engineering. With a squirrel-cage rotor it is easy to operate, and requires little maintenance.

19 Three-phase asynchronous motor with squirrel-cage rotor

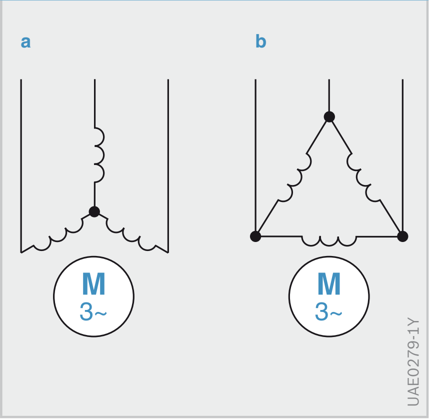


Fig. 19
a Stator winding, star-connected
b Stator winding, delta-connected

2 Examples of rotating-field speeds

Table 2

No. of poles (2 p)	**Frequency**		
	50 Hz	**150 Hz**	**200 Hz**
	Rotating-field speed in rpm		
2	3,000	9,000	12,000
4	1,500	4,500	6,000
6	1,000	3,000	4,000
8	750	2,250	3,000
10	600	1,800	2,400
12	500	1,500	2,000

Synchronous machines

In the rotor (here, also called the pole wheel), the poles are magnetized by direct-current coils. The excitation current is usually transferred via two sliprings to the rotor. The pole wheel can be made of solid steel, because the magnetic flux remains constant over time. Constant torque is generated as long as the rotor rotates at a speed of n_0. At other speeds, the torque fluctuates periodically between a positive and a negative maximum value, and excessively high current is produced. For this reason, a synchronous machine is not self-starting. The synchronous machine also differs from the asynchronous machine in that the reactive power absorption and generation are adjustable.

The synchronous machine is most frequently used as a generator of energy supply in electric power plants. Synchronous motors are used in cases where constant motor speed based on constant line frequency is desired, or where a reactive power demand exists. The automotive three-phase alternator is a special type of synchronous machine.

The rotational speed of all three-phase machines is determined by the stator frequency. Such machines can operate over a wide range of speeds if used in conjunction with static converters which vary the frequency.

EC motors

The “electronically commutated direct-current” or “EC” motor is becoming increasingly popular (Fig. 21). It is essentially a permanent-magnet synchronous machine, and is brushless. The EC motor is equipped with a rotor-position sensor, and is connected to the DC power source through its control and power electronics. The electronic transfer circuit switches the current in the stator winding according to rotor position – the magnets which induce the excitation current are attached to the rotor – to provide the interdependence between rotational speed and torque which is normally associated with a separately excited direct-current machine. The respective magnetic functions of the stator and rotor are the opposite of what they would be in a classical direct-current machine.

20 Star-connected three-phase synchronous generator

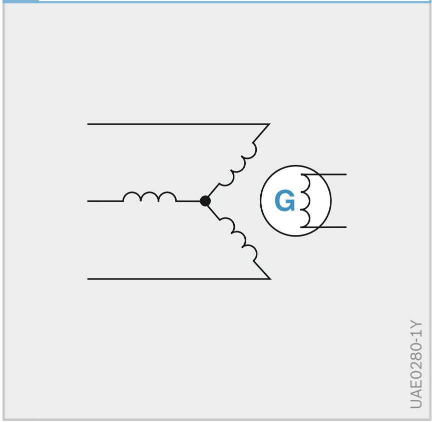


Fig. 20
Slip-ring rotor with excitation winding

21 EC motor

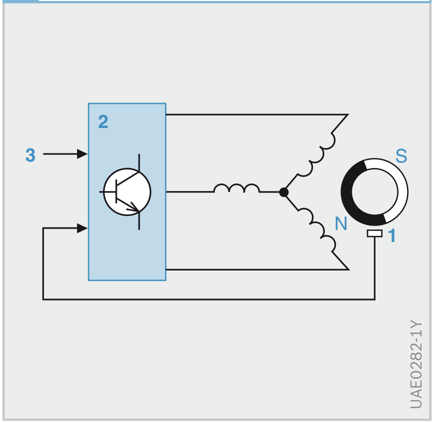


Fig. 21

1 Electrical machine with rotor-position sensor
2 Control and power electronics
3 Input

The EC motor's potential applications are a result of the advantages which this drive principle provides: commutator and carbon brushes are replaced by electronics, dispensing with both brush noise and wear. EC motors are maintenance-free (long service life) and can be constructed to meet high degrees of protection. The electronic control feature makes it easy for drive units with EC motors to incorporate auxiliary functions such as infinitely variable speed governing, direction reversal, soft starts, and antilock protection.

The main areas of automotive application are in the HVAC (Heating/Ventilation/Air-Conditioning) sectors, and for pumps and servo units. In the area of production machinery, EC motors are chiefly employed as precision drive units for feed-control in machine tools. Here the decisive advantages are freedom from maintenance, favorable dynamic properties and consistent torque output with minimal ripple.

Single-phase alternating-current machines

Universal motors

The direct-current series-wound motor can be operated on alternating current if a laminated rather than a solid iron stator is used. It is then called a universal motor.

When operated on alternating current, a torque component at twice the frequency of the current is superposed on the constant torque component.

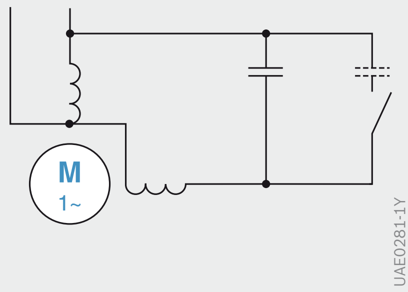
Single-phase asynchronous motors with squirrel-cage rotor

The simplest design of a single-phase asynchronous motor is a three-phase asynchronous machine in which alternating current is supplied to only two stator phases. Although its operation remains largely the same, the power and the maximum torque are reduced. In addition, the single-phase asynchronous machine is not self-starting.

Machines which are intended only for single-phase operation have only a single-phase main winding in the stator, as well as auxiliary starting circuits. The stator also contains an auxiliary winding connected in parallel with the main winding for this purpose. The necessary phase displacement of the auxiliary winding current can be achieved through increased winding resistance (low breakaway torque) or by means of a capacitor connected in series with the auxiliary winding (somewhat greater breakaway torque).

The auxiliary winding is switched off after the motor starts. The direction of rotation of the motor is changed by reversing the two auxiliary or main winding connections. A motor which has a capacitor in series with the auxiliary winding is called a capacitor motor. Capacitor motors with a starting and running capacitor also operate continuously with capacitor and auxiliary winding. Optimum operation for a specific operating point can be achieved by correct selection of capacitor. An additional capacitor is often used in order to increase the starting torque; this capacitor is then disconnected after the motor starts.

22 Two-value capacitor motor



Duty-type ratings for electrical machines

(VDE 0530)

S1: Continuous-running duty

Operation under constant load (rated output) of sufficient duration to reach the thermal steady-state condition.

S2: Short-time-duty type

Operation under constant load is so brief that the thermal steady-state condition is not reached. The rest period is so long that the machine is able to cool down to the temperature of the coolant.

Recommended short-time-duty types: 10, 30, 60 and 90 min.

S3 to S5: Intermittent-periodic duty

Continuous alternating sequence of load and idle periods. The thermal steady-state condition is not reached during the load period or during the cooling period of one duty cycle.

- S3 intermittent-periodic duty without influence of starting on temperature
- S4 intermittent-periodic duty with influence of starting on temperature
- S5 intermittent-periodic duty with influence of starting and braking on temperature

S6: Continuous operation with intermittent loading

Operation with intermittent loading. Continuous alternating sequence of load periods and no-load periods, otherwise as S3.

S7: Uninterrupted duty

Operation with starting and braking.

S8: Uninterrupted duty

Operation with pole-changing.
For S3 and S6, the duty cycle time is 10 mins unless otherwise agreed; and recommended values for relative switch-on duration are 15, 25, 40 and 60 %. For S2, S3 and S6, the operating time or the duty cycle time and the switch-on duration are to be specified after the rating; the duty cycle time is only to be specified if it differs from 10 mins. Example: S2 – 60 mins, S3 – 25 %.

Relative switch-on duration

The relative switch-on duration is the ratio of the loading period, including starting and braking, to the cycle time.

Winding temperature

The mean temperature t_2 of the windings of an electrical machine can be determined by measuring the resistance (R_2) and referring it to an initial resistance R_1 at a temperature t_1:

$$t_2 = \frac{R_2 - R_1}{R_1} (\tau + t_1) + t_1$$

where

$$\tau = \frac{1}{\alpha} - 20 \text{ K}$$

α = temperature coefficient