2 Basics of electromechanical energy converters / electrical drives

Driving means the movement of masses. **Mechanical Energy** is required to initiate or maintain this movement. The required energy can be obtained from the electrical supply network via **electromechanical energy converters** (electrical machines). Compared to other solutions (combustion engine, hydraulic or pneumatic actuators), electrical drives have following advantages:

- electrical energy is generally available **at all locations and times**. Storage is not generally required (except for mobile applications);
- **high efficiency** and favorable primary energy yield;
- **emission-free** and **low-noise** operation;
- **Energy recovery** possible during braking;
- electrical **energy flows** can be controlled **fast** and with **low loss**;
- electromechanical energy converters are available in a **wide power range** (from a few mW to approx. 1.5 GW) and **economically** viable;
- electrical machines can be practically **maintenance-free**;
- very **uniform** force and torque curves.

For the sake of completeness, the two main disadvantages of electric drives should also be mentioned: they have a **lower force density** ($\mathrm{N/kg}$) than pneumatic or hydraulic energy converters with at the same time **higher acquisition costs**. In robotic applications, however, the advantages of electromechanical converters clearly outweigh these disadvantages, so that electric drives are mainly found in robot systems. Hydraulic actuators are only used in industrial robots with high force requirements. Pneumatic actuators are also used in „Soft-Robotics“ and in grippers.

In robots, electrical machines typically convert electrical energy into mechanical energy (**motor operation**). In principle, however, the reversal is also possible with every electrical machine. Then the electrical machine works as a **generator** and converts mechanical energy into electrical energy, for example in power plants. The mechanical energy is either directly available in this form (e.g. in wind power or hydroelectric power plants) or is provided via a turbine with thermal energy as primary source. The electrical drives in roboters also work as generator in the braking process.

2.1 Electrodynamic principle

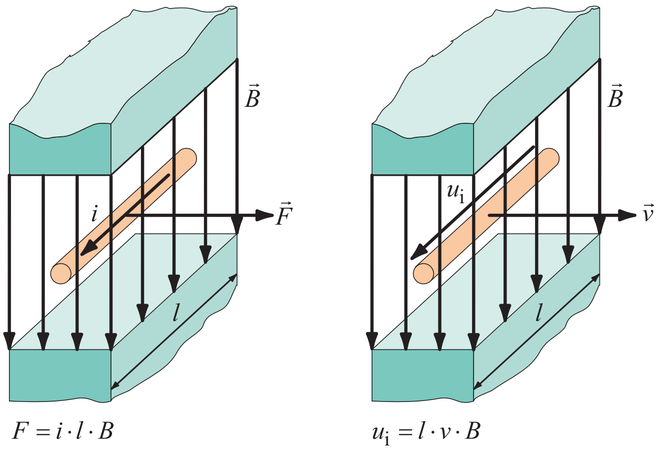


Figure 2.1: Lorentz force and induced voltage

The energy conversion in electrical machines can be explained with two physical principles:

1. **Lorentz force**: a conductor carrying a current inside an external magnetic field experiments a force proportional to the value of the current, the external magnetic field and the angle between current and magnetic field (figure 2.1 left).

2. **induced voltage by movement**: in a moving conductor placed in an external magnetic field, a voltage is induced by the change of magnetic flux seen by the conductor due to the movement (figure 2.1 right)

If the conductor, under the influence of the force F, performs a movement with the speed v in the same direction, mechanical work is done. If the current direction i is perpendicular to the magnetic flux density B, the force must also be perpendicular to these two quantities. The mechanical work can be specified as follows:

$$P_{\text{mech}} = F \cdot v = (i \cdot l \cdot B) \cdot \frac{u_{\text{i}}}{l \cdot B} = u_{\text{i}} \cdot i = P_{\text{el}} \tag{2.1}$$

The mechanical power output is therefore equal to the electrical power fed in. So there is a flow of power or energy from the electrical to the mechanical side. This is called **Motor operation**. The magnetic field B does not participate in the energy turnover, but only has a mediating effect, since no energy is drawn from the magnetic field.

Electrical machines are seldom built for linear movements (linear drives, e.g. for magnetic levitation vehicles), so the velocity vector in the above illustration usually corresponds to the tangential velocity of a circular movement. If the distance from the conductor to the center of rotation is equal to $d/2$, the mechanical power can also be expressed in terms of the torque M and the speed n of the shaft:

$$P_{\text{mech}} = M \cdot 2\pi n = \left(F \cdot \frac{d}{2}\right) \cdot \left(\frac{v}{d/2}\right) = F \cdot v = u_{\text{i}} \cdot i = P_{\text{el}} \tag{2.2}$$

2.2 Basic configuration and types of electrical machines

Electrical machines are mainly designed as rotating machines, consisting of a stationary part, the stator or stator, and a rotatably mounted part, the rotor (figure 2.2). There is an air gap between the stator and the rotor, which is usually only needed mechanically, and from an electrical point of view should be as small as possible.

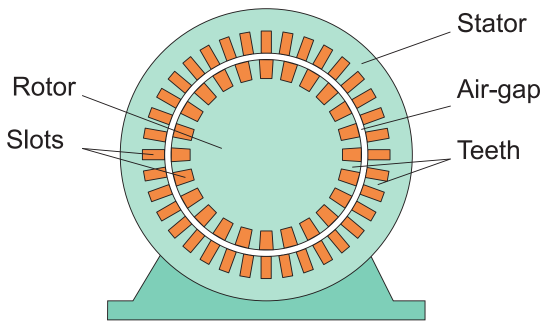


Figure 2.2: Basic configuration of electrical machines

Both the stator and the rotor can have a current-carrying winding. These windings are constructed differently depending on the type of the electrical machine but always generate a magnetic field. A constant excitation field can also be generated by permanent magnets instead of a winding. To direct and strengthen the magnetic field, the windings or permanent magnets are embedded in a structure of ferromagnetic material (iron or electrical steel).

The stator and rotor magnetic fields interact and can generate torque, if the relative angle between both of them is suitable. Rotating electrical machines are optimally designed with regard to their magnetic utilization if the excitation field lines are all perpendicular to the direction of the current. Then, with a winding distributed over several slots, the forces all act in one direction.

The distribution of the excitation or stator field can be described using a vector $\vec{B}_{\text{s}}$ (describes the size and main direction of the excitation or stator flux density distribution). However, the current distribution of the rotor or armature also generates a magnetic field, which can also be described with a vector $\vec{B}_{\text{r}}$. Its direction is linked to the currents by a right-hand helix rule.

If the two vectors $\vec{B}_{\text{s}}$ and $\vec{B}_{\text{r}}$ are perpendicular to each other, there is obviously a maximum torque. However, if the two vectors are in the same direction, the torque generated is zero. If the angle between the two vectors is denoted by γ and counted from the armature field vector $\vec{B}_{\text{r}}$ to the excitation field vector $\vec{B}_{\text{s}}$, the torque acting

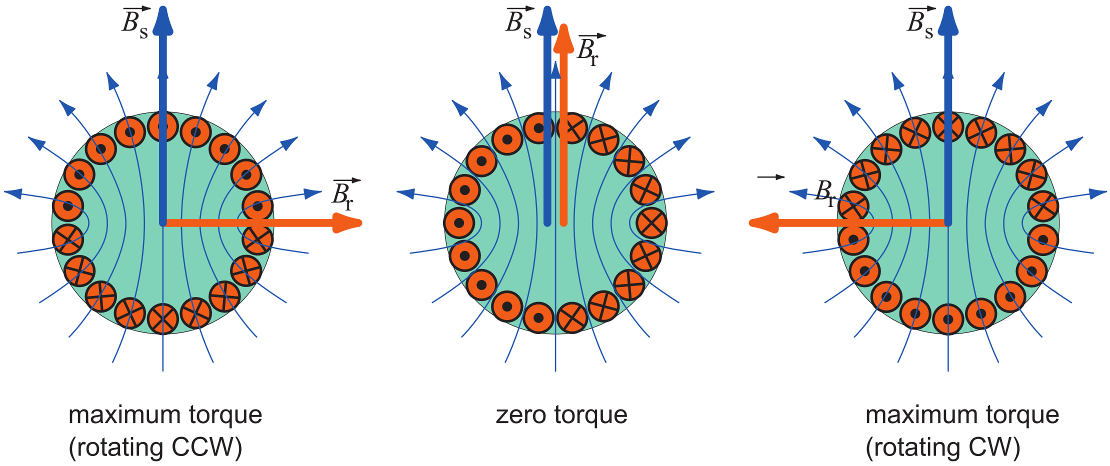


Figure 2.3: Torque depending on the relative position of stator (excitation) and rotor (armature) field

on the rotor can be specified:

$$M \sim B_s \cdot B_r \cdot \sin\gamma \qquad B_r \sim i$$

On this basis, the main types of rotating electrical machines can already be explained. There are basically two different designs: Machines with a fixed magnetic field (direct current machines) and machines with a revolving magnetic field (rotating field machines).

DC Machine

In the DC machine, a stationary magnetic field is generated by DC-excited coils or by permanent magnets in the stator. In the rotor a DC-excited coil is needed. However, it must be ensured that the current directions under the excitation (stator) poles are maintained even when the rotor rotates. For this reason, the current direction in a conductor must be reversed when passing the so-called neutral zone between the excitation poles. In the direct current machine, the currents are switched with the so-called **commutator** and the **brushes** that slide on it.

With this configuration, the magnetic field of the excitationn (stator) and of the armature (rotor) are always perpendicular resulting in maximum torque. The current in the excitation coil is constant (frequency $f_S = 0$); however, the currents

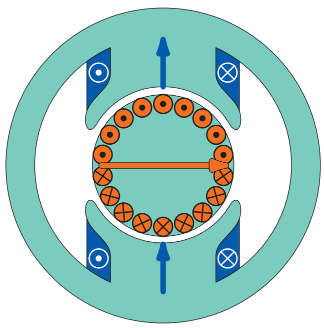


Figure 2.4: Operating principle DC machine

in the individual armature coils are rectangular alternating currents (frequency $f_\mathrm{R} \neq 0$).

Synchronous Machine

The stator winding can also generate a rotating stator field thanks to several stator coils with phase-shifted currents (stator frequency $f_\mathrm{S} \neq 0$). However, so that a constant torque can be achieved, the rotor field needs to rotate in phase with the stator field, the rotor field must follow the stator field with the same speed (Figure 2.5).

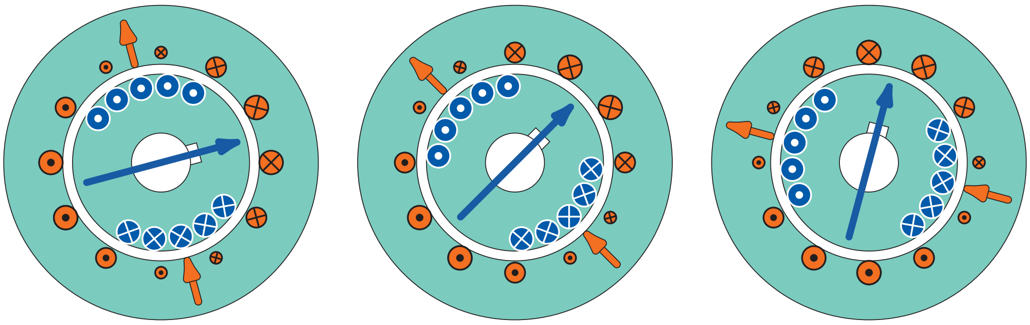


Figure 2.5: Functional principle synchronous machine

If the rotor has a winding supplied with a constant direct current (rotor frequency $f_\mathrm{R} = 0$) or has a permanent magnetic excitation, the rotor must rotate mechanically at the same speed as the rotating field of the stator. This corresponds to the operating principle of the synchronous machine, the speed of which is then fixed by the stator frequency.

Asynchronous Machine

Of course, it is also possible that not only the stator has a three-phase winding with time-varying currents (stator frequency $f_\mathrm{S} \neq 0$), but also that the rotor has a three-phase winding with time-varying currents (Figure 2.6), i.e. with rotor frequency $f_\mathrm{R} \neq 0$.

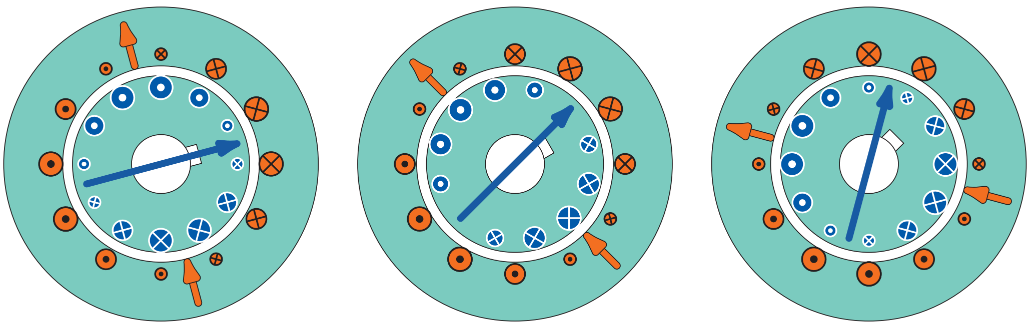


Figure 2.6: Functional principle of asynchronous machines

If the rotor field rotates at a speed n_R relative to the rotor coordinates and the stator field rotates at a speed n_S relative to the stator coordinates, the rotor itself must rotate with the difference $n_{\mathrm{mech}} = n_{\mathrm{S}} - n_{\mathrm{R}}$ so that the angle between stator field and rotor field can remain constant and so a constant torque can be achieved.

In the case of the asynchronous machine, a short-circuited winding without any possibility of connection to the outside is used often in the rotor due to its robustness and easy manufacturing. This kind of rotor is known due to its form as squirrel cage rotor. If the rotor is stationary, voltages and currents are induced in the rotor coils by the change of the stator rotating field. The two rotating fields generate a torque that accelerates the rotor. This acceleration continues until the torque generated by the motor (i.e. the „internal torque“ M_{i}) is exactly the same as the sum of the torque M_{Load} of the load and the frictional torque M_{Fric} of the motor itself.

However, if the asynchronous machine is completely unloaded (not even by a friction torque), acceleration takes place until the rotor rotates at the same speed as the stator field. At this speed (idle speed or synchronous speed n_0), no more voltages or currents can be induced in the rotor, since the stator only generates a time-constant field „seen“ from the rotor. Because the rotor field is then missing, the asynchronous machine cannot generate any torque, so that it has to slow down again under load (subsynchronous operation).

If, on the other hand, it is actively driven, it naturally has to become faster. In this oversynchronous mode, the asynchronous machine is in generator mode.

2.3 Power balance

As in any technical system, electromechanical energy conversion is of course associated with losses. Currents flowing in an electrical conductor cause the conductor to heat up. The Joule heat losses P_{Cu} associated with heating are irreversibly lost during energy conversion. In addition, the magnetic dipoles in a ferromagnetic material must be constantly realigned with a changing magnetic field. This leads to additional heating of the machine and is known as iron losses P_{Fe}. In addition, friction losses P_{Fric} (bearing, fan friction) practically always occur.

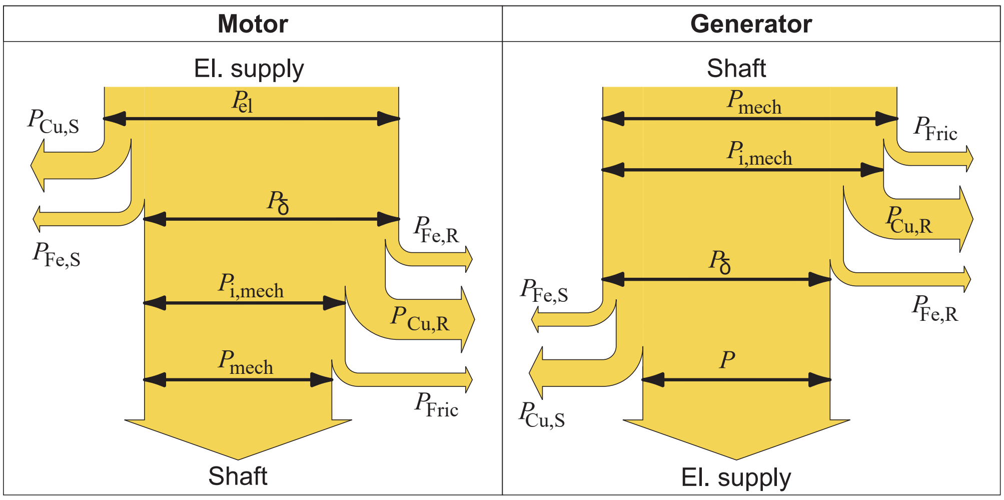


Figure 2.7: General power flow in an electrical machine

The air-gap power P_{δ} is the active power P_{el} taken from the mains minus the losses in the stator winding or the stator iron losses. This power is converted in the air gap of the electrical machine. The mechanical power output is determined from the product of the internal torque and the mechanical angular velocity of the rotor minus the friction losses:

$$P_{\text{mech}} = P_{\text{i,mech}} - P_{\text{Fric}} \tag{2.3}$$

$$M \cdot 2\pi n = M_{\text{i}} \cdot 2\pi n - M_{\text{Fric}} \cdot 2\pi n$$

$$\text{bzw.} \qquad M = M_{\text{i}} - M_{\text{Fric}} \tag{2.4}$$

Both diagrams in Figure 2.7 assume an exchange of electrical power exclusively via the stator terminals. An electrical machine can of course also be (additionally) fed via the rotor winding.

2.4 Design variants and relevance for robotics

All electrical machines can be classified according to the basic operating principles seen previously. However, every working principle leads to a whole series of technical variants, some of which are presented in Figure 2.8.

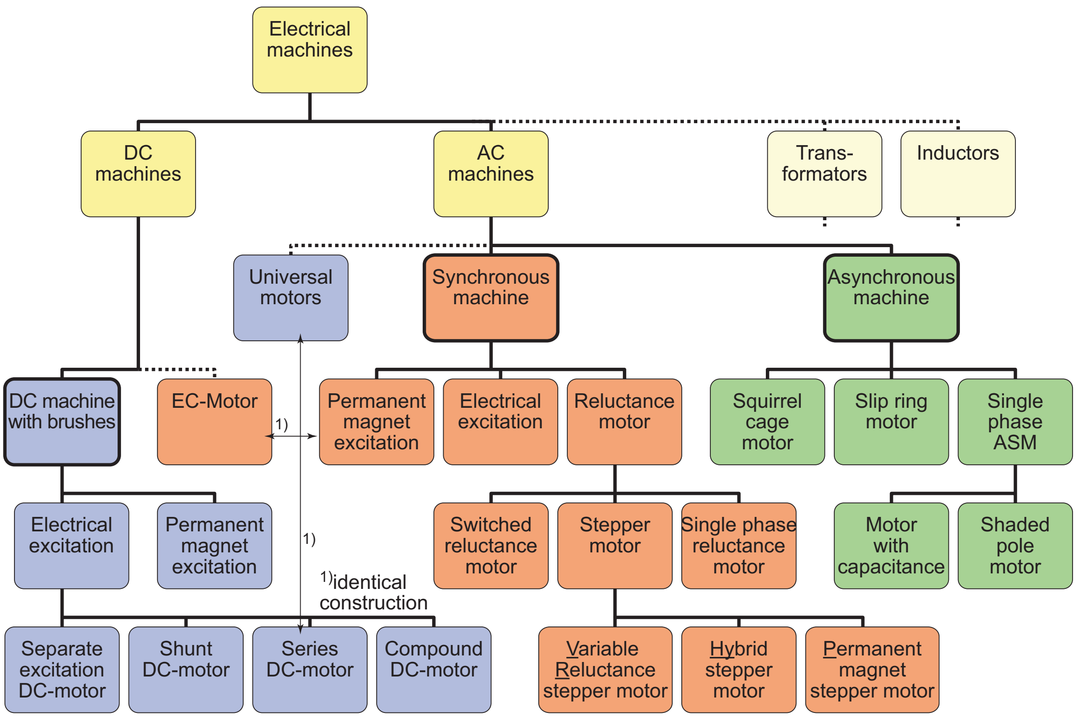


Figure 2.8: Design variants of electrical machines

Each sub-variant result in different technical properties, which are summarized in the illustrations 2.9, 2.10 and 2.11. These different properties justify the use of the different concepts for the different application of electrical machines.

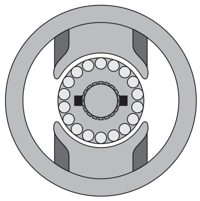
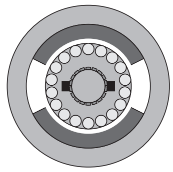
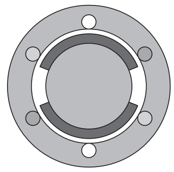
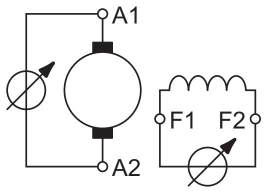
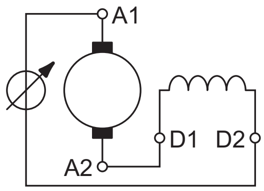
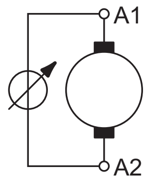
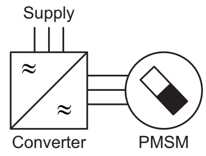
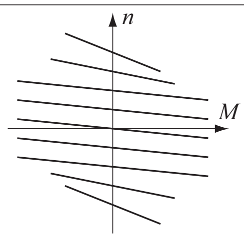
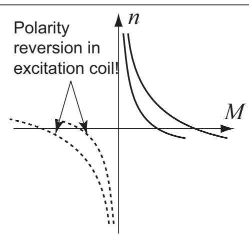
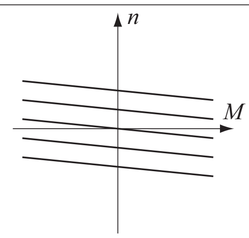
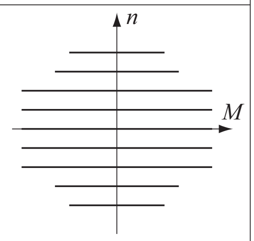
	DC machine Separate excited DC motor	 Series DC motor	 Perm. excited DC motor	Synchronous machine Permanent. excited SM
Construction				
Connection				
M-n characteristics	Parameter: U_A, U_f	Parameter: U_{Af}	Parameter: U_A	Parameter: f_S, (U_S)
Power balance	$P_{V,Cu,S} = R_f I_f^2$ $P_{V,Fe,S} = 0$ $P_{V,Cu,R} = R_A I_A^2$ $P_{V,Fe,R} > 0$ $P_\delta = U_i \cdot I_A$ $P_{i,mech} = P_\delta$	$P_{V,Cu,S} = R_f I_f^2$ $P_{V,Fe,S} = 0$ $P_{V,Cu,R} = R_A I_A^2$ $P_{V,Fe,R} > 0$ $P_\delta = U_i \cdot I_A$ $P_{i,mech} = P_\delta$	$P_{V,Cu,S} = 0$ $P_{V,Fe,S} = 0$ $P_{V,Cu,R} = R_A I_A^2$ $P_{V,Fe,R} > 0$ $P_\delta = U_i \cdot I_A$ $P_{i,mech} = P_\delta$	$P_{V,Cu,S} = 3 R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = 0$ $P_{V,Fe,R} = 0$ $P_\delta = 3\, U_P\, I_S \cos\psi$ $P_{i,mech} = P_\delta$
Regulation and control	Easy controllable if variable voltages are available (power electronics). Torque can be controlled via armature current, speed can be controlled via armature voltage. Excitation voltage can be reduced to increase speed (field weakening).	Practically only speed regulation (no control). Very strongly load-dependent speed. Simple/cost-effective control electronics possible on single-phase AC mains (universal motor).	Easy controllable if variable voltages are available (power electronics). Torque can be controlled via armature current, speed can be controlled via armature voltage. Field weakening not possible.	Can be controlled easily if variable frequency or voltage is available (converter). The torque can be controlled via the current, the speed via the frequency. Limited possibility of field weakening ("active" field weakening).
Main applications	Was widely used as a servo motor in many applications (machine tools, manufacturing technology, paper machines, etc.). Today strongly declining market shares, used still in market niches.	Starter motor in motor vehicles, speed-controlled universal motor in AC-operated power tools, kitchen appliances.	Very high volume in automotive equipment (windshield wipers, window regulators, etc.), battery-powered power tools, some still used as servo motors.	Has practically replaced the DC machine as a servo motor, used in automotive equipment from approx. 300 W instead of DC motors as an EC motor, drive for electric/hybrid cars, propeller drive for cruise ships and ferries.

Figure 2.9: Technical characteristics of electrical machine sub-variants (1/3)

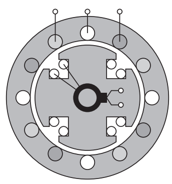
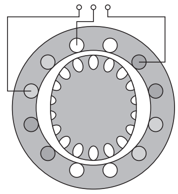
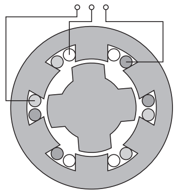
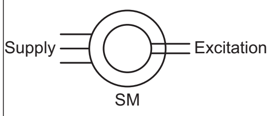
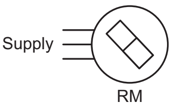
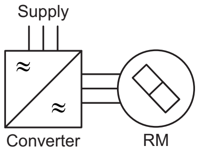
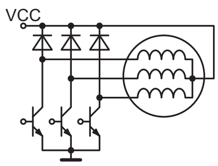
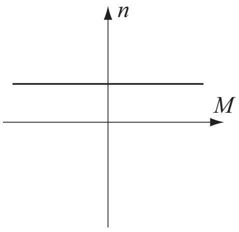
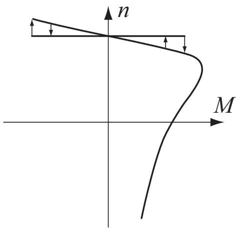
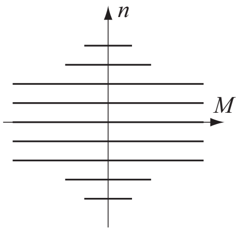
	Electrical excited SM	Synchronous machine Reluctance machine		Stepper motor
Construction				
Connection				
M-n characteristics			Parameter: f_S, (U_S)	Maximum speed is limited by the moving mass. If the step frequency (or the load torque) is too high, the stepper motor gets out of step.
Power balance	$P_{V,Cu,S} = 3R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = R_f I_f^2$ $P_{V,Fe,R} = 0$ $P_\delta = 3\,U_P\,I_S \cos$ $P_{i,mech} = P_\delta$	$P_{V,Cu,S} = 3R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = 0$ $P_{V,Fe,R} = 0$ $P_\delta = \frac{3}{2}\left(X_d - X_q\right) I_S^2 \sin 2\psi$ $P_{i,mech} = P_\delta$		Losses and efficiency of stepper motors are not of prime importance and cannot be specified in general terms due to the large number of different designs.
Regulation and control	Speed is constant on the network. Via the excitation current, the reactive power can be controlled for inductive reactive power compensation in the mains.	Motor runs up asynchronously on the mains and "falls" into synchronism. If the reluctance motor is not too heavily loaded, the speed remains constant or strictly proportional to the mains frequency.	As with the PMSM, the motor runs synchronously with the stator rotating field. If the reluctance motor is not loaded too much, the speed remains constant or strictly proportional to the supply frequency.	Stepper motors are only regulated not controlled. Phases are fed cyclically with the step frequency. Pulse number and step number are identical, so that positioning drives without(!) position encoder are possible.
Main applications	Generator in power plants. Drives with outputs up to 40 MW: compressors for gas production, blowers for blast furnaces, etc.	Applications in the field of production and process engineering, when constant speed or synchronously running axes are required without having to control the speed.	Used in production and process engineering, often as group drive, i.e. several drives are fed from a common converter and thus run synchronously with each other. Field weakening only possible with power reduction.	Positioning drives of low power (up to a few watts), IT terminals (printers, scanners), clock (hand) drives, automotive equipment (e.g. mirror adjustment).

Figure 2.10: Technical characteristics of electrical machine sub-variants (2/3)

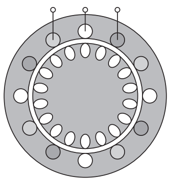
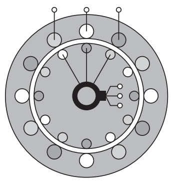
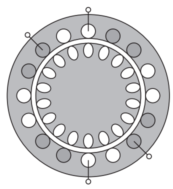
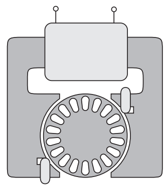
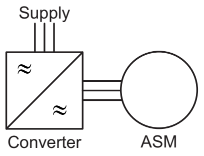
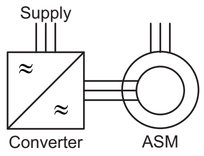
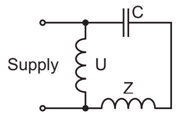
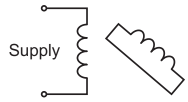
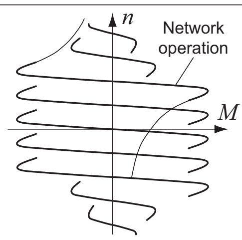
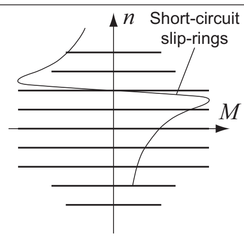
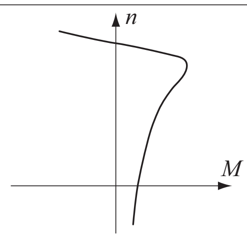
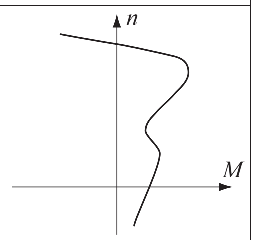
	Asynchronous machine (ASM)			
	Squirrel-cage ASM	Slip-ring ASM	Single-phase ASM	Shaded pole motor
Construction				
Connection				
M-n characteristics	 Parameter: f_S, (U_S)	 Parameter: f_R		
Power balance	$P_{V,Cu,S} = 3R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = \frac{1-n}{n_0} P_\delta$ $P_{V,Fe,R} \approx 0$ $P_\delta = 2\pi n_0 \cdot M_i$ $P_{i,mech} = 2\pi n \cdot M_i$	$P_{V,Cu,S} = 3R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = 3R_R I_R^2$ $P_{V,Fe,R} \approx 0$ $P_\delta = 2\pi n_0 \cdot M_i$ $P_{i,mech} = 2\pi n \cdot M_i$	Power losses cannot be specified in a standardized way. Winding resistances are not the same in both phases, rotating field is often elliptical.	Power losses cannot be specified in a standardized way. Relatively strong harmonics in the air gap field generate additional losses and strongly influence the operating behavior.
Regulation and control	Well controllable if variable frequency or voltage (converter) but less precise than SM. Field weakening possible with additional power reduction.	Good controllability if variable frequency or voltage (converter) is available. Speed is set via the rotor frequency.	Used only if no speed adjustment is required.	Used only if no speed adjustment is required.
Main applications	As the "workhorse" of the drive technology, it can be used in practically all areas with outputs from approx. 250 W to several 10 MW. Usually represents the most cost-effective solution.	Wind power generator. In the past, often used with external starting resistors on the slip rings as conveyor belt, cement mill or pump drives.	Low-power drive (usually up to a few 100 W) on a single-phase AC mains supply without the possibility of speed adjustment. Used in power tools, production and process engineering.	Simplest possible AC motor, very poor efficiency (about 10%), cheap to produce. Drive for small fans, pumps (e.g. lye pump washing machine), power up to some 10 W.

Figure 2.11: Technical characteristics of electrical machine sub-variants (3/3)

The following requirements are particularly important for the use as robot drives:

1. Simple but highly accurate position regulation or control
2. High dynamics, i.e. high maximum torque, low moment of inertia and small electrical time constant

Asynchronous motor position control is complex and prone to error due to rotor heating and saturation. This machine type is therefore not used in robot systems. The use of permanent magnets, both in the direct current machine and in the synchronous machine, offers improved dynamics in addition to other advantages. This results from a reduction in the electrical time constant and the moment of inertia. For this reason, electromechanical actuators for robot systems are almost exclusively permanent-magnet synchronous or DC motors. Stepper motors, a special type of synchronous motor that allows good position control without complex sensors, are often used for small systems.

An appendix containing relevant information for the selection of a suitable electric motor depending on the environment, type of load and much more will be published before the end of the course.

2.5 Comprehension questions

Q2-1: What are the main advantages and disadvantages of electric drives?

Q2-2: How does the conversion of electrical to mechanical power take place in an electrical machine?

Q2-3: Explain the three basic types of electrical machines.

Q2-4: What types of motors are used in robotics and why?