Principles of electromechanic energy conversion

Actuators - IRO6

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Advantages and disadvantages of electric drives

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Electrical drives move masses (mechanical energy)
using electrical energy (from the supply network) as input

Advantages of electric drives

- electrical energy available *location independent*
  ⇒ storage only required for mobile applications
- *high efficiency* and favorable primary energy yield;
- *emission-free* and *noiseless* operation;
- *energy recovery* possible during braking ⇒ Two-way operation motor ⇔ generator;
- electrical *energy flows* can be controlled *fast* and *with low-loss*;
- electrical drives 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*;
- highly *uniform* force and torque curves.

Disadvantages of electric drives:

- Lower force density than pneumatic and hydraulic drives
- Higher acquisition costs (but generally lower total cost of ownership)

Introduction - Actuators in robotics

Electric drives

Mostly used in robotic applications $\Rightarrow$ Focus on this course

Hydraulic drives

Niche application in industrial robots with high force density requirement

Pneumatic drives

Used in some soft-robotic applications and grippers

Electrodynamic Principle

Two phenomena as a basis for the energy conversion:

- **Lorentz force**: a conductor carrying a current inside an external magnetic field experiments a force.
- **Induced voltage by movement**: in a moving conductor placed in an external magnetic field, a voltage is induced.

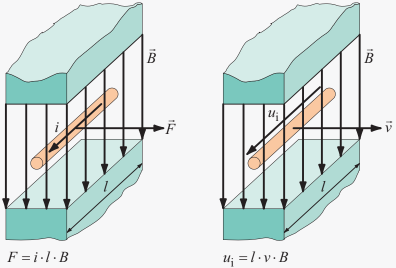

Figure Lorentz force and induced voltage

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

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

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Construction of rotating electrical machines

- Two parts: stator (also field excitation) and rotor (also armature)
- Structure: ferromagnetic material (iron, electrical steel)
- Winding: placed in slots

To maximize the power output:

- Field lines always perpendicular to the current direction
- with several coils:
  partial forces in the same direction
- fields can be described as vectors:
  - $\vec{B}_\mathrm{s}$: excitation or stator field
  - $\vec{B}_\mathrm{r}$: armature field or rotor field

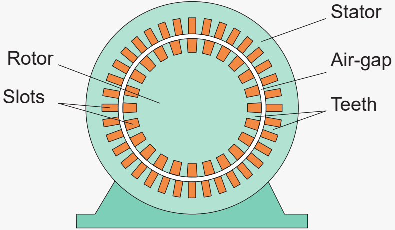

Figure Basic configuration of electrical machines

Optimal position between stator and rotor field

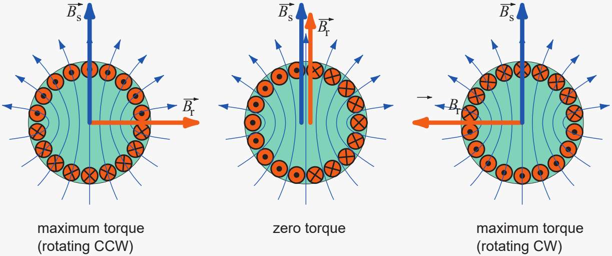

Figure Torque depending on the position of excitation and armature field

γ: angle between $\vec{B}_s$ and $\vec{B}_r$: $M \sim B_s \cdot B_r \cdot \sin\gamma$ $B_r \sim i$

Basic types of rotating electrical machines:

- Machines with a fixed magnetic field (DC machines)
- Machines with rotating magnetic field (3 phase machines)

DC machine

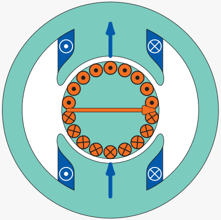

Figure Working principle DC machine

- $f_S = 0$
  - ⇒ Coil with direct current or permanent magnet in the stator
- $f_R \neq 0$
  - ⇒ Rotor coils are switched mechanically when passing the neutral zone
  - ⇒ brushes and commutator
  - ⇒ f_R depends on the speed

Synchronous machine

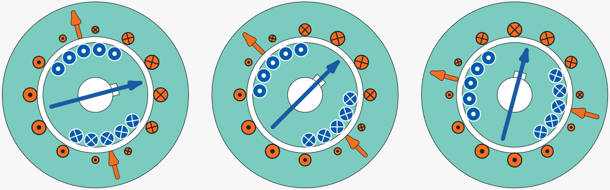

Figure Working principle synchronous machine

- $f_R = 0$
  - $\Rightarrow$ Coil with direct current or permanent magnet in rotor
- $f_S \neq 0$
  - $\Rightarrow$ **phase-shifted** currents are provided from the outside
  - $\Rightarrow$ Speed of the stator field n_0 results from f_S
  - $\Rightarrow$ Rotor speed = Speed of stator field,
    so that the angle between the stator and rotor field remains constant
    $\Rightarrow$ constant torque

Asynchronous machine

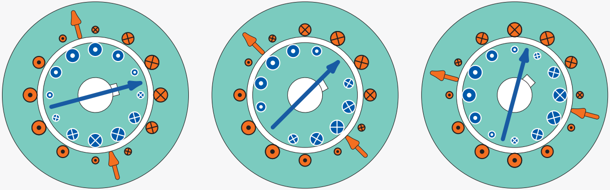

Figure Working principle of asynchronous machines

- $f_S \neq 0$
  - ⇒ **phase-shifted** currents provided from the outside (like the stator of a synchronous machines)
  - ⇒ Speed n_0 of stator field results from f_S
- $f_R \neq 0$
  - ⇒ **phase-shifted** currents **can** be provided from the outside
  - ⇒ Rotor field speed n_R (related to rotor coordinates) results from f_R
  - ⇒ mechanical speed $n = n_0 - n_R$,
    so that the angle between the stator and rotor field remains constant

Asynchronous machine with squirrel cage rotor

Construction

- Stator: 3-phase winding with frequency $f_s \Rightarrow$ Stator field with $\frac{f_s}{p}$
- Rotor: short-circuited polyphase winding

Three different cases (example for $p = 1$)

1. $n = 0$
   - Rotor coils see the stator field rotate with $f_s \Rightarrow$ induced voltage with frequency f_s.
   - Due to the short-circuit in rotor, current flows with the frequency f_s.
   - Rotor current generates rotor field rotating with f_s.
   - Interaction of stator and rotor field produces torque.
2. $0 < n < f_s$
   - Rotor coils see the stator field rotate with $f_s - n \Rightarrow$ induced voltage with frequency $f_s - n$.
   - Due to the short-circuit in rotor, current flows with the frequency $f_s - n$.
   - Rotor current generates rotor field rotating with $f_s - n$.
   - Interaction of stator and rotor field produces torque.
3. $n = f_s$
   - Rotor coils see a constant stator field ($f_s - n = 0$)

   $\Rightarrow$ no voltage is induced in the rotor, no rotor current and field, no torque.

Power balance

Transformation electrical energy ⟷ mechanical energy produces losses:

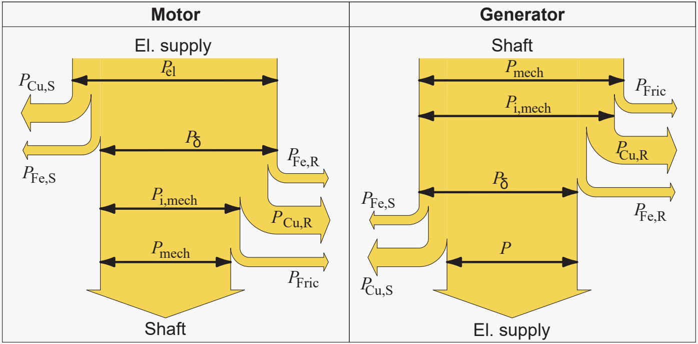

Figure Power flow in electrical machines

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Power losses

- Joule heat losses P_{Cu}
- iron losses P_{Fe}
- friction losses P_{Fric} (bearing, fan friction)
- active power consumed from the grid P_{Net}
- air-gap power $P_{\delta} = P_{\mathrm{Net}} \mp P_{\mathrm{Cu,S}} \mp P_{\mathrm{Fe,S}}$

$$P_{\mathrm{mech}} = P_{\mathrm{i,mech}} \mp P_{\mathrm{Fric}} \tag{2.3}$$

$$M \cdot 2\,\pi\,n = M_{\mathrm{i}} \cdot 2\,\pi\,n \mp M_{\mathrm{Fric}} \cdot 2\,\pi\,n$$

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$$M = M_{\mathrm{i}} \mp M_{\mathrm{Fric}} \tag{2.4}$$

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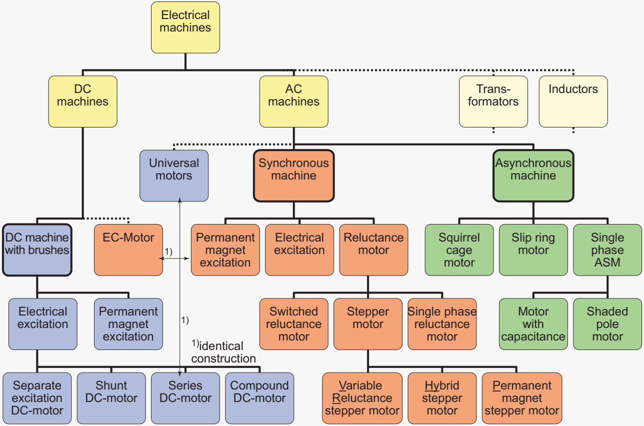
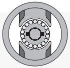
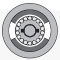
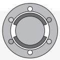
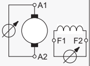
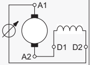
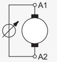
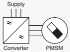
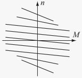
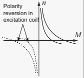
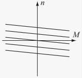
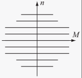
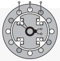
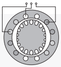
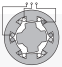
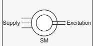
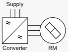
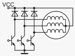
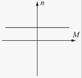
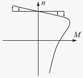
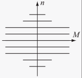
Version variants

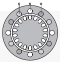
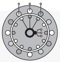
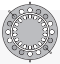
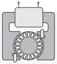
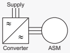
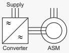
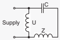
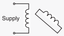
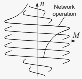
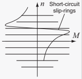
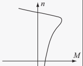
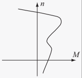


Design variants - Summary 1/2

	DC machine Separate excited DC motor	DC machine Series DC motor	DC machine 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.

	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	$P_{V,Cu,S} = 3 R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = R_f I_f^2$ $P_{V,Fe,R} = 0$ $P_\delta = 3\, U_P\, I_S \cos$ $P_{i,mech} = P_\delta$	$P_{V,Cu,S} = 3 R_S I_S^2$ $P_{V,Fe,S} > 0$ $P_{V,Cu,R} = 0$ $P_{V,Fe,R} = 0$ $P_\delta = \frac{3}{2}\left(X_d - X_q\right) I_S^2 \sin 2\psi$ $P_{i,mech} = P_\delta$		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).

Design variants - Summary 2/2

	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.

Market Shares

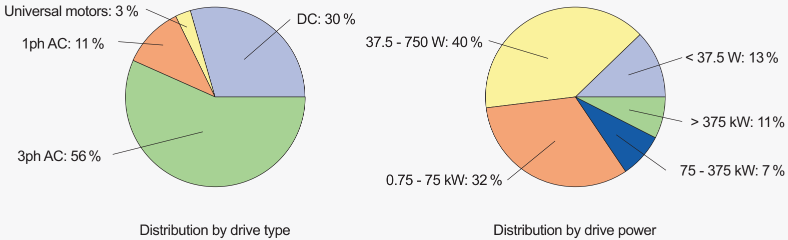


Figure Market shares in the EU-27 (2020), total 11.3 Mrd. € (determined from: Prodcom production statistics NACE Rev. 2 , ec.europa.eu/eurostat, April 2022)

- Electric motors with $P > 37.5\,W$ in 2020 approx. 11.3 bil. €
- 3ph AC has stagnated at 6.4 bil. € to 6.5 bil. € since 2014
- DC since 2015 from 2.4 bil. € to 3.3 bil. € up!
- Micro ($< 37.5\,W$) and small motors ($< 750\,W$): 6.7 bil. € in 2020!
- Small motors: sometimes several 100,000/day in one(!) manufacturing site

Motors for robots

Requirements

- Simple but highly accurate position control
- High dynamic behavior
  - high maximum torque
  - low inertia
  - low electrical time constant

- Asynchronous motor: accurate position control is complex (rotor temperature)
- **DC-motor and synchronous motor with permanent magnets**
  - Easy and accurate position control
  - Permanent magnets improve the dynamic
    - lower rotating mass $\Rightarrow$ low inertia
    - lower inductance $\Rightarrow$ low electrical time constant
- **Stepper motor** special synchronous motor design for small systems
  - Accurate position control without sensors