DC Motor - Part 1

Actuators - IRO6

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DC Motor

- DC small motors:
  - Cordless power tools
  - Drives in vehicles
    (approx. 70 DC motors/middle class cars, upper class significantly more)
- DC motors in very large quantities as a universal motor:
  - Household appliances and power tools
- DC machine until a few decades(decades) ago:
  - the only electric machine that can be easily controlled
- today still industrial drives with outputs from a few kW up to 8000 kW:
  - machine tool drives, rolling motors, drives for paper machines, ...
- DC machine as generator:
  - practically no longer relevant, has now been replaced by rectifiers

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Basic Structure

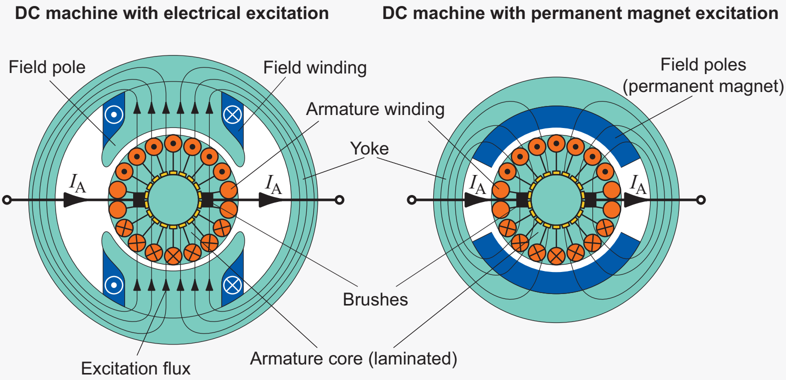
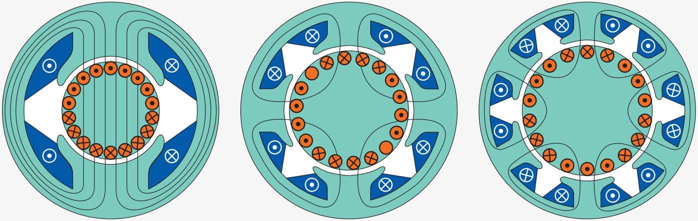


Figure Electrically (left) and permanent magnet excited (right) DC motor

Basic structure

- Fixed part (stator): yoke and excitation / field poles with excitation / field windings
  - Yoke: cast iron or rolled steel (magnetic return and mechanical supporting structure)
  - AC mains operation: yoke and excitation poles must be laminated
  - small DC machines: yoke with the excitation poles laminated (production)
- Rotor (armature) is always laminated (armature winding in slots)
  - Power supply to the armature coils via carbon brushes (in brush holders)
  - Brushes are held against the brush by springs in the brush holder
- Commutator consists of copper segments (insulated with mica sheets)
  - copper segments of the commutator are connected with the coil ends of the armature winding
  - Commutator acts like a mechanical inverter or rectifier
- DC machines often have four or six poles

Number of poles and number of pole pairs



$p = 1$ $p = 2$ $p = 3$

Figure Structure of DC motors with number of poles $2p = 2, 4, 6$

- Total flux of the machine is divided into $2p$ sub-fluxes
  - ⇒ smaller yoke cross-sections
  - ⇒ smaller end windings of the excitation and of the armature winding
  - ⇒ in the armature larger iron losses due to higher flux reversal frequency ($f_A = n \cdot p$)

Armature Structure

- Simplest and oldest type of winding: ring winding (Pacinotti 1860)
- Disadvantage: Return conductor magnetically shielded from the excitation field, practical only executable as disc rotor
- Drum armature (Hefner-Alteneck 1872) with two-layer winding

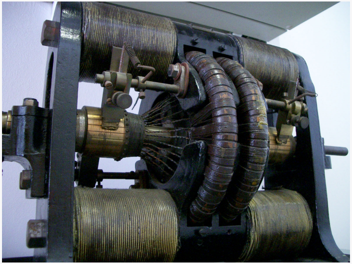
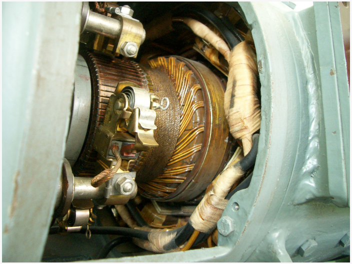



Figure Armature with ring winding (left) and drum winding (right)

Winding Construction

- Ensure same current direction under the excitation poles regardless of the rotor position
- Example: 4-pole machine ($2p = 4$) with 16 slots ($Q_A = 16$)

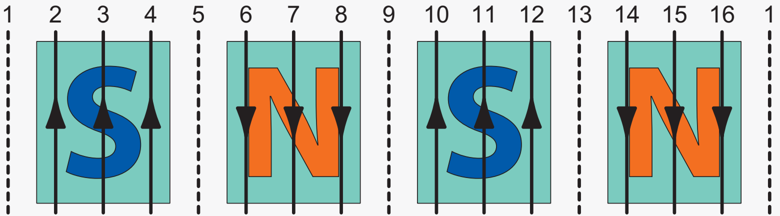
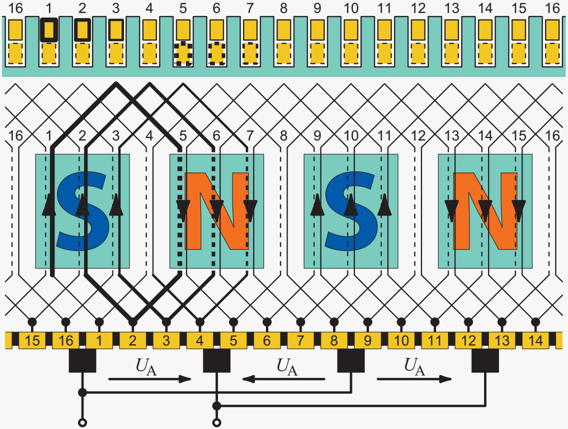


Figure Current directions on a 4-pole, 16-slot machine

Example of an armature winding



Examples

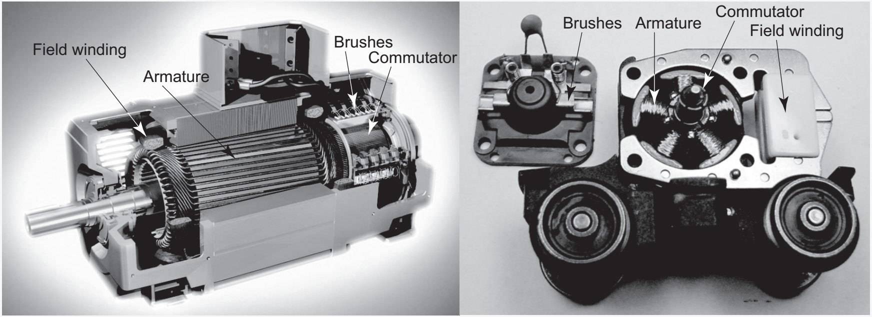
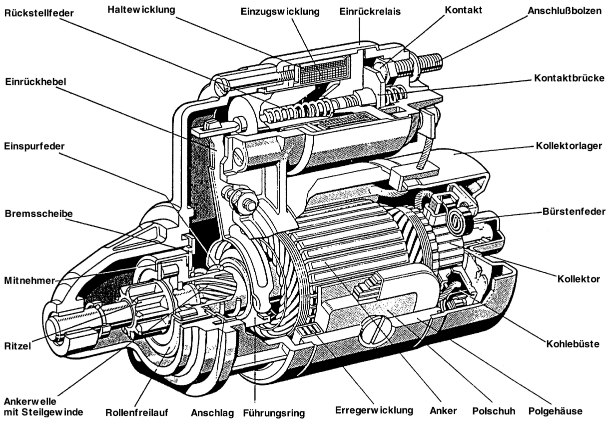


Figure Example for an industrial and a micro drive (ABB/Märklin)

Examples



Source: Robert Bosch GmbH

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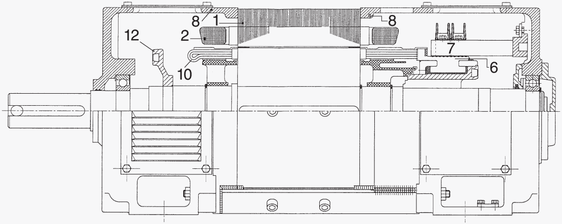
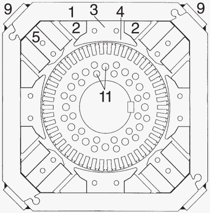
Examples



1 Ständerjoch
2 Erregerwicklung
3 Polkern
4 Polschuh
5 Wendepol mit Wendepolwicklung
6 Kommutator
7 Bürstenapparat mit Bürsten
8 Druckstücke
9 Zugleisten
10 Ankerwicklung
11 Kühllöcher
12 Wuchtscheibe

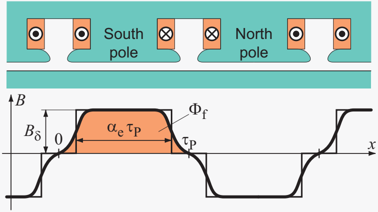


Source: Siemens AG

Disadvantages of mechanical commutation:

- Brushes are subject to wear ⇒ Maintenance may be necessary;
- Maximum power is limited by speed and current-dependent brush fire (electric arc);
- Commutator requires extra overall length (higher moment of inertia);
- Additional losses due to brush friction and voltage drop in the brushes ($\approx 0.6 \ldots 2\,V$)

Excitation Flux



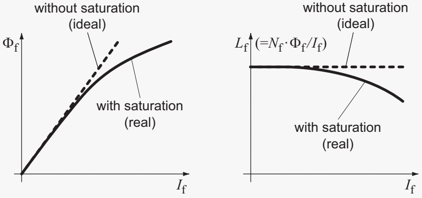


Figure Magnetization characteristic

$$\Phi_f = l_{Fe} \cdot \int_0^{\tau_P} B(x)\,dx = l_{Fe} \cdot B_\delta \cdot \alpha_e \cdot \tau_P \qquad \text{mit } \tau_P = \frac{\pi\, d_{Re}}{2\,p}$$

α_e: ideal pole-covering

l_{Fe}: iron length

$\Phi_f = f(I_f)$ Non-linearity!

Induced Voltage

Induced voltage in a single rotor bar:

$$u_{\mathrm{i,B}} = l_{\mathrm{Fe}} \cdot v_{\mathrm{A}} \cdot B_{\delta}(x) \qquad \text{mit } v_{\mathrm{A}} = \pi \cdot d_{\mathrm{Re}} \cdot n$$

(Length l_{Fe}, speed v_{A})

Average value over half a period:

$$U_{\mathrm{i,B}} = l_{\mathrm{Fe}} \cdot v_{\mathrm{A}} \cdot B_{\delta} \cdot \alpha_{\mathrm{e}}$$

- K (=number of commutator bars) coils have the Number of turns N_{Coil}

⇒ Number of armature windings N_{A}:

$$N_{\mathrm{A}} = \frac{K \cdot N_{\mathrm{Coil}}}{2\,a}$$

1. Main Equation of DC Machine

Induced voltage (directly measurable on the brushes at no-load):

$$U_\mathrm{i} = 2 \cdot N_\mathrm{A} \cdot U_\mathrm{i,B}, \text{ (Factor 2 due to forward and return conductor)}$$

$$U_\mathrm{i} = 2 \cdot N_\mathrm{A} \cdot l_\mathrm{Fe} \cdot \underbrace{\pi d_\mathrm{Re} \cdot n}_{v_\mathrm{A}} \cdot B_\delta \cdot \alpha_\mathrm{e} \frac{2p}{2p}$$

$$U_\mathrm{i} = \underbrace{\frac{\pi \cdot d_\mathrm{Re}}{2p} \cdot l_\mathrm{Fe} \cdot B_\delta \cdot \alpha_\mathrm{e}}_{= \Phi_\mathrm{f}} \cdot 2n \cdot N_\mathrm{A} \cdot 2p = \underbrace{\frac{4pN_\mathrm{A}}{2\pi}}_{= c} \cdot \Phi_\mathrm{f} \cdot \underbrace{2\pi n}_{= \Omega_\mathrm{m}}$$

$$\text{mit } c = \frac{4pN_\mathrm{A}}{2\pi} = \frac{K}{a} \frac{p}{\pi} N_\mathrm{A}$$

⇒ 1. Main Equation of DC Machine:

$$\boxed{U_\mathrm{i} = c\Phi_\mathrm{f} \cdot \Omega_\mathrm{m}} \tag{3.1}$$

Torque and Losses

- Torque?

$\Rightarrow$ Power balance: delivered mechanical power = electrical power

$$\boxed{P_{\mathrm{i,mech}} = P_{\mathrm{mech}} + P_{\mathrm{Fric}} = M_{\mathrm{i}} \cdot \Omega_{\mathrm{m}} = U_{\mathrm{i}} \cdot I_{\mathrm{A}}} \tag{3.2}$$

$$U_{\mathrm{i}} \cdot I_{\mathrm{A}} = c\Phi_{\mathrm{f}} \Omega_{\mathrm{m}} I_{\mathrm{A}} \qquad \Rightarrow \qquad \boxed{M_{\mathrm{i}} = c\Phi_{\mathrm{f}} \cdot I_{\mathrm{A}}} \tag{3.3}$$

2. Main Equation of DC Machine

Joule heat losses:

$$P_{\mathrm{V,Cu}} = K\, N_{\mathrm{Sp}} \cdot \underbrace{\frac{2\, l_{\mathrm{av}}}{q_{\mathrm{C}}} \cdot \rho_{\mathrm{Cu}} \cdot \underbrace{\left(\frac{I_{\mathrm{A}}}{2\,a}\right)^2}_{\text{Current in one bar}}}_{\text{Losses in one bar}}$$

$l_{\mathrm{av}} \approx (l_{\mathrm{Fe}} + 0,9\tau_{\mathrm{P}})$: mean turn length (approximation)

$$P_{\mathrm{V,Cu}} = K \underbrace{\frac{2\,a}{K} N_{\mathrm{A}}}_{N_{\mathrm{Sp}}} \cdot \frac{2\, l_{\mathrm{av}}}{q_{\mathrm{C}}} \cdot \rho_{\mathrm{Cu}} \cdot \left(\frac{I_{\mathrm{A}}}{2\,a}\right)^2 = \frac{N_{\mathrm{A}}}{2\,a} \frac{2\, l_{\mathrm{av}}}{q_{\mathrm{C}}} \rho_{\mathrm{Cu}} \cdot I_{\mathrm{A}}^2 = R_{\mathrm{A}} \cdot I_{\mathrm{A}}^2 \tag{3.4}$$

3. Main Equation of DC Machine

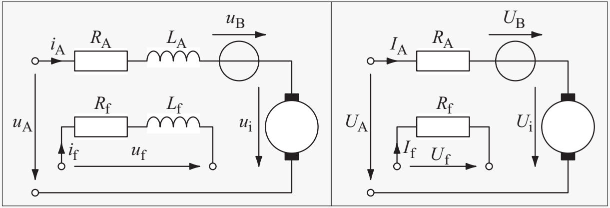


Figure Transient (left) and steady-state (right) equivalent circuit diagram of the DC machine

steady-state: $$U_A = U_i + U_B \cdot \mathrm{sign}(I_A) + R_A I_A \tag{3.5a}$$

transient: $$u_A(t) = u_i(t) + U_B \cdot \mathrm{sign}(i_A(t)) + R_A\, i_A(t) + L_A \frac{\mathrm{d}i_A}{\mathrm{d}t} \tag{3.5b}$$

steady-state: $$U_f = R_f I_f \tag{3.5c}$$

transient: $$u_f(t) = R_f\, i_f(t) + L_f \frac{\mathrm{d}i_f}{\mathrm{d}t} \tag{3.5d}$$

Sign convention:

Motor operation is assumed by the arrow directions of the equivalent circuit

- U_i has the same sign as I_A, i.e.: $P_\mathrm{i,mech} = I_\mathrm{A} \cdot U_\mathrm{i} > 0$
  - Consumption of electrical power
  - Delivery of mechanical power

  $\Rightarrow$ Motor mode

- U_i has not the same sign as I_A, i.e.: $P_\mathrm{i,mech} = I_\mathrm{A} \cdot U_\mathrm{i} < 0$
  - Consumption of mechanical power
  - Delivery of electrical power

  $\Rightarrow$ Generator mode

- $U_\mathrm{i} > 0 \Rightarrow$ Clockwise rotation of the machine (CW)

- $U_\mathrm{i} < 0 \Rightarrow$ Counterclockwise rotation of the machine (CCW)

Example 3-1: Estimation of equivalent circuit data

- DC motor with $3\,kW$ at $1500\,min^{-1}$
- Armature/excitation nominal voltage $230\,V$
- Overall efficiency of 84% (16% losses)
  - Armature winding 8%
  - Excitation winding 5%
  - Friction 3%

Connection designations according to DIN VDE 0530

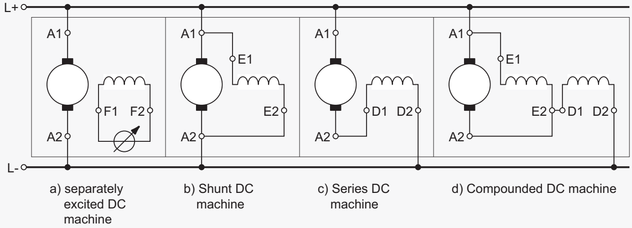


Figure DC machine connection designations

- A: Armature winding
- D: Series winding
- E: Shunt winding
- F: Separately excited winding

Connection options

- separately excited DC machine: Excitation winding is fed separately
  - $\Rightarrow$ constant and load-independent excitation flux
- shunt machine: Excitation winding parallel to the armature circuit
  - $\Rightarrow$ for mains operation: constant and load-independent excitation flux
- series machine: excitation winding in series with the armature winding
  - $\Rightarrow$ Excitation flux is load dependent $\Rightarrow$ infinite no-load speed
- compounded machine: like externally excited DC-motor with additional series winding
  - $\Rightarrow$ superposition of shunt and series behavior

In robotics

only direct current machines with **separate excitation** are relevant due to the simple controllability.

Hazard warning

DC machine without excitation is dangerous $\Rightarrow$ Infinite no-load speed!

- Switch on the excitation before the armature and switch off the excitation after the armature!
- Never switch off the excitation circuit during operation!

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Separately excited DC machine

$$U_\mathrm{A} = U_\mathrm{i} + R_\mathrm{A} \cdot I_\mathrm{A} + U_\mathrm{B} \approx c\Phi_\mathrm{f} \cdot \Omega_\mathrm{m} + R_\mathrm{A} \cdot \frac{M_\mathrm{i}}{c\Phi_\mathrm{f}}$$

$$\Omega_\mathrm{m} = \frac{U_\mathrm{A}}{c\Phi_\mathrm{f}} - \frac{R_\mathrm{A}}{(c\Phi_\mathrm{f})^2} M_\mathrm{i}$$

Line equation $\Omega_\mathrm{m}(M_\mathrm{i})$ with two terms:

- First term is load independent
  - $\Rightarrow$ No-load angular velocity / speed $\sim U_\mathrm{A}$ and $\sim 1/c\Phi_\mathrm{f}$
- Second term $\sim M_\mathrm{i}$
  - $\Rightarrow$ Load dependent reduction of the motor speed $\sim R_\mathrm{A}$ and $\sim 1/(c\Phi_\mathrm{f})^2$

Separately excited DC machine

$$\Omega_\mathrm{m} = \frac{U_\mathrm{A}}{c\Phi_\mathrm{f}} - \frac{R_\mathrm{A}}{(c\Phi_\mathrm{f})^2} M_\mathrm{i}$$

Options for speed adjustment:

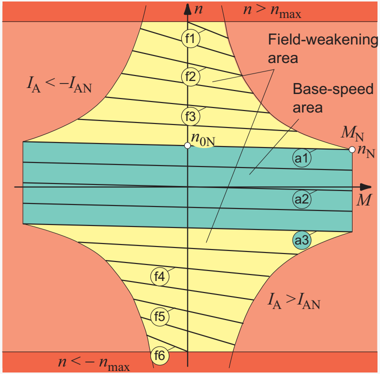
- Changing the armature voltage
- Changing the excitation current
- Additional resistance (**starter**) in the armature circuit

How to increase speed above rated no-load speed?

⇒ Reduction of the excitation field

$$\text{Field weakening factor } f := \frac{c\Phi_\mathrm{fN}}{c\Phi_\mathrm{f}} \tag{3.7}$$

n(M) characteristics



Field-weakening:
f1: $U_A = U_{AN},\quad f = 4$
f2: $U_A = U_{AN},\quad f = 3$
f3: $U_A = U_{AN},\quad f = 2$

Base speed:
a1: $U_A = U_{AN},\quad f = 1$
a2: $U_A = 0,\quad f = 1$
a3: $U_A = -U_{AN}, f = 1$

Field-weakening:
f4: $U_A = -U_{AN}, f = 2$
f5: $U_A = -U_{AN}, f = 3$
f6: $U_A = -U_{AN}, f = 4$

Figure Operating diagram of the separately excited DC machine

Operating Limits:

- Current ≤ Rated current (commutation, heating)
- Maximum speed (commutation, mechanical stress)

2 operating areas

- Armature adjustment area (also base speed area)
- Field weakening area

Discussion n(M)-characteristics

Basically, the speed can be adjusted in three different ways:

1. Changing the terminal voltage (armature adjustment area, $|n| < n_{0N}$, $f = 1$).
   - No-load speed proportional to armature voltage
   - ⇒ Shunt behavior:
     - slight speed drop under load
     - speed drop proportional to torque
   - ⇒ maximum torque constant
2. Increasing the field weakening factor (field weakening area, $|n| > n_{0N}, U_A = U_{AN}$)
   - Enlargement of the field weakening factor
   - ⇒ No-load speed increases
   - ⇒ Torque decreases for the same current
   - Direction of rotation cannot be changed with the polarity of the excitation winding!!
3. Series resistor in the armature circuit
   - ⇒ high losses - method is not longer used