DC Motor - Part 1

Actuators - IRO6

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  - Cordless power tools
  - Drives in vehicles
    (approx. 70 DC motors/middle class cars, upper class significantly more)

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- DC machine as generator:
  - practically no longer relevant, has now been replaced by rectifiers

DC Motor - Part 1

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Stator in DC motor: exciter or field excitation

Rotor in DC motor: Armature

Basic Structure

Commutator plates
- Copper isolated with mica

Brushes
Carbon (Graphite)

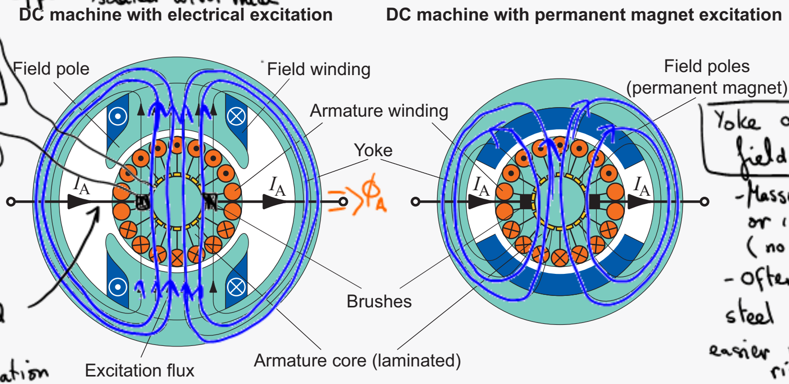

Figure Electrically (left) and permanent magnet excited (right) DC motor

Neutral zone: no excitation flux, where commutation is done and brushes are placed

Yoke and field poles:
- Massive steel or iron (no flux change)
- Often laminated steel due to easier manufacturing or AC-operation

Armature
- Always laminated due to eddy currents

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)

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  - copper segments of the commutator are connected with the coil ends of the armature winding
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- DC machines often have four or six poles

p = number of pole pairs = number of repetitions of the magnetic structure in the circumference

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Number of poles and number of pole pairs

$\underbrace{\text{Number of poles}}_{2p}$

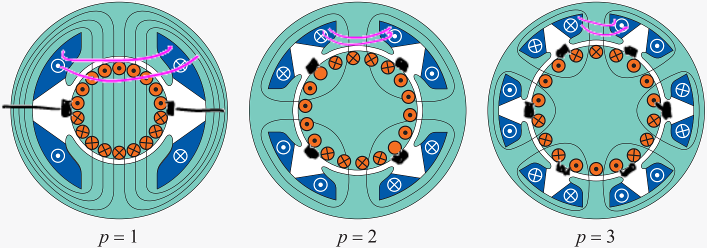


Figure Structure of DC motors with number of poles $2p = 2, 4, 6$

Why p↑ ?

⊕ Flux per pole ↓ → Yoke thickness ↓ → Motor weight ↓

⊕ Distance between coil sides ↓ → Winding overhang ↓ → Shorten motor
→ motor weight ↓

⊖ Complexity

⊖ The changing flux frequency ↑ → Iron losses ↑↑ → Efficiency ↓

Number of poles and number of pole pairs

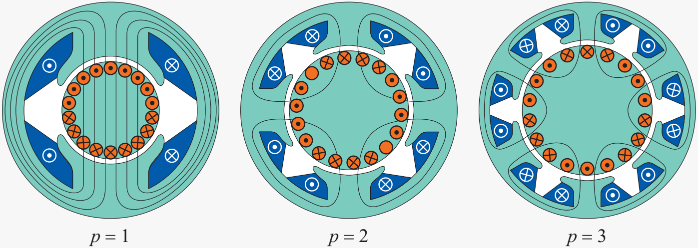
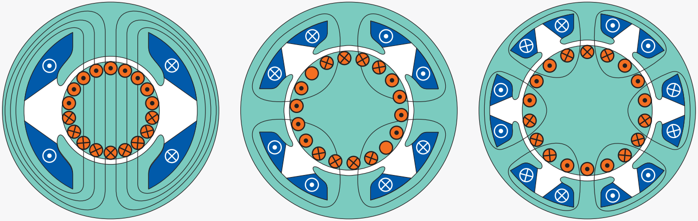


Figure Structure of DC motors with number of poles $2p = 2, 4, 6$

- 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

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 ($f_A = n \cdot p$)

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DC Motor - Part 1

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Armature Structure

$F = I \cdot B \cdot l$

On the outside $B \neq 0$

inside $B = 0 \rightarrow F = 0$

- 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

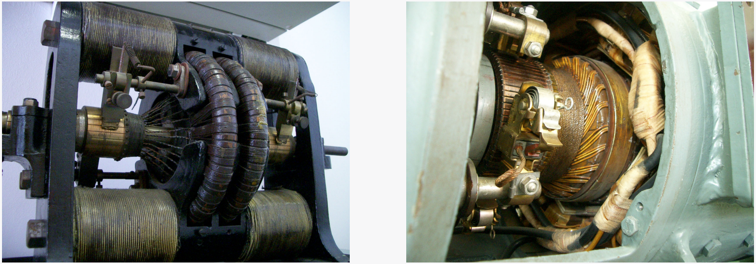

Figure Armature with ring winding (left) and drum winding (right)

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Winding Construction

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

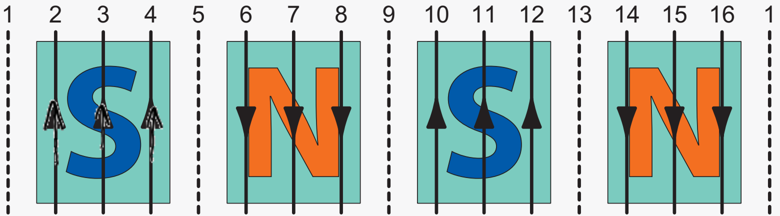

Figure Current directions on a 4-pole, 16-slot machine

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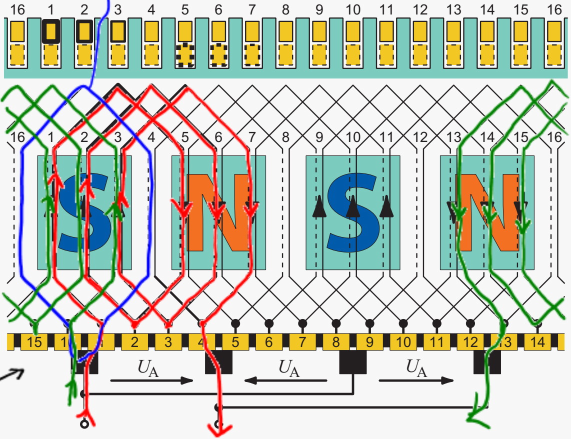
Example of an armature winding

$\Delta U = 0 \rightarrow I = 0$



Commutator plates

Brushes

Examples

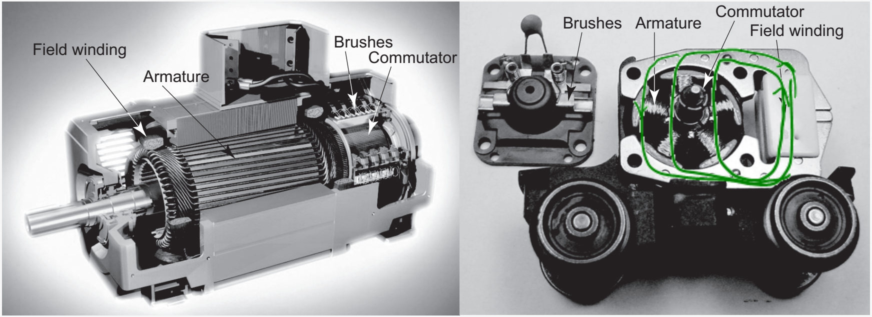
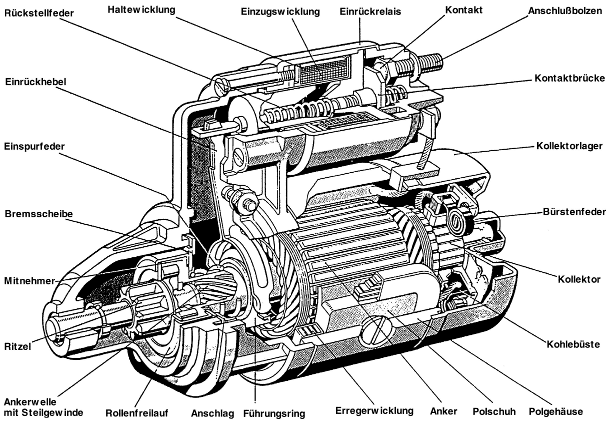


Figure Example for an industrial and a micro drive (ABB/Märklin)

Examples



Source: Robert Bosch GmbH

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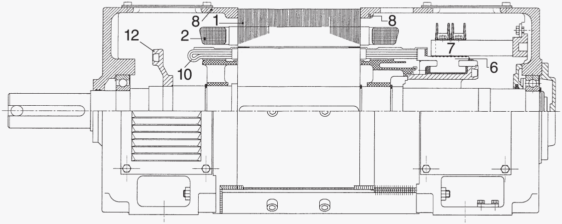
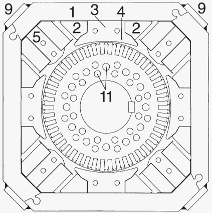
Examples



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



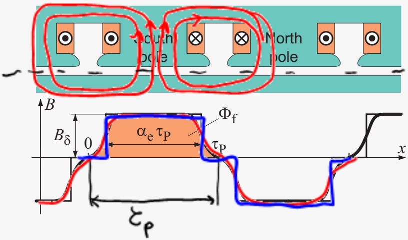
Source: Siemens AG

Disadvantages of mechanical commutation:

- Brushes are subject to wear $\Rightarrow$ 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 ($\approx 0.6 \ldots 2\,V$)

DC Motor - Part 1

Excitation Flux



$$\Phi_f = l_{Fe} \cdot \int_0^{\tau_P} B(x)\,dx = l_{Fe} \cdot B_\delta \cdot \alpha_e \cdot \tau_P$$

Maximum air-gap flux density

pole pitch $= \frac{2\pi \cdot R}{2p}$

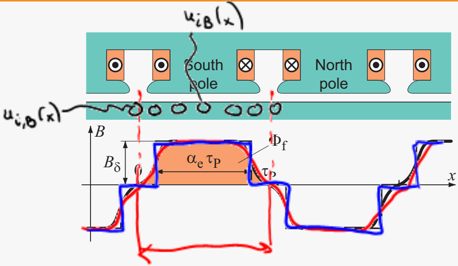
$=$

mit $\tau_P = \frac{\pi d_{Re}}{2p}$

α_e: ideal pole-covering

l_{Fe}: iron length

Excitation Flux



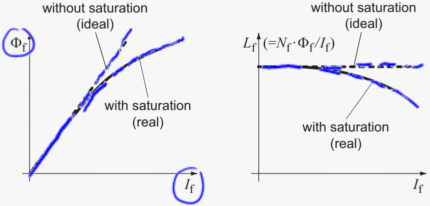


Figure Magnetization characteristic

$\tau_p = \frac{2\pi R}{\# \text{ of poles}} = \frac{2\pi R}{2p}$

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

Excitation flux

Maximum air-gap flux-density

= Pole-pitch

Length of a pole in the air-gap

α_e: ideal pole-covering

l_{Fe}: iron length

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

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Induced Voltage

Induced voltage in a single rotor bar:

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

(Length l_{Fe}, speed v_A)

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

⇒ Number of armature windings N_A:

$$N_A = \frac{K \cdot N_{Coil}}{2a}$$

number of parallel connected coils

1. Main Equation of DC Machine

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

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

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

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

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

p = pole pair number
$2p$ = number of poles

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v_A Armature conductor
linear speed of armature conductor

$v_A = 2\pi \cdot n \cdot \underbrace{R}_{d_{Re}/2}$

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

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⇒ 1. Main Equation of DC Machine:

$[c\Phi_f] = V \cdot s \; (/\text{rad})$

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

$c\Phi_f$ = Motor constant x excitation flux = Variable for the calculations

Torque and Losses

- Torque?

⇒ Power balance: delivered mechanical power = electrical power

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⇒ Power balance: delivered mechanical power = electrical power

Armature current = current of the rotor

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

$$M_i \cdot \cancel{\Omega_m} = U_{\mathrm{i}} \cdot I_{\mathrm{A}} = c\Phi_{\mathrm{f}} \cancel{\Omega_{\mathrm{m}}} I_{\mathrm{A}} \quad \Rightarrow \quad \boxed{M_{\mathrm{i}} = c\Phi_{\mathrm{f}} \cdot I_{\mathrm{A}}} \quad (3.3)$$

$$M_i = M + M_{Fric}$$

2. Main Equation of DC Machine

$$[c\Phi_F] = V \cdot s = Nm/A \equiv$$

In data-sheets often as "torque constant"

Torque and Losses

- Torque?

⇒ Power balance: delivered mechanical power = electrical power

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

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

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)

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

Stator of DC motor ≡ Excitation ≡ "F"
Rotor of DC motor ≡ Armature ≡ "A"

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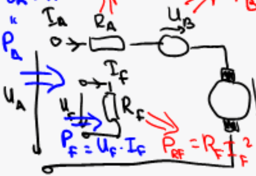
3. Main Equation of DC Machine

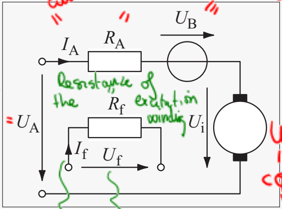
$P_B = U_B \cdot I_A$ = Losses in the brush contact



$$\boxed{\begin{aligned} U_i &= c\phi_f \cdot \Omega_m \\ M_i &= c\phi_f \cdot I_A \end{aligned}}$$

$U_i \cdot I_A = P_{i,mech} = P_{mech} + P_{Fric}$

Armature voltage



Armature current
Resistance of the armature winding
Voltage drop in the contact between brushes and commutator (0.6 - 1V per brush typically)
Resistance of the excitation winding

$U_i = c\phi_f \cdot \Omega_m$, $\phi_f = f(I_f)$

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

Excitation current
Excitation voltage

steady-state: $$U_A = U_i + U_B \cdot \underbrace{\mathrm{sign}(I_A)}_{\frac{I_A}{|I_A|}} + R_A I_A \qquad (3.5a)$$

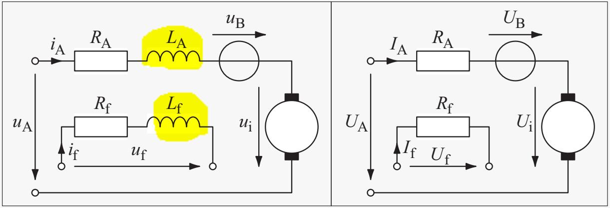
Input power: $P_A + P_F$

Output power: $P_{mech} = P_A - P_{RA} - P_B - P_{Fric}$

steady-state: $$U_f = R_f I_f \qquad (3.5c)$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mech}}{P_A + P_F} \qquad (3.5d)$$

3. Main Equation of DC Machine



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

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

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

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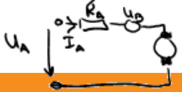

$U_i = c\phi_f \cdot \Omega_m$

$M_i = c\phi_f \cdot I_f$

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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

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  - Delivery of electrical power

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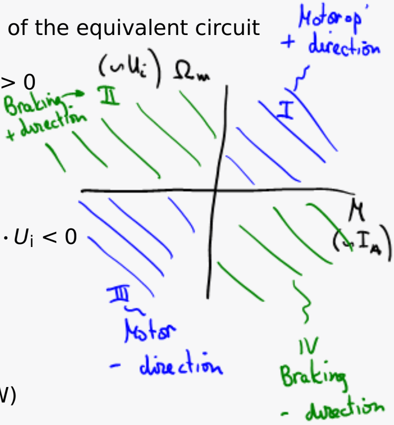
  - Consumption of mechanical power
  - Delivery of electrical power

  $\Rightarrow$ Generator mode

- $U_i > 0 \Rightarrow$ Clockwise rotation of the machine (CW)

- $U_i < 0 \Rightarrow$ Counterclockwise rotation of the machine (CCW)



η = Greek eta \eta = Efficiency

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Example 3-1: Estimation of equivalent circuit data

P_{mech}

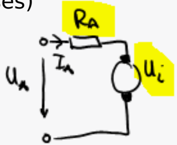
- DC motor with $3\,kW$ at $1500\,min^{-1}$
- Armature/excitation nominal voltage $230\,V$
- Overall efficiency of 84% (16% losses)
  - Armature winding 8%
  - Excitation winding 5%
  - Friction 3%
  - Brushes → 0%

$\cdot P_{In}$

$P_N = 3kW$ = Nominal or rated power

$n_N = 1500\,min^{-1}$

$U_{AN} = 230V$ $\quad U_{FN} = 230V$



$$P_{In} = \frac{P_N}{\eta} = \frac{3000W}{0.84} = 3.571\,kW$$

$$P_{RA} = 0.08 \cdot P_{In} = 286W$$

$$P_{RF} = 0.05\,P_{in} = 179W = \frac{U_{FN}^2}{R_F} \rightarrow R_F = \frac{(230V)^2}{179W} = 295.5\,\Omega$$

$$P_{fric} = 0.03\,P_{in} = 107W$$

$$P_A = U_{AN} \cdot I_A = P_{IN} - P_F = P_{IN} - P_{RF} = 3571\,W - 179\,W = 3392\,W$$

$$I_A = \frac{P_A}{U_{AN}} = \frac{3392\,W}{230\,V} = 14.75\,A$$

$$U_i = \frac{P_{i,mech}}{I_A} = \frac{P_N + P_{Fric}}{I_A} = \frac{3000\,W + 107\,W}{14.75\,A} = \underline{\underline{210.6\,V}}$$

$$R_A = \frac{U_A - U_i}{I_A} = \frac{230\,V - 210.6\,V}{14.75\,A} = \underline{\underline{1.31\,\Omega}}$$

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%

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DC Motor - Part 1

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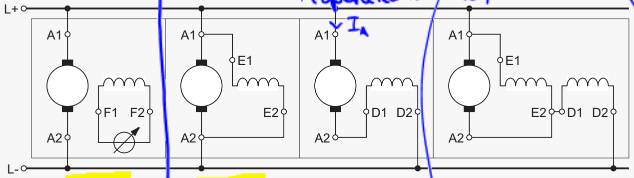
Connection designations according to DIN VDE 0530

Best solution of control => robots

→ No control possible → not for robots but as universal motors (operated with AC)

Only for big machines. Out-of-scope of robotics



a) separately excited DC machine

b) Shunt DC machine

c) Series DC machine

d) Compounded DC machine

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

Figure DC machine connection designations

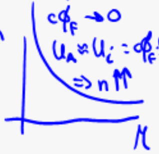
$c\Phi_F = f(U_F, I_F) \neq f(U_A, I_A)$

$c\Phi_F = f(U_F) = f(U_A)$

$c\Phi_F = f(I_F) = f(I_A) = f(M)$

$M_i = c\Phi_F \cdot I_A$

$M \to 0$,
$I_A \to 0$
$c\Phi_F \to 0$
$U_A \approx U_i = c\Phi_F \Omega$
$\Rightarrow n \uparrow$



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Connection options

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

Connection options

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  $\Rightarrow$ superposition of shunt and series behavior

In robotics

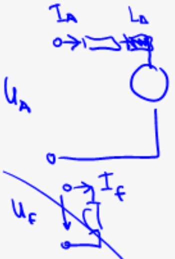
only direct current machines with **separate excitation** are relevant due to the simple controllability.

DC Motor - Part 1

Hazard warning

DC machine without excitation is dangerous ⇒ 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!



$U_i = c\Phi_F \cdot \Omega_m$

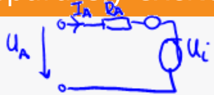
$U_A \rightarrow U_i$

$U_F \rightarrow 0 \rightarrow I_F \rightarrow 0 \rightarrow c\Phi_F \rightarrow 0$

$U_i \approx \text{constant} \rightarrow n \uparrow\uparrow$

DC Motor - Part 1

Separately excited DC machine



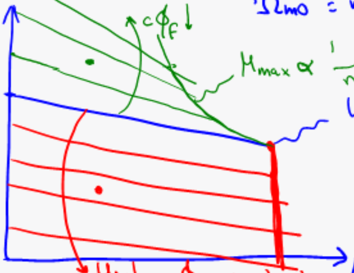
$U_i = c\Phi_f \cdot \Omega_m$ $\quad M_i = c\Phi_f \cdot I_A$

$$U_A = U_i + R_A \cdot I_A + \cancel{U_B} \approx c\Phi_f \cdot \Omega_m + R_A \cdot \frac{M_i}{c\Phi_f}$$

$$\boxed{\underset{2\pi n}{\Omega_m} = \frac{U_A}{c\Phi_f} - \frac{R_A}{(c\Phi_f)^2} M_i}$$

Ω_{m0} = no-load (torque = 0) angular velocity

Field-weakening area (only possible with electrical excitation)



$M_i = c\Phi_f \cdot I_A \rightarrow M_{i,max} = c\Phi_f \cdot I_{Amax}$

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
  - ⇒ No-load angular velocity / speed $\sim U_\mathrm{A}$ and $\sim 1/c\Phi_\mathrm{f}$
- Second term $\sim M_\mathrm{i}$
  - ⇒ 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

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How to increase speed above rated no-load speed?

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Separately excited DC machine

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Options for speed adjustment:

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

Nominal values (often maximum values in steady-state operation)

How to increase speed above rated no-load speed?

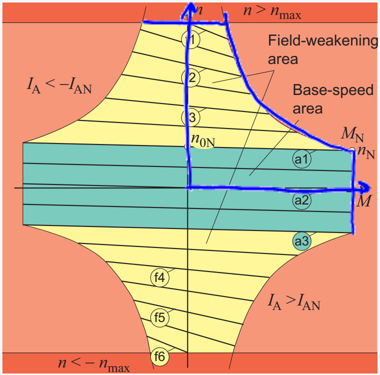
⇒ Reduction of the excitation field

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

1 → Armature adjustment area

>1 → Field weakening area

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:

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1. Changing the terminal voltage (armature adjustment area, $|n| < n_{0\mathrm{N}},\ f = 1$).
   - No-load speed proportional to armature voltage

   ⇒ Shunt behavior:
     - slight speed drop under load
     - speed drop proportional to torque

   ⇒ maximum torque constant

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   - ⇒ 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!!

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   - ⇒ 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