Stepper Motor

Actuators - IRO6

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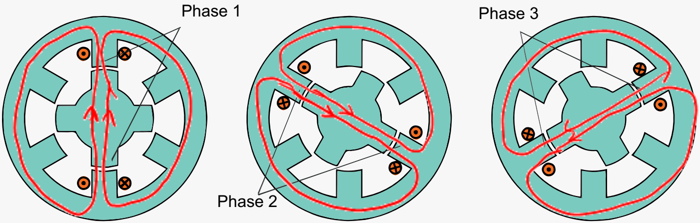
13.06.2024

Stepper Motor

- Special type of the synchronous motor
- Step-by-step positioning only through impulses
  - ⇒ No closed loop and position sensor
- \+ Large holding torque, robust, inexpensive
- – Electronics need to match the motor
- – Lose step at high loads and frequencies
- ⇒ Use in robotics for small loads and medium dynamic requirements

How it works

Simplest variant (without PM in rotor)



- Stator and rotor with different numbers of teeth (here six stator teeth and four rotor teeth).
- Coils around each stator tooth. Phase winding with 2 coils (180° distance)

⇒ Stator tooth aligned to a rotor tooth ⇝ preferred magnetic directions

- with power on, rest positions with $M = 0$
- cyclic switching of the phase windings to the DC source

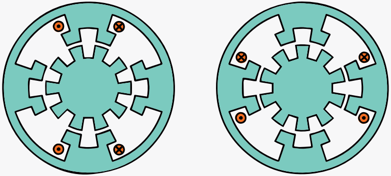
⇒ Rotor moves abruptly from one rest position to the next.

Characteristic values

- m: Number of systems or phases in the stator
- $2 \cdot p$: Number of poles or number of rotor teeth
- z: Number of steps or rest positions per revolution.
  - Full-step operation:
    - always the same number of winding phases with current
    - $z = 2 \cdot p \cdot m$.
  - Half-step operation:
    - The number of winding phases with current varies from step to step
    - $z = 4 \cdot p \cdot m$
- α: Step of the motor $\frac{360°}{z}$.

As a rule, a high number of steps is aimed:

- several sub-motors offset axially
- additional toothing of the stator and rotor poles



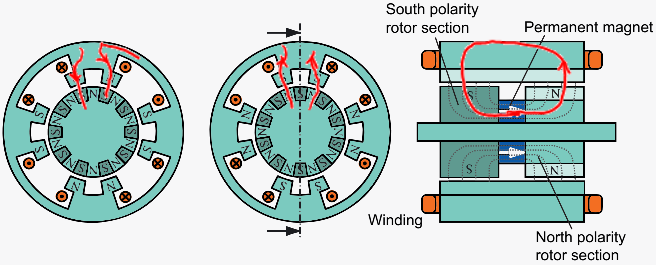
Rotor variants

- VR stepper motors: Variable-Reluctance (use the position-dependent variation of the magnetic reluctance)
- PM stepper motors: Permanentmagnet excitation in rotor
- Hybrid stepper motors: combination of both

Rotor Type	Typical step (with $m = 2$)	Holding Torque without current
Reluctance	7.5°-1.8°	No
Permanent magnet	45°-7.5°	Yes
Hybrid	7.5°-1.8°	Yes

Hybrid stepper motors are the most widespread ⇒ Here in focus

Hybrid Stepper Motor



- Rotor with two soft magnetic sections, arranged axially in the shaft and with the same number of teeth
- Second section offset by half a tooth pitch
- Axially magnetized permanent magnet between the two pole sections.
- Field lines emerge at the teeth of the north pole section, close via the excitation poles and stator yoke and re-enter the rotor at the south pole section
- When energized: the teeth in each pole section align with the nearest stator tooth of the opposite polarity on the energized pole

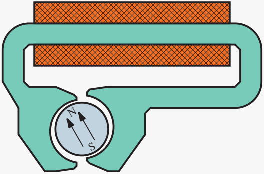
⇒ Higher torque than VR motors and also a small holding torque without current

Number of phases

$m = 2$: most common number of phases

$m = 1$ e.g. for clock drives

$\Rightarrow$ Rotor diameters of approx. 2 to 4 mm, very filigree, concentrated coil

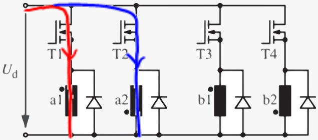


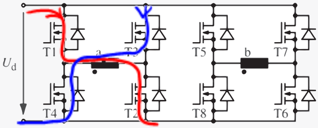
$m = 3, 5$ for hydrid stepper motors with minimum step sizes of up to 0.36°.

$\Rightarrow$ High effort for power electronics and control

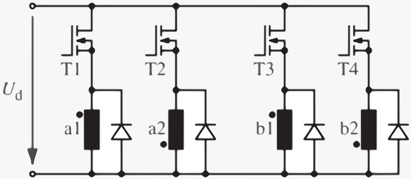
Unipolar vs. Bipolar Control

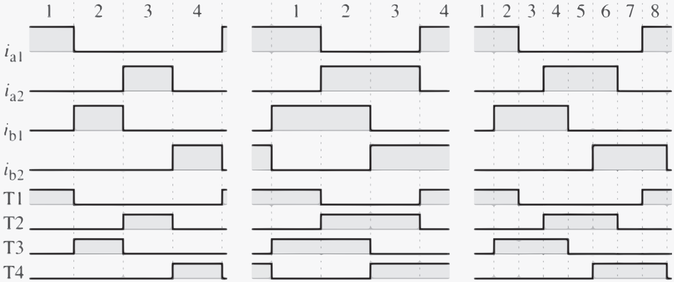
- Unipolar control: the current direction in a winding cannot change.
  - Polarity change required for operation
  - ⇒ 2 different windings per phase
  - \+ Only 2 transistors per phase
  - – Only half of the winding is energized ⇝ low motor utilization
- Bipolar control: the current direction in a winding can change.
  - \+ Entire winding is energized
  - – 4 transistors per phase required





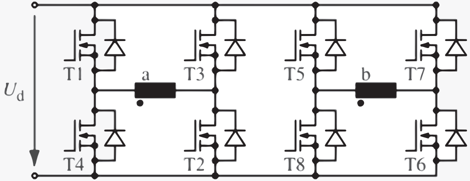
Unipolar control - full-step mode, half-step mode

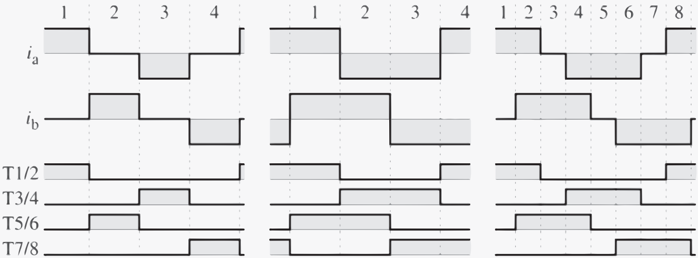




Full step 1 of 2 | Fullstep 2 of 2 | Half-step 1 of 2 / 2 of 2

Bipolar control - full-step mode, half-step mode





Full step 1 of 2

Fullstep 2 of 2

Half-step 1 of 2 / 2 of 2

Control - Microstepping mode

In addition to full-step and half-step mode, also **microstep mode**

- different current levels in the winding phases
- any intermediate positions can be reached
- significantly more power electronics effort
- controlled position increasingly inaccurate

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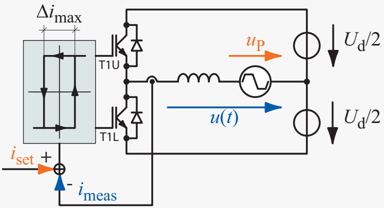
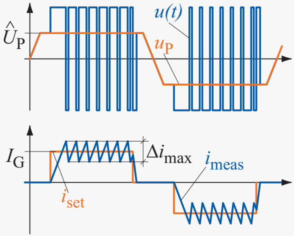
Control - constant current

The operation of a stepper motor requires constant currents.

- Constant current source
- „Chopper“: voltage source and hysteresis current controller (similar to EC motor)





- Voltage source and pulse width modulation (PWM): complex, mostly used for microstepping

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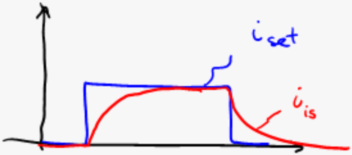
Control - current build-up

Stepper motors are designed with frequencies up to the kilohertz range.

- electrical time constant of the winding is relevant
- no rectangular form but e-function.
- acceleration of the increase desirable:
  - Resistors in series with the winding
  - Additional diode parallel to the winding
- exponential function of the current remains ⇒ crucial for the dynamic limits

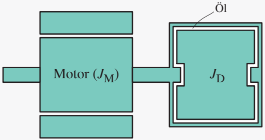


Damping in Stepper Motors

- Stepper motors ⇒ no running with absolutely constant speed possible
- The rotor always moves abruptly due to the switching of the currents
- For many applications it is desirable to only approach discrete positions.
- Problematic: Oscillating around the final end position

⇒ damping required

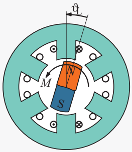
- Mechanical damping:
  - ⇒ additional moment of inertia due to hollow cylinder with oil.

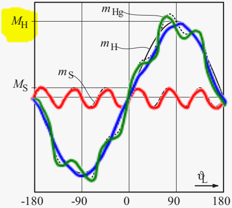


- Electromagnetic damping: short circuit of the unused windings ⇝ not very effective
- Electronic damping:
  - „back phase damping“: Reverse impulses for braking the stepper motor shortly before reaching the end position
  - „delayed last step“: delayed last control signal

Static Torque Characteristic

- Static torque characteristic = torque of the stepping motor at standstill.
- Here, PM stepper motor example. Similar for HY stepper motors.



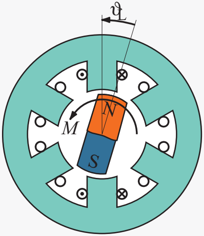


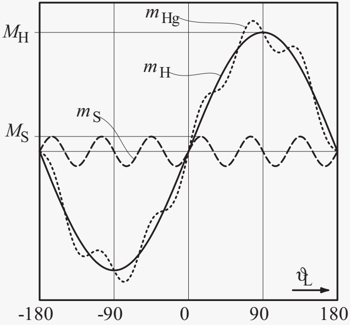
- Self-holding torque M_S when de-energized ⇒ Useful, but small! ← without current
- Same principle of operation as cogging torque for servo motors.

⇒ Function m_S depending on the rotor position angle Θ_L can usually only be determined by measurement

- For $p = 1$, as many periods as stator poles or teeth. $p > 1$ correspondingly more.
- Maximum holding torque when energizing a phase M_H ⇒ Equivalent to the breakdown torque of the synchronous motor. with current
- Torque curve m_H sinusoidal (PM stepper motors) or trapezoidal (HY stepper motors)
- Total torque curve m_{Hg} is superposition of both curves.

Static Torque Characteristic





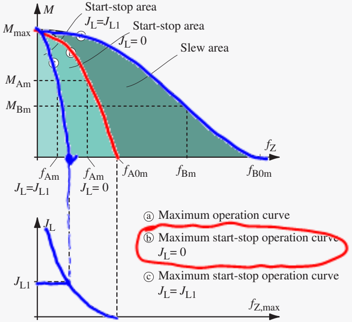
- M_H crucial for stepper motor:
  - maximum static load torque that can hold the excited motor without continuous rotation.
  - at no load, rotor positions itself under the excited poles.
  - at load < M_H increases θ_L until a motor-load balance is established.
  - under load > M_H motor rotates.

Dynamic Torque Characteristic

- With increasing step frequency, the electrical time constant of the winding becomes more and more relevant

⇒ Maximum current is not reached at all.

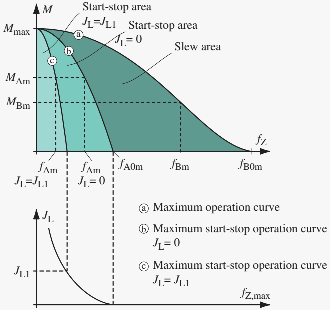
⇒ maximum load moment decreases with stepping frequency



2 areas in the dynamic characteristic

1. Start-stop area: Stepper motor can be started and stopped in the area
   - Limit curve depends on moment of inertia
2. Slew area: area can only be reached from the start-stop area by successively increasing the frequency.
   - Direct start and stop in the area leads to step errors.

Dynamic Torque Characteristic



- f_{Am}: maximum start frequency $= f(M, J)$. Max frequency at which the motor can start or stop without losing steps.
- M_{Am}: pull-in torque $= f(f_Z, J)$. Maximum torque that the motor can deliver without stepping errors
- f_{A0m}: maximum starting frequency for the motor without any load
- f_{Bm}: maximum running frequency $= f(M)$ with which the motor can be controlled without step errors.
- f_{B0m}: maximum running frequency for the motor without any load
- M_{Bm}: pull-out torque $= f(f_Z)$. Maximum running torque for the motor without stepping errors

Dynamic limit characteristic...

... must be respected, since step errors cannot be compensated (no control loop).

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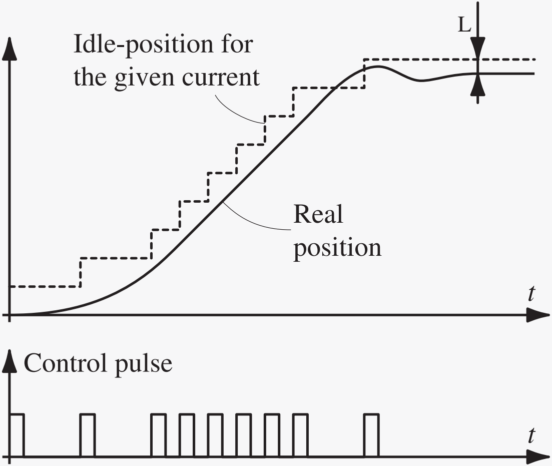
Positioning process



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Positioning Error

Two different values:

- $\Delta\alpha_m$ = systematic angular deviation:
  - ⇒ maximum deviation between the absolute target value and the actual position
- $\Delta\alpha_S$ = systematic angle tolerance per step
  - maximum error that can occur when changing position by an angle $\Delta\varphi$
  - in extreme cases it can be twice as large as the systematic angular deviation

    ⇒ start position: $\varphi_{1,Soll} - \Delta\alpha_m$

    ⇒ end position: $\varphi_{2,Soll} + \Delta\alpha_m$

Causes of step angle errors:

- Manufacturing tolerances of the geometry (pole and tooth geometry, ...)
- Assembly errors (offset between stator and rotor, eccentricities, ...)
- Material defects (inhomogeneities in the sheet metal and magnet material, uneven magnetization of the rotor)

⇒ Typical values for the systemic angle tolerance per step are $\Delta\alpha_S = (0,02..0,10)\alpha_S$ (only measurable)

Electric Drive Technology

3 technologies are suitable for robotics applications

- Permanent magnet excited DC motor as servo drive
- Permanent magnet excited synchronous motor as servo drive (with rectangular or sinusoidal current supply)
- Stepper motor, especially hybrid stepper motor

Open question

Which of these three technologies is best suited for a specific robotic application?

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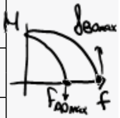
Electric Drive Technology Selection

Parameter	DC Motor	Synchronous Motor	Stepper Motor
Regulation	closed position control loop	closed position control loop	open control chain
Position sensor	required	required	not required
Minimum step angle	2.5×10^{-3}°	2.5×10^{-3}°	0.36° or 14.4×10^{-3}° in microstepping mode ·0.1
Favorable step angle	$\geq 36 \times 10^{-3}$°	$\geq 36 \times 10^{-3}$°	≥ 0.36°
Max Torque	unlimited (for robotics)	unlimited (for robotics)	$\leq 1\,Nm (10\,Nm)$
Operation with load changes	possible	possible	limited possible (dynamic limit characteristic)
Speed / frequency	$20\,000\,min^{-1}$ Due to the contact commutator and the brushes	$100\,000\,min^{-1}$	$\alpha_S \cdot f_{A0max} = 5000\,°\,s^{-1}$ Start-Stop area $\rightsquigarrow 833\,min^{-1}$ $\alpha_S \cdot f_{B0max} = 45\,000\,°\,s^{-1}$ Acceleration area $\rightsquigarrow 7500\,min^{-1}$
EMC behavior	critical (commutation)		
Operating life	Brushes → $5000\,h$	$25\,000\,h$ ← Bearings →	$25\,000\,h$
Cost ranking	∘	−	+



Values without load. They are reduced with the load.

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Select electric drive technology

Servo drives (direct current or synchronous technology) with

+ 10 times higher resolution
+ about 5 times higher dynamics
+ unlimited torques (for robot applications)
– complex control and power electronics
– higher costs

Applications for stepper motors:

- limited torque
- not too high dynamic requirements
- medium resolutions