6 Stepper motors

Stepper motors are a special type of synchronous motor. Due to its functional principle, step-by-step positioning can be achieved only by impulses without position sensors. When excited, they can develop a large holding torque and are robust and low-noise. That is why they are used for simple positioning tasks, including for robots. They require electronics that are matched to the motor and become out of step at high load torques or frequencies. This limits its use to small loads and only medium dynamic requirements.

6.1 Functional principle and design variants

Stepper motors are built in many variants. Figure 6.1 shows the simplest variant (based on the reluctance principle i.e. without permanent magnets). This simplest variant consists of a stator and a rotor with different numbers of teeth (here six stator teeth and four rotor teeth). Coils are wound around each stator tooth. Each 2 coils, which are 180° apart, are connected to form a phase or system. With this geometry (and with stepper motors in general), preferred magnetic positions result when a stator tooth lies opposite a rotor tooth. If the current is switched on, these positions shows negligible torque. The individual phases are cyclically connected to

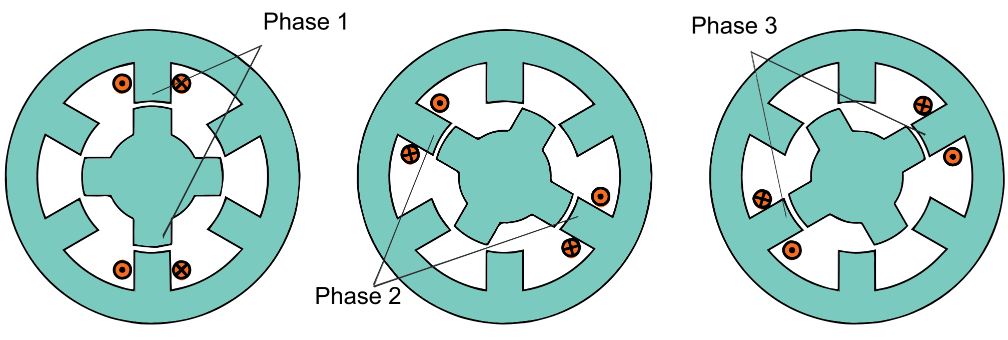

Figure 6.1: Functional principle of stepper motors

a DC voltage source so that the rotor moves from one rest position to the next. This enables position control without a closed loop and position encoder. If the current change between the strands is too fast or the load on the shaft is too high, the stepper motor will lose step and stop.

Characteristic sizes of the stepper motor are:

- 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. There are 2 cases to be distinguished here:
  - Full-step mode: the number of winding phases carrying current is always the same. In this case the number of steps is $z = 2 \cdot p \cdot m$.
  - Half-step mode: the number of winding phases carrying current varies from step to step, resulting in additional rest positions. The number of steps is then $z = 4 \cdot p \cdot m$.
- α: Step size of the motor $\frac{360°}{z}$.

If the number of steps is to be increased, such a stepping motor can be composed of several sub-motors. Another way to achieve smaller step angles is an additional toothing in the stator and rotor (see Figure 6.2).

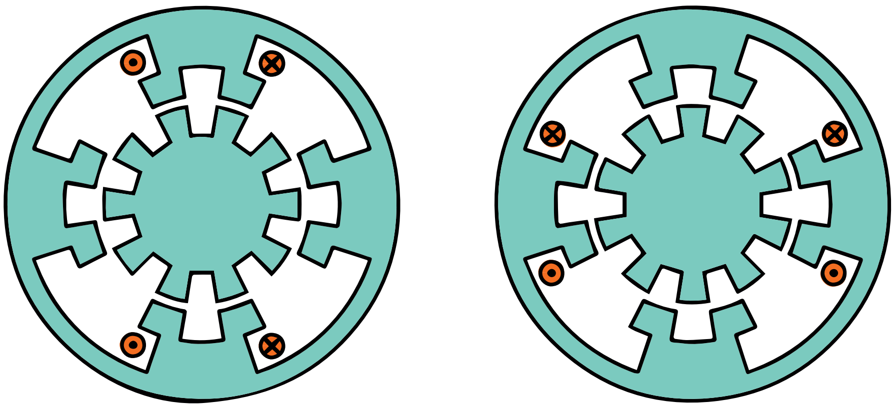

Figure 6.2: Stepper motor with toothed rotor and stator poles

The stepper motors described so far are only excited in the stator. The rotor receives neither an electrical excitation nor a permanent magnetic excitation. Since the torque is only generated by the position-dependent magnetic reluctance, these motors are referred to as VR motors (variable reluctance motors). Stepper motors are sometimes also designed with a permanent magnet excited rotor (PM motor). The combination of both concepts, the hybrid stepper motor (HY motor) is the most frequently used concept.

The functional principle of the hybrid stepper motor is shown in Figure 6.3. The rotor has two soft-magnetic sections, which are arranged axially in the shaft and have the same number of teeth. The second section is offset by half a tooth pitch, so that teeth and slots alternate not only radially but also axially. There is a permanent magnet between the two pole wheels, which is magnetized in the axial direction. The 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 a stator phase is energized, the teeth in each half of the rotor align with the nearest stator tooth of the opposite polarity in the energized pole. Due to the additional excitation with a permanent magnet, hybrid stepper motors have a higher torque than other stepper motors of the same size. In addition, hybrid stepper motors hold a certain torque even without current (cogging torque).

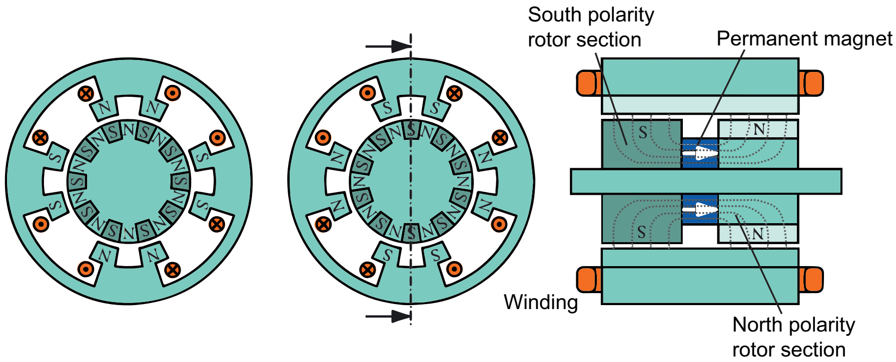

Figure 6.3: Hybrid stepper motor with $m = 1$ system, $2p = 20$ poles $\rightsquigarrow z = 20$

Table 6.1 summarizes the typical step size (for 2 phases) and the holding torque without current for the rotor concepts described. From this it becomes clear why the hybrid concept is dominant.

Rotor Type	Typical Step Size (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

Table 6.1: Comparison rotor concepts

In addition to the most commonly used two-phase version, other numbers of phases are also possible:

- Single-phase versions are often used in clock drives. With rotor diameters of approx. 2 to 4 mm, these motors have a very filigree design, so that practically only two-pole versions come into question here. The single-phase stator winding is designed as a single coil carrying a current whose direction is reversed with the rotational frequency of the rotor (Figure 6.4).
- Three- and five-phase versions are used with hydrid stepper motors in order to achieve minimum step sizes of up to $0.36°$. However, the effort for power electronics and control increases significantly.

6.2 Control

The input signals of a stepper motor are the step signal and the direction signal. The switching signals for the individual transistors are generated from these two input signals in the impulse distributor. Two different controls are possible:

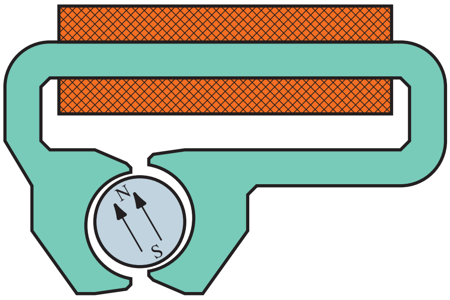

Figure 6.4: Clock drive as single phase stepper motor

- Unipolar control (Figure 6.5): the current direction in a winding is not changed. In order to change the polarization of a phase, two different windings per phase are required. Only one of these can be energized, i.e. only half of the phase, so that the motor utilization is limited. However, the advantage is that only 2 transistors are required per phase.
- Bipolar control (Figure 6.6): the current direction in a winding can be changed so that the entire copper of a phase is used. However, a complete H-bridge with 4 transistors is required per phase for bipolar control.

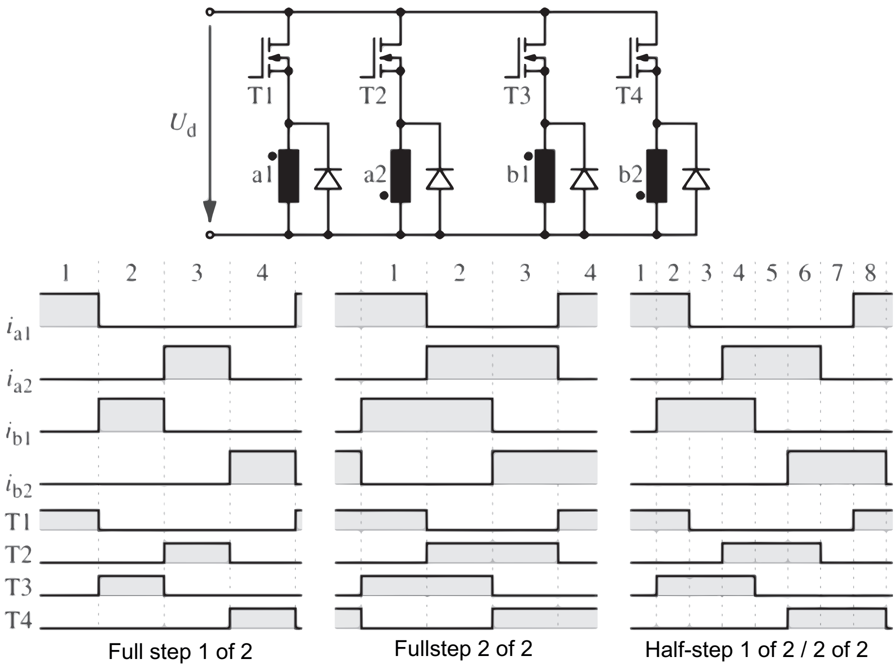

Figure 6.5: Unipolar control of a two-phase configuration

In Figure 6.5 are also the switching signals and the ideal currents for three different operating modes of a unipolar control:

- full-step operation with current in 1 of 2 phases: in the first step, the winding $a1$ is energized by switching on $T1$. In the second step, $T1$ is switched off and by switching on $T3$, the winding $b1$ is energized. In the third step, $T3$ is then switched off and by switching on $T2$, the winding $a2$ is energized, i.e. the

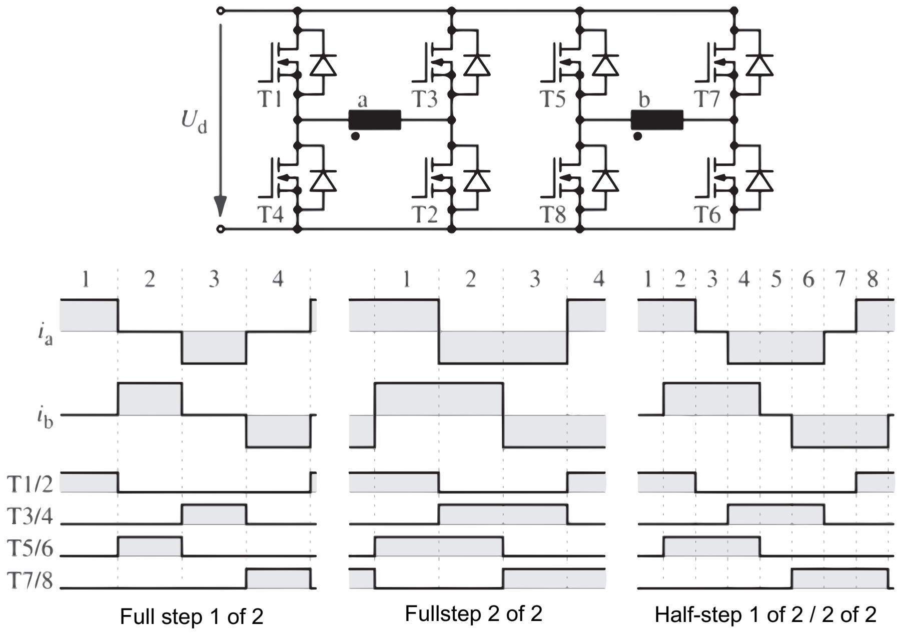

Figure 6.6: Bipolar control of a two-phase configuration

phase a is energized in the opposite direction to step 1. In the last step, then $T2$ is switched off and by switching on $T4$ the winding $b2$ is energized, i.e. the phase b is energized in the opposite direction to step 2.

- Full-step operation with current in 2 of 2 phases: in the first step, the windings $a1$ and $b1$ are energized by switching on $T1$ and $T3$. In the second step, $T1$ is then switched off and by switching on $T2$, the winding $a2$ is energized. The winding $b1$ remains energized. In the third step, $T3$ is switched off and by switching on $T4$, winding $b2$ is energized. The winding $a2$ remains energized. In the last step, $T2$ is switched off and by switching on $T1$, the winding $a1$ is energized. The winding $b2$ remains energized. Compared to operation with 1 of 2 strands, higher holding torques are achieved in this operation, but with correspondingly higher losses per $\mathrm{N} \cdot \mathrm{m}$.

- Half-step operation with current in 1 of 2 phases and 2 of 2 phases: in this operating mode, 8 steps per revolution are possible, i.e. the step size is half as large as in full-step operation. This is achieved in that alternately one phase and two phases are energized and thus intermediate rest positions are generated. In the first step, only phase $a1$ ($T1$ on) is energized. In the second step, phase $b1$ is also energized. In the third step, this alone remains energized since $a1$ is switched off by $T1$. In the fourth step, in addition to $b1$, $a2$ is now also energized ($T2$ on). In the fifth step, $a2$ remains switched on and $b1$ is switched off. In the sixth step, $b2$ ($T4$) is switched on in addition to $a2$. In the seventh step, $b2$ remains switched on alone. In the last step, $a1$ is switched on again in addition to $b2$.

Also for bipolar control, Figure 6.6 contains the switching signals and the ideal currents for the three different operating modes. The transistors are always controlled in pairs ($T1/T2$, $T3/T4$, $T5/T6$ and $T7/T8$):

- full-step operation with current in 1 of 2 phases: in the first step, $T1/2$ are switched on to switch a positive current in string a. In the second step, only a positive current flows in phase b ($T5/6$ switched on). In the third step, the transistors $T3/4$ are switched on, so that a negative current flows in phase a. In the last step, a negative current flows in phase b ($T7/8$ switched on).

- full-step operation with current in 2 of 2 phases: in the first step, $T1/2$ and $T5/6$ are switched on to simultaneously generate a positive current in the phases a and b. In the second step, a positive current continues to flow in line b ($T5/6$ switched on). However, the current in phase a changes polarity by turning $T1/2$ off and $T3/4$ on. In the third step, the current in phase a remains negative ($T3/4$ on) and the current in phase b becomes negative by turning off $T4/5$ and turning on $T6/7$. In the last step, the negative current continues to flow in phase b ($T7/8$ switched on). The current in phase a becomes positive by turning $T3/4$ off and turning on $T1/2$.

- half-step operation with current in 1 of 2 phases or 2 of 2 phases: in this operating mode, 8 steps per revolution are possible as with unipolar control, i.e. the step size is half as large as in full-step operation. In the first step, only a positive current flows in phase a ($T1/2$ switched on). In the second step, the current in phase a remains positive and a positive current also flows in phase b ($T5/6$ switched on). In the third step, current no longer flows in phase a ($T1/2$ switched off). A positive current continues to flow in phase b. In the fourth step, the current in phase b remains positive and a negative current is added in phase b ($T5/6$ switched on). In the fifth step, a negative current continues to flow in phase b, but phase a is de-energized ($T1/2$ switched off). In the sixth step, the negative current remains in phase b and a negative current is added in phase b. In the seventh step, only this negative current remains in phase b (phase a is de-energized by switching off $T3/4$). In the last step, a positive current in phase a is switched on ($T1/2$) and the positive current in phase b remains.

In addition to full-step and half-step operation, operation is also possible in which the different phases are energized with different current values. Any intermediate position can be reached with this microstep or ministep operation. However, the effort in the power electronics increases significantly and the controlled position becomes increasingly imprecise.

The operation of a stepper motor requires constant currents. This can be achieved by a constant current source or by a so-called „chopper“. Similar to the EC motor, a constant current is generated from a voltage source via a hysteresis controller. This is shown in Figure 6.7. Alternatively, pulse width modulation (PWM) can be used, particularly in microstep mode.

In principle, stepper motors are operated with frequencies up to the kilohertz range. In this frequency range, the electrical time constant of the winding plays a role and the current follows an e-function in contrast to Figure 6.5 and Figure 6.6. The increase in current can be accelerated by series resistors in the winding or by additional diodes in parallel with the winding. However, the exponential current curve is preserved and plays a crucial role in dynamic operation, as discussed in the next section.

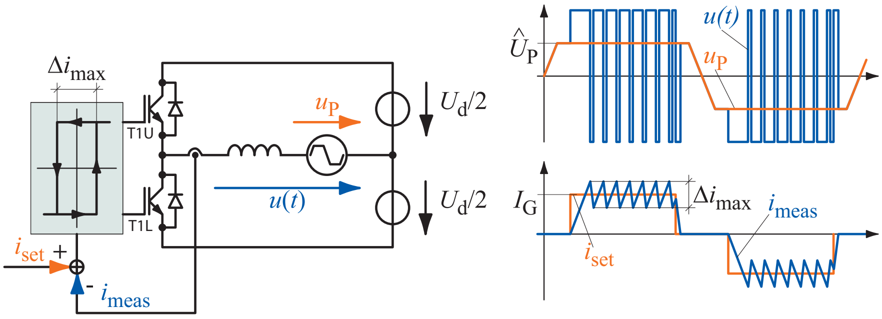

Figure 6.7: Functional principle of a chopper with hysteresis control

6.3 Damping of stepper motors

In the case of stepping motors, running at an absolutely constant speed is not possible, since the rotor always has to move abruptly as a result of the switching on of the individual winding currents. Even if it is desired in the application to move to discrete positions, at the end of a positioning process, a oscillation around the final position can always occur. Appropriate measures must be taken in some applications to reduce these mechanical oscillations around the end position.

In principle, three different damping methods are possible:

- Mechanical damping: in this case,with an additional hollow cylinder attached to the motor shaft, an additional moment of inertia is coupled to the motor shaft via a viscous fluid (oil). As long as this freely rotatable moment of inertia J_D does not have the same speed as the motor shaft, an additional friction torque is generated due to the oil-hydraulic clutch, with which speed changes can be damped (Figure 6.8). Although such mechanical damping elements are quite effective, they are only used very rarely due to the significant additional moment of inertia ($J_D > 4 \cdot J_M$), which reduces the dynamic properties of the drive.

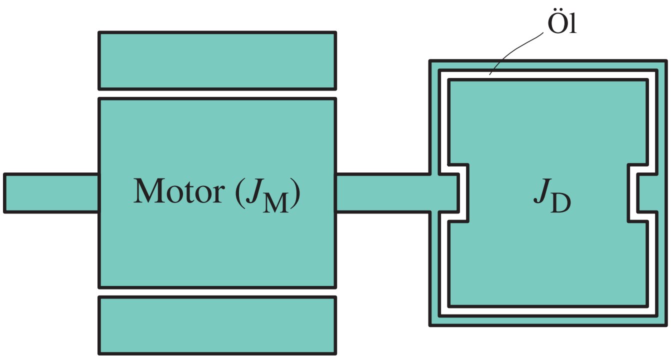

Figure 6.8: Mechanical damping

- Electromagnetic damping: if windings that are not in use are short-circuited, the voltages and currents induced in these windings generate a braking torque when the speed changes, which have a damping effect. However, the electromagnetic damping in stepping motors is very weak because the time constants of the stator windings are always of the same order of magnitude as the mechanical time constant.

- Electronic damping: a method that is used quite frequently nowadays is electronic damping. Here, just before the end position is reached, reverse pulses are generated to brake the stepping motor („back phase damping") or the last control pulse delayed till the end position has just been reached due to overshooting as a result of the penultimate signal („delayed last step")

6.4 Operating behavior

The principle of operation of stepper motors is basically the same as that of synchronous motors. However, the operating behavior differs significantly from that of conventional servomotors. The most important terms related to stepper motors are explained below.

Static torque characteristic

The static torque characteristic describes the torque of the stepper motor at standstill. For the sake of simplicity, this is explained here using a two-pole and three-phase PM stepper motor as an example.

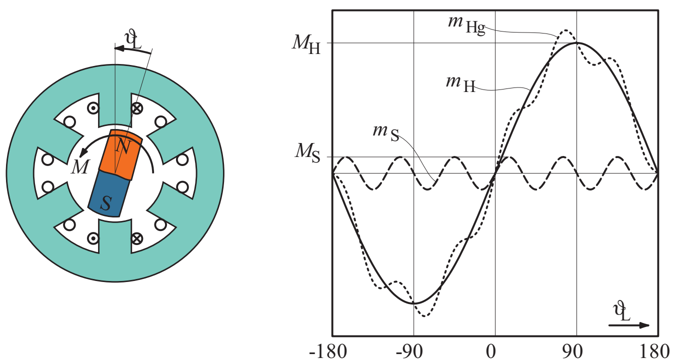

Figure 6.9: Static torque characteristic of a stepper motor (example with $m = 3$, $2p = 2 \rightsquigarrow z = 6$ in full-step operation)

The characteristic is shown in Figure 6.9. In the de-energized state, the motor can already achieve a certain self-holding torque M_S, which, however, is compared to its maximum holding torque M_H significantly smaller. The self-holding torque M_S corresponds to the cogging torque of a permanent-magnet synchronous machine. As a servo drive, the cogging torque is undesired. As a stepper motor, it is used as a holding torque in the de-energized state. If the cogging torque m_S is determined as a function of the rotor position angle Θ_L, a periodic function is obtained. For a two-pole rotor, the number of periods is the number of stator poles. With a higher number of rotor poles, there are correspondingly more periods. A pre-calculation of the cogging torque is usually not sufficiently reliable, so that it can usually only be determined by measurement. The holding torque m_H results when a phase is electrically excited and it is approximately sinusoidal, as in the case of a synchronous machine. The maximum of this curve is called the holding torque M_H, which corresponds to the maximum torque of the synchronous machine. The excited motor can therefore be statically loaded with the holding torque M_H without rotating continuously. The superimposition of both curves results in the total torque curve m_{Hg}, which can only be reliably determined via a measurement. With a completely unloaded motor, the rotor would align itself exactly under the excited poles, as shown above. When the motor is loaded, the static load angle Θ_L increases until the motor and load torque are balanced. If the load torque is greater than the holding torque, the stable position is left. The motor then drops to the next stable point if the load torque has been reduced in the meantime. If this is not the case, the motor will continue to turn in the direction in which it is pushed by the load torque, or if the load torque is passive (e.g. in the case of friction processes), the motor simply stops. If several phases are excited at the same time, their holding torque curves are superimposed to form a resulting torque curve.

A similar static torque characteristic results for a hybrid stepping motor. The only differences are that there are significantly more rest positions and that the function of the holding torque is trapezoidal instead of sinusoidal. This results in less static rotation under load.

Dynamic torque characteristic

The static torque curve can only be assumed with the motor at a standstill. The maximum torque when the motor is running is significantly lower. With increasing speed or step frequency, the electrical time constant, which is large compared to the duration of current flow, becomes so noticeable that the maximum possible current cannot be reached within the duration of current flow. If there are also massive iron parts in the rotor poles, the current increase is additionally impeded by the eddy currents. For this reason, the manufacturer specifies so-called limit frequency characteristics, in which the maximum torque is shown as a function of the step frequency. If these values are exceeded, the stepper motor falls out of step while running and makes at least one step error. Due to the lack of position feedback to the controller, such a step error must be avoided in any case, limitung the values for the step frequency as a function of the load torque.

The step frequency is the number of steps taken per second, while the control frequency is the number of step pulses per second. As long as the stepping motor can accurately follow the driving pulses, the driving frequency is equal to the step frequency. If the step frequency is increased or decreased too quickly, the motor will lose step and a step error will occur.

Figure 6.10 shows the dynamic torque curve of a stepper motor. A distinction is made here between two operating ranges: the start-stop range and the slew range. In the start-stop range, the stepper motor can be started and stopped with any combination of load torque M and stepping frequency f_Z without stepping errors occurring. The slew range can only be approached from the start-stop range by successively increasing the step frequency. Directly approaching the slew area or stopping out of the slew area usually leads to step errors. The limit frequency curve between start-stop and slew area depends on the moment of inertia as it can be seen in the diagram with the curve for $J_L = 0$ and $J_L > 0$. Once the motor has started, after a certain number of start impulses, the system can switch to the slew area. In this operating range, too, the stepping motor is controlled with a constant control frequency. The motor does not usually accelerate in this range, but is operated at an almost constant speed. In some applications (e.g. with high load moments of

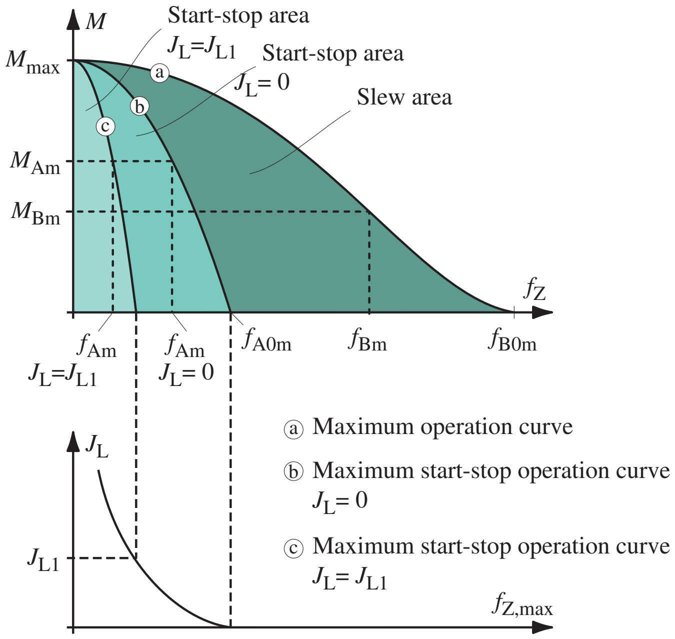

Figure 6.10: Dynamic torque characteristic of a stepper motor

inertia), the control frequency is gradually increased even with a ramp function, so that the motor continues to accelerate from the starting range. As an example, the positioning process and the correspondent control pulses are shown in Figure **??**. The different control frequencies for starting, accelerating and stopping the motor can be seen in this curve.

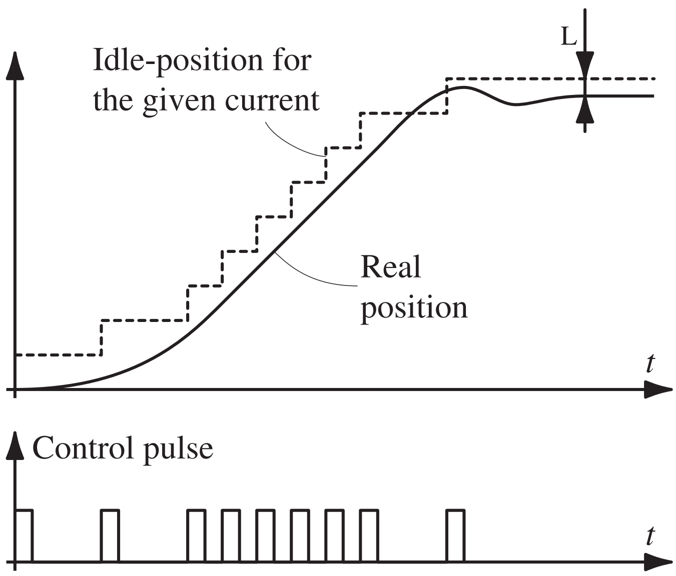

Figure 6.11: Stepper motor positioning process

The parameters shown in Figure 6.10 are defined as follows: **limit starting frequency** f_{Am} is the maximum step frequency as a function of the load moment of inertia and torque with which the motor can start or stop without stepping errors. The maximum torque that the motor can deliver without a step error is referred to as **pull-in torque** M_{Am}. The theoretical absolute limit value for the **maximum starting frequency** f_{A0m} applies for a motor without any load.

The **maximum running frequency** f_{Bm} is the control frequency with which the motor can be controlled without step error at a given **pull-out torque** M_{Bm}. Here, too, a theoretical value for the **maximum running frequency** f_{B0m} for the absolutely idling motor can be specified.

Step angle error

To discuss the positioning accuracy, the deviation between the target and actual value for the rotor position must be considered. One distinguishes between two different angle errors. The largest systematic angular deviation $\Delta\alpha_m$ is the maximum deviation between the absolute setpoint and actual position that can occur during positioning. The systematic angle tolerance per step $\Delta\alpha_S$, on the other hand, is the maximum error that can occur when changing position for an angle $\Delta\varphi$. In extreme cases, this error can be twice as large as the systematic angular deviation, since the rotor can be in position $\varphi_{1,Soll} - \Delta\alpha_m$ at the beginning of the positioning process and reach position $\varphi_{2,Soll} + \Delta\alpha_m$ at the end of the positioning process.

The causes of step angle errors are mainly due to the limited possibilities in production and to material defects. On the one hand, the geometry can only be manufactured with a limited level of accuracy (pole and tooth geometry, asymmetrical magnetic bridges, ...). Furthermore, the assembly of the individual parts is also error prone (offset between stator and rotor, eccentricities, ...). Material defects (inhomogeneities in the sheet metal and magnetic material, uneven magnetization of the rotor) and the application itself (gear defects, different static load angles due to a fluctuating load) can also cause further errors. Many of these causes of step angle errors can only be investigated by measurements, so that the construction of a prototype is much more important than the calculation in comparison to motors and drives of greater power and size. Typical values for the systemic angular tolerance per step are $\Delta\alpha_S = (0,02..0,10)\alpha_S$.

6.5 Selection of the electric drive technology

In the second chapter of this course, the different electric drive concepts were discussed and the following three technologies were identified as suitable for robotic applications:

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

But which of these three technologies is best suited for a specific robotic application? The table 6.5 shows the most important differences from the point of view of the application[1]. This results in servo drive having a resolution that is up to 10 times higher (direct current or synchronous technology), about 5 times higher dynamics and unlimited torques (for robot applications). The complex control and

[1] H.D. Stölting. **Handbuch elektrische Kleinantriebe: mit 36 Tabellen**. Hanser, 2011.

power electronics and the associated higher costs are on the other hand a disadvantage.

The primary area of application for stepper motors results from the combination of the following factors:

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

Parameter	DC Motor	Synchronous Motor	Stepper Motor
Regulation	closed position control loop	closed position control loop	open open control chain
Position sensor	required	required	not required
Minimum step angle	$2.5 \times 10^{-3\circ}$	$2.5 \times 10^{-3\circ}$	$0.36°$ or $14.4 \times 10^{-3\circ}$ in microstepping mode
Favorable step angle	$\geq 36 \times 10^{-3\circ}$	$\geq 36 \times 10^{-3\circ}$	$\geq 0.36°$
Max Torque	unlimited (for robotics)	unlimited (for robotics)	$\leq 1\,\mathrm{Nm}(10\,\mathrm{Nm})$
Operation with load changes	possible	possible	limited possible (dynamic limit characteristic)
Speed / frequency	$20\,000\,\mathrm{min}^{-1}$	$100\,000\,\mathrm{min}^{-1}$	$\alpha_S \cdot f_{A0max} = 5000\,°\,\mathrm{s}^{-1}$ $\rightsquigarrow 833\,\mathrm{min}^{-1}$ $\alpha_S \cdot f_{B0max} = 45\,000\,°\,\mathrm{s}^{-1}$ $\rightsquigarrow 7500\,\mathrm{min}^{-1}$
EMC behavior	critical (commutation)		
Operating life	$5000\,\mathrm{h}$	$25\,000\,\mathrm{h}$	$25\,000\,\mathrm{h}$
Cost ranking	$\circ$	$-$	$+$

6.6 comprehension questions

Q6-1: How does a stepper motor work?
Q6-2: Which rotor types are possible with a stepper motor? Which one is dominant and why?
Q6-3: Does a de-energized stepper motor develop a holding torque?
Q6-4: Draw the static torque characteristic of a stepper motor
Q6-5: What is the start-stop range and slew range of a stepper motor?
Q6-6: What is the difference between full-step, half-step and micro-step operation?
Q6-7: What are the advantages and disadvantages of unipolar control compared to bipolar control?
Q6-8: How is a constant current per phase achieved for stepper motors?
Q6-9: Why are the static and dynamic torque characteristics of a stepper motor different?
Q6-10: What are the advantages and disadvantages of a stepper motor compared to a servo motor?