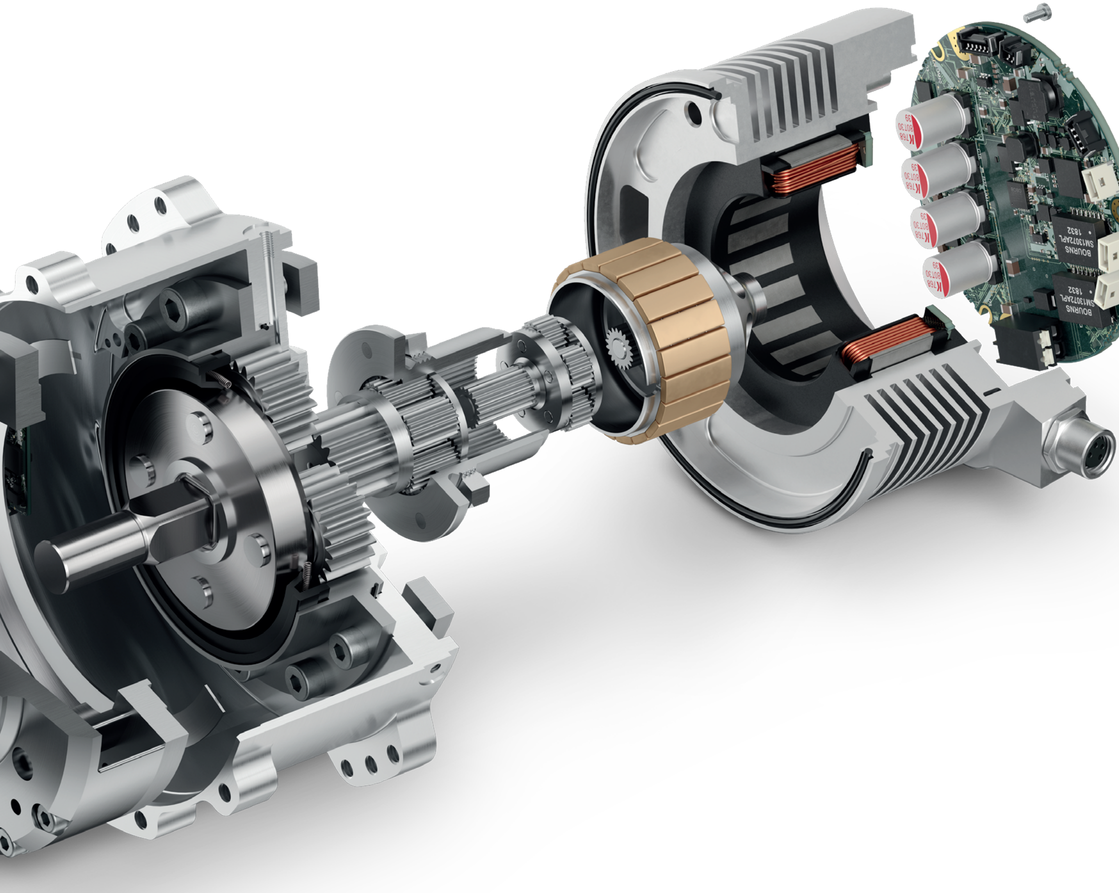
Precision Drive Systems

maxon

# Selection of DC Drives

## Guideline with Calculations



maxon academy

First Edition 2025

# *Preface*

*The core idea behind this work is twofold: on the one hand, it presents a systematic approach to drive selection and on the other hand, it explains the necessary formulas and underlying relationships.*

*The flow chart on page 7 illustrates the systematic approach in six steps, which also serve as the structural foundation of the booklet. Additionally, the respective chapters include the selection criteria and supplementary formulas. Numerous illustrations and the descriptions of the variables on the respective page help the reader to understand the formulas.*

*Roughly speaking, it is a brief overview of the most important selection criteria from the maxon catalog, as well as from the book "The selection of high-precision microdrives," published by maxon academy Verlag.*

*Additionally, you can find various short videos at academy.maxongroup.com.*

**_Acknowledgment_**

*First of all, I would like to thank Dr. Urs Kafader. He supported me in the creation of this book with valuable inputs and made a significant contribution. His experience has shaped this book into what it is today.*

*Although they were not directly involved, I thank all those whose sources I was able to access, especially my (former) colleagues at the maxon Academy: Urs Kafader, Stefan Enz, and Jan Braun.*

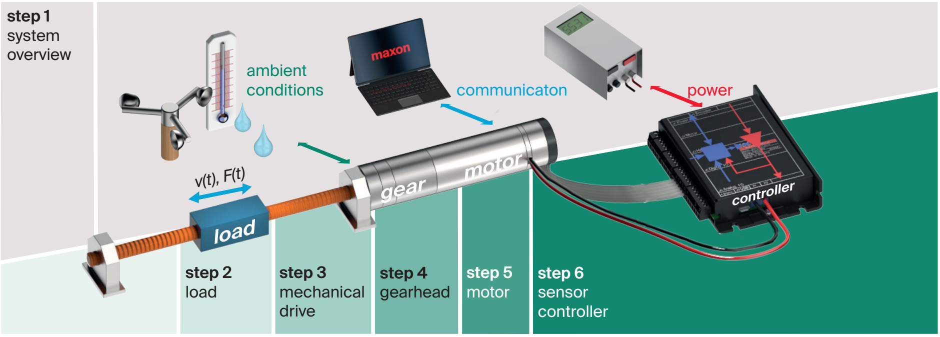
*I would also like to thank Patricia Gabriel for her excellent cooperation and professional implementation and design, as well as Franzisca Hunkeler, Bianca Durrer, Erika Halter, and Jeremias Wieland for creating the illustrations.*

*Without your support, this book would not have been as good.*

*Sachseln, Winter 2025*
*Walter Schmid*

# Contents

# 1. Drive Selection
## 1.1 Selection process




The situation analysis in step 1 considers the drive as a whole together with its environment. The objective is to obtain an overview of the situation, to determine the theoretical feasibility of a solution, and to get a picture of the boundary conditions and special requirements. What type of control is needed, and how will the drive be incorporated into the overall system?

In step 2, the motion of the load is broken down into a few key requirements, like forces/torques and velocities/speeds. How long must they be applied? What is the required control accuracy? *See chapter 1.3 Evaluation of the load movements.*

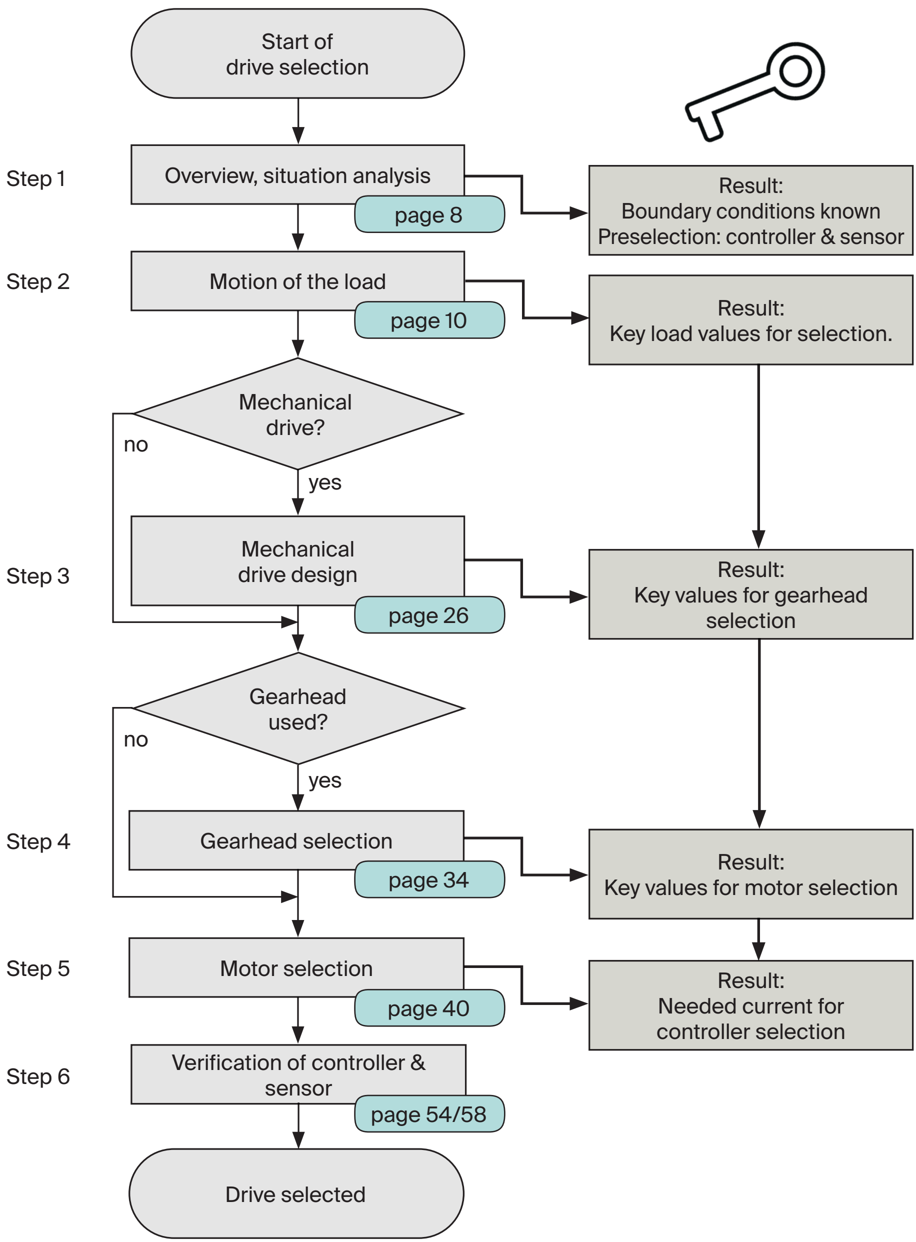
Step 3 focuses on the mechanical drive. The aim is to calculate the output of the gearhead or motor to be selected based on the key values identified in step 2. *See chapter 4. Mechanical Drives*. This step can be skipped if the load is driven directly without needing a mechanical drive.

In step 4, the gearhead is selected. This step is skipped if no (maxon) gearhead is used. Gearheads are typically used for load speeds lower than 1000 rpm. The key data for the motor selection can be calculated from the gearhead reduction and efficiency. *See chapter 5. Gearheads.*

In step 5, suitable motor types are selected based on the torque and speed requirements. The useful life, commutation, and bearing systems also have to be considered. By selecting the appropriate winding, the motor is matched to the existing power supply. *See chapter 6. DC Motors.*

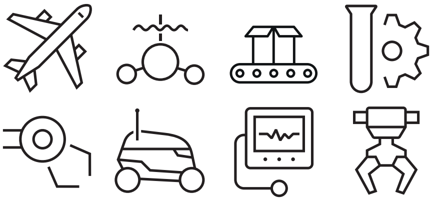
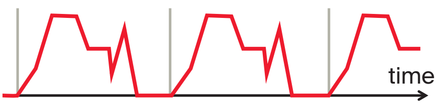
Step 6 involves verifying the controller and sensor selected in advance during the situation analysis (step 1). It is necessary to confirm whether both are compatible with the chosen motor. *See chapter 7. maxon Encoders* and *chapter 8. maxon Controllers.*

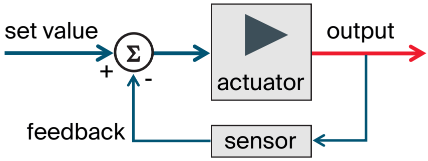
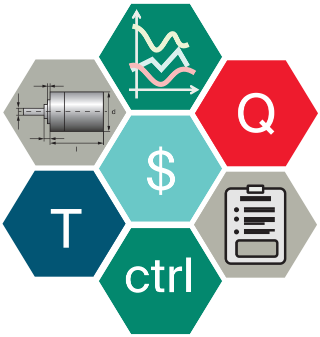
Finding the right drive in 6 steps



## 1.2 Overview, situation analysis (step 1)

Before the actual selection process, the drive situation is evaluated as a whole. The aspects presented below are often closely interconnected and the descriptions are intended to help clarify them and establish a framework for the selection process ahead.

| | |
|---|---|
| **Application** | |
|  | Type of application (pump, plotter, SCARA robot, etc.).<br>Industry-specific requirements.<br>Description of how the drive works.<br>A diagram or sketch provides clarity. |
| **Typical load cycle** | |
|  | Continuous operation (S1) |
|  | Short time operation (S2) |
|  | Duty cycles (S3-S8)<br>Intermittent operation (on – off) (S3) |
| **Mechanical configuration** | |
|  | – mechanical drive (screw, conveyor belt, toothed belt, etc.) or drive combination or direct drive?<br>– bearing loads, mechanical support of forces<br>A diagram or sketch helps avoid misunderstandings. |
| **Verifying the power components** | |
|  | Available electrical power<br>– voltage<br>– current<br>Sufficient for all operating conditions? |

| Control concept (chapter 8) | |
|---|---|
|   | – variable: current, speed, position?<br>– control accuracy?<br>– sensor type?<br>– communication: where do the commands and set values come from?<br><br>Result: preliminary selection of potential controllers and sensors; see selection step 6. |
| **Determining the boundary conditions** | |
|   | How can the drive be designed to be as cost-effective as possible and still meet the specifications regarding technology and service life, as well as the normative requirements and quality standards?<br><br>Are there any restrictions on the dimensions? Are there special environmental conditions? |

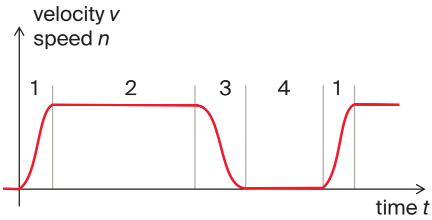
For detailed information, refer to the book “The selection of high-precision microdrives”, chapter 3.

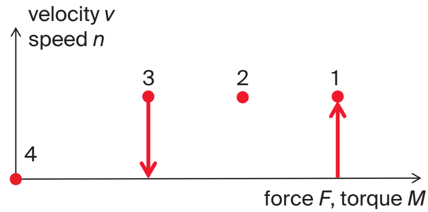
 

## 1.3 Evaluation of the load movements (step 2)

The power requirements depend on the load movements to be carried out. The motion profiles, along with the operating times, form the basis for the subsequent drive selection.

### Operating points




The operating points (value pairs of torque and speed or force and velocity) are determined by the motion profiles.

For the respective total forces/torques, components from friction, acceleration, and constant forces or torques (e.g. gravity or springs) must be taken into account.

Typically, an accuracy of about 10% is sufficient for the selection process.

→ Guidelines and calculation formulas can be found in chapters 2 and 3.

### Average effective load

To find the effective load, the load torque values (friction, acceleration, etc.) from all phases of the cycle, including dwell, are determined, and the time-weighted root mean square is calculated.

**Continuous operation (S1)**


Continuous operation for several minutes

$$F_{L,eff} = F_{L,cont}$$

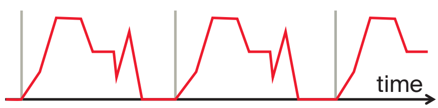
$$M_{L,eff} = M_{L,cont}$$

**Short time operation (S2)**


$$F_{L,eff} = F_{L,RMS} = \sqrt{\frac{t_{on}}{t_{tot}}} \cdot F_{L,on}$$

$$M_{L,eff} = M_{L,RMS} = \sqrt{\frac{t_{on}}{t_{tot}}} \cdot M_{L,on}$$

**Duty cycles (S3-S8)**




$$F_{L,eff} = F_{L,RMS} = \sqrt{\frac{(t_1 \cdot F_1^2) + (t_2 \cdot F_2^2) + ... + (t_n \cdot F_n^2)}{t_{tot}}}$$

$$M_{L,eff} = M_{L,RMS} = \sqrt{\frac{(t_1 \cdot M_1^2) + (t_2 \cdot M_2^2) + ... + (t_n \cdot M_n^2)}{t_{tot}}}$$

## 1.4 Key parameters for selection

As a result and summary of the situation analysis (step 1) and load evaluation (step 2), the parameters relevant for selecting the drive can be identified.

### Key parameters of the situation analysis

Electrical power from power supply
- voltage $U$
- current $I$

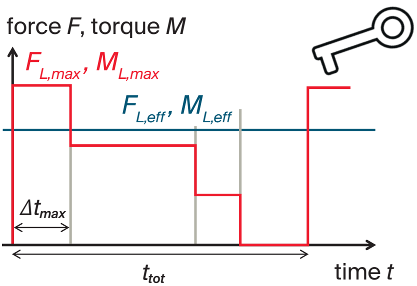
Controller family
- ESCON servo controller
- EPOS positioning controller
- etc.

Sensor type (encoder, Hall sensors, etc.)
- encoder type and resolution range
- etc.

Control accuracy

| | |
|---|---|
| – desired positioning resolution | $\Delta s_L, \Delta\varphi_L$ |
| – required speed accuracy | $\Delta v_L, \Delta n_L$ |

### Key values for the load evaluation



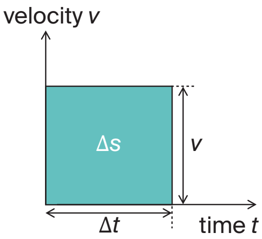

| | |
|---|---|
| – max. velocity or speed | $v_{L,max}$, $n_{L,max}$ |
| – max. load | $F_{L,max}$, $M_{L,max}$ |
| – duration of the max. load | $\Delta t_{max}$ |
| – average effective load | $F_{L,eff}$, $M_{L,eff}$ |
| – max. power | $P_{L,max}$ |
| – bearing and shaft loads | |

- For information on the load evaluation, refer to chapters 2 and 3.
- Next step of the drive selection in chapter 4 (mechanical drives)

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_{L,eff}$ | Effective value of the force | N | $P_{L,max}$ | Maximum power | W |
| $F_{L,cont}$ | Force in continuous operation | N | $v_{L,max}$ | Maximum velocity | m/s |
| $F_{L,RMS}$ | Root mean square | N | $n_{L,max}$ | Maximum speed | rpm |
| $F_{L,max}$ | Maximum force | N | $t$ | Time | s |
| $F_1 \ldots F_n$ | Individual forces in cycle | N | $t_{tot}$ | Total cycle time | s |
| $M_{L,eff}$ | Effective value of the torque | Nm | $t_{on}$ | ON time | s |
| $M_{L,cont}$ | Torque in continuous operation | Nm | $\Delta t_{max}$ | Duration of maximum load | s |
| $M_{L,RMS}$ | Root mean square | Nm | $t_1 \ldots t_n$ | Individual durations in cycle | s |
| $M_{L,max}$ | Maximum torque | Nm | $\Delta s_L$ | Desired positioning resolution | m |
| $M_1 \ldots M_n$ | Individual torques in cycle | Nm | $\Delta\varphi_L$ | Desired positioning resolution | rad |
| $\Delta v_L$ | Required velocity accuracy | m/s | $\Delta n_L$ | Required speed accuracy | rpm |

# 2. Kinematics
## 2.1 Linear (translative) motion

### Uniform motion



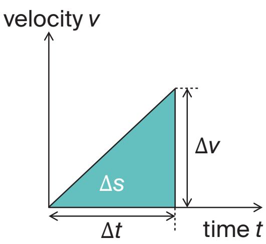

Velocity v = constant

[v] = m/s

(1 m/s = 3.6 km/h)

$$v = \frac{\Delta s}{\Delta t} \qquad \Delta s = v \cdot \Delta t \qquad \Delta t = \frac{\Delta s}{v}$$

### Constant acceleration from a standstill




Acceleration a = constant

[$a$] = m/s²

$$a = \frac{\Delta v}{\Delta t} \qquad \Delta v = a \cdot \Delta t \qquad \Delta t = \frac{\Delta v}{a}$$

$$\Delta s = \frac{1}{2} \cdot a \cdot \Delta t^2$$

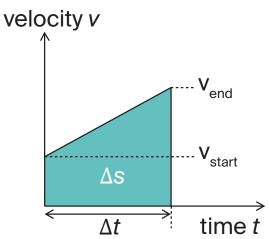
Free fall

$g$ = 9.81 m/s²

$$g = \frac{\Delta v}{\Delta t} \qquad \Delta v = g \cdot \Delta t \qquad \Delta t = \frac{\Delta v}{g}$$

$$h = \frac{1}{2} \cdot g \cdot \Delta t^2$$

### Constant acceleration from initial velocity




$$v_{end} = v_{start} + a \cdot \Delta t$$

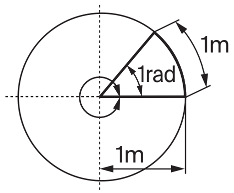
$$\Delta s = v_{start} \cdot \Delta t + \frac{1}{2} \cdot a \cdot \Delta t^2$$

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $a$ | Acceleration | m/s² | $t$, $\Delta t$ | Time, duration | s |
| $g$ | Gravitational acceleration | m/s² | $v$, $\Delta v$ | Velocity, velocity change | m/s |
| $h$ | Drop height | m | $v_{end}$ | Velocity after acceleration | m/s |
| $\Delta s$ | Distance change | m | $v_{start}$ | Velocity before acceleration | m/s |

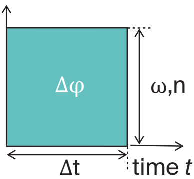
**Note:**
– The shaded areas represent the distance $\Delta s$ traveled during time period $\Delta t$.

## 2.2 Rotary motion

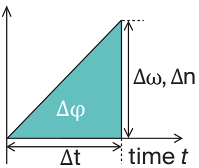
**General**

| | | |
|---|---|---|
|  | Conversion between radian and degrees (the unit rad is often omitted.) | $1\text{ rad} = \frac{360°}{2\pi} = 57.2958°$ <br> $1° = \frac{2\pi\text{ rad}}{360} = 0.01745\text{ rad}$ |
| | Conversion between angular velocity and speed | $\omega = \frac{\pi}{30} \cdot n \quad n = \frac{30}{\pi} \cdot \omega$ |

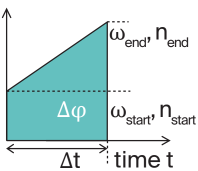
**Uniform motion**

| | | |
|---|---|---|
| angular velocity ω, speed n  | Angular velocity $\omega$ = constant <br> $[\omega]$ = rad/s | $\omega = \frac{\Delta\varphi}{\Delta t} \quad \Delta\varphi = \omega \cdot \Delta t \quad \Delta t = \frac{\Delta\varphi}{\omega}$ |
| | Speed n = constant <br> [n] = 1/min = rpm | $n = \frac{30}{\pi} \cdot \frac{\Delta\varphi}{\Delta t}$ |

**Constant acceleration from standstill**

| | | |
|---|---|---|
| angular velocity ω, speed n  | Acceleration $\alpha$ = constant <br> $[\alpha]$ = rad/s² | $\alpha = \frac{\Delta\omega}{\Delta t} \quad \Delta\omega = \alpha \cdot \Delta t \quad \Delta t = \frac{\Delta\omega}{\alpha}$ <br> $\Delta n = \frac{30}{\pi} \cdot \alpha \cdot \Delta t$ |
| | | $\Delta\varphi = \frac{1}{2} \cdot \alpha \cdot \Delta t^2 = \frac{1}{2} \cdot \frac{\pi}{30} \cdot \Delta n \cdot \Delta t$ |

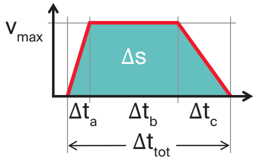
**Constant acceleration from initial speed**

| | | |
|---|---|---|
| angular velocity ω, speed n  | | $\omega_{end} = \omega_{start} + \alpha \cdot \Delta t$ <br> $n_{end} = n_{start} + \frac{30}{\pi} \cdot \alpha \cdot \Delta t$ |
| | | $\Delta\varphi = \omega_{start} \cdot \Delta t + \frac{1}{2} \cdot \alpha \cdot \Delta t^2$ <br> $\Delta\varphi = \frac{\pi}{30} \cdot n_{start} \cdot \Delta t + \frac{\pi}{60} \cdot \Delta n \cdot \Delta t$ |

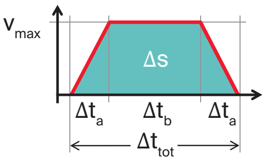
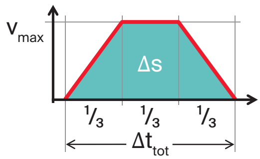
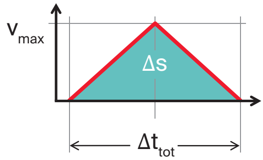
| Symbol | Name | Unit | Symbol | Name | maxon |
|---|---|---|---|---|---|
| $\alpha$ | Angular acceleration | rad/s² | $t, \Delta t$ | Time, duration | s |
| $\Delta\varphi$ | Rotation angle change | rad | $n, \Delta n$ | Speed, speed change | rpm |
| $\omega, \Delta\omega$ | Angular velocity (change) | rad/s | $n_{end}$ | Speed after acceleration | rpm |
| $\omega_{end}$ | Angular velocity after acceleration | rad/s | $n_{start}$ | Speed before acceleration | rpm |
| $\omega_{start}$ | Angular velocity before acceleration | rad/s | | | |

**Notes:**
- The shaded areas represent the rotation angle $\Delta\varphi$ traveled during time period $\Delta t$.
- Angle of rotation $\Delta\varphi = 2\pi$ rad · number of revolutions = 360° · number of revolutions

## 2.3 Typical linear (translative) motion profiles

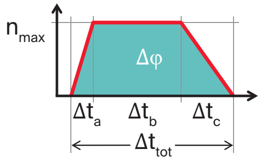
| Profile | General |
|---|---|
| **Suitability** | **Adapted acceleration and decceleration ramps** |
| **Graph** |  |
| **Task:** | |
| Travel a distance $\Delta s$ in time $\Delta t_{tot}$ | $v_{max} = \frac{\Delta s}{\Delta t_{tot} - \frac{\Delta t_a + \Delta t_c}{2}}$ <br> $a_{max} = \frac{v_{max}}{\Delta t_{a,c}}$ |
| Travel a distance $\Delta s$ at maximum velocity $v_{max}$ | $\Delta t_{tot} = \frac{\Delta s}{v_{max}} + \frac{\Delta t_a + \Delta t_c}{2}$ <br> $a_{max} = \frac{v_{max}}{\Delta t_{a,c}}$ |
| Travel a distance $\Delta s$ at maximum acceleration $a_{max}$ | |
| Complete motion in time $\Delta t_{tot}$ at maximum velocity $v_{max}$ | $\Delta s = \left(\frac{\Delta t_a + \Delta t_c}{2} + \Delta t_b\right) \cdot v_{max}$ <br> $a_{max} = \frac{v_{max}}{\Delta t_{a,c}}$ |
| Complete motion in time $\Delta t_{tot}$ at maximum acceleration $a_{max}$ | |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $a_{max}$ | Maximum acceleration | m/s² | $\Delta t_{a,b,c}$ | Section times | s |
| $v_{max}$ | Maximum velocity | m/s | $\Delta t_{tot}$ | Total time | s |
| $\Delta s$ | Distance change | m | | | |

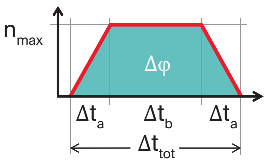
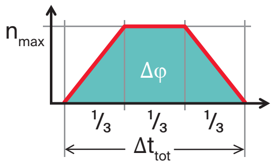
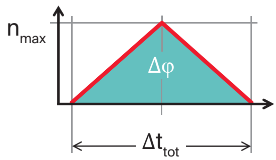
| Symmetrical | 3/3 Trapezoidal | Triangle |
|---|---|---|
| **Continuous motion** | **Efficient motion**<br>Optimized for<br>– minimum power<br>– minimum losses<br>Mostly thermally advantageous | **Fast movement**<br>Optimized for<br>– minimum acceleration<br>– minimum torque<br>– minimum time |
|  |  |  |
| | | |
| $v_{max} = \frac{\Delta s}{(\Delta t_{tot} - \Delta t_a)}$<br>$a_{max} = \frac{\Delta s}{(\Delta t_{tot} - \Delta t_a) \cdot \Delta t_a}$ | $v_{max} = 1.5 \cdot \frac{\Delta s}{\Delta t_{tot}}$<br>$a_{max} = 4.5 \cdot \frac{\Delta s}{\Delta t_{tot}^2}$ | $v_{max} = 2 \cdot \frac{\Delta s}{\Delta t_{tot}}$<br>$a_{max} = 4 \cdot \frac{\Delta s}{\Delta t_{tot}^2}$ |
| $\Delta t_{tot} = \frac{\Delta s}{v_{max}} + \Delta t_a$<br>$a_{max} = \frac{v_{max}}{\Delta t_a}$ | $\Delta t_{tot} = 1.5 \cdot \frac{\Delta s}{v_{max}}$<br>$a_{max} = 2 \cdot \frac{v_{max}^2}{\Delta s}$ | $\Delta t_{tot} = 2 \cdot \frac{\Delta s}{v_{max}}$<br>$a_{max} = \frac{v_{max}^2}{\Delta s}$ |
| $\Delta t_{tot} = \frac{\Delta s}{a_{max} \cdot \Delta t_a} + \Delta t_a$<br>$v_{max} = a_{max} \cdot \Delta t_a$ | $\Delta t_{tot} = \frac{3}{\sqrt{2}} \cdot \sqrt{\frac{\Delta s}{a_{max}}}$<br>$v_{max} = \frac{1}{\sqrt{2}} \cdot \sqrt{\Delta s \cdot a_{max}}$ | $\Delta t_{tot} = 2 \cdot \sqrt{\frac{\Delta s}{a_{max}}}$<br>$v_{max} = \sqrt{\Delta s \cdot a_{max}}$ |
| $\Delta s = (\Delta t_{tot} - \Delta t_a) \cdot v_{max}$<br>$a_{max} = \frac{v_{max}}{\Delta t_a}$ | $\Delta s = \frac{2}{3} \cdot \Delta t_{tot} \cdot v_{max}$<br>$a_{max} = 3 \cdot \frac{v_{max}}{\Delta t_{tot}}$ | $\Delta s = \frac{1}{2} \cdot \Delta t_{tot} \cdot v_{max}$<br>$a_{max} = 2 \cdot \frac{v_{max}}{\Delta t_{tot}}$ |
| $\Delta s = a_{max} \cdot (\Delta t_{tot} - \Delta t_a) \cdot \Delta t_a$<br>$v_{max} = a_{max} \cdot \Delta t_a$ | $\Delta s = \frac{2}{9} \cdot a_{max} \cdot \Delta t_{tot}^2$<br>$v_{max} = \frac{1}{3} \cdot a_{max} \cdot \Delta t_{tot}$ | $\Delta s = \frac{1}{4} \cdot a_{max} \cdot \Delta t_{tot}^2$<br>$v_{max} = \frac{1}{2} \cdot a_{max} \cdot \Delta t_{tot}$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $a_{max}$ | Maximum acceleration | m/s² | $\Delta t_{a,b,c}$ | Section times | s |
| $v_{max}$ | Maximum velocity | m/s | $\Delta t_{tot}$ | Total time | s |
| $\Delta s$ | Distance change | m | | | |

## 2.4 Typical rotary motion profiles

| Profile | General |
|---|---|
| **Suitability** | **Adapted acceleration and decceleration ramps** |
| **Graph** |  |
| **Task:** | |
| Travel an angle $\Delta\varphi$ in time $\Delta t_{tot}$ | $n_{max} = \frac{30}{\pi} \cdot \frac{\Delta\varphi}{\Delta t_{tot} - \frac{\Delta t_a + \Delta t_c}{2}}$ <br> $\alpha_{max} = \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_{a,c}}$ |
| Travel an angle $\Delta\varphi$ at maximum speed $n_{max}$ | $\Delta t_{tot} = \frac{30}{\pi} \cdot \frac{\Delta\varphi}{n_{max}} + \frac{\Delta t_a + \Delta t_c}{2}$ <br> $\alpha_{max} = \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_{a,c}}$ |
| Travel an angle $\Delta\varphi$ at maximum angular acceleration $\alpha_{max}$ | |
| Complete motion in time $\Delta t_{tot}$ at maximum speed $n_{max}$ | $\Delta\varphi = \frac{\pi}{30} \cdot n_{max} \cdot \left(\frac{\Delta t_a + \Delta t_c}{2} + \Delta t_b\right)$ <br> $\alpha_{max} = \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_{a,c}}$ |
| Complete motion in time $\Delta t_{tot}$ at maximum angular acceleration $\alpha_{max}$ | |

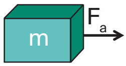
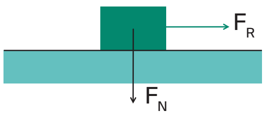
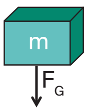
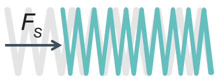
| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $\alpha_{max}$ | Maximum angular acceleration | rad/s² | $\Delta t_{a,b,c}$ | Section times | s |
| $n_{max}$ | Maximum speed in load cycle | rpm | $\Delta t_{tot}$ | Total time | s |
| $\Delta\varphi$ | Rotation angle change | rad | | | |

<table>
<tr><th>Symmetrical</th><th>3/3 Trapezoidal</th><th>Triangle</th></tr>
<tr><td>Continuous motion</td><td>Efficient motion<br>Optimized for<br>– minimum power<br>– minimum losses<br>Mostly thermally advantageous</td><td>Fast movement<br>Optimized for<br>– minimum acceleration<br>– minimum torque<br>– minimum time</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>$n_{max} = \frac{30}{\pi} \cdot \frac{\Delta\varphi}{(\Delta t_{tot} - \Delta t_a)}$<br>$\alpha_{max} = \frac{\Delta\varphi}{(\Delta t_{tot} - \Delta t_a) \cdot \Delta t_a}$</td><td>$n_{max} = 1.5 \cdot \frac{30}{\pi} \cdot \frac{\Delta\varphi}{\Delta t_{tot}}$<br>$\alpha_{max} = 4.5 \cdot \frac{\Delta\varphi}{\Delta t_{tot}^2}$</td><td>$n_{max} = 2 \cdot \frac{30}{\pi} \cdot \frac{\Delta\varphi}{\Delta t_{tot}}$<br>$\alpha_{max} = 4 \cdot \frac{\Delta\varphi}{\Delta t_{tot}^2}$</td></tr>
<tr><td>$\Delta t_{tot} = \frac{30}{\pi} \cdot \frac{\Delta\varphi}{n_{max}} + \Delta t_a$<br>$\alpha_{max} = \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_a}$</td><td>$\Delta t_{tot} = 1.5 \cdot \frac{30}{\pi} \cdot \frac{\Delta\varphi}{n_{max}}$<br>$\alpha_{max} = 2 \cdot \frac{\pi^2}{30^2} \cdot \frac{n_{max}^2}{\Delta\varphi}$</td><td>$\Delta t_{tot} = 2 \cdot \frac{30}{\pi} \cdot \frac{\Delta\varphi}{n_{max}}$<br>$\alpha_{max} = \frac{\pi^2}{30^2} \cdot \frac{n_{max}^2}{\Delta\varphi}$</td></tr>
<tr><td>$\Delta t_{tot} = \frac{\Delta\varphi}{\alpha_{max} \cdot \Delta t_a} + \Delta t_a$<br>$n_{max} = \frac{30}{\pi} \cdot \alpha_{max} \cdot \Delta t_a$</td><td>$\Delta t_{tot} = \frac{3}{\sqrt{2}} \cdot \sqrt{\frac{\Delta\varphi}{\alpha_{max}}}$<br>$n_{max} = \frac{1}{\sqrt{2}} \cdot \frac{30}{\pi} \cdot \sqrt{\Delta\varphi \cdot \alpha_{max}}$</td><td>$\Delta t_{tot} = 2 \cdot \sqrt{\frac{\Delta\varphi}{\alpha_{max}}}$<br>$n_{max} = \frac{30}{\pi} \sqrt{\Delta\varphi \cdot \alpha_{max}}$</td></tr>
<tr><td>$\Delta\varphi = \frac{\pi}{30} \cdot n_{max} \cdot (\Delta t_{tot} - \Delta t_a)$<br>$\alpha_{max} = \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_a}$</td><td>$\Delta\varphi = \frac{2}{3} \cdot \frac{\pi}{30} \cdot n_{max} \cdot \Delta t_{tot}$<br>$\alpha_{max} = 3 \cdot \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_{tot}}$</td><td>$\Delta\varphi = \frac{1}{2} \cdot \frac{\pi}{30} \cdot n_{max} \cdot \Delta t_{tot}$<br>$\alpha_{max} = 2 \cdot \frac{\pi}{30} \cdot \frac{n_{max}}{\Delta t_{tot}}$</td></tr>
<tr><td>$\Delta\varphi = \alpha_{max} \cdot (\Delta t_{tot} - \Delta t_a) \cdot \Delta t_a$<br>$n_{max} = \frac{30}{\pi} \cdot \alpha_{max} \cdot \Delta t_a$</td><td>$\Delta\varphi = \frac{2}{9} \cdot \alpha_{max} \cdot \Delta t_{tot}^2$<br>$n_{max} = \frac{1}{3} \cdot \frac{30}{\pi} \cdot \alpha_{max} \cdot \Delta t_{tot}$</td><td>$\Delta\varphi = \frac{1}{4} \cdot \alpha_{max} \cdot \Delta t_{tot}^2$<br>$n_{max} = \frac{1}{2} \cdot \frac{30}{\pi} \cdot \alpha_{max} \cdot \Delta t_{tot}$</td></tr>
</table>

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $\alpha_{max}$ | Maximum angular acceleration | rad/s² | $\Delta t_{a,b,c}$ | Section times | s |
| $n_{max}$ | Maximum speed in load cycle | rpm | $\Delta t_{tot}$ | Total time | s |
| $\Delta\varphi$ | Rotation angle change | rad | | | |

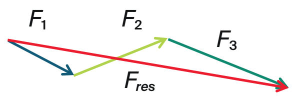
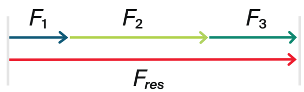
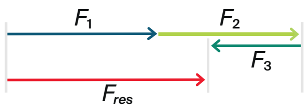
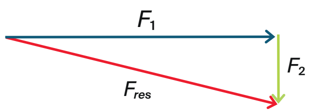
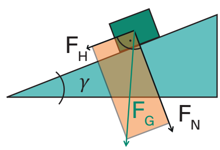
# 3. Force, Torque and Power
## 3.1 General information: forces

The force required to accelerate a mass of 1 kg by 1 m/s within 1 s has the unit kg · m/s², with the special unit name Newton (N).

| Typical partial forces in drive systems | | |
|---|---|---|
|  | Force for acceleration = mass · acceleration<br>$1\,N = 1\,kg \cdot \frac{m}{s^2} = 1\,\frac{kg \cdot m}{s^2}$ | $F_a = m \cdot a = m \cdot \frac{\Delta v}{\Delta t}$ |
|  | Friction force = Friction coefficient · normal force | $F_R = \mu \cdot F_N$ |
|  | Gravity (gravitational acceleration)<br>$g = 9.81\,\frac{m}{s^2} = 9.81\,\frac{N}{kg}$ | $F_G = m \cdot g$ |
|  | Spring force (compression, extension springs) = spring constant · deflection | $F_S = k \cdot \Delta l$ |
|  | Compressive force<br>$1\,bar = 100\,000\,Pa = 10\,\frac{N}{cm^2}$<br>$1\,Pa = 1\,\frac{N}{m^2} = 10^{-5}\,bar$ | $F_p = p \cdot A$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $\Delta v$ | Velocity change | m/s | $a$ | Acceleration | m/s² |
| $\Delta t$ | Duration | s | $g$ | Gravitational acceleration | m/s² |
| $F$ | Force | N | $m$ | Mass | kg |
| $F_a$ | Acceleration force | N | $\mu$ | Friction coefficient (chapter 3.3) | |
| $F_R$ | Friction force | N | $k$ | Spring constant | N/m |
| $F_G$ | Weight force of the body | N | $\Delta l$ | Deflection from rest position | m |
| $F_S$ | Spring force | N | $p$ | Pressure (1 Pa = 1 N/m² = $10^{-5}$ bar) | Pa |
| $F_P$ | Compressive force | N | $A$ | Cross-sectional area | m² |
| $F_N$ | Normal force (perpendicular to the plane) | N | | | |

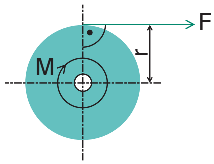
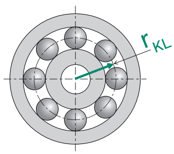
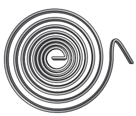
Two or more forces acting simultaneously on a body can be replaced by a single resulting force $F_{res}$. The direction and amount (strength) of the resulting force can be determined graphically. Forces pointing in different directions are added by means of a parallelogram or triangle of forces.

| Addition of partial forces | | |
|---|---|---|
|  | Vector addition | |
|  | Addition of forces acting in the same direction | $F_{res} = F_1 + F_2 + ... + F_x$ |
|  | Addition of forces acting in opposite directions | $F_{res} = F_1 + F_2 - F_3 - ... - F_x$ |
|  | Addition of perpendicular forces | $F_{res} = \sqrt{F_1^2 + F_2^2}$ |
| **Forces on the inclined plane** | | |
|  | Division of the gravitational force $F_G$ on the inclined plane into downhill-slope force $F_H$ and normal force $F_N$ | $F_H = F_G \cdot \sin\gamma$<br>$F_N = F_G \cdot \cos\gamma$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_1, F_2, F_3$ | Partial forces | N | $F_G$ | Weight force of a body | N |
| $F_x$ | Additional partial forces | N | $F_N$ | Normal force (perpendicular to the plane) | N |
| $F_{res}$ | Resulting force | N | $F_H$ | Downhill-slope force | N |
| | | | $\gamma$ | Angle of the inclined plane | ° |

## 3.2 Torques in general

The torque is a measure of the rotational effect that a force exerts on a rotating system. It plays the same role for rotation that the force plays for linear motion. The equations always apply for a defined axis of rotation.

| General | | |
|---|---|---|
|   | Torque = force · lever arm<br><br>[*M*] = N · m = Nm | $M = F \cdot r$ |
| **Typical partial torques in drive systems** | | |
| Torque for acceleration of moments of inertia<br>Torque = moment of inertia · angular acceleration<br><br>(For information on calculating moments of inertia, see chapter 3.4) | | $M_\alpha = J \cdot \alpha = J \cdot \frac{\Delta\omega}{\Delta t} = J \cdot \frac{\pi}{30} \cdot \frac{\Delta n}{\Delta t}$ |
|   | Friction of ball bearing and sintered sleeve bearing (simplified) | $M_R = \mu \cdot F_{KL} \cdot r_{KL}$ |
|  | Torque of spiral or leg springs | $M_S = k_m \cdot \Delta\varphi$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $\Delta n$ | Speed change | rpm | $r$ | Radius | m |
| $\Delta\omega$ | Angular velocity change | rad/s | $r_{KL}$ | Mean radius bearing | m |
| $F$ | Force | N | $J$ | Moment of inertia | kg m$^2$ |
| $F_{KL}$ | Bearing load, axial / radial | N | $\alpha$ | Angular acceleration | rad/s$^2$ |
| $M$ | Torque | Nm | $\Delta t$ | Duration | s |
| $M_\alpha$ | Torque for acceleration | Nm | $\mu$ | Coefficient of friction (chapter 3.3) | |
| $M_R$ | Friction torque | Nm | $k_m$ | Torsion coefficient (spring constant) | Nm/rad |
| $M_S$ | Torque, spiral spring | Nm | $\Delta\varphi$ | Rotation angle change | rad |

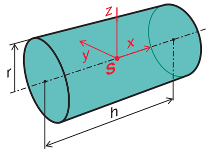
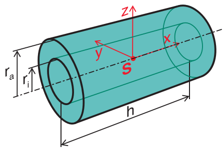
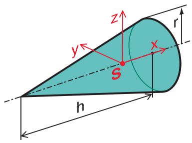
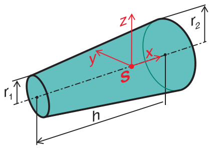
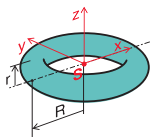
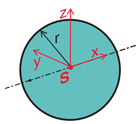
## 3.3 Typical coefficients of friction for rolling, kinetic and static friction

Frictional forces are always directed against the movement of the body. This leads to a slowing down of the body. The origin of friction lies in the surface condition of the bodies. This list shows typical figures for coefficients of friction.

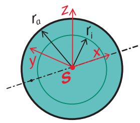
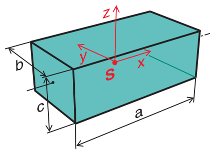
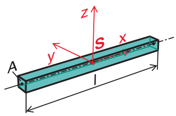
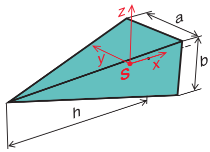
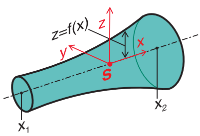
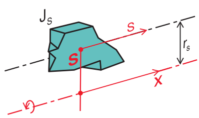
| Rolling friction | | |
|---|---|---|
| **Rolling friction**<br>Bodies separated by lubricated roller bearings | Typical coefficient of friction μ:<br><br>Example:<br>– ball bearing | 0.001 … 0.005<br><br><br>0.001 … 0.0025 |
| **Combined rolling and sliding friction**<br>Rolling friction with a kinetic component | Typical coefficient of friction μ: | 0.001 … 0.1 |
| Kinetic (sliding) friction | | |
| **Solid-to-solid friction** (dry friction)<br>Direct contact between the friction partners | Typical coefficient of friction μ:<br><br>Examples:<br>– Sintered bronze ↔ Steel<br>– Plastic ↔ Gray cast iron<br>– Steel ↔ Steel<br>– Al alloy ↔ Al alloy | 0.1 … 1<br><br><br>0.15 … 0.3<br>0.3 … 0.4<br>0.4 … 0.7<br>0.15 … 0.6 |
| **Boundary friction** (lubricated kinetic friction)<br>Special case of solid-to-solid friction with adsorbed lubricant on the surfaces | Typical coefficient of friction μ:<br><br>Example:<br>Steel ↔ Steel | 0.1 … 0.2<br><br><br>0.1 |
| **Mixed friction**<br>Solid-to-solid friction and fluid friction combined<br><br>For example: sintered sleeve bearing | Typical coefficient of friction μ:<br><br>Sleeve bearing, lubricated, at low speeds:<br>– Sintered bronze ↔ Steel<br>– Sintered iron ↔ Steel<br>– Hardened steel ↔ Hardened steel | 0.01 … 0.1<br><br><br>0.05 … 0.1<br>0.07 … 0.1<br>0.05 … 0.08 |
| **Fluid friction**<br>Friction partners are completely separated from each other by a film of fluid (produced hydrostatically or hydrodynamically) | Typical coefficient of friction μ:<br><br>Sintered sleeve bearing, lubricated, at high speeds and low radial load | 0.001 … 0.01 |
| **Gas friction**<br>Friction partners are completely separated from each other by a gas film (produced aerostatically or aerodynamically) | Typical coefficient of friction μ: | 0.0001 |
| Static friction | | |
| **Static friction**<br>20…100 % higher than kinetic friction | Typical coefficient of friction μ: | 0.1 … 1.2 |

## 3.4 Mass inertia of various bodies

with reference to the principal axes through the center of gravity S

| Body type | Illustration | Mass, moment of inertia |
|---|---|---|
| Circular cylinder |  | $m = \rho \cdot \pi \cdot r^2 \cdot h$<br>$J_x = \frac{1}{2} \cdot m \cdot r^2$<br>$J_y = J_z = \frac{1}{12} \cdot m \cdot (3 \cdot r^2 + h^2)$ |
| Hollow cylinder |  | $m = \rho \cdot \pi \cdot (r_a^2 - r_i^2) \cdot h$<br>$J_x = \frac{1}{2} \cdot m \cdot (r_a^2 + r_i^2)$<br>$J_y = J_z = \frac{1}{4} \cdot m \cdot \left(r_a^2 + r_i^2 + \frac{h^2}{3}\right)$ |
| Circular cone |  | $m = \frac{1}{3} \cdot \rho \cdot \pi \cdot r^2 \cdot h$<br>$J_x = \frac{3}{10} \cdot m \cdot r^2$<br>$J_y = J_z = \frac{3}{80} \cdot m \cdot (4 \cdot r^2 + h^2)$ |
| Truncated circular cone |  | $m = \frac{1}{3} \cdot \rho \cdot \pi \cdot (r_2^2 + r_2 \cdot r_1 + r_1^2) \cdot h$<br>$J_x = \frac{3}{10} \cdot m \cdot \frac{r_2^5 - r_1^5}{r_2^3 - r_1^3}$ |
| Circular torus |  | $m = 2 \cdot \rho \cdot \pi^2 \cdot r^2 \cdot R$<br>$J_x = J_y = \frac{1}{8} \cdot m \cdot (4 \cdot R^2 + 5 \cdot r^2)$<br>$J_z = \frac{1}{4} \cdot m \cdot (4 \cdot R^2 + 3 \cdot r^2)$ |
| Sphere |  | $m = \frac{4}{3} \cdot \rho \cdot \pi \cdot r^3$<br>$J_x = J_y = J_z = \frac{2}{5} \cdot m \cdot r^2$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $J_x$ | Mass moment of inertia with reference to the rotary axis x | kg m² | $h$ | Height | m |
| | | | $m$ | Mass | kg |
| $J_y$ | Mass moment of inertia with reference to the rotary axis y | kg m² | $r$ | Radius | m |
| | | | $r_a$ | Outer radius | m |
| $J_z$ | Mass moment of inertia with reference to the rotary axis z | kg m² | $r_i$ | Inner radius | m |
| | | | $r_1$ | Radius 1 | m |
| $R$ | Radius of circular torus around Z axis | m | $r_2$ | Radius 2 | m |
| | | | $\rho$ | Density | kg/m³ |

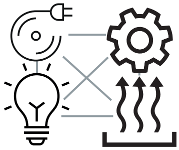
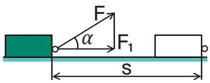
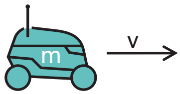
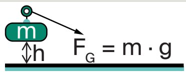
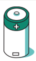
| Body type | Illustration | Mass, moment of inertia |
|---|---|---|
| Hollow sphere |   | $m = \frac{4}{3} \cdot \rho \cdot \pi \cdot (r_a^3 - r_i^3)$ <br> $J_x = J_y = J_z = \frac{2}{5} \cdot m \cdot \frac{r_a^5 - r_i^5}{r_a^3 - r_i^3}$ |
| Cuboid |   | $m = \rho \cdot a \cdot b \cdot c$ <br> $J_x = \frac{1}{12} \cdot m \cdot (b^2 + c^2)$ |
| Thin rod |   | $m = \rho \cdot A \cdot l$ <br> $J_y = J_z = \frac{1}{12} \cdot m \cdot l^2$ |
| Square pyramid |   | $m = \frac{1}{3} \cdot \rho \cdot a \cdot b \cdot h$ <br> $J_x = \frac{1}{20} \cdot m \cdot (a^2 + b^2)$ <br> $J_y = \frac{1}{20} \cdot m \cdot (b^2 + \frac{3}{4} \cdot h^2)$ |
| Arbitrary rotation body |   | $m = \rho \cdot \pi \cdot \int_{x1}^{x2} f^2(x) \cdot dx$ <br> $J_x = \frac{1}{2} \cdot \rho \cdot \pi \cdot \int_{x1}^{x2} f^4(x) \cdot dx$ |
| **Steiner's theorem** <br> Mass inertia with reference to a parallel axis of rotation *x* at a distance of $r_s$ to axis *s* through the center of gravity *S*. |   | $J_x = m \cdot r_s^2 + J_s$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $A$ | Cross section | $m^2$ | $b$ | Length of side *b* | m |
| $J_s$ | Mass moment of inertia on the axis *s* through the center of gravity *S* | kg $m^2$ | $c$ | Length of side *c* | m |
| | | | $h$ | Height | m |
| $J_x$ | Mass moment of inertia with reference to the rotary axis *x* | kg $m^2$ | $l$ | Length | m |
| | | | $m$ | Mass | kg |
| $J_y$ | Mass moment of inertia with reference to the rotary axis *y* | kg $m^2$ | $r_a$ | Outer radius | m |
| | | | $r_i$ | Inner radius | m |
| $J_z$ | Mass moment of inertia with reference to the rotary axis *z* | kg $m^2$ | $r_s$ | Distance of axis *s* from center of gravity *S* | m |
| | | | $\rho$ | Density | kg/$m^3$ |
| $a$ | Length of side a | m | $x_1$ | Point 1 on the *x*-axis | m |
| | | | $x_2$ | Point 2 on the *x*-axis | m |

## 3.5 Energy, work, power

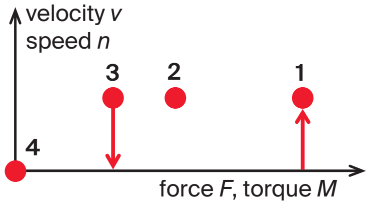
Energy *E* characterizes the state of a body or a spatial area. Work *W* signifies a process or procedure. Physically, work is stored in the form of energy, and energy is released in the form of work.

Energy and work have the same units: 1 J = 1 Nm = 1 Ws

| Energy and work | | |
|---|---|---|
|  | **Work**<br>Work is the amount of energy converted or transferred between different systems. | $W = E_{end} - E_{start} = \Delta E$ |
|  | Work for moving an object using force. | $F_1 = F \cdot \cos\alpha$<br>$W = F_1 \cdot \Delta s$ |
|  | Kinetic energy<br>= energy an object possesses due to its motion | $E = \frac{1}{2} \cdot m \cdot v^2$<br>$E = \frac{1}{2} \cdot J \cdot \omega^2$ |
|  | Potential energy<br>= energy an object possesses due to its position | $E = m \cdot g \cdot h$ |
|  | (Potential) energy of the tensioned spring | $E = \frac{1}{2} \cdot k \cdot \Delta l^2$ |
|  | Pressure energy | $E = p \cdot V$ |
|  | Thermal energy | $E = m \cdot c \cdot T$ |
|  | Electrical energy | $E = U \cdot I \cdot t$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $W$ | Work (1 J = 1 Nm = 1 Ws) | Nm \| J \| Ws | $\Delta s$ | Distance change | m |
| $E$ | Energy (1 J = 1 Nm = 1 Ws) | Nm \| J \| Ws | $h$ | Height | m |
| $E_{end}$ | Energy after process | Nm \| J \| Ws | $\Delta l$ | Deflection from rest position | m |
| $E_{start}$ | Energy before process | Nm \| J \| Ws | $v$ | Velocity | m/s |
| $\Delta E$ | Energy change | Nm \| J \| Ws | $T$ | Temperature | K |
| $F$ | Force | N | $V$ | Volume | $m^3$ |
| $F_1$ | Force in the direction of motion | N | $t$ | Time | s |
| $F_G$ | Weight force of the body | N | $p$ | Pressure (1 Pa = 1 N/$m^2$ = $10^{-5}$ bar) | Pa |
| $\omega$ | Angular velocity | rad/s | $k$ | Spring constant | N/m |
| $J$ | Mass moment of inertia | kg $m^2$ | $g$ | Gravitational acceleration | m/$s^2$ |
| $U$ | Voltage | V | $c$ | Heat capacity of the material | |
| $I$ | Current | A | | (water c = 4182 J/(K kg)) | J/(K kg) |
| $m$ | Mass | kg | | | |

Power is typically the rate of change of the energy $E$ during a process over time. As this energy equals the work $W$ done during the process, it can also expressed as: “power is work divided by time"

| | Work | Power |
|---|---|---|
|   | $W = F \cdot \Delta s$<br>$W = M \cdot \Delta\varphi$ | $P = F \cdot v$<br>$P = M \cdot \omega = M \cdot \frac{\pi}{30} \cdot n$ |
| Friction | $W = \mu \cdot F_N \cdot \Delta s$ | $P = \mu \cdot F_N \cdot v$ |
| (Constant) acceleration | $W = m \cdot a \cdot \Delta s$<br>$W = J \cdot \alpha \cdot \Delta\varphi$ | $P = m \cdot a \cdot \frac{\Delta s}{\Delta t}$<br>$P = J \cdot \alpha \cdot \frac{\Delta\varphi}{\Delta t}$ |
| Gravitation (lift) | $W = m \cdot g \cdot \Delta h$ | $P = m \cdot g \cdot v$ |
| Spring force | $W = \frac{1}{2} \cdot k \cdot \Delta l$ | $P = \frac{1}{2} \cdot k \cdot \frac{\Delta l}{\Delta t}$ |
| Volume change at constant pressure | $W = p \cdot \Delta V$ | $P = p \cdot \frac{\Delta V}{\Delta t}$ |
| Heat | $Q = m \cdot c \cdot \Delta T$ | $P = \frac{m \cdot c \cdot \Delta T}{\Delta t}$ |
| Electrical | $W = U \cdot I \cdot \Delta t = R \cdot I^2 \cdot \Delta t$ | $P = U \cdot I = R \cdot I^2 = \frac{U^2}{R}$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $W, Q$ | Work (1 J = 1 Nm = 1 Ws) | Nm \| J \| Ws | $\Delta\varphi$ | Rotation angle change | rad |
| $P$ | Power | W | $\Delta s$ | Distance change | m |
| $F$ | Force | N | $\Delta h$ | Height change | m |
| $F_N$ | Normal force (perpendicular to the plane) | N | $\Delta l$ | Deflection from rest position | m |
| $M$ | Torque | Nm | $v$ | Velocity | m/s |
| $n$ | Speed | rpm | $\Delta T$ | Temperature change | K |
| $\omega$ | Angular velocity | rad/s | $\Delta V$ | Volume change | $m^3$ |
| $J$ | Mass moment of inertia | kg $m^2$ | $\Delta t$ | Duration | s |
| $U$ | Voltage | V | $\mu$ | Friction coefficient (chapter 3.3) | |
| $I$ | Current | A | $\alpha$ | Angular acceleration | rad/$s^2$ |
| $R$ | Resistance | Ω | $a$ | Acceleration | m/$s^2$ |
| $m$ | Mass | kg | $g$ | Gravitational acceleration | m/$s^2$ |
| $k$ | Spring constant | N/m | $c$ | Heat capacity of the material (water c = 4182 J/(K·kg)) | J/(K·kg) |
| p | Pressure (1 Pa = 1 N/$m^2$ = $10^{-5}$ bar) | Pa | | | |

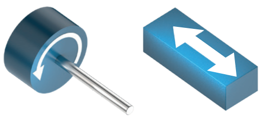
# 4. Mechanical Drives

## 4.1 Transformation of the key parameters (step 3)

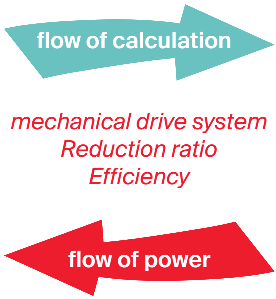
In step 3, the task is to transform the load parameters to the output shaft of the desired drive system (gearhead or motor). The information in this chapter will help you do that.

**Transformation of the key parameters**

load: rotary or linear



key values: load

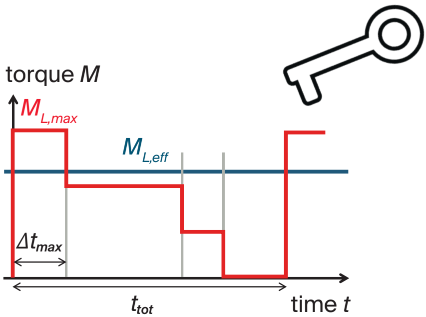



motor or gear motor

key values for gearhead selection

More information and conversion formulas can be found on the following pages

**Result: new, transformed key load values for gearhead or motor selection**



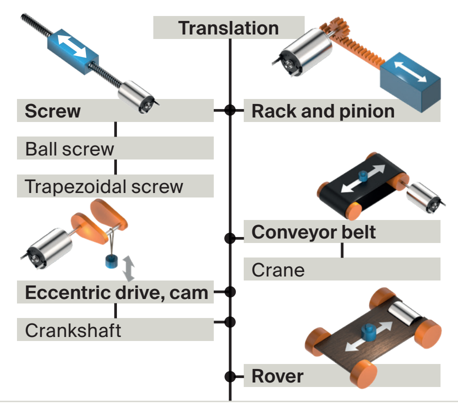

| | |
|---|---|
| – max. speed | $n_{L,max}$ |
| – max. torque | $M_{L,max}$ |
| – duration of max. torque | $\Delta t_{max}$ |
| – average effective load | $M_{L,eff}$ |
| – max. power | $P_{L,max}$ |
| – axial load | $F_{axial}$ |
| – radial load | $F_{radial}$ |
| – control accuracy | |
| – angular resolution | $\Delta\varphi_L$ |
| – speed accuracy | $\Delta n_L$ |

Next step in drive selection: gearhead selection (chapter 5.1) or motor selection (chapter 6.1).

## 4.2 Mechanical transmission

We distinguish between linear drives (translation), which convert the rotational movement of the motor into linear load movement, and rotary drives, which produce a rotation. Mechanical drives can also be connected in series. In this case, the output power of the preceding element becomes the input power of the subsequent element.

| Classification | General information: transmission |
|---|---|

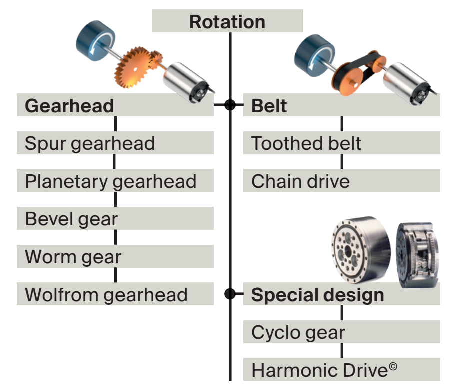



$$\eta = \frac{P_{L,out}}{P_{L,in}} = \frac{F_{L,out} \cdot v_{L,out}}{M_{L,in} \cdot \omega_{L,in}} = \frac{30}{\pi} \cdot \frac{F_{L,out} \cdot v_{L,out}}{M_{L,in} \cdot n_{L,in}}$$

$$P_{L,out} = \eta \cdot P_{L,in}$$

$$F_{L,out} \cdot v_{L,out} = \eta \cdot M_{L,in} \cdot \omega_{L,in}$$

$$F_{L,out} \cdot v_{L,out} = \eta \cdot M_{L,in} \cdot \frac{\pi}{30} \cdot n_{L,in}$$




$$\eta = \frac{P_{L,out}}{P_{L,in}} = \frac{n_{L,out} \cdot M_{L,out}}{n_{L,in} \cdot M_{L,in}}$$

$$P_{L,out} = \eta \cdot P_{L,in}$$

$$M_{L,out} \cdot \omega_{L,out} = \eta \cdot M_{L,in} \cdot \omega_{L,in}$$

$$M_{L,out} \cdot n_{L,out} = \eta \cdot M_{L,in} \cdot n_{L,in}$$

### Designations in the formulas

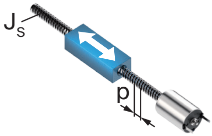
- The load-side variables at the output are identified by the index *L,out*.
- The input-side variables are identified by the index *L,in*. These variables become the new load requirements for choosing a motor or gear motor.

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $P_{L,in}$ | Power at input | W | $P_{L,out}$ | Power at output | W |
| $M_{L,in}$ | Torque at input | Nm | $M_{L,out}$ | Torque at output | Nm |
| $F_{L,in}$ | Force at input | N | $F_{L,out}$ | Force at output | N |
| $n_{L,in}$ | Speed at input | rpm | $n_{L,out}$ | Speed at output | rpm |
| $\omega_{L,in}$ | Angular velocity at input | rad/s | $\omega_{L,out}$ | Angular velocity at output | rad/s |
| $\eta$ | Efficiency | | $v_{L,out}$ | Velocity at output | m/s |

## 4.3 Mechanical drives, rotation → translation

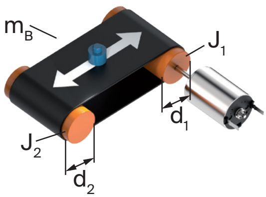
The “additional torques for acceleration” should only be taken into account if these components are not already included in the load-side forces or torques.

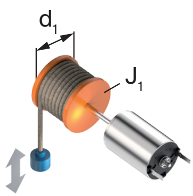
### Screw drive




| | |
|---|---|
| Speed | $n_{L,in} = \frac{60}{p} \cdot v_{L,out}$ |
| Torque | $M_{L,in} = \frac{p}{2\pi} \cdot \frac{F_{L,out}}{\eta}$ |
| Additional torque for constant acceleration (Speed change $\Delta n_{L,in}$ during period $\Delta t_a$) | $M_{L,in,\alpha} = \left( J_{in} + J_S + \frac{m_L + m_S}{\eta} \cdot \frac{p^2}{4 \cdot \pi^2} \right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$ |
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta s_{L,out} \cdot \frac{2\pi}{p}$ |

### Belt drive/conveyor belt/crane

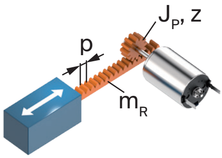



| | | |
|---|---|---|
| Speed | $n_{L,in} = \frac{60}{\pi} \cdot \frac{v_{L,out}}{d_1}$ | (assumption: no slip) |
| Torque | $M_{L,in} = \frac{d_1}{2} \cdot \frac{F_{L,out}}{\eta}$ | |
| Additional torque for constant acceleration (speed change $\Delta n_{L,in}$ during period $\Delta t_a$) | $M_{L,in,\alpha} = \left( J_{in} + J_1 + \frac{J_2}{\eta} \cdot \frac{d_1^2}{d_2^2} + \frac{J_x}{\eta} \cdot \frac{d_1^2}{d_x^2} + \frac{m_L + m_B}{\eta} \cdot \frac{d_1^2}{4} \right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$ | |
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta s_{L,out} \cdot \frac{2}{d_1}$ | |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_{L,out}$ | Output load force | N | $d_x$ | Diameter, deflector pulley X | m |
| $J_{in}$ | Moment of inertia, input (motor, encoder, brake) | kg m² | $d_1$ | Diameter, drive pulley | m |
| | | | $d_2$ | Diameter, deflector pulley 2 | m |
| $J_S$ | Moment of inertia, screw | kg m² | $m_B$ | Mass of the belt | kg |
| $J_X$ | Moment of inertia, deflector pulley X | kg m² | $m_L$ | Mass of the load | kg |
| $J_1$ | Moment of inertia, driving end | kg m² | $m_S$ | Mass, screw nut | kg |
| $J_2$ | Moment of inertia, deflector pulley 2 | kg m² | $p$ | Screw lead (pitch) | m |
| $M_{L,in}$ | Input torque | Nm | $\Delta s_{L,out}$ | Mechanical play, output | m |
| $M_{L,in,\alpha}$ | Torque for acceleration | Nm | $\Delta t_a$ | Acceleration time | s |
| $n_{L,in}$ | Input speed | rpm | $\Delta\varphi_{L,in}$ | Mechanical play, input | rad |
| $\Delta n_{L,in}$ | Input speed change | rpm | $\eta$ | Efficiency | |
| $v_{L,out}$ | Output load velocity | m/s | | | |

## Rack and pinion

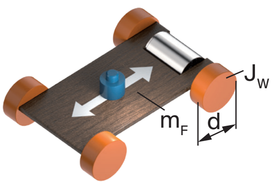



| | |
|---|---|
| Speed | $n_{L,in} = \frac{60}{p \cdot z} \cdot v_{L,out}$ |
| Torque | $M_{L,in} = \frac{p \cdot z}{2\pi} \cdot \frac{F_{L,out}}{\eta}$ |
| Module | $mod_R = \frac{p}{\pi} = mod_P = \frac{d_P}{z}$ $\quad p \cdot z = d_P \cdot \pi$ |
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta s_{L,out} \cdot \frac{2\pi}{p \cdot z} = \Delta s_{L,out} \cdot \frac{2}{d_P}$ |

Additional torque for constant acceleration (speed change $\Delta n_{L,in}$ during period $\Delta t_a$)

$$M_{L,in,\alpha} = \left(J_{in} + J_P + \frac{m_L + m_R}{\eta} \cdot \frac{p^2 \cdot z^2}{4 \cdot \pi^2}\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$$

## Rover




| | | |
|---|---|---|
| Speed | $n_{L,in} = \frac{60}{\pi} \cdot \frac{v_{L,out}}{d}$ | (assumption: no slip) |
| Torque | $M_{L,in} = \frac{d}{2} \cdot \frac{F_{L,out}}{\eta}$ | |
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta s_{L,out} \cdot \frac{2}{d}$ | |

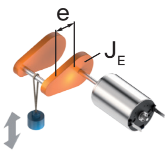
Additional torque for constant acceleration (speed change $\Delta n_{L,in}$ during period $\Delta t_a$)

$$M_{L,in,\alpha} = \left(J_{in} + J_W + \frac{m_L + m_F}{\eta} \cdot \frac{d^2}{4}\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$$

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_{L,out}$ | Output load force | N | $d$ | Diameter, drive wheel | m |
| $J_{in}$ | Moment of inertia, input (motor, encoder, brake) | kg m² | $d_P$ | Reference/pitch diameter, pinion | m |
| | | | $mod_R$ | Module, rack | m |
| $J_P$ | Moment of inertia, pinion | kg m² | $mod_P$ | Module, pinion | m |
| $J_W$ | Moment of inertia, all wheels together | kg m² | $m_F$ | Mass, rover | kg |
| | | | $m_L$ | Mass, load | kg |
| $M_{L,in}$ | Input torque | Nm | $m_R$ | Mass, rack | kg |
| $M_{L,in,\alpha}$ | Torque for acceleration | Nm | $p$ | Pitch of the toothing | m |
| $n_{L,in}$ | Input speed | rpm | $z$ | Number of teeth of the pinion | |
| $\Delta n_{L,in}$ | Input speed change | rpm | $\Delta s_{L,out}$ | Mechanical play, load | m |
| $v_{L,out}$ | Output load velocity | m/s | $\Delta t_a$ | Acceleration time | s |
| $\eta$ | Efficiency | | $\Delta\varphi_{L,n}$ | Mechanical play, input | rad |

## Eccentric drive, cam




Sinusoidal velocity curve of the load
(assumption: constant input speed $n_{L,in}$)

$$v_{L,out}(t) = \frac{\pi}{30} \cdot n_{L,in} \cdot e \cdot sin\left(\frac{\pi}{30} \cdot n_{L,in} \cdot t\right)$$

Angle-dependent periodic acceleration force for load, pistons and rods ($m_L$)

$$F_a(\varphi) = F_a \cdot cos\varphi = m_L \cdot \left(\frac{\pi}{30} \cdot n_{L,in}\right)^2 \cdot e \cdot cos\,\varphi$$

Angle-dependent torques through different load conditions in the two half cycles of the back and forth motion

$$M_{L,in1}(\varphi) = e \cdot (F_{L,out1} \cdot sin\,\varphi + F_{a1} \cdot cos\,\varphi) \quad 0 \leq \varphi \leq \pi$$
$$M_{L,in2}(\varphi) = e \cdot (F_{L,out2} \cdot sin\,\varphi + F_{a2} \cdot cos\,\varphi) \quad \pi \leq \varphi \leq 2\pi$$

Average effective torque load

$$M_{L,in,RMS} = \frac{e}{\sqrt{2 \cdot \eta}} \cdot \sqrt{F_{L,out1}^2 + F_{a1}^2 + F_{L,out2}^2 + F_{a2}^2}$$

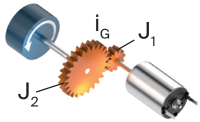
Additional torque for acceleration of the eccentric disk
(speed change $\Delta n_{L,in}$ during period $\Delta t_a$)

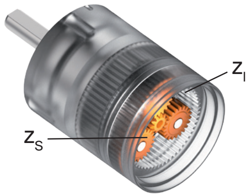
$$M_{L,in,\alpha} = \left(J_{in} + J_E\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$$

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_{L,out1}$ | Load force, 1st half of cycle | N | $M_{L,in,RMS}$ | Effective torque (RMS) | Nm |
| $F_{L,out2}$ | Load force, 2nd half of cycle | N | $M_{L,in,\alpha}$ | Torque for acceleration | Nm |
| $F_a$ | Acceleration force | N | $M_{L,in1}(\varphi)$ | Torque, 1st half of cycle | Nm |
| $F_a(\varphi)$ | Angle-dependent periodic acceleration force | N | $M_{L,in1}(\varphi)$ | Torque, 2nd half of cycle | Nm |
| | | | $e$ | Eccentricity | m |
| $F_{a1}$ | Acceleration force, 1st half of cycle | N | $m_L$ | Mass of the load | kg |
| $F_{a2}$ | Acceleration force, 2nd half of cycle | N | $v_{L,out}(t)$ | Sinusoidal velocity curve of the load | m/s |
| $J_{in}$ | Moment of inertia, input (motor, encoder, brake) | kg m² | $t$ | Time | s |
| | | | $\Delta t_a$ | Acceleration time | s |
| $J_E$ | Moment of inertia, eccentric disk | kg m² | $\varphi$ | Rotation angle | rad |
| $n_{L,in}$ | Input speed | rpm | $\eta$ | Efficiency | |
| $\Delta n_{L,in}$ | Input speed change | rpm | | | |

## 4.4 Mechanical drives, rotation → rotation

### Gearhead



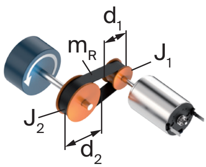

| | |
|---|---|
| Speed | $n_{L,in} = n_{L,out} \cdot i_G$ |
| Torque | $M_{L,in} = \dfrac{M_{L,out}}{i_G \cdot \eta}$ |

Additional torque for constant acceleration (speed change $\Delta n_{L,in}$ during period $\Delta t_a$)

$$M_{L,in,\alpha} = \left(J_{in} + J_1 + \frac{J_L + J_2}{i_G^{\,2} \cdot \eta}\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a} = \left(J_{in} + J_G + \frac{J_L}{i_G^{\,2} \cdot \eta}\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$$

| | |
|---|---|
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta\varphi_{L,out} \cdot i_G$ |
| Reduction Planetary gearhead | $i_G = \dfrac{z_S + z_l}{z_S}$ |

### Belt drive, toothed belt drive, chain drive




| | | |
|---|---|---|
| Speed | $n_{L,in} = \dfrac{d_2}{d_1} \cdot n_{L,in} = \dfrac{z_2}{z_1} \cdot n_{L,in}$ | (assumption: no slip) |
| Torque | $M_{L,in} = \dfrac{d_1}{d_2} \cdot \dfrac{M_{L,out}}{\eta} = \dfrac{z_1}{z_2} \cdot \dfrac{M_{L,out}}{\eta}$ | |

Additional torque for constant acceleration (speed change $\Delta n_{L,in}$ during period $\Delta t_a$)

$$M_{in,\alpha} = \left(J_{in} + J_1 + \frac{J_L + J_2}{\eta} \cdot \frac{d_1^{\,2}}{d_2^{\,2}} + \frac{J_x}{\eta} \cdot \frac{d_1^{\,2}}{d_x^{\,2}} + \frac{m_R + d_1^{\,2}}{4 \cdot \eta}\right) \cdot \frac{\pi}{30} \cdot \frac{\Delta n_{L,in}}{\Delta t_a}$$

| | |
|---|---|
| Play, positioning error | $\Delta\varphi_{L,in} = \Delta\varphi_{L,out} \cdot \dfrac{d_2}{d_1} = \Delta\varphi_{L,out} \cdot \dfrac{z_2}{z_1}$ |

| Symbol | Name | Unit |
|---|---|---|
| $J_G$ | Moment of inertia, gearhead transformed | kg m² |
| $J_{in}$ | Moment of inertia, input (motor, encoder, brake) | kg m² |
| $J_L$ | Moment of inertia, load | kg m² |
| $J_X$ | Mom. of inertia, deflector pulley X | kg m² |
| $J_1$ | Moment of inertia, driving end | kg m² |
| $J_2$ | Moment of inertia, output side | kg m² |
| $M_{L,in}$ | Input torque | Nm |
| $M_{L,in,\alpha}$ | Torque for acceleration | Nm |
| $M_{L,out}$ | Output torque | Nm |
| $n_{L,in}$ | Input speed | rpm |
| $n_{L,out}$ | Output speed | rpm |
| $\Delta n_{L,in}$ | Input speed change | rpm |

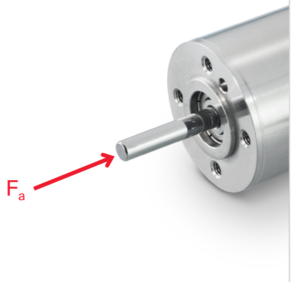
| Symbol | Name | Unit |
|---|---|---|
| $d_x$ | Diameter, deflector pulley X | m |
| $d_1$ | Diameter, drive pulley | m |
| $d_2$ | Diameter, load pulley | m |
| $i_G$ | Reduction, gearhead (catalog value) | |
| $m_R$ | Mass, belt, chain | kg |
| $z_S$ | Number of teeth, sun wheel | |
| $z_l$ | Number of teeth, internal gear | |
| $z_1$ | Number of teeth, drive pulley | |
| $z_2$ | Number of teeth, load pulley | |
| $\Delta t_a$ | Acceleration time | s |
| $\Delta\varphi_{L,in}$ | Mechanical play, input | rad |
| $\Delta\varphi_{L,out}$ | Mechanical play, load | rad |
| $\eta$ | Efficiency | |

## 4.5 Bearings

Comparison of characteristics of sintered sleeve bearings and ball bearings.

| | Sintered sleeve bearings | Ball bearings |
|---|---|---|
| |  |  |
| Operating modes | – continuous operation | – suitable for all operating modes<br>– especially for start-stop operation and low-speed applications |
| Speed range | – ideal above approx. 500 rpm (range for hydrodynamic lubrication)<br>– with special material pairings and lubrication even at lower speeds | – up to several 10 000 rpm<br>– in special cases up to 100 000 rpm and higher (e.g., with ceramic balls) |
| Radial/ axial load | – only small bearing loads | – higher loads<br>– preloaded ball bearings allow an axial load up to the value of the preload |
| Additional operating criteria | – not suitable for<br>  – rotating load<br>  – vacuum applications (outgassing)<br>  – low temperatures (<-20°C) | – preloaded ball bearings for a very long service life and smooth operation |
| Bearing play | – axial: typically 0.02 ... 0.15 mm<br>– radial: typically 0.014 mm | – axial: typically 0.05 ... 0.15 mm (no axial play if preloaded)<br>– radial: typically 0.015 mm |
| Coefficient of friction, typical | – 0.001 ... 0.01 (hydrodynamic lubrication) | – 0.001 ... 0.0025 |
| Lubrication | – hydrodynamic lubrication only at high speeds<br>– shaft/bearing material pairing very important, pore size of the sintered bearing and viscosity of the lubricant at operating temperature are critical<br>– special extras: sintered iron bearings with ceramic shaft for high radial loads and long service life | – temperature range for standard lubrication: typically -40 ... 100°C<br>– special lubrication possible for very high or very low operating temperatures<br>– sealing possible (but greater friction, short service life, and low maximum motor speed) |
| Cost | – economical | – more expensive |

## Axial load on the bearings

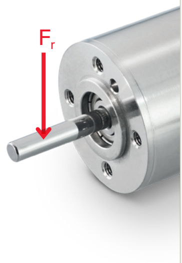



Permissible axial load in operation $F_a$.

If different values apply for pulling and pushing, the smaller value is usually specified in the data.

Ball bearings can withstand higher axial loads than the sintered sleeve bearings.

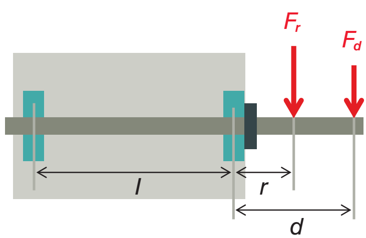
## Radial load on the bearings




Permissible radial load in operation.

The permissible radial load $F_r$ is specified in the data sheet with a defined distance r to the front ball bearing (typically $r$ = 5 mm).

Ball bearings can withstand higher radial loads than sintered sleeve bearings.




When the radial load is applied at a different distance *d*, the maximum radial load $F_d$ can be calculated as follows:

$$F_d = F_r \cdot \frac{l + r}{l + d}$$

If *l* is unknown, the following approximation applies:

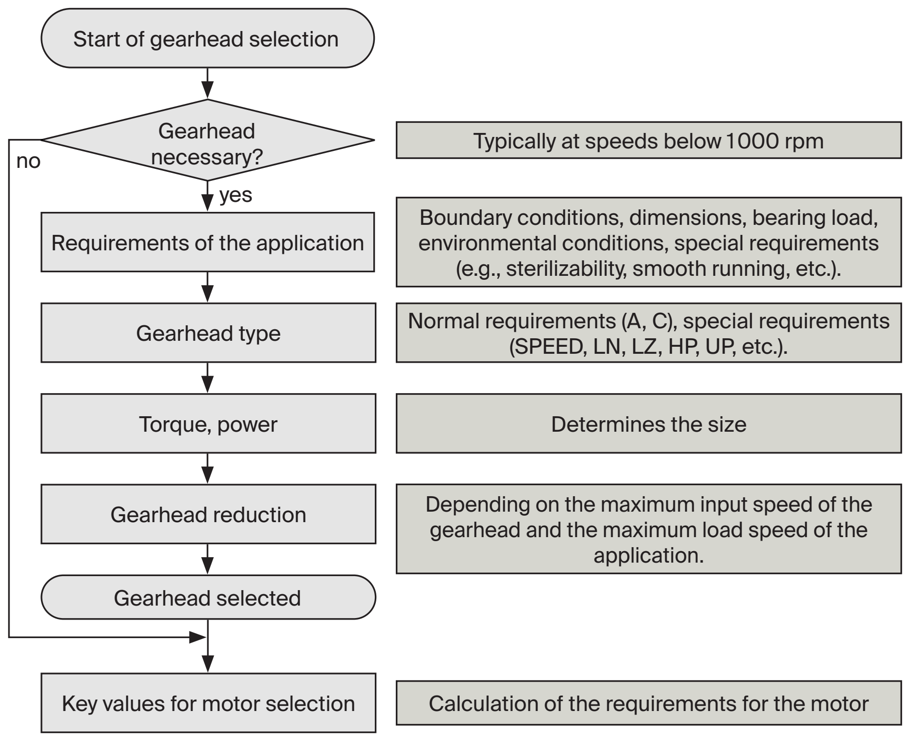
| Long motors<br>(*l* significantly longer than *r* or *d*) | Flat motors and gearheads<br>(*l* very short) |
|---|---|
| $F_d \approx F_r$ | $F_d \approx F_r \cdot \frac{r}{d}$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $F_a$ | Max. axial load (catalog value) | N | $r$ | Distance $F_r$ (catalog value) | mm |
| $F_r$ | Max. radial load (catalog value) | N | $d$ | Distance $F_d$ | mm |
| $F_d$ | Max. radial load at distance *d* | N | $l$ | Distance of the two bearings | mm |

# 5. Gearheads

## 5.1 Selection process (step 4)

**Step-by-step guide to finding the right gearhead**




**Converting the key values to the motor shaft**

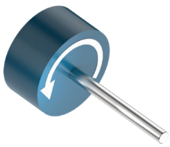
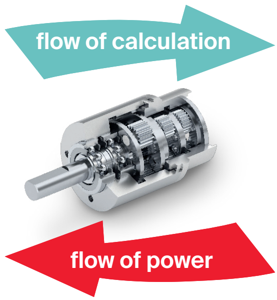
Once a suitable gearhead has been selected, the key values from the mechanical drive layout (load) are transformed to the motor shaft.

The primary relationships between the gearhead's load side (index *L,out*) and the gearhead input (index *L,in* motor side) are:

| | | | |
|---|---|---|---|
| Speeds | $n_{L,in} = i_G \cdot n_{L,out}$ | Torques | $M_{L,in,eff} = \frac{M_{L,out,eff}}{i_G \cdot \eta}$ |
| Positioning resolution (without backlash) | $\Delta\varphi_{L,in} = i_G \cdot \Delta\varphi_{L,out}$ | | $M_{L,in,max} = \frac{M_{L,out,max}}{i_G \cdot \eta}$ |

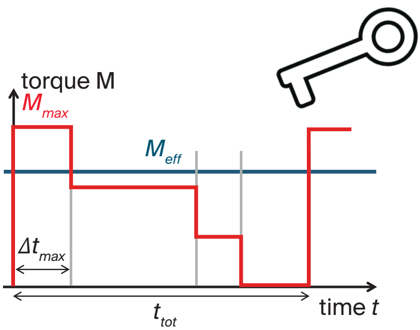
| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n_{L,in}$ | (Motor) speed, gearhead input | rpm | $M_{L,in,eff}$ | Effective input torque | Nm |
| $n_{L,out}$ | Load speed | rpm | $M_{L,in,max}$ | Maximum input torque | Nm |
| $i_G$ | Reduction, gearhead (catalog value) | | $M_{L,out,eff}$ | Effective output torque | Nm |
| $\eta$ | Gearhead efficiency (catalog value) | | $M_{L,out,max}$ | Maximum output torque | Nm |
| $\Delta\varphi_{L,in}$ | Mechanical play, gearhead input | rad | | | |
| $\Delta\varphi_{L,out}$ | Mechanical play, gearhead output | rad | | | |

## Transformation of the key parameters

| load requirements from the mechanical layout | | motor |
|---|---|---|
|  |  |  |
| key values: load | | **key values for motor selection** |

→ More information and conversion formulas can be found on the following pages

## Result: new, transformed key load values at the motor level




| | |
|---|---|
| – max. speed | $n_{L,max}$ |
| – max. torque | $M_{L,max}$ |
| – duration of max. torque | $\Delta t_{max}$ |
| – average effective load | $M_{L,eff}$ |
| – max. power | $P_{L,max}$ |
| – axial load | $F_{axial}$ |
| – radial load | $F_{radial}$ |
| – control accuracy | |
| – angular resolution | $\Delta\varphi$ |
| – speed accuracy | $\Delta n$ |

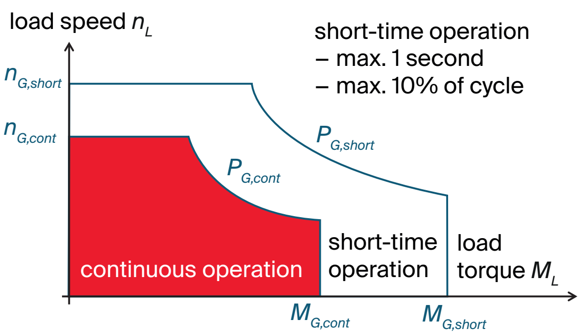
These key load values at the motor level are derived from the calculated input values of the selected gearhead.

– For the next step of the drive selection, refer to chapter 6.1 (motor selection).

## 5.2 Power selection: gearhead

A gearhead is used if the application does not require high speeds, typically with load speeds below 1000 rpm.
For the selection criteria, the load operating points derived from the mechanical analysis (power, speed, and torque) must fall within the corresponding operating ranges of the gearhead.

### Selection criteria: power




**Output power**

continuous $P_{G,cont} > P_{L,out,eff}$
short-time $P_{G,short} > P_{L,out,max}$

**Output torque**

continuous $M_{G,cont} > M_{L,out,eff}$
short-time $M_{G,short} > M_{L,out,max}$

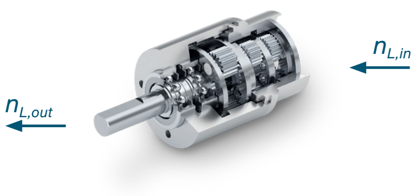
**Output speed**

continuous $n_{G,cont} > n_{L,out}$
short-time $n_{G,short} > n_{L,out,max}$

- The permissible output speed is determined from the specified permissible maximum input speed is of the gearhead in combination with the reduction $i_G$.
- Exceeding these limits will decrease the service life of the gearhead.
- The time limitations in short-time operation have to be taken into account.

### Selection criterion: reduction

The maximum possible reduction is determined from the required load speed and the permissible maximum input speed of the gearhead.




**Selection: reduction**

$$i_G < i_{G,max} = \frac{n_{L,in,max}}{n_{L,out,max}}$$

| Symbol | Name | Unit |
|---|---|---|
| $n_{L,in}$ | (Motor) speed, gearhead input | rpm |
| $n_{L,in,max}$ | Max. input speed, continuous/short-time (catalog value, gearhead) | rpm |
| $n_{L,out}$ | Load speed | rpm |
| $n_{L,out,max}$ | Maximum load speed | rpm |
| $n_{G,cont}$ | Maximum speed, gearhead output | rpm |
| $n_{G,short}$ | Maximum short-time speed, gearhead output | rpm |
| $i_{G,max}$ | Max. possible reduction, gearhead | |
| $i_G$ | Selected reduction, gearhead | |
| $\eta$ | Efficiency (catalog value) | |
| $M_{L,out,eff}$ | Effective load torque | Nm |
| $M_{L,out,max}$ | Max. load torque | Nm |
| $M_{G,cont}$ | Max. continuous torque (catalog value, gearhead) | Nm |
| $M_{G,short}$ | Intermittent torque (catalog value, gearhead) | Nm |
| $P_{G,cont}$ | Max. transmittable power, continuous (catalog value, gearhead) | W |
| $P_{G,short}$ | Max. transmittable power, short-time (catalog value, gearhead) | W |

## 5.3 Gearhead properties

Other properties that could be relevant for the selection.

| maxon GPX gearhead types | | |
|---|---|---|
| **Type** | **Designation** | **Properties** |
| A | Standard | Basic version |
| C | Ceramic | Optimized for long service life |
| LN | Low Noise | Reduced noise |
| LZ | Low Backlash | Reduced backlash |
| HP | High Power | High power density, sterilizable version |
| UP | Ultra Performance | High power density, high efficiency and minimal backlash |
| SPEED | Speed | High speeds, sterilizable version, sealing possible |

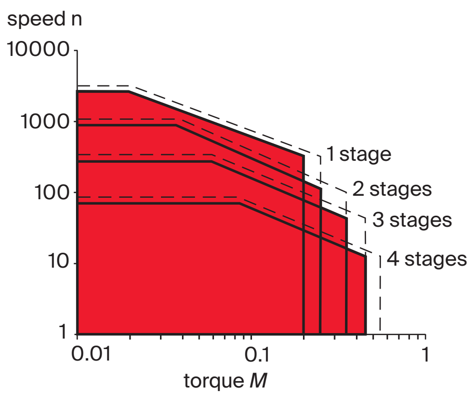
**Maximum service life**

The gearhead service life is generally limited by lubrication failure. Typically, 1000 to 3 000 operating hours are achieved in continuous operation at the maximum permissible continuous power. If this limit is not pushed, the service life can be increased considerably.

Influencing factors that reduce service life
– high lubricant temperature
– local temperature peaks during gear meshing
– exceeding the maximum torque/power values
– massive exceeding of the gearhead input speed
– radial and axial bearing loads

At very high and/or very low ambient temperatures, special lubrication is recommended.

**Transmittable power**

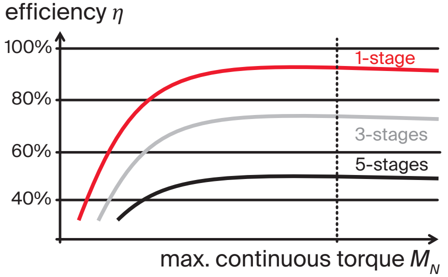



The gearhead losses are stage-dependent (usually about 10% per stage).

Since the gearhead length does not increase linearly with the number of stages, less heat dissipation per area is possible with a higher number of stages.

→ The transmittable power decreases as the number of gear stages increase.

## Efficiency



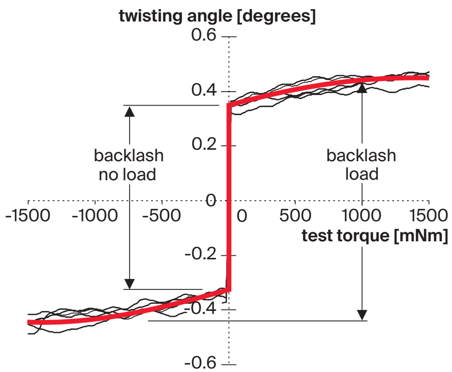

The efficiency specified in the data sheet is a maximum value that applies at loads from approximately 50% of the continuous torque.

At very low loads, the efficiency decreases significantly (see graph). The efficiency is stage-dependent, but is almost unaffected by the motor speed.

The torque dependence can be approximated with this formula:

$$\eta = \frac{M_{L,out}}{\frac{M_{L,out}}{\eta_{max}} + i_G \cdot (M_{VA} + c_5 \cdot n_{in})}$$

## Gearhead backlash




Gear backlash is the turning angle of the gear output shaft which, when the input shaft is blocked, the gear output shaft covers when it is turned from one end position to the opposite position. The end positions depend on the torque applied to the output shaft.

When changing the direction of rotation, the motor shaft must cover a larger angle multiplied by the reduction ratio before the output shaft reacts to the change of direction.

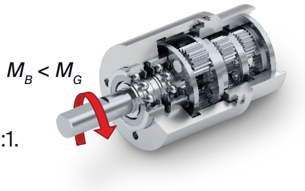
In positioning tasks in particular, the gearhead backlash must be taken into account.

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n_{in}$ | (Motor-) speed, gearhead input | rpm | $M_{L,out}$ | Effective load torque | Nm |
| $i_G$ | Reduction, gearhead (catalog value) | | $M_{VA}$ | Static damping (loss torque) | Nm |
| $\eta$ | Load-dependent efficiency | | $c_5$ | Viscous damping (loss torque) | Nm/rpm |
| $\eta_{max}$ | Maximum efficiency (catalog value) | | | | |

## 5.4 Application requirements

### Backdrivability: driven by the gearhead output

maxon planetary gearheads are not specifically designed to being driven from the output. Backdrivable motor-gearhead combinations are defined as units that can be made rotating when driven with less than the permissable gearhead torque.
Whether the backdrivability is available in a specific application depends on many factors and must be verified individually.




Experience with backdrivability
- 1- and 2-stage gearheads are usually backdrivable.
- 4- and multi-stage gearheads are usually not backdrivable.
- The limit is typically around gearhead reductions of about 100:1.
- The efficiency is similar in both directions.

**Influencing factors**
- tooth geometry → kinetic friction
- gearhead efficiency: friction in the gearhead
- friction at the gearhead input, e.g. motor friction
- vibration and impacts
- age, condition of the lubricant
- motor type, e.g. motor with or without cogging torque

**Backdrivability likely**
- UP planetary gearheads due to their very high efficiency at all stages
- spur gearheads
- planetary gearheads with very low reduction

### Optimal reduction for dynamic applications

This optimization criterion relates the load inertia to the motor inertia. It is only relevant for applications in which acceleration processes for a large part of the power consumption.

Motor torque for load acceleration

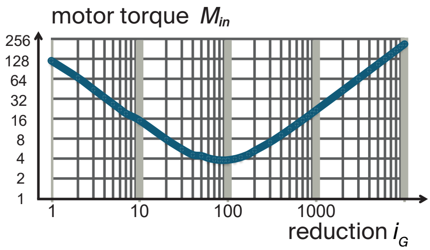
$$M_{in}(i_G) = \left(\frac{J_L}{\eta \cdot i_G^2} + J_{mot}\right) \cdot \alpha_{mot} = \left(\frac{J_L}{\eta \cdot i_G^2} + J_{mot}\right) \cdot i_G \cdot \alpha_L$$

Minimum motor torque occurs at

$$i_G = \sqrt{\frac{J_L}{\eta \cdot J_{mot}}}$$

Example (image)

$$i_G = \sqrt{\frac{120000}{0.72 \cdot 21.4}} = 88{:}1$$



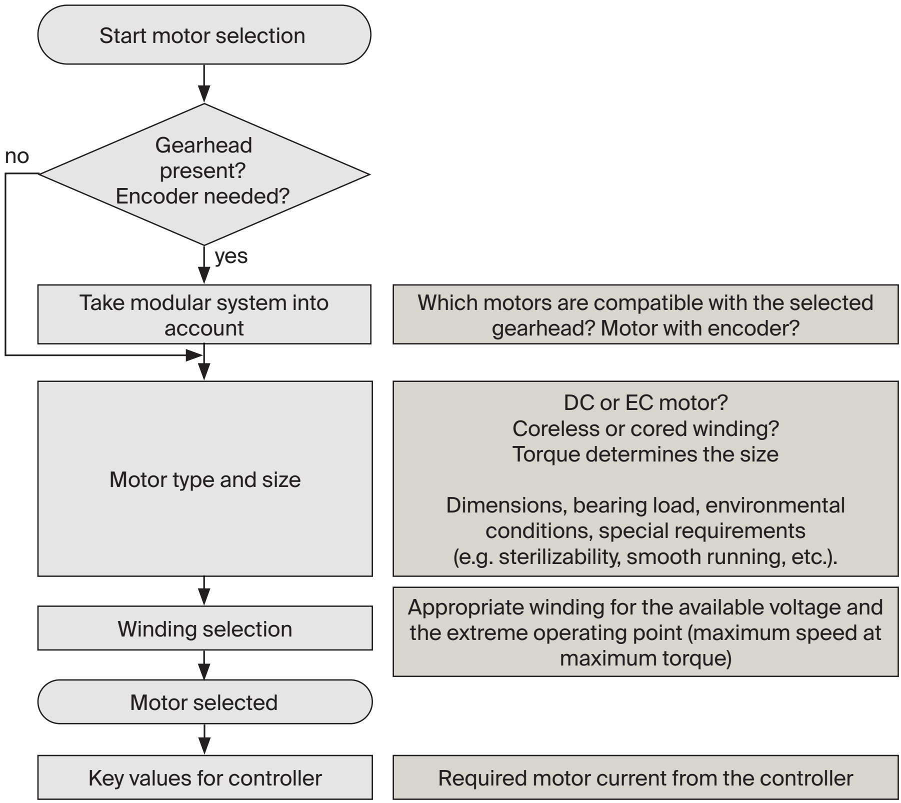

| Symbol | Name | Unit |
|---|---|---|
| $M_B$ | Backdriving torque | Nm |
| $M_G$ | Max. torque, gearhead (catalog value) | Nm |
| $M_{in}$ | Input (motor) torque, gearhead | Nm |
| $J_L$ | Moment of inertia, load | kg m² |
| $J_{mot}$ | Moment of inertia, motor (catalog value) | kg m² |

| Symbol | Name | Unit |
|---|---|---|
| $i_G$ | Gearhead reduction (catalog value) | |
| $\eta$ | Gearhead efficiency (catalog value) | |
| $\alpha_{mot}$ | Motor acceleration | rad/s² |
| $\alpha_L$ | Load acceleration | rad/s² |

# 6. DC Motors

## 6.1 Selection process (step 5)

**Step-by-step guide to finding the right motor**




**Key values for selecting encoders and controllers**

Additional key values from the motor selection

- max. motor current $I_{max}$
- duration of the max. current $\Delta t_{max}$
- average effective current load $I_{eff}$

Additionally, the following continue to apply

- supply voltage $V_{CC}$
- control accuracy at the motor
  - angular resolution $\Delta\varphi$
  - required speed accuracy $\Delta n$
- environmental conditions

Next step of the drive selection in chapter 7 (Encoder Selection)

## 6.2 Modular system and power selection

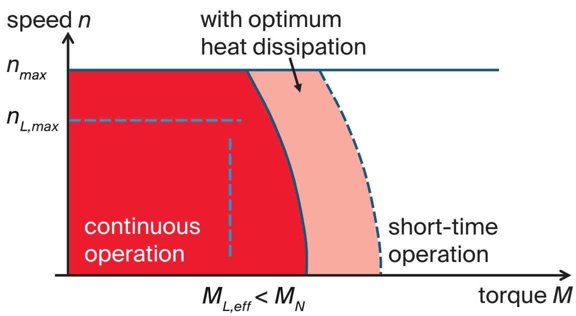
If a gearhead is used, the choice of appropriate motor types is limited by the maxon modular system.
The operating points (speed and torque) resulting from the mechanical layout and gearhead selection determine the motor size. The operating points must fall within the corresponding operating range of the motor.

### Selection criterion: maxon modular system

Which motors are compatible with the selected gearhead? (Example: GPX 22)

| Modular system | | | |
|---|---|---|---|
| **DC motor** | no. of stages [opt.] | **EC motor** | no. of stages [opt.] |
| DCX 19 S | 3–4 | ECX SPEED 19 M | 3–4 |
| DCX 22 S | 1–2 [3–4] | ECX SPEED 19 L | 3–4 |
| DCX 22 L | 1–2 [3–4] | ECX SPEED 22 M | 1–2 [3–4] |
| DC-max 22 S* | 1–2 [3–4] | ECX SPEED 22 L | 1–2 [3–4] |
| | | ECX TORQUE 22 M | 1–2 |
| | | ECX TORQUE 22 L | 1–2 |
| | | ECX TORQUE 22 XL | 1–2 |

### Selection criteria: speed and continuous torque




Speed
$n_{L,max} < n_{max}$

Continuous torque
$M_{L,eff} < M_N$

The continuous torque of the motor $M_N$ depends on the thermal coupling to the environment.
(calculation in chapter 6.5)

### Selection criteria: short-time operation

Individual operating points may fall within the short-time operating range, as long as they are brief enough.

The natural time scale is the **thermal time constant of the winding** $\tau_W$. Typically, a motor can handle double its **nominal torque** $M_N$ for a few seconds.

Simplified rules of thumb:

$0 < M_{L,max} \leq 1\ M_N \rightarrow t_{max} = \text{continuous}$

$1\ M_N < M_{L,max} \leq 2\ M_N \rightarrow t_{max} \approx 4 - 5\ \tau_W$

$2\ M_N < M_{L,max} \leq 2.5\ M_N \rightarrow t_{max} \approx 1\ \tau_W$

$2.5\ M_N < M_{L,max} \leq 3\ M_N \rightarrow t_{max} \approx 0.5\ \tau_W$

(calculation in chapter 9.3)

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n_{max}$ | Max. permissible speed, motor (catalog value) | rpm | $\tau_W$ | Thermal time constant of the winding (catalog value) | s |
| $n_{L,max}$ | Maximum load speed | rpm | $M_N$ | Nominal torque, motor (catalog value) | mNm |
| $t_{max}$ | Maximum duration of overload | s | $M_{L,eff}$ | Effective load torque | mNm |
| | | | $M_{L,max}$ | Max. short-time load torque | mNm |

## 6.3 Selection criteria: motor type (DC or EC)

The required service life is the main criterion for choosing between a brushed DC motor and a brushless EC motor.
EC motors are also available in versions for particularly high speeds or high torque, as flat motors, or in autoclavable versions.

| | brushed DC motor with coreless winding | brushless EC motor with coreless winding | brushless EC motor with cored winding |
|---|---|---|---|
| Commutation | graphite or precious metal brushes | electronic block or sinusoidal commutation | |
| Service life | typically 1000-3000 h | typically several 10 000 h | |
| Max. speeds | up to 20 000 rpm | up to 120 000 rpm | up to 20 000 rpm |
| Torque density | high | | very high |
| Special versions | | – autoclavable<br>– high speeds | – autoclavable<br>– flat motors with/ without ventilation<br>– with integrated electronics |
| Dimensions, design | elongated cylinder | | flat motor or medium-length cylinders |
| Cogging torque | no | | yes |
| Connections, cables | typically 2-wire | typically 8-wire | |

| Max. service life of DC motor | Max. service life of EC motor |
|---|---|
| Limited by brush system.<br><br>No general statement possible<br>– average requirements: 1000-3000 h<br>– extreme conditions: fewer than 100 h<br>– favorable conditions: more than 20 000 h<br><br>Influencing factors<br>– **higher currents** = more brush fire<br>– **high speed** = greater brush wear<br>– continuous operation better than start-stop operation<br>– **environmental conditions**: Temperature, humidity, vibration, etc.<br>– **load** of the shaft (bearing) | Limited by the bearing life.<br><br>Service life at **nominal speed** and at **bearing load as specified in the catalog:**<br>approx. 20 000 h<br>– inversely proportional to the speed<br>– inversely proportional to the third power of the bearing load. (half load: 8x service life)<br><br>Influencing factors<br>– **condition of the bearing lubricant**<br>– **environmental conditions:** dust and moisture in the bearing, shock, vibration, temperature, airflow through bearing, etc. |

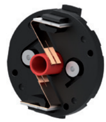
## Commutation of DC motors

**Graphite brushes**

- suitable for high currents and current peaks
- suitable for start-stop and reversing operation
- larger motors

- higher friction, higher no load current
- unsuitable for low currents
- more noise
- higher electromagnetic emissions
- more complex and more expensive

**Precious metal brushes**



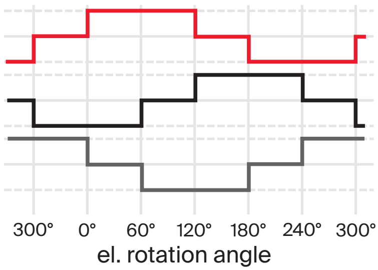
- suitable for small currents and voltages
- suitable for continuous operation
- smaller motors
- lower friction, less noise
- lower electromagnetic emissions
- attractively priced
- CLL for longer service life

- unsuitable for high currents and current peaks
- unsuitable for start-stop operation

## Commutation of EC motors (using external electronics)

**Block commutation**

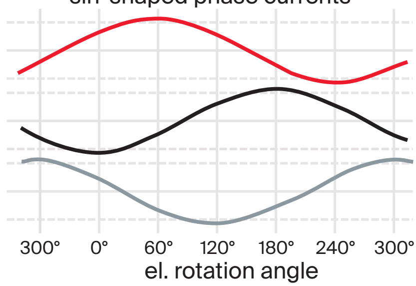
block-shaped phase currents




**Properties**
- torque ripple of 14%
- controlled startup
- high startup torques and accelerations possible
- servo drives, start-stop operation
- positioning tasks
- The data of the maxon EC motors are determined by means of block commutation

**Sinusoidal commutation**

sin-shaped phase currents




**Properties**
- field-oriented control (FOC), encoder often necessary
- no torque ripple, very good synchronous running even at low speeds.
- approx. 5% higher continuous torque than with block commutation (chapter 6.7)
- highly dynamic servo drives
- positioning tasks

**Sensorless block commutation**

The rotor position is determined by the progression of the induced voltage.
- no defined startup
- not suitable for low speeds and for dynamic applications
- continuous operation at higher speeds (fans, milling tools, drills)

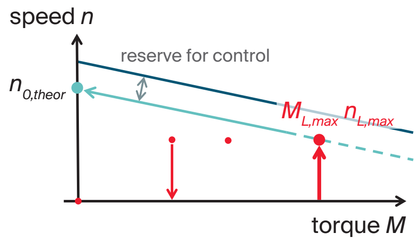
**Sensorless sinusoidal commutation**

The rotor position is determined by the variance in inductance.
- jerk-free startup also under load
- suitable for very high dynamic range from very small to very large speeds
- complex parameterization

Sensorless commutation requires significant initial effort and complicates commissioning. Therefore, EC motors equipped with Hall sensor signals always are to be preferred.

## 6.4 Winding selection

To achieve optimal alignment between the available voltage and mechanical requirements, choose the winding with the most suitable speed constant $k_n$.

| Recommended procedure | |
|---|---|
| First determine the theoretical speed constant required to reach the extreme operating point ($n_{L,max}$; $M_{L,max}$) with the available voltage at the motor. | |
|  | $n_{0,theor} = n_{L,max} + \frac{\Delta n}{\Delta M} \cdot M_{L,max}$<br>$k_{n,theor} = \frac{n_{0,theor}}{U_{mot}} = \frac{n_{L,max} + \frac{\Delta n}{\Delta M} \cdot M_{L,max}}{U_{mot}}$ |
| Next, from the data sheet of the selected motor, select the winding with the appropriate speed constant, depending on the operation type. | |
| **Operation with a fixed voltage source** | |
| Operation without control, at fixed operating point ($n_L$; $M_L$) and fixed motor voltage $U_{mot}$ | $k_n \cong k_{n,theor} = \frac{n_{0,theor}}{U_{mot}} = \frac{n_L + \frac{\Delta n}{\Delta M} \cdot M_L}{U_{mot}}$ |
| Choose the winding with the speed constant $k_n$ as close as possible to the calculated value $k_{n,theor}$. | |
| **Operation with a controller** | |
| Operation with control loop, at the maximum voltage $U_{mot}$ available at the motor | $k_n \geq 1.2 \cdot k_{n,theor} = 1.2 \cdot \frac{n_{L,max} + \frac{\Delta n}{\Delta M} \cdot M_{L,max}}{U_{mot}}$ |
| Add 20% to the calculated speed constant $k_{n,theor}$ and then select the winding with the next highest speed constant $k_n$. The 20% serves as a control reserve when operating at maximum load and is used to account for tolerances.<br><br>**Recommendation:** avoid selecting a speed constant that is too high, to ensure that the available voltage is efficiently used and that the required motor currents do not get too high. | |

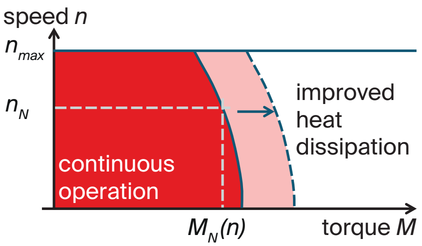
| Required motor current | | |
|---|---|---|
| $I = \frac{M_L}{k_M} + I_0$ | $I_{max} = \frac{M_{L,max}}{k_M} + I_0$ | $I_{eff} = \frac{M_{L,eff}}{k_M} + I_0$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n_{0,theor}$ | No load speed, theoretical | rpm | $I_{eff}$ | Effective motor current | A |
| $n_L$ | Load speed | rpm | $I_{max}$ | Max. required motor current | A |
| $n_{L,max}$ | Max. speed of all operating points | rpm | $I_0$ | No load current (catalog value) | A |
| $M_L$ | Load torque | mNm | $k_M$ | Torque constant (catalog value) | mNm/A |
| $M_{L,max}$ | Max. torque of all operating points | mNm | $k_n$ | Speed constant (catalog value) | rpm/V |
| $M_{L,eff}$ | Effective load torque | mNm | $k_{n,theor}$ | Speed constant, theoretical | rpm/V |
| $U_{mot}$ | Motor voltage | V | $\Delta n/\Delta M$ | Speed/torque gradient (cat. value) | rpm/mNm |
| $I$ | Required motor current | A | | | |

## 6.5 Special environmental conditions

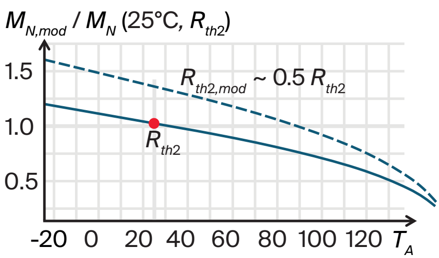
### Derating of the motor

The maximum permissible continuous torque $M_N$ corresponds to the heat dissipation at the maximum permissible winding temperature $T_{max}$ and is determined under standard conditions (25° ambient temperature) at nominal speed. However, in a practical application, $M_N$ can vary.




Factors influencing heat dissipation
- ambient temperature $T_A$
- active cooling by means of air circulation
- installation: material and size of contact surfaces (e.g. heat sink)
- heat exchange with the gearhead

The speed dependency is visible in the curvature of the continuous operation range.

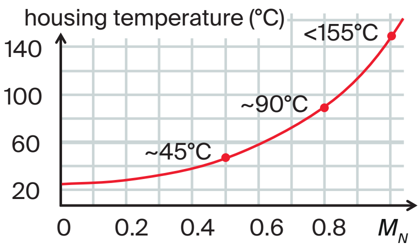



Continuous torque under different
- ambient temperatures $T_A \neq 25°C$ and/or
- installation conditions $R_{th2,mod} \neq R_{th2}$

$$M_{N,mod} = M_N \cdot \sqrt{\frac{T_{max} - T_A}{T_{max} - 25°C} \cdot \frac{R_{th1} + R_{th2}}{R_{th1} + R_{th2,mod}}}$$

More in chapter 9

### Housing temperature during continuous operation




Typical heat build-up in the motor housing in continuous operation ($T_A$ = 25°C)
- up to 155°C at $M_N$
- approx. 90°C at 80% $M_N$
- approx. 45°C at 50% $M_N$ (lukewarm)

### Additional selection guidelines

Suitability for autoclaving:
- sterilizable units (motor, gearhead, encoder)

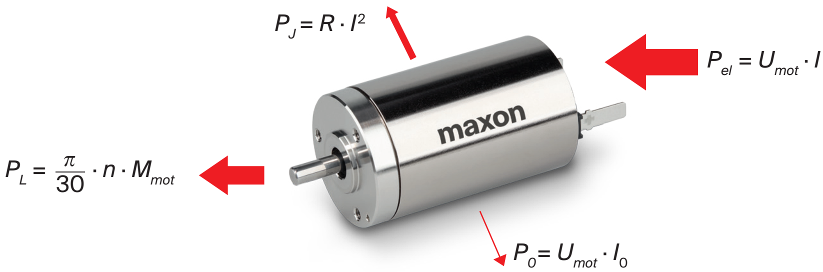
Suitability for vacuum, vibration, very high/low temperatures:
- potentially special aerospace units

| Symbol | Name | Unit |
|---|---|---|
| $n_N$ | Nominal speed (catalog value) | rpm |
| $M_N$ | Nominal torque (catalog value) | mNm |
| $M_{N,mod}$ | Modified nominal torque | mNm |
| $T_{max}$ | Max. permissible winding temperature (catalog value) | °C |
| $T_A$ | Ambient temperature | °C |

| Symbol | Name | Unit |
|---|---|---|
| $R_{th1}$ | Therm. resistance, winding–housing (catalog value) | K/W |
| $R_{th2}$ | Therm. resistance, housing–environment (catalog value) | K/W |
| $R_{th2,mod}$ | Therm. resistance, housing–environment with modified installation conditions | K/W |

## 6.6 Motor behavior and speed-torque line

### Motor as energy converter




| | |
|---|---|
| Power balance, motor | $P_{el} = P_L + P_J + P_0$<br>$U_{mot} \cdot I = \frac{\pi}{30} \cdot n \cdot M_{mot} + R \cdot I^2 + U_{mot} \cdot I_0$ |

### Power losses, motor

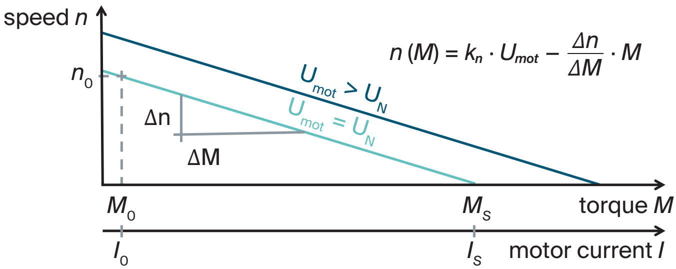
| | |
|---|---|
| **Electrical heat losses**<br>– increase quadratically with the motor current.<br><br>Keep in mind: the electrical resistance *R* is temperature-dependent (see page 50). | $P_J = R \cdot I^2$ |
| **Iron losses**<br>– remagnetization (hysteresis) losses<br>– eddy current losses<br><br>**Friction losses**<br>– in bearings and brushes<br><br>these are modeled in combination, as<br>– constant (static) loss torque $M_{VA}$<br>– speed-dependent (dynamic) loss torque $c_5$ | $P_0 = \frac{\pi}{30} \cdot n \cdot (M_{VA} + c_5 \cdot n) \approx U_{mot} \cdot I_0$ |

Comment on the magnitudes
- DC motors have no load currents $I_0$ in the range of 2 - 7% of the maximum continuous load current.
- Brushless EC motors have a higher percentage of no load current (typically 5–10%) due to the iron losses. This percentage can also be highly dependent on speed (evident from the curvature of the continuous operating range).

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $P_{el}$ | Electrical input power | W | $M_{mot}$ | Motor output torque | Nm |
| $P_L$ | Mechanical output power | W | $M_{VA}$ | Static damping (loss torque) | Nm |
| $P_J$ | Joule power loss | W | $c_5$ | Viscous damping (loss torque) | Nm/rpm |
| $P_0$ | Power loss caused by friction and iron losses | W | $U_{mot}$ | Motor voltage | V |
| | | | $I$ | Motor current | A |
| $n$ | Motor speed | rpm | $I_0$ | No load current (catalog value) | A |
| | | | $R$ | Terminal resistance, motor (catalog value) | Ω |

## Speed-torque line

Describes ideal motor behavior — possible operating points ($n$, $M$) — at constant voltage $U_{mot}$




The values of the no load, nominal, and startup operating points specified in the catalog apply at nominal voltage.

| | |
|---|---|
| **No-load speed $n_0$**<br>Speed without load | $n_0 = k_n \cdot U_{mot} - \frac{\Delta n}{\Delta M} \cdot M_0 \approx k_n \cdot U_{mot}$ |
| **Loss torque in the motor $M_0$**<br>Friction and iron losses that occur during operation (not only at no-load) | $M_0 = M_{VA} + c_5 \cdot n \approx k_M \cdot I_0$ |
| **Startup/stall torque $M_S$**<br>In real-world applications, this is not achievable with most motors. | $M_S = k_M \cdot I_S - M_0 \approx k_M \cdot I_S$ |

## Derivation of the speed-torque line

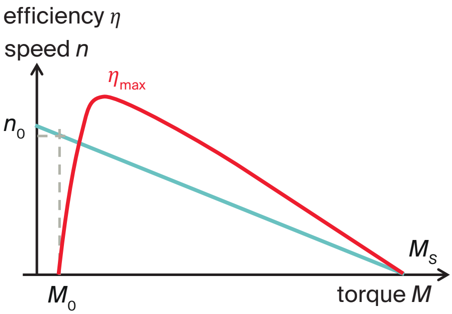
| | |
|---|---|
| From the power balance<br>$U_{mot} \cdot I = \frac{\pi}{30} n \cdot M + R \cdot I^2$<br><br>and the definition of the torque constant<br>$k_M = \frac{M}{I}$<br><br>(all torques in mNm) | $U_{mot} \cdot \frac{M}{k_M} = \frac{\pi}{30000} \cdot n \cdot M + R \cdot \left(\frac{M}{k_M}\right)^2$<br><br>$n = k_n \cdot U_{mot} - \frac{30000}{\pi} \cdot \frac{R}{k_M^2} \cdot M$<br><br>$n = k_n \cdot U_{mot} - \frac{\Delta n}{\Delta M} \cdot M$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n$ | Speed | rpm | $U_{mot}$ | Motor voltage | V |
| $n_0$ | No load speed (catalog value) | rpm | $U_N$ | Nominal voltage (catalog value) | V |
| $M$ | Generated motor torque | mNm | $I$ | Motor current | A |
| $M_S$ | Startup/stall torque (catalog value) | mNm | $I_0$ | No load current (catalog value) | A |
| $M_0$ | Loss torque | mNm | $I_S$ | Startup/stall current (catalog value) | A |
| $M_{VA}$ | Static damping (loss torque) | mNm | $k_M$ | Torque constant (catalog value) | mNm/A |
| $c_5$ | Viscous damping (loss torque) | mNm/rpm | $k_n$ | Speed constant (catalog value) | rpm/V |
| $R$ | Terminal resistance, motor (catalog value) | Ω | $\Delta n/\Delta M$ | Speed/torque gradient (cat. value) | rpm/mNm |

## Motor constants

| | |
|---|---|
| **Speed constant $k_n$**<br>The voltage induced in the winding $U_{ind}$ (=EMF) is proportional to the speed *n*. | $k_n = \frac{n}{U_{ind}}$ |
| **Generator constant $k_G$**<br>It is the reciprocal of the speed constant, also called the back-EMF constant $k_e$. | $k_G = \frac{1}{k_n} = \frac{U_{ind}}{n}$ |
| **Torque constant $k_M$**<br>Links the torque *M* generated in the motor with the electrical current *I*. | $k_M = \frac{M}{I}$ |
| Dependency between $k_n$ and $k_M$ | $k_n \cdot k_M = \frac{30\,000}{\pi} \left[ \frac{min^{-1}}{V} \cdot \frac{mNm}{A} \right] = 1$ |
| **Motor constant *K*** (use SI units!)<br>The motor constant represents the torque per square root of the electrical heat losses. | $K = \frac{M}{\sqrt{P_J}} = \frac{k_M}{\sqrt{R}} = \frac{1}{\sqrt{\frac{\Delta n}{\Delta M}}}$ |
| **Speed/torque gradient $\Delta n/\Delta M$**<br>The speed/torque gradient indicates how much the speed decreases as the torque increases. | $\frac{\Delta n}{\Delta M} = \frac{\pi}{30\,000} \cdot \frac{R}{k_M^2} \approx \frac{n_0}{M_S}$ |

## Efficiency at constant motor voltage




Efficiency

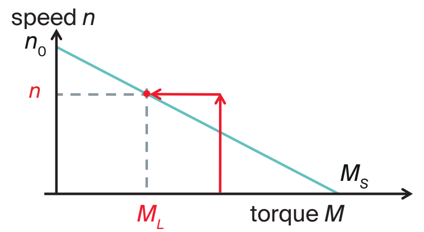
$$\eta = \frac{\pi}{30\,000} \cdot \frac{n \cdot (M - M_0)}{U_{mot} \cdot I}$$

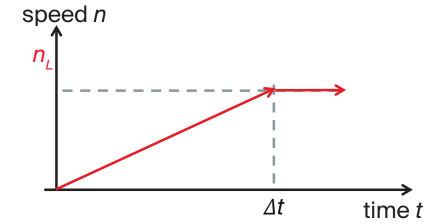
Maximum efficiency

$$\eta_{max} = \left(1 - \sqrt{\frac{M_0}{M_S}}\right)^2 = \left(1 - \sqrt{\frac{I_0}{I_S}}\right)^2$$

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n$ | Speed | rpm | $I$ | Motor current | A |
| $n_0$ | No load speed (catalog value) | rpm | $I_0$ | No load current (catalog value) | A |
| $M$ | Torque | mNm | $I_S$ | Startup/stall current (catalog value) | A |
| $M_0$ | Loss torque | mNm | $R$ | Terminal resistance, motor (catalog value) | Ω |
| $M_S$ | Startup/stall torque (catalog value) | mNm | $P_J$ | Joule power loss | W |
| $U_{ind}$ | Induced voltage | V | $k_M$ | Torque constant (catalog value) | mNm/A |
| $U_{mot}$ | Motor voltage | V | $k_n$ | Speed constant (catalog value) | rpm/V |
| $\eta$ | Efficiency | | $k_G$ | Generator constant | V/rpm |
| $\eta_{max}$ | Max. efficiency at $U_N$ (catalog value) | | $K$ | Motor constant | $Nm/W^{1/2}$ |
| | | | $\Delta n/\Delta M$ | Speed/torque gradient (cat. value) | rpm/mNm |

## Angular acceleration: start with constant current




Acceleration

$$\alpha = 10^4 \cdot \frac{M}{J_R + J_L} = 10^4 \cdot \frac{k_M \cdot I_{mot}}{J_R + J_L}$$

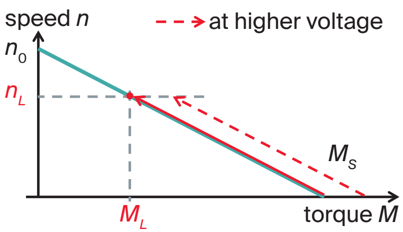
Speed when accelerating from standstill

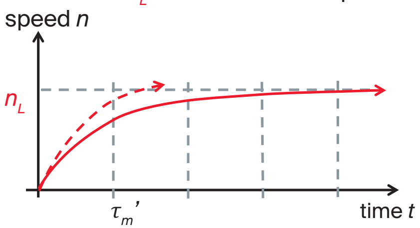
$$n_L = \frac{30}{\pi} \cdot \alpha \cdot \Delta t$$

Ramp-up time up to load speed

$$\Delta t = \frac{\pi}{300} \cdot n_L \cdot \frac{J_R + J_L}{M} = \frac{\pi}{300} \cdot n_L \cdot \frac{J_R + J_L}{k_M \cdot I_{mot}}$$

## Angular acceleration: start with constant terminal voltage




Acceleration

$$\alpha_{max} = 10^4 \cdot \frac{M_S}{J_R + J_L}$$

Speed when accelerating from standstill

$$n(t) = n_L \cdot \left(1 - e^{-\frac{t}{\tau_m'}}\right)$$

Mechanical time constant with load inertia

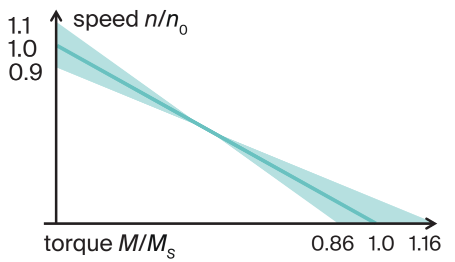
$$\tau_m' = 100 \cdot \frac{(J_R + J_L) \cdot R}{k_M^{\ 2}}$$

| Symbol | Name | Unit |
|---|---|---|
| $J_R$ | Moment of inertia, rotor (catalog value) | $gcm^2$ |
| $J_L$ | Moment of inertia, load | $gcm^2$ |
| $k_M$ | Torque constant (catalog value) | mNm/A |
| $M$ | Torque | mNm |
| $M_S$ | Startup/stall torque (catalog value) | mNm |
| $M_L$ | Load torque | mNm |
| $\alpha$ | Angular acceleration | $rad/s^2$ |
| $\alpha_{max}$ | Maximum angular acceleration | $rad/s^2$ |

| Symbol | Name | Unit |
|---|---|---|
| $n$ | Speed | rpm |
| $\Delta n$ | Speed change | rpm |
| $n_L$ | Load speed | rpm |
| $n_0$ | No load speed (catalog value) | rpm |
| $I_{mot}$ | Motor current | A |
| $R$ | Terminal resistance, motor (catalog value) | Ω |
| $t$ | Time | ms |
| $\Delta t$ | Ramp-up time | ms |
| $\tau_m'$ | Mechanical time constant with additional $J_L$ | ms |

## maxon standard tolerances

The motor parameters in the maxon catalog are presented with three decimal places, which seems to indicate very small tolerances. However, in reality, the following applies:



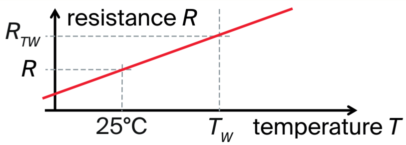

Resulting tolerances

| | |
|---|---|
| – general tolerance level | 5 ... 10% |
| – tolerance in no load current | ±50% |
| – tolerance in no load speed | ±10% |
| – weaker magnet => | higher $n_0$ |
| – stronger magnet => | smaller $n_0$ |

Causes

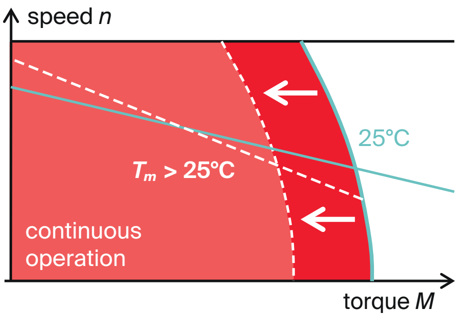
| | |
|---|---|
| – winding resistance | ±7% |
| – magnet properties | ±8% |
| – friction and iron losses | ±33 % |

## Influence of the operating temperature on the motor data




During operation, the winding heats up, and as a result, the winding resistance increases

$$R_{TW} = R \cdot [1 + \alpha_{Cu} \cdot (T_W - 25°C)]$$




Due to the elevated temperature

- the permanent magnet gets weaker
- the winding resistance increases
- the power losses increase
- the bearing lubrication changes

$$k_{M,Tm} \approx k_M \cdot [1 - \alpha_{NdFeB} \cdot (T_m - 25°C)]$$

$$k_{n,Tm} \approx k_n \cdot [1 + \alpha_{NdFeB} \cdot (T_m - 25°C)]$$

Result: the hotter the motor

- the weaker the motor
- the steeper the speed-torque line
- the lower the continuous torque

## Consequence

The tolerances and the influence of motor temperature on performance data are the reasons why a control reserve of at least 20% is recommended when selecting the winding.

| Symbol | Name | Unit |
|---|---|---|
| $M$ | Torque | mNm |
| $n$ | Speed | rpm |
| $n_0$ | No load speed | rpm |
| $k_M$ | Torque constant (catalog value) | mNm/A |
| $k_{M,Tm}$ | Torque constant, temperature $T_m$ | mNm/A |
| $k_n$ | Speed constant (catalog value) | rpm/V |
| $k_{n,Tm}$ | Speed constant, temperature $T_m$ | rpm/V |

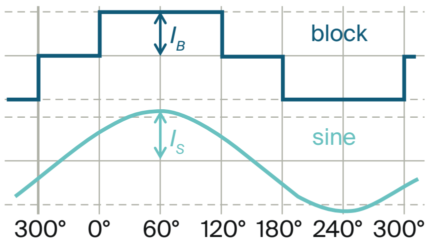
| Symbol | Name | Unit |
|---|---|---|
| $R$ | Terminal resistance, motor (catalog value) | Ω |
| $R_{Tw}$ | Winding resistance, temperature $T_W$ | Ω |
| $T_W$ | Winding temperature | °C |
| $T_m$ | Magnet temperature | °C |

| Symbol | Name | Value |
|---|---|---|
| $\alpha_{Cu}$ | Resistance coefficient, copper | 0.0039 $K^{-1}$ |
| $\alpha_{NdFeB}$ | Temp. coefficient, neodymium | ~0.0011 $K^{-1}$ |

## 6.7 EC motor parameters with sinusoidal commutation (FOC)

The motor data for EC motors are specified in the data sheet for block commutation. In the case of sinusoidal commutation or FOC (field-oriented control), the load on the motor can be greater and certain motor parameters change. The equations apply to the following definition of the current.

### Definition of the reference current




Amplitude as current reference
– for block commutation: $I_B$ (DC current)
– for sinusoidal commutation: $I_S$ (AC amplitude)

Losses in the winding

$$P_V = 2 \cdot R \cdot I_B^2 = \frac{3}{2} \cdot R \cdot I_S^2$$

For sinusoidal commutation the nominal current amplitude $I_{N,S}$ is greater than the nominal current listed in the catalog for block commutation $I_{N,B}$.

$$I_{N,S} = \frac{2}{\sqrt{3}} \cdot I_{N,B} \approx 1.15 \cdot I_{N,B}$$

### Torque constant

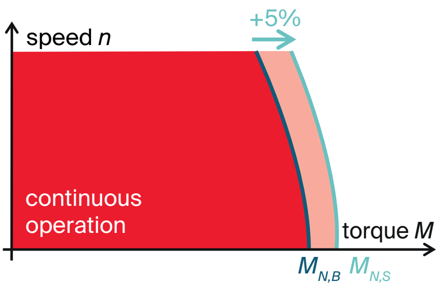
The torque constant for sinusoidal commutation $k_{M,S}$ indicates the relationship between the produced torque and the reference current $I_S$.

The torque constant is “smaller” with sinusoidal commutation:

$$k_{M,S} = \frac{\pi}{2 \cdot \sqrt{3}} \cdot k_{M,B} \approx 0.9 \cdot k_{M,B}$$

A higher current amplitude is required for the same torque.

### Continuous operation range




The continuous torque is slightly higher with sinusoidal commutation:

$$M_{N,S} = k_{M,S} \cdot I_{N,S}$$

$$M_{N,S} = \frac{\pi}{2 \cdot \sqrt{3}} \cdot k_{M,B} \cdot \frac{2}{\sqrt{3}} \cdot I_{N,B} = \frac{\pi}{3} \cdot k_{M,B} \cdot I_{N,B}$$

$$M_{N,S} = \frac{\pi}{3} \cdot M_{N,B} \approx 1.05 \cdot M_{N,B}$$

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $R$ | Terminal resistance, motor (catalog value) | Ω | $P_V$ | Power losses in the winding | W |
| **B** | **Block commutation** | | **S** | **Sinusoidal commutation (FOC)** | |
| $I_B$ | Current | A | $I_S$ | Current amplitude | A |
| $I_{N,B}$ | Nominal current (catalog value) | A | $I_{N,S}$ | Nominal current amplitude | A |
| $k_{M,B}$ | Torque constant (catalog value) | mNm/A | $k_{M,S}$ | Torque constant | mNm/A |
| $M_{N,B}$ | Nominal torque (catalog value) | mNm | $M_{N,S}$ | Nominal torque | mNm |

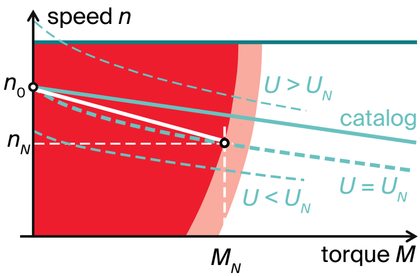
## 6.8 Speed-torque line of multi-pole EC motors with cored winding

The behavior of multipole EC motors with iron core winding can deviate significantly from the simple linear relationships. This applies in particular to the speed-torque line at high speeds and the torque constant at high torques.

### High speeds

Multi-pole EC motors feature very short commutation intervals and, due to the iron core, a higher terminal inductance. This means that the current cannot fully form at high speeds, leading to a smaller generated torque.

As a result, the speed-torque line deviates from the ideal straight line at higher speeds. The motor is weaker, and the slope of the gradient is steeper.

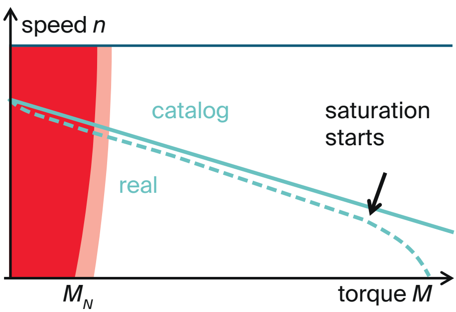



A line drawn between the no load speed and the nominal operating point (white line) can approximate the real gradient in the continuous operating range.

$$\frac{\Delta n}{\Delta M} \approx \frac{n_0 - n_N}{M_N}$$

For the winding selection, this calculated speed/torque gradient should be used instead of the catalog value.

### High torques



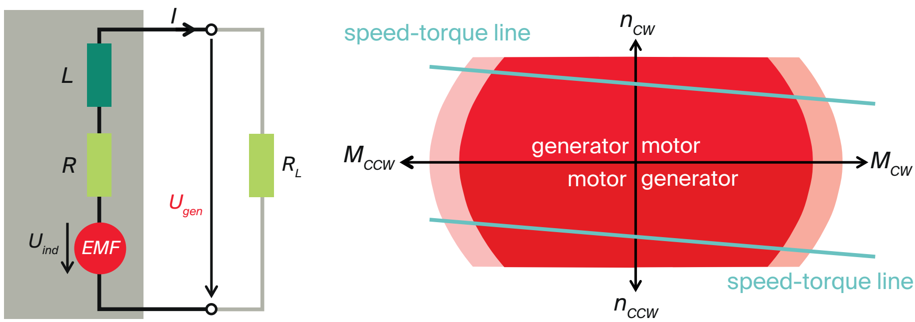

The magnetic saturation of the iron core at high currents leads to a reduction of the torque constant and, consequently, to a decrease of the stall torque $M_S$.
This deviation is often not taken into account in the data sheet of EC motors with iron core windings.

Since these saturation effects only occur at multiples of the nominal current, they are largely irrelevant in practice.

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n_0$ | No load speed (catalog value) | rpm | $I_N$ | Nominal current (catalog value) | A |
| $n_N$ | Nominal speed (catalog value) | rpm | $U$ | Voltage at motor | V |
| $M_N$ | Nominal torque (catalog value) | mNm | $U_N$ | Nominal voltage (catalog value) | V |
| $M_S$ | Startup/stall torque (catalog value) | mNm | $\Delta n/\Delta M$ | Speed/torque gradient (calculated) | rpm/mNm |

## 6.9 DC motor in generator operation

### Operating range and speed-torque line




All motor data and limits also apply in generator operation.

The same formulas also apply. However, since the direction of current $I$ and torque $M$ changes, the respective signs switch when ***absolute values*** are used.

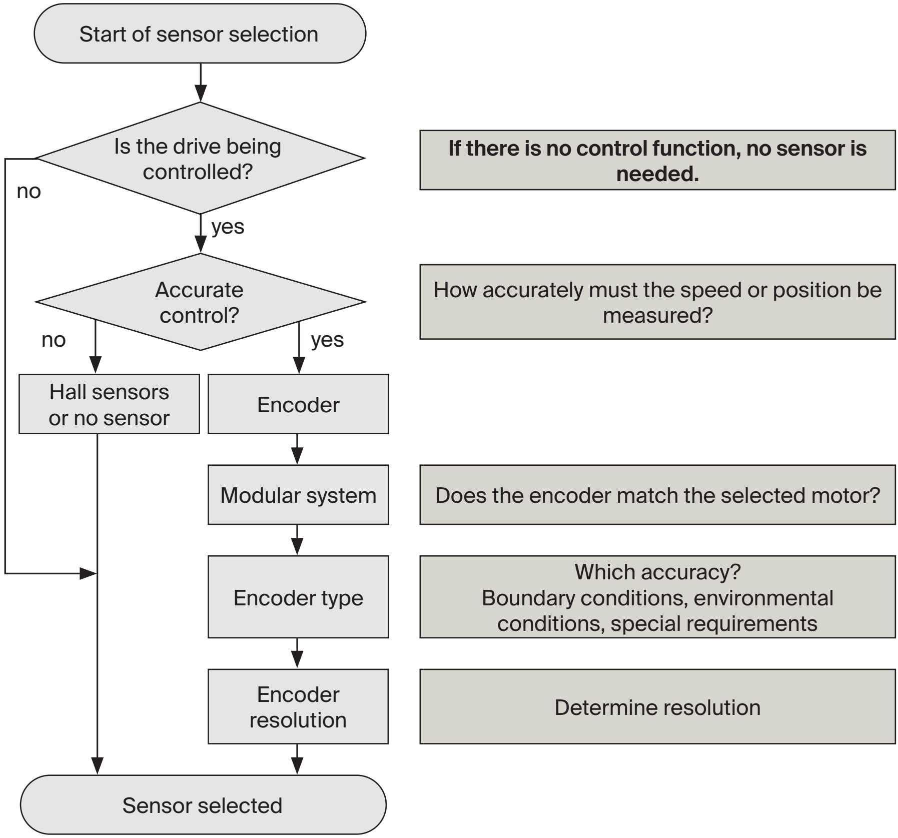
| Generator | Motor |
|---|---|
| Speed-torque line<br>$n = k_n \cdot U_{gen} + \frac{\Delta n}{\Delta M} \cdot M$<br>$n = k_n \cdot (U_{gen} + R \cdot I)$ | Speed-torque line<br>$n = k_n \cdot U_{mot} - \frac{\Delta n}{\Delta M} \cdot M$<br>$n = k_n \cdot (U_{mot} - R \cdot I)$ |
| Winding selection:<br>$k_n \leq \frac{n_{max} - \frac{\Delta n}{\Delta M} \cdot M_{max}}{U_{gen}} = \frac{n_{max}}{U_{gen} + R \cdot I}$<br>Since the resistance of the winding only becomes known after the selection has been made, it is initially estimated and then verified afterwards. | Winding selection:<br>$k_n \geq \frac{n_{max} + \frac{\Delta n}{\Delta M} \cdot M_{max}}{U_{mot}} = \frac{n_{max}}{U_{mot} - R \cdot I}$<br>Since the resistance of the winding only becomes known after the selection has been made, the winding is usually chosen using the left-hand formula. |
| Resulting voltage:<br>$U_{gen} = \frac{n - \frac{\Delta n}{\Delta M} \cdot M}{k_n} = \frac{n}{k_n} - R \cdot I$ | Required voltage:<br>$U_{mot} = \frac{n + \frac{\Delta n}{\Delta M} \cdot M}{k_n} = \frac{n}{k_n} + R \cdot I$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $n$ | Speed | rpm | $U_{ind}$ | Induced voltage | V |
| $n_{CW}$ | Speed, clockwise | rpm | $U_{mot}$ | Motor voltage | V |
| $n_{CCW}$ | Speed, counterclockwise | rpm | $U_{gen}$ | Generator voltage | V |
| $n_{max}$ | Max. speed of the application | rpm | $I$ | Current | A |
| $M$ | Torque | mNm | $R$ | Terminal resistance, motor (catalog value) | Ω |
| $M_{CW}$ | Torque, clockwise | mNm | $R_L$ | Load resistance | Ω |
| $M_{CCW}$ | Torque, counterclockwise | mNm | $k_M$ | Torque constant (catalog value) | mNm/A |
| $M_{max}$ | Max. torque of the application | mNm | $k_n$ | Speed constant (catalog value) | rpm/V |
| $L$ | Terminal inductance, motor (cat. value) | mH | $\Delta n/\Delta M$ | Speed/torque gradient (cat. value) | rpm/mNm |

# 7. maxon Encoder

## 7.1 Selection process (step 6)

Step-by-step guide to finding the right sensor




Key values for controller

We need these key values to select the controller.

– supply voltage $V_{CC}$

– max. motor current $I_{max}$

– duration of the max. current $\Delta t_{max}$

– average effective current $I_{eff}$

– encoders: supply voltage and signal type (incremental, absolute)

Next step of the drive selection in chapter 8 (Controller Selection)

## 7.2 Selection criteria: Encoder

| Criterion: maxon modular system | Criterion: accuracy of the encoder |
|---|---|
| Example<br>**Modular system**<br>**Sensor**<br>ENX 16 EASY<br>ENX 16 EASY XT<br>ENX 16 EASY Abs.<br>ENX 16 EASY Abs. XT<br>ENX 22 EMT<br>ENX 16 RIO | High accuracy<br>– direct sampling, without interpolation<br>– typically optical encoders<br><br>Average accuracy<br>– with interpolation<br>– typically magnetic and inductive encoders<br><br>Low accuracy<br>– hall sensor feedback |
| **Criterion: incremental or absolute encoder** | |
| **Incremental encoder**<br>– maxon standard encoder<br>– requires a homing procedure for absolute positioning after a restart | **Single-turn absolute encoder**<br>– angle values repeat after each shaft rotation<br>– for absolute positioning within a single turn without a homing procedure<br>– for absolute positioning over several turns, a homing procedure is needed after a restart<br><br>**Multi-turn absolute encoder**<br>– unique angle values across multiple shaft rotations<br>– no homing procedure necessary, not even after a restart |
| **Additional criteria for selecting the encoder type** | |
| – required resolution available?<br>– signal transmission: line driver, signal standard (TTL, RS422, CMOS, SSI, BISS-C, etc.)<br>– max. motor speed, max. pulse frequency<br>– mechanical and electromagnetic robustness<br>– environmental conditions, temperature range | |
| **Other feedback options** | |
| **Hall sensors of EC motors**<br>– correspond to an encoder with low resolution: 6 increments per magnetic pole pair of the motor | **DC Tacho**<br>– analog speed-proportional signal<br>– only speed control possible<br><br>**Resolver**<br>– requires special interface in the controller<br>– not possible with maxon controllers |

## Preliminary note on resolution

maxon specifies the resolution of the incremental encoders as number *N* of pulses or counts per turn and channel. The unit is cpt (counts per turn). Evaluating the edges on both encoder channels results in a fourfold higher resolution (see next page). These 4*N* states are also referred to as increments or quad counts.

In the case of **absolute encoders**, the resolution is specified in steps. The steps correspond to the 4*N* states (increment).

## Resolution *N* for positioning tasks


Required minimum counts per turn *N* (cpt) of the encoder for a required angular resolution $\Delta\varphi$ at the motor shaft.

$$N > X \cdot \frac{360°}{4 \cdot \Delta\varphi} \qquad \text{(with } X \geq 4\text{)}$$

**Comments:**
– The evaluation of the signal edges in incremental encoders results in a fourfold finer resolution in the formula (factor 4 in the denominator).
– To achieve precise measurement and corresponding accurate control, it is advisable to increase the resolution by a factor *X* between 4 and 10. For highly dynamic control, an even higher value can be chosen for *X*.

## Counts per turn (resolution) *N* for speed control

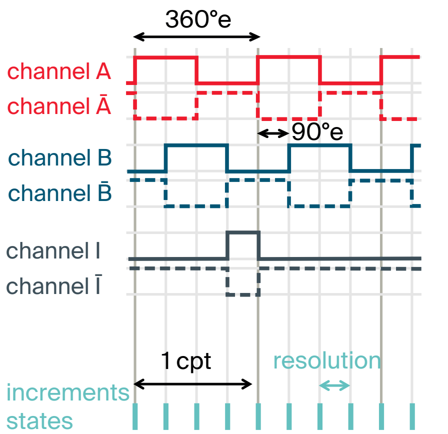
The speed to be controlled is the most important criterion for determining the counts per turn *N*. The counts per turn selected has to be set higher
– the lower the speed to be controlled
– the faster the control cycle
– the more dynamic speed deviations need to be corrected
– the lower the moment of inertia

Real-world experience:
– high resolution for direct drive with low motor speed
  n < 100 rpm requires > 10 000 cpt
  n < 1000 rpm requires > 1000 cpt
– low resolution for high motor speed
  n > 1000 rpm → 100 … 1000 cpt
– low resolution in the event of downstream mechanical drives (e.g. gearheads)

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $N$ | Counts per turn | cpt | $X$ | Selection factor (higher for very dynamic control) | 4 … 10 |
| $\Delta\varphi$ | Positioning resolution | ° | | | |

## 7.3 Signals and accuracy

### Signals of digital incremental encoders




2 channels, A and B, each with *N* counts per turn (cpt). If channel A comes before channel B, the direction of rotation is clockwise.

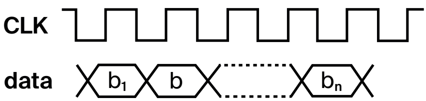
In the controller, the signal edges of both channels are detected. Each pulse (*cpt*) corresponds to 4 position data points (increments *inc*, quad counts *qc*).

The index channel *I* provides one count per turn and can be used for high-precision homing.

**Line driver: complementary signals**
The line driver generates a complementary signal for each signal. This significantly improves the signal transmission.

Tip: whenever possible, use an encoder with complementary signals.

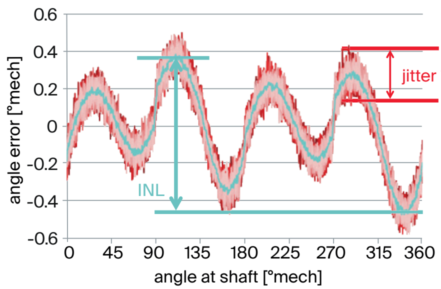
### Signals of digital absolute encoders




Signal protocols
- SSI
- Biss-C

Tip: use differential signal transmission whenever possible.

### Measuring accuracy




**Jitter:** measurement deviation at the same position across several turns. Frequently caused by axial play.

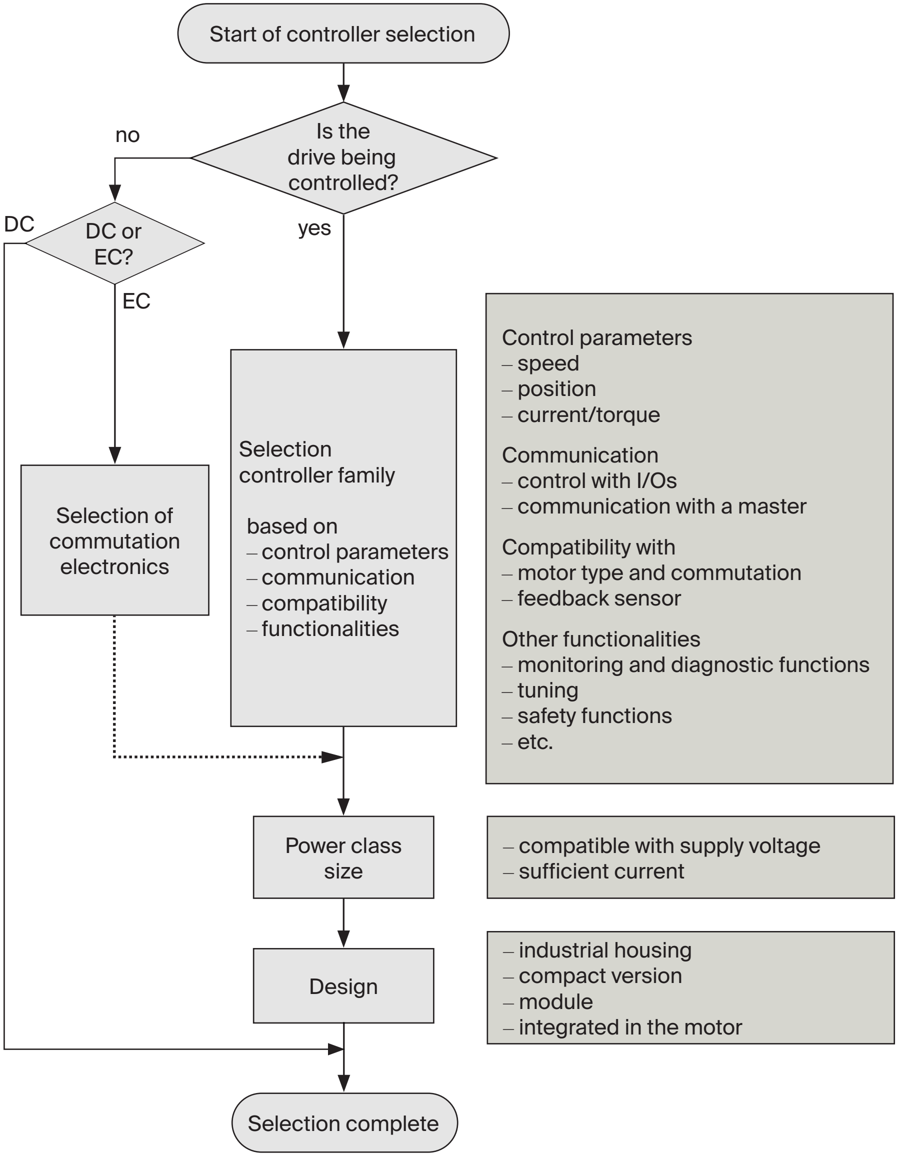
**INL** (integrated non-linearity): maximum angular deviation in a single turn. Caused by tolerances.

- repeatability → Jitter
- absolute accuracy → Jitter + INL

**Comments:**
- Resolution (number of states) and accuracy (INL, jitter) are not the same.
- Optical encoders have the highest accuracy (INL).
- The quality of the original signal and its interpolation influence the accuracy.
- Additional factors related to accuracy can be found in the product information of the respective encoder.

# 8. maxon Controllers
## 8.1 Selection process (step 6)

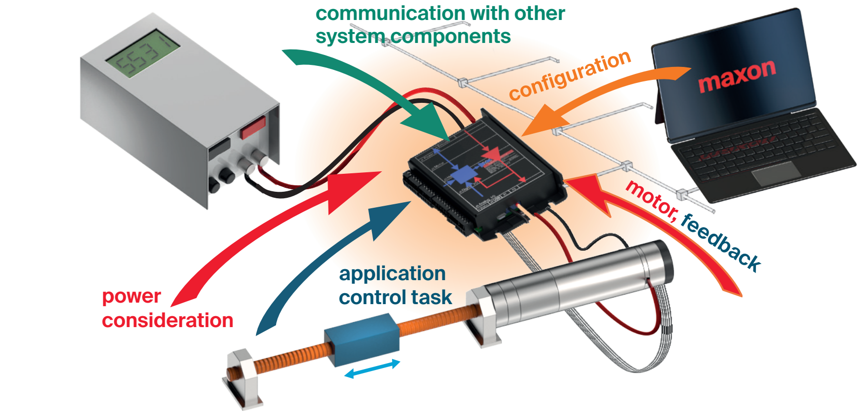
Step-by-step guide to finding the right controller



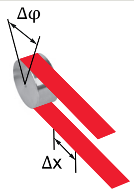
## 8.2. Selection criteria: controllers

### The controller as key element in the drive system

Commercial controllers can usually be configured to meet the specific requirements of an application and the components used.




### What is the regulation task?





The controller has to be suitable for being configured for the operating mode required in the application.
- speed controller (closed loop)
- speed controller (open loop)
- position controller
- current/torque controller

### Integration into the complete system, communication

How is communication with the higher-level system achieved? Where do the commands come from?
- control with I/Os
- communication with a master
  - serial (USB, RS232, etc.)
  - bus system (CAN, EtherCAT, etc.)
  - via I/Os

Are special input and outputs with predefined functionality needed? For example: limit switch or homing reference.

When performing parameterization, always keep the entire system in mind, for example any speed or current limits.

### Compatibility with motor

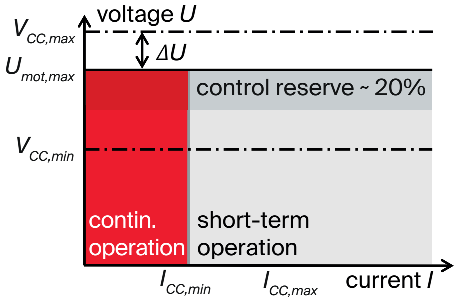
Can the controller be used with the selected motor type and commutation?
- DC motor, EC motor, etc.
- block commutation, sinusoidal commutation, sensorless commutation
- adapters and cables that might be required

For configuration, motor parameters are required, such as number of pole pairs, nominal current, thermal time constant, etc.

### Compatibility with feedback sensor

- Can the selected sensor type be connected to the controller (power supply, any adapters and cables that might be required)?
- Does the controller “understand” the signals from the sensor (Hall sensors, incremental or absolute encoder signals, line driver, index channel, etc.)?
- The resolution of the encoder is an important configuration parameter.

## Selection criteria: power




The control reserve is taken into account in the winding selection (speed constant).

Voltage criteria
$V_{CC,min} \leq V_{CC} \leq V_{CC,max}$
$U_{mot} \leq V_{CC} - \Delta U$

($\Delta U$ typically 1...10%)

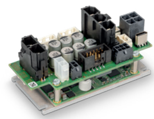
Current criteria
$I_{CC,cont} > I_{eff}$
$I_{CC,max} > I_{max}$

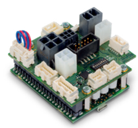
(with $t_{CC,max} > \Delta t_{max}$)

## Form factor (examples)

Complete controller in industrial housing

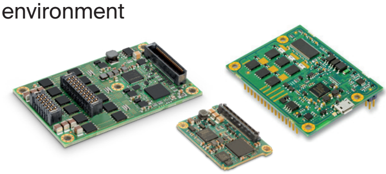
Compact version with the required connections and protective circuits





Integrated into the motor as compact drive


Module for integration into your own electronic environment



## Additional criteria for controller selection

– controller cycle (control speed)
– special control algorithms: dual loop, etc.
– PWM frequency
– integrated chokes, capacities
– power and velocity of I/Os
– etc.

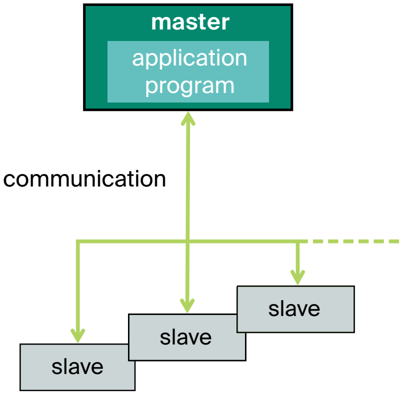
– functionality of the configuration interface
  – tuning, autotuning
  – Data Recorder
  – Command Analyzer
  – etc.

| Symbol | Name | Unit |
|---|---|---|
| $V_{CC,min}$ | Min. supply voltage (catalog value) | V |
| $V_{CC,max}$ | Max. supply voltage (catalog value) | V |
| $V_{CC}$ | Available supply voltage | V |
| $U_{mot}$ | Required motor voltage | V |
| $\Delta U$ | Voltage drop in the controller (catalog value) (typically 1...10%) | V |

| Symbol | Name | Unit |
|---|---|---|
| $I_{CC,cont}$ | Continuous current of the controller (catalog value) | A |
| $I_{CC,max}$ | Short-time peak current (catalog value) | A |
| $I_{eff}$ | Required motor current, continuous | A |
| $I_{max}$ | Required maximum motor current | A |
| $\Delta t_{max}$ | Duration of max. motor current | s |
| $t_{CC,max}$ | Duration of peak current (catalog value) | s |

## 8.3 System architecture and control loops

### Master-slave system architecture




Master
- e.g. MACS controller, PLC, PC, etc.
- contains the application program
- coordinates all slaves and subsystems to ensure the application runs as intended
- commands all slaves, gives them tasks to fulfill
- receives information back from the slaves

Communication
- fieldbus (CANopen, EtherCAT, etc.)
- seriell (USB, RS232, etc.)
- alternatively via digital and analog I/Os

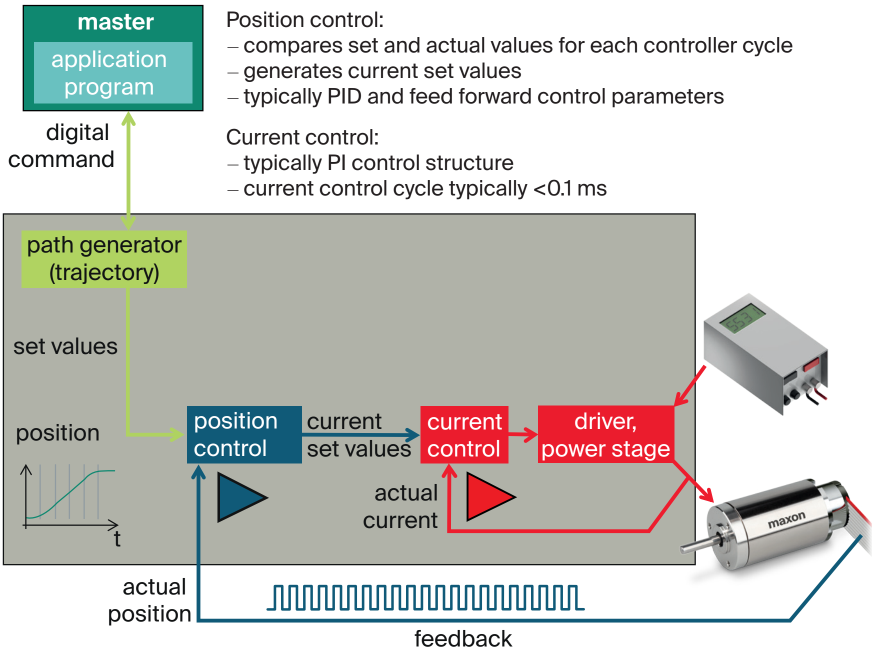
Slaves
- e.g. motor controllers such as EPOS or ESCON
- execute the commands of the master
- often with firmware

### Position controller

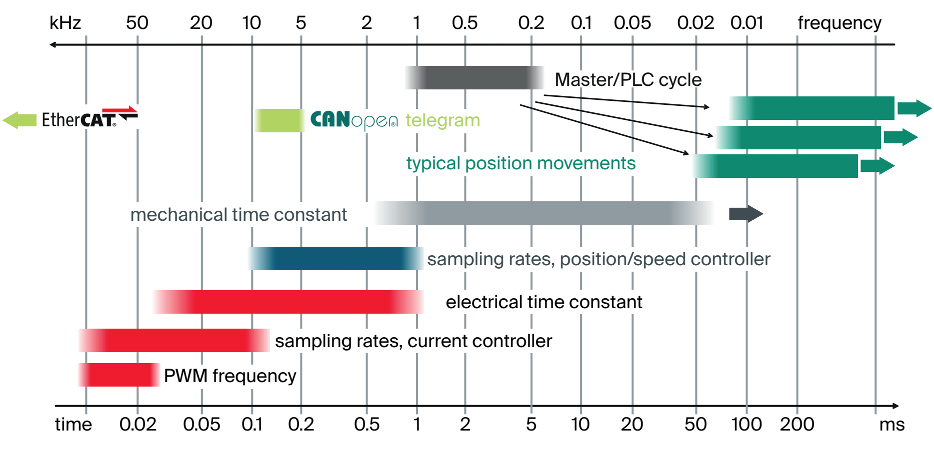
Path generator
- can also be integrated into the master
- generates new set values for each controller cycle (typically <1 ms)

Position control:
- compares set and actual values for each controller cycle
- generates current set values
- typically PID and feed forward control parameters

Current control:
- typically PI control structure
- current control cycle typically <0.1 ms



## What happens how fast?

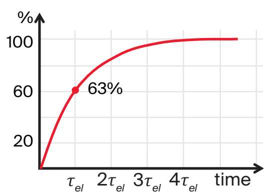



Here the duration of the processes is examined in relation to the mechanical time constant, a measure of how quickly controlled movements can be executed.
Usually, it is sufficient to regulate speed and position in the millisecond range. Therefore, the sampling rates of the controllers are in the range of 0.2 to 1 ms. The motor current can respond much quicker. Accordingly, the control loop is ten times faster.

The communication with higher-level systems such as PLCs or microcontrollers determines how many and how quickly multiple axes can be coordinated or synchronized. CANopen allows for the synchronization of 3 axes within a 1 ms cycle. High-end systems use much faster communication, e.g., EtherCAT. RS232, on the other hand, is not suitable for synchronization.

## Electrical time constant

The electrical time constant describes the response time of the current when a voltage is turned on or off.



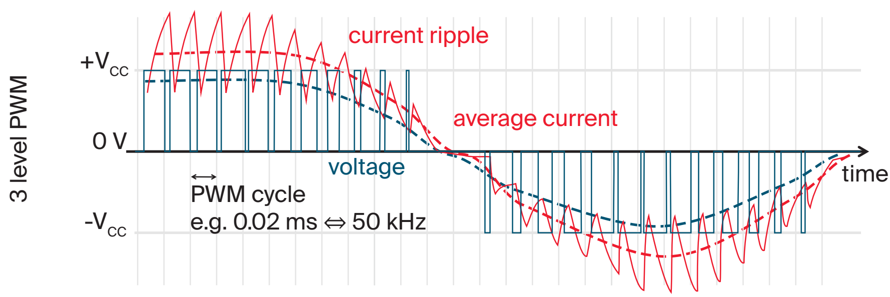

| | |
|---|---|
| Time constant of an inductive load<br><br>Typical values in motors<br>– with ironless winding: <0.2 ms<br>– winding with iron core: 0.2 ... 3 ms | $\tau_{el} = \frac{L}{R}$ |
| Time constant of a capacitive load | $\tau_{el} = R \cdot C$ |

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $L$ | Inductance | H | $\tau_{el}$ | Electrical time constant | s |
| $R$ | Electrical resistance | Ω | | | |
| $C$ | Capacity | F | | | |

## 8.4 Pulsed power stage (PWM)

### Pulsed PWM power stage

Most modern controllers have a pulsed power stage. In three-level PWM (pulse width modulation), the voltage is switched between the positive or negative supply voltage $V_{CC}$ of the controller and 0 V at a high constant frequency (typically 50-100 kHz). The motor is unable to mechanically follow these fast voltage transitions and only "sees" the average voltage. This average is set by means of the relative duration of $V_{CC}$ (pulse width).




Properties of pulsed power stages

- no losses in the power stage (high efficiency)
- electrical interferences in the MW and VHF frequency bands
- losses in the motor due to the current ripple

### Current ripple

Problem: excessive current ripples heat up the motor additionally. This is seen particularly in low-inductance motors with a small electrical time constant.

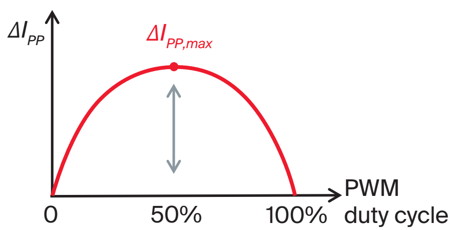
Measures for reducing the current ripple:

- **Reduce the supply voltage** $V_{CC}$ , if the application allows this.
- Select controller with a **high PWM frequency** $f_{PWM}$. However, this frequency is usually specified. maxon controllers have a PWM frequency of 50 or 100 kHz.
- Increase the **total inductance** $L_{tot}$ and thus enlarge the time constant $\tau_{el}$. The current response is slowed down. Therefore, maxon controllers have additional chokes built in.

Depending on the electrical time constant, the motor current can follow the voltage changes and will vary around an average value.

The analysis yields the following dependency for the maximum current ripple (peak to peak):

$$\Delta I_{PP,max} = \frac{V_{CC}}{4 \cdot L_{tot} \cdot f_{PWM}}$$




| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $V_{CC}$ | Supply voltage | V | $L_{tot}$ | Total inductance | H |
| $\Delta I_{PP}$ | Current ripple | A | $f_{PWM}$ | PWM frequency | Hz |
| $\Delta I_{PP,max}$ | Max. current ripple (at 50% duty cycle) | A | $\tau_{el}$ | Electrical time constant | s |

## Inductances in PWM operation

**Terminal inductance, motor $L_{mot}$**
In the maxon motor data the terminal inductance is specified for sinusoidal excitation with a frequency of 1 kHz. The effective motor inductance in the case of square PWM excitation only amounts to approx. 30 – 80% of this value.

**Inductance, controller $L_{int}$**
In most controllers, there is a choke integrated into each phase. For the calculations, the double value of the inductance of one phase must be taken into consideration

**Total inductance $L_{tot}$**
The total inductance consists of the inductance of the controller, the effective inductance of the motor, and any additional external inductance.

$$L_{tot} = L_{int} + 0.3 \dots 0.8 \cdot L_{mot} + L_{ext}$$

## Calculation an additional motor choke

The size of an additional motor choke is derived from the maximum permissible current ripple $\Delta I_{PP,max}$.

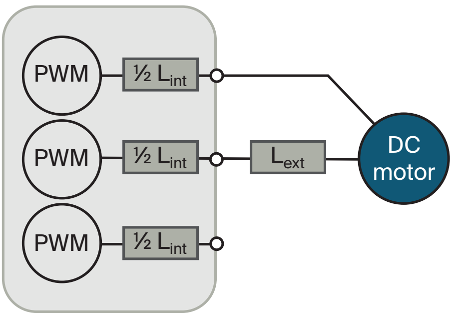
$$L_{ext} \geq \frac{V_{CC}}{4 \cdot \Delta I_{PP,max} \cdot f_{PWM}} - L_{int} - 0.3 \cdot L_{mot}$$

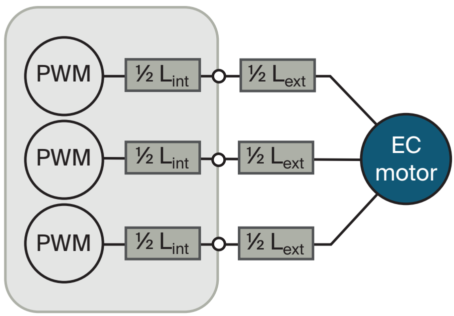
Recommendation:
For current ripples of $\Delta I_{PP,max} \leq 1.5 \cdot I_N$, the motor can still thermally handle a load of about 90% of the specified nominal current $I_N$. For larger current ripples, it is recommended to use an additional external motor choke based on this formula.

$$L_{ext} \geq \frac{V_{CC}}{4 \cdot (1.5 \cdot I_N) \cdot f_{PWM}} - L_{int} - 0.3 \cdot L_{mot}$$

## Placement of additional motor choke

$L_{ext} \leq 0$ => no additional motor choke required
$L_{ext} > 0$ => add additional motor chokes according to these schematics




| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $V_{CC}$ | Supply voltage | V | $L_{tot}$ | Total inductance | H |
| $I_N$ | Nominal current, motor (catalog value) | A | $L_{int}$ | Inductance, 2 built-in chokes, controller | H |
| $\Delta I_{PP}$ | Current ripple | A | $L_{ext}$ | Inductance, additional external choke | H |
| $\Delta I_{PP,max}$ | Max. permissible current ripple | A | $L_{mot}$ | Terminal inductance, motor (cat. value) | s |
| $f_{PWM}$ | PWM frequency | Hz | | | |

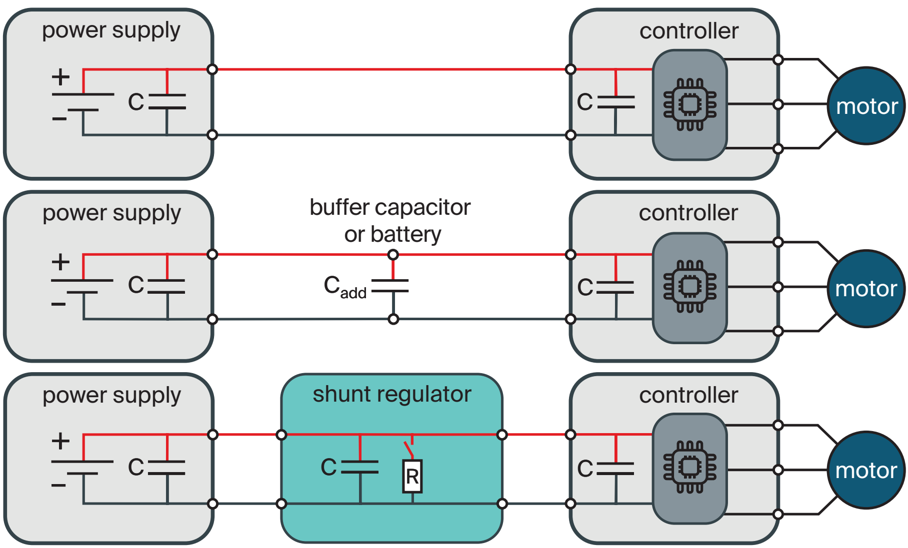
## 8.5 Energy recovery

**Measures against unwanted energy recovery**

When decelerating large inertias (e.g., centrifuges or flywheels) or downward movements (e.g., crane or elevator drives), the motor acts as a generator and feeds energy back. If the power supply cannot absorb the energy, the voltage at the controller will increase. Exceeding the maximum allowable supply voltage activates the overvoltage protection and generates an error.

Recommended countermeasures (increasing effort)

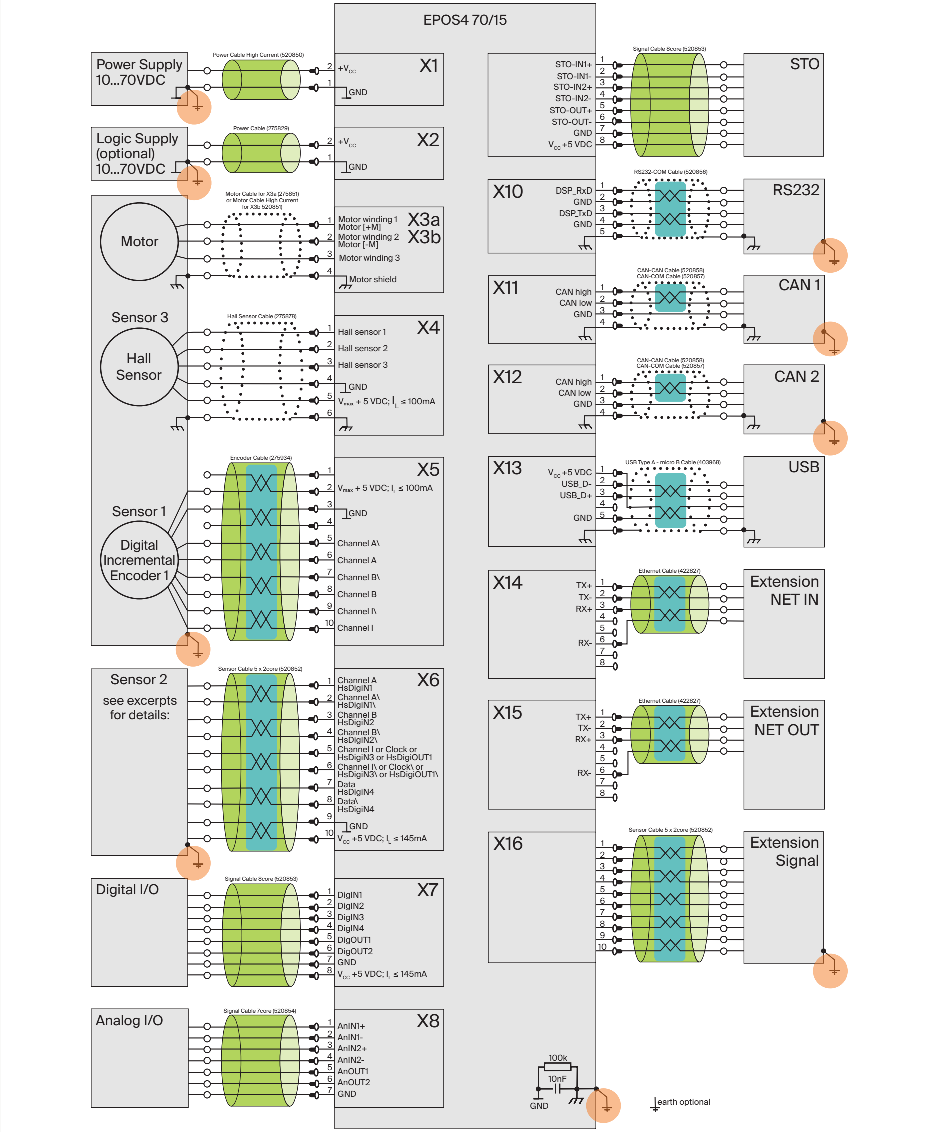
1. Increase the decceleration time (reduce the decceleration ramps) to break up voltage spikes, if this is possible with the application concerned.
2. Choose a controller with a higher maximum supply voltage than the current supply voltage of the power supply unit (e.g., $V_{CC,max}$ = 48V at $V_{CC}$ = 24V).
3. Select a power supply unit that can absorb energy (with high output capacity).
4. Add a buffer capacitor (electrolytic capacitor >1 mF) or battery for storing the power.
5. Add a shunt regulator (e.g., maxon DSR 70/30 #235811 or maxon DSR 50/5 #309687).




| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $V_{CC,max}$ | Max. supply voltage, controller | V | $R$ | Built-in resistance | Ω |
| $V_{CC}$ | Voltage, power supply | V | $C$ | Build-in capacity | mF |
| | | | $C_{add}$ | Additional capacity (battery) | mF |

## 8.6 EMC and electrical circuits

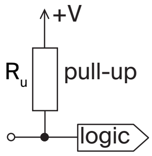
### Guidelines for EMC-compatible cabling (example: EPOS4 70/15)



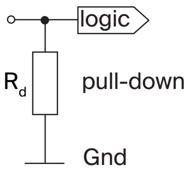



- Separate signal and power cables.
- Use HF filter on power cables.

## Pull-up / pull-down

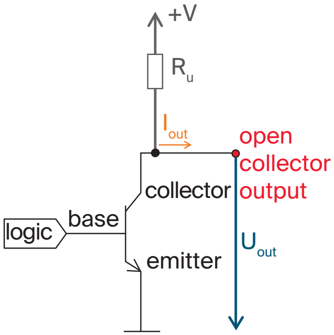



**Pull-up:** (relatively high-impedance) resistor
- connects signal line with higher voltage potential
- pulls the line up to the higher potential, if no external voltage actively pulls the line to a lower potential




**Pull-down:** (relatively high-impedance) resistor
- connects signal line with lower voltage potential
- pulls the line down to the lower potential, if no external voltage actively pulls the line to a higher potential

## Open-collector output

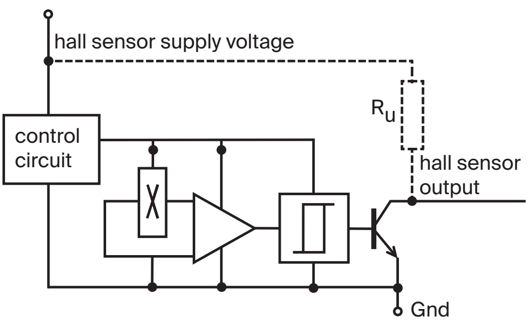



**Open-collector output (OC):**
("open"= "not connected")

- output of an integrated circuit with a bipolar transistor with an open collector output.
- usually the outputs are used in combination with a pull-up resistor that pulls the output to a higher potential in the inactive state.

$U_{out} = +V - (I_{out} \cdot R_U)$

## Circuit diagram for Hall sensor




**Hall sensors** usually have an open-collector output without pull-up resistor. Therefore it is integrated into the maxon controllers.

The power consumption of a Hall sensor is typically 4 mA
(if Hall sensor output = "high").

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $+V$ | Input voltage | V | $R_d$ | Pull-down resistance | Ω |
| $U_{out}$ | Output voltage | V | $R_u$ | Pull-up resistance | Ω |
| $Gnd$ | Ground | V | $I_{out}$ | Output current | A |

# 9. Thermal Assessments

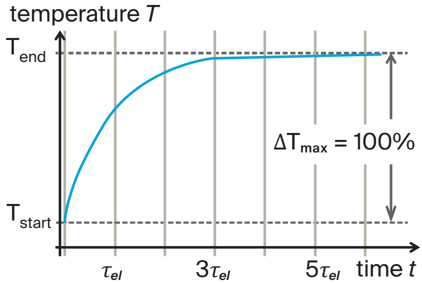
## 9.1 Continuous operation: motor

**Continuous operation is characterized by thermal equilibrium.**

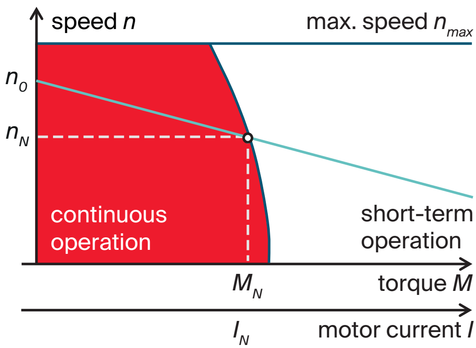
The drive components have reached their final temperature. The heat loss dissipates to the environment due to temperature differences, and the temperatures of the components no longer change.

The preceding motor heating follows an exponential curve, characterized by the motor's thermal time constant. The time needed to achieve thermal equilibrium varies depending on the mass of the motor.

- small motors up to Ø 10 mm: approx. 10 min
- medium-sized motors (Ø 19-26 mm): approx. 30 min
- large motors from Ø 32 mm: approx. 60 min




**Permissible continuous load current (nominal current $I_N$)**




The nominal current $I_N$ (= max. permissible continuous current) limits the red continuous operating range. Operation at $I_N$ will heat the winding to the maximum permissible temperature $T_{max}$.

The catalog value $I_N$ is specified at

- nominal speed $n_N$
- ambient temperature $T_A$ = 25°C
- standard mounting conditions (free convection at 25°C; horizontal coupling to plastic plate) with the thermal resistance $R_{th2}$.

**Factors influencing the nominal current**

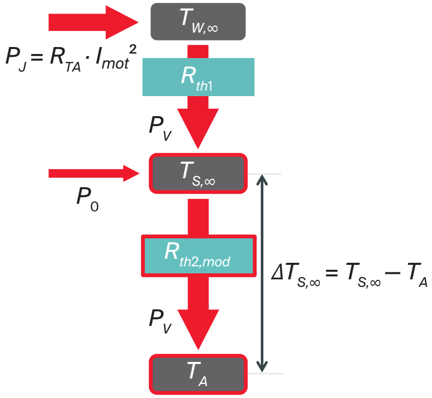
Nominal current at deviating temperature ($T_A \neq 25°C$), installation conditions ($R_{th2,mod}$) and speed ($n \neq n_N$)

$$I_N(n, T_A, R_{th2,mod}) = I_N(n) \cdot \sqrt{\frac{T_{max} - T_A}{T_{max} - 25°C} \cdot \frac{R_{th1} + R_{th2}}{R_{th1} + R_{th2,mod}}}$$

- The speed dependence $I_N$(n) can be graphically approximated based on the limit of the continuous operating range.
- $R_{th2,mod}$ can be determined by means of a separate measurement (see next page).

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $I_{mot}$ | Motor current | A | $n_N$ | Nominal speed, motor (catalog value) | rpm |
| $I_N$ | Nominal current, motor (catalog value) | A | $R_{th1}$ | Therm. resistance, winding-housing (catalog value) | K/W |
| $I_N$(n) | Nominal current, depending on n | A | | | |
| $T_A$ | Ambient temperature | °C | $R_{th2}$ | Therm. resistance, housing-ambient (catalog value) | K/W |
| $T_{max}$ | Maximum permissible winding temperature (catalog value) | °C | $R_{th2,mod}$ | Therm. resistance, housing-ambient, modified | K/W |
| $n$ | Motor speed | rpm | | | |

## Determination of $R_{th2,mod}$



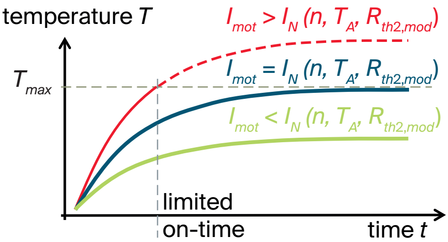

Step 1: operation of the motor
- under original conditions (mounting, air circulation, ambient temperature)
- in continuous operation
- up to thermal equilibrium

Step 2: measurement of
- motor current $I_{mot}$
- housing temperature $T_{S,\infty}$
- ambient temperature $T_A$

Step 3: determination of $R_{th2,mod}$

$$R_{th2,\,mod} = \Delta T_{S,\infty} \cdot \frac{1 - \alpha_{Cu} \cdot R_{th1} \cdot R_{TA} \cdot I_{mot}^2}{R_{TA} \cdot I_{mot}^2 \cdot (1 + \alpha_{Cu} \cdot \Delta T_{S,\infty})}$$

## Meaning of $I_N(n,T_A,R_{th2,mod})$




Motor current $I_{mot} > I_N(n, T_A, R_{th2mod})$
- ON time limited (see short time operation)

Motor current $I_{mot} = I_N(n, T_A, R_{th2mod})$
- at the end, $T_{max}$ is reached (85°C, 100°C, 125°C, or 155°C)

Motor current $I_{mot} < I_N(n, T_A, R_{th2mod})$
- no time limit
- max. temperature is not reached.

## Winding and housing temperature of the motor

| | |
|---|---|
| Basic equation | $\Delta T_{W,\infty} = T_{W,\infty} - T_A = (R_{th1} + R_{th2}) \cdot P_J$ |
| Heating of the winding | $\Delta T_{W,\infty} = \dfrac{(R_{th1} + R_{th2}) \cdot R_{TA} \cdot I_{mot}^2}{1 - \alpha_{Cu} \cdot (R_{th1} + R_{th2}) \cdot R_{TA} \cdot I_{mot}^2}$ |
| Heating of the housing | $\Delta T_{S,\infty} = T_{S,\infty} - T_A = \dfrac{R_{th2}}{R_{th1} + R_{th2}} \cdot \Delta T_{W,\infty}$ |

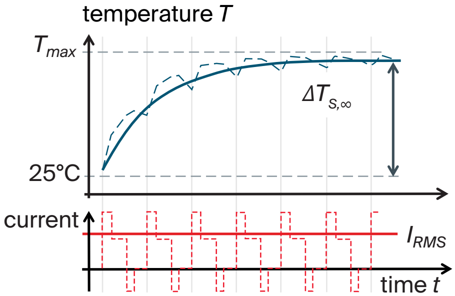
| Symbol | Name | Unit |
|---|---|---|
| $I_{mot}$ | Motor current | A |
| $I_N$ | Nominal current, motor (catalog value) | A |
| $P_J$ | Joule power loss | W |
| $P_V$ | Power loss | W |
| $P_0$ | Losses in stator (e.g., iron losses) | W |
| $R_{TA}$ | Winding resistance at $T_A$ | Ω |
| $n$ | Motor speed | rpm |
| $T_{max}$ | Maximum permissible winding temperature (catalog value) | °C |

| Symbol | Name | Value |
|---|---|---|
| $\alpha_{Cu}$ | Resistance coefficient, copper | $0.0039\ K^{-1}$ |

| Symbol | Name | Unit |
|---|---|---|
| $T_A$ | Ambient temperature | °C |
| $T_{W,\infty}$ | End temperature, winding | °C |
| $T_{S,\infty}$ | End temperature, housing | °C |
| $\Delta T_{W,\infty}$ | Temp. difference, winding–ambient | K |
| $\Delta T_{S,\infty}$ | Temp. difference, housing–ambient | K |
| $R_{th1}$ | Therm. resistance, winding-housing (catalog value) | K/W |
| $R_{th2}$ | Therm. resistance, housing–ambient (catalog value) | K/W |
| $R_{th2,mod}$ | Therm. resistance, housing–ambient under modified mounting conditions | K/W |

## 9.2 Cyclic and periodic duty (continuously repeated)

### Average effective load (RMS)




Repetitive work cycles with short durations (typically only a few seconds) can be approximated as continuous operation with the RMS value of the load.
This involves determining the currents of all operating phases and calculating the time-weighted root mean square (RMS).

$$I_{RMS} = \sqrt{\frac{(t_1 \cdot I_1^2) + (t_2 \cdot I_2^2) + \ldots + (t_n \cdot I_n^2)}{t_{tot}}}$$

### Average heat increase

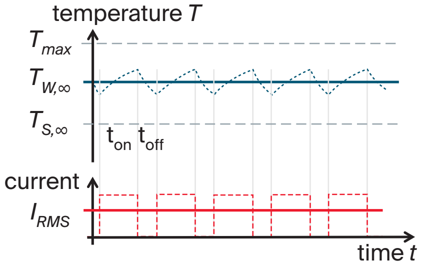
Use the effective current value (RMS) as motor load.

$$\Delta T_{W,\infty} = \frac{(R_{th1} + R_{th2}) \cdot R_{TA} \cdot I_{RMS}^2}{1 - \alpha_{Cu} \cdot (R_{th1} + R_{th2}) \cdot R_{TA} \cdot I_{RMS}^2}$$

$$\Delta T_{S,\infty} = \frac{R_{th2}}{R_{th1} + R_{th2}} \cdot \Delta T_{W,\infty}$$

### Special case: intermittent operation

Effective current value $I_{RMS} = I_{on} \cdot \sqrt{\frac{t_{on}}{t_{on} + t_{off}}}$




From the basic condition: $I_{RMS} \leq I_{N,TA}$, follows

– maximum load current $I_{on}$ for the given time cycle

$$I_{on} \leq I_N \cdot \sqrt{\frac{T_{max} - T_A}{T_{max} - 25°C} \cdot \frac{t_{on} + t_{off}}{t_{on}}}$$

– OFF duration $t_{off}$ for a load of $I_{on}$ during $t_{on}$

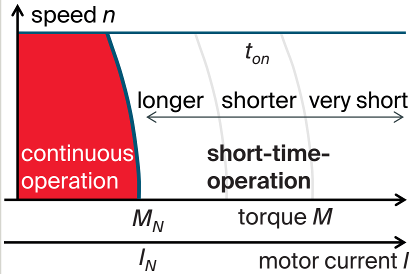
$$t_{off} \geq \left[ \frac{I_{on}^2}{I_N^2 \cdot \frac{T_{max} - T_A}{T_{max} - 25°C}} - 1 \right] \cdot t_{on}$$

| Symbol | Name | Unit |
|---|---|---|
| $I, I_1, I_2, I_n$ | (Section) current | A |
| $I_N$ | Nominal current, motor (catalog value) | A |
| $I_{N,TA}$ | Nominal current, depending on $T_A$ | A |
| $I_{on}$ | Current during ON phase | A |
| $I_{RMS}$ | Effective value, current (RMS) | A |
| $R_{TA}$ | Winding resistance at $T_A$ | Ω |
| $R_{th1}$ | Therm. resistance, winding–housing (catalog value) | K/W |
| $R_{th2}$ | Therm. resistance, housing–ambient (catalog value) | K/W |
| $T$ | Temperature | °C |
| $T_A$ | Ambient temperature | °C |

| Symbol | Name | Unit |
|---|---|---|
| $T_{max}$ | Maximum permissible winding temperature (catalog value) | °C |
| $T_{S,\infty}$ | Final temperature, stator | °C |
| $T_{W,\infty}$ | Average final temperature, winding | °C |
| $t, t_1, t_2, t_n$ | (Section) time | s |
| $t_{off}, t_{on}$ | OFF time, ON time | s |
| $t_{tot}$ | Cycle time, including breaks | s |
| $\Delta T_{W,\infty}$ | Temp. difference, winding–ambient | K |
| $\Delta T_{S,\infty}$ | Temp. difference, housing–ambient | |

| Symbol | Name | Value |
|---|---|---|
| $\alpha_{CU}$ | Resistance coefficient, copper | 0.0039 $K^{-1}$ |

## 9.3 Short time operation

| Definition | |
|---|---|
| High one-time overload of the motor with $I_{mot} > I_N (n, T_A, R_{th2mod})$<br><br>The operation duration has to be so short that the temperature of the thermally slow-reacting stator does not increase significantly; thus $T_S \approx T_A$.<br><br>Only the heating of the winding has to be taken into account, which corresponds to an exponential heating of a simple body with the thermal time constant of the winding. | <br> |
| This leads to time constraints for the equations in this section. | $t_{on} < \frac{\tau_M}{10}$     $t_{on} < 5 \cdot \tau_W$ |
| **Maximum heating of the winding** | |
| The maximum winding temperature $T_W$ compared to the current stator temperature $T_S$<br><br>If $T_W > T_{max}$, the overload must be terminated prematurely. | $\Delta T_W = T_W - T_S$<br><br>$\Delta T_W = \frac{R_{th1} \cdot R_{TA} \cdot I_{mot}^2}{1 - \alpha_{Cu} \cdot R_{th1} \cdot R_{TA} \cdot I_{mot}^2}$ |
| **Calculations for short-time operation** | |
| Definition of overload factor $K$ for short-time operation<br><br>Meaning:<br>– $K < 1 \rightarrow T_{max}$ is not reached in short-time operation<br>– $K > 1 \rightarrow$ Limit the maximum ON time $t_{on}$ | $K = \frac{I_{mot}}{I_N} \cdot \sqrt{\frac{T_{max} - 25°C}{T_{max} - T_S} \cdot \frac{R_{th1}}{R_{th1} + R_{th2}}}$<br><br>$I_N$ *to be understood as* $I_N (n, T_A, R_{th2,mod})$ |
| Maximum permissible overload at given ON time $t_{on}$ | $K \leq \sqrt{\frac{1}{1 - e^{-\frac{t_{on}}{\tau_W}}}}$ |
| Maximum ON time $t_{on}$ at given overload factor $K$ | $t_{on} = \tau_W \cdot \ln \frac{K^2}{K^2 - 1}$ |

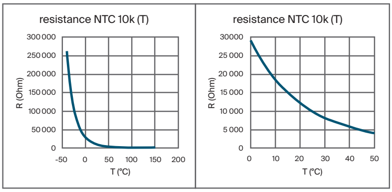
| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $I_{mot}$ | Motor current | A | $T_A$ | Ambient temperature | °C |
| $I_N$ | Nominal motor current $I_N (n,T_A,R_{th2,mod})$ | A | $T_W$ | Winding temperature | °C |
| $K$ | Overload factor | | $T_S$ | Housing temperature | °C |
| $R_{TA}$ | Winding resistance at $T_A$ | Ω | $t_{on}$ | ON time | s |
| $R_{th1}$ | Therm. resistance, winding–housing (catalog value) | K/W | $\Delta T_W$ | Temp. difference, winding-ambient | K |
| $R_{th2}$ | Therm. resistance, housing–ambient (catalog value) | K/W | $\tau_M$ | Thermal time constant, motor (catalog value) | s |
| $T_{max}$ | Maximum permissible winding temperature (catalog value) | °C | $\tau_W$ | Thermal time constant, winding (catalog value) | s |

| Symbol | Name | Value |
|---|---|---|
| $\alpha_{Cu}$ | Resistance coefficient, copper | 0.0039 $K^{-1}$ |

## 9.4 NTC thermistor as temperature sensor

A thermistor is a resistor that is highly dependent on temperature. In a NTC (negative temperature coefficient) thermistor, the resistance decreases as the temperature increases.

### Calculating the temperature of an NTC

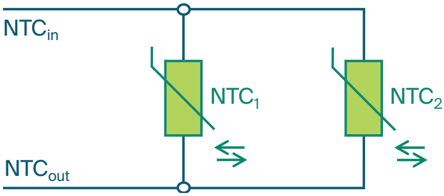



$$T(R) = \frac{1}{\frac{\ln\left(\frac{R}{R_{25}}\right)}{beta} + \frac{1}{T_{25}}} \quad [K]$$

### Parallel connection of two NTCs

In slotted motors, the temperature in different winding segments can vary (e.g. at standstill). For this reason, two NTCs are often placed in different winding phases and connected in parallel.

The parameters ($R_{25}$, beta) for calculating the temperature apply to the combination of both parallel-connected NTCs.




When both NTCs are at the same temperature, the measured resistance $NTC_{IN\text{-}OUT}$ can be used directly to calculate the temperature.

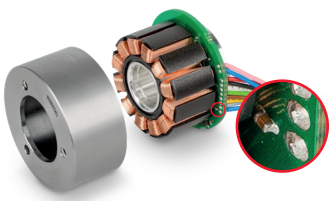
$$R = NTC_{in\text{-}out} = \frac{NTC_1}{2} = \frac{NTC_2}{2}$$

If the two NTCs are at different temperatures (e.g. at standstill), the measured value of resistance $NTC_{IN\text{-}OUT}$ will move closer to the smaller (critical) resistance value.

To determine the maximum temperature (worst case), only half of the measured value of resistance is used at standstill.

$$R \approx \frac{NTC_{in\text{-}out}}{2} \approx \frac{min\,(NTC_1; NTC_2)}{2}$$

### SMD version of an NTC



To measure or estimate the winding temperature of a motor, an SMD (surface-mounted device) version of an NTC can be placed on the printed circuit board inside the motor.

The placement on the circuit board does not provide direct contact with the winding. The temperature is measured with a delay and is likely to be slightly lower than the winding temperature. Therefore, this version is only suitable for continuous operation.

| Symbol | Name | Unit | Symbol | Name | Unit |
|---|---|---|---|---|---|
| $T$ | Measured temperature | K | $R$ | Resistance at temperature T | Ω |
| $beta$ | Temperature coefficient (catalog value) | K | $NTC_{In\text{-}Out}$ | Measured NTC resistance at terminal | Ω |
| $T_{25}$ | Standard temperature of 298.15 K (25°C) | K | $NTC_1$ | NTC resistance 1 | Ω |
| $R_{25}$ | Nominal resistance at temperature T25 (catalog value) | Ω | $NTC_2$ | NTC resistance 2 | Ω |