The motor as an energy converter

The electrical motor converts electrical power P_{el} (current I_{mot} and voltage U_{mot}) into mechanical power P_{mech} (speed n and torque M). The losses that arise are divided into frictional losses, attributable to P_{mech} and in Joule power losses P_J of the winding (resistance R). Iron losses do not occur in the coreless maxon DC motors. In maxon EC motors, they are treated formally like an additional friction torque. The power balance can therefore be formulated as:

$$P_{el} = P_{mech} + P_J$$

The detailed result is as follows

$$U_{mot} \cdot I_{mot} = \frac{\pi}{30\,000} n \cdot M + R \cdot I_{mot}^2$$

Electromechanical motor constants
The geometric arrangement of the magnetic circuit and winding defines in detail how the motor converts the electrical input power (current, voltage) into mechanical output power (speed, torque). Two important characteristic values of this energy conversion are the speed constant k_n and the torque constant k_M. The speed constant combines the speed n with the voltage induced in the winding U_{ind} (= EMF). U_{ind} is proportional to the speed; the following applies:

$$n = k_n \cdot U_{ind}$$

Similarly, the torque constant links the mechanical torque M with the electrical current I_{mot}.

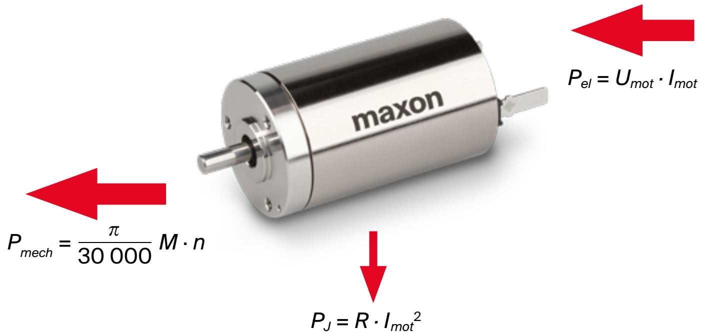
$$M = k_M \cdot I_{mot}$$

The main point of this proportionality is that torque and current are equivalent for the maxon motor.
The current axis in the motor diagrams is therefore shown as parallel to the torque axis as well.

See also: explanation of the motor

Units
In all formulas, the variables are to be used in the units according to the catalog (cf. physical variables and their units on page 82).

The following applies in particular:
– All torques in mNm
– All currents in A (even no load currents)
– Speeds (rpm) instead of angular velocity (rad/s)



Motor constants
Speed constant k_n and torque constant k_M are not independent of one another. The following applies:

$$k_n \cdot k_M = \frac{30\,000}{\pi}$$

The speed constant is also called specific speed. Specific voltage, generator or voltage constants are mainly the reciprocal value of the speed constant and describe the voltage induced in the motor per speed. The torque constant is also called specific torque. The reciprocal value is called specific current or current constant.

Motor diagrams

A diagram can be drawn for every maxon DC and EC motor, from which key motor data can be taken. Although tolerances and temperature influences are not taken into consideration, the values are sufficient for a first estimation in most applications. In the diagram, speed n, current I_{mot}, power output P_2 and efficiency η are applied as a function of torque M at constant voltage U_{mot}.

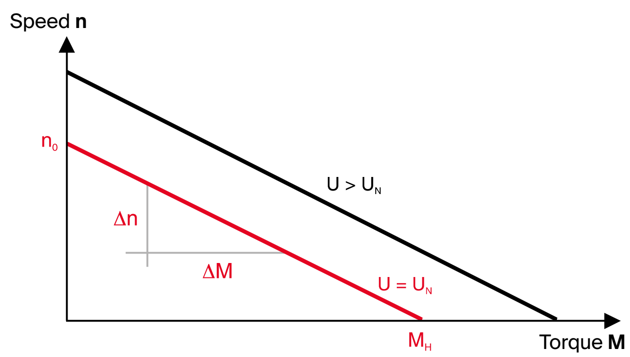
Speed-torque line
This curve describes the mechanical behavior of the motor at a constant voltage U_{mot}:
– Speed decreases linearly with increasing torque.
– The faster the motor turns, the less torque it can provide.
The curve can be described with the help of the two end points, no load speed n_0 and stall torque M_H (cf. lines 2 and 7 in the motor data).
DC motors can be operated at any voltage. No load speed and stall torque change proportionally to the applied voltage. This is equivalent to a parallel shift of the speed-torque line in the diagram. Between the no load speed and voltage, the following proportionality applies in good approximation

$$n_0 \approx k_n \cdot U_{mot}$$

where k_n is the speed constant (line 13 of the motor data).

Independent of the voltage, the speed-torque line is described most practically by the slope or gradient of the curve (line 14 of the motor data).

$$\frac{\Delta n}{\Delta M} = \frac{n_0}{M_H}$$



Derivation of the speed-torque line
The following occurs if one replaces current I_{mot} with torque M using the torque constant in the detailed power balance:

$$U_{mot} \cdot \frac{M}{k_M} = \frac{\pi}{30\,000} n \cdot M + R \cdot \left(\frac{M}{k_M}\right)^2$$

Transformed and taking account of the close relationship of k_M and k_n, an equation is produced of a straight line between speed n and torque M.

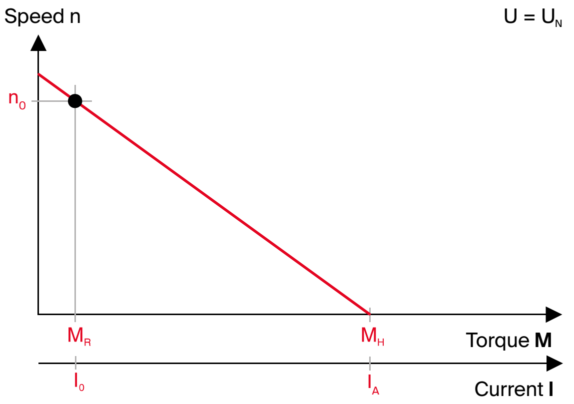
$$n = k_n \cdot U_{mot} - \frac{30\,000}{\pi} \cdot \frac{R}{k_M^2} \cdot M$$

or with the gradient and the no load speed n_0

$$n = n_0 - \frac{\Delta n}{\Delta M} \cdot M$$

April 2022 edition / subject to change

The speed-torque gradient is one of the most informative pieces of data and allows direct comparison between different motors. The smaller the speed-torque gradient, the less sensitive the speed reacts to torque (load) changes and the stronger the motor. With the maxon motor, the speed-torque gradient within the winding series of a motor type (i.e. on one catalog page) remains practically constant.



Current gradient
The equivalence of current to torque is shown by an axis parallel to the torque: more current flowing through the motor produces more torque. The current scale is determined by the two points no load current I_0 and starting current I_A (lines 3 and 8 of motor data).
The no load current is equivalent to the friction torque M_R, that describes the internal friction in the bearings and commutation system.

$M_R = k_M \cdot I_0$

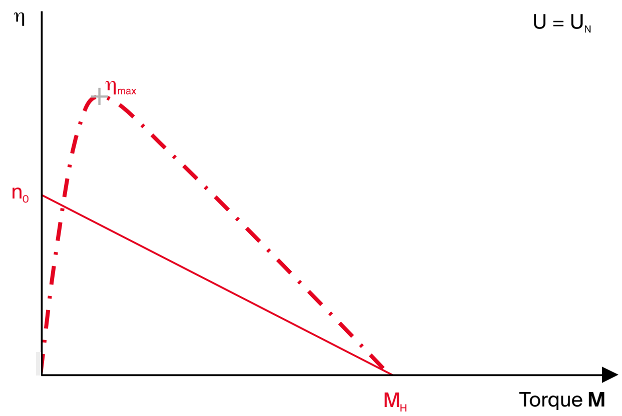
In the maxon EC motor, there are strong, speed dependent iron losses in the stator iron stack instead of friction losses in the commutation system.

The motors develop the highest torque when starting. It is many times greater than the normal operating torque, so the current uptake is the greatest as well.
The following applies for the stall torque M_H and starting current I_A

$M_H = k_M \cdot I_A$

Efficiency curve
The efficiency η describes the relationship of mechanical power delivered to electrical power consumed.

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



One can see that at constant applied voltage U and due to the proportionality of torque and current, the efficiency increases with increasing speed (decreasing torque). At low torques, friction losses become increasingly significant and efficiency rapidly approaches zero. Maximum efficiency (line 9 of motor data) is calculated using the starting current and no load current and is dependent on voltage.

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

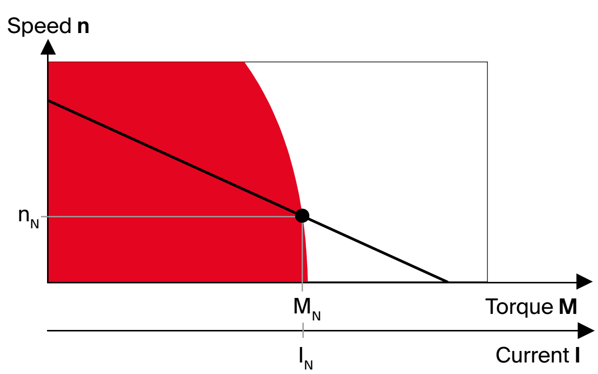
Maximum efficiency and maximum output power do not occur at the same torque.

Rated operating point

The rated operating point is an ideal operating point for the motor and derives from operation at nominal voltage U_N (line 1 of motor data) and nominal current I_N (line 6). The nominal torque M_N produced (line 5) in this operating point follows from the equivalence of torque and current.

$M_N \cong k_M \cdot (I_N - I_0)$

Nominal speed n_N (line 4) is reached in line with the speed gradient. The choice of nominal voltage follows from considerations of where the maximum no load speed should be. The nominal current derives from the motor's thermally maximum permissible continuous current.



Motor diagrams, operating ranges

The catalog contains a diagram of every maxon DC and EC motor type that shows the operating ranges of the different winding types using a typical motor.

Permanent operating range
The two criteria “maximum continuous torque” and “maximum permissible speed” limit the continuous operating range. Operating points within this range are not critical thermally and do not generally cause increased wear of the commutation system.

Short-term operating range
The motor may only be loaded with the maximum continuous current for thermal reasons. However, temporary higher currents (torques) are allowed. As long as the winding temperature is below the critical value, the winding will not be damaged. Phases with increased currents are time limited. A measure of how long the temporary overload can last is provided by the thermal time constant of the winding (line 19 of the motor data). The magnitude of the times with overload ranges from several seconds for the smallest motors (6 mm to 13 mm diameter) up to roughly one minute for the largest (60 mm to 90 mm diameter). The calculation of the exact overload duration depends highly on the motor current and the winding temperature at the beginning.

Max. permissible winding temperature
Due to the winding resistance, the motor current causes the winding to heat up. To prevent the motor from overheating, this heat needs to be dissipated to the environment via the stator. The maximum winding temperature (line 22 of the motor data) must not be exceeded even for a short time. For graphite brush motors and EC motors with their usually higher current load, it is 125°C (in some cases up to 155°C). Precious metal commutated motors only allow for low current loads, so that the rotor temperature must not exceed 85°C. Precautions taken during installation, such as good air circulation or cooling plates, may significantly lower the temperature.

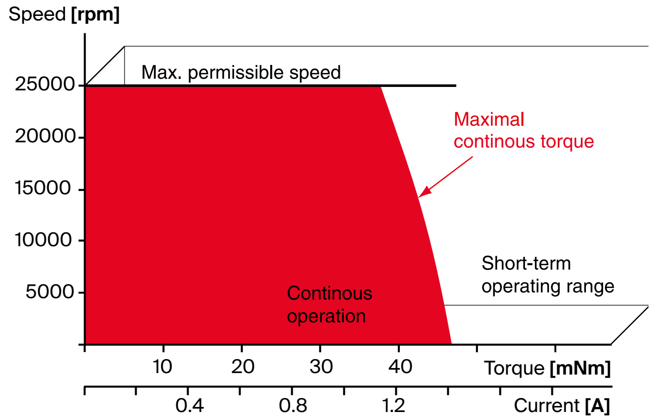
Permissible continuous current, permissible continuous torque
The electrical heat losses define the max. permissible continuous current at which the maximum winding temperature is reached under standard conditions (25°C ambient temperature, no heat dissipation via the flange, air circulating freely). Larger motor currents result in too high winding temperatures.

The nominal current is selected to correspond with this maximum permissible continuous current. It is highly dependent on the winding. Windings with thin wire have lower nominal currents than windings with thick wire. In the case of windings with very low resistance, the current capacity of the brush system can further restrict the permissible continuous current. The graphite brush motors significantly increase the friction losses at high speeds. In EC motors, the eddy current loss in the magnetic return increases when the speed increases and generates additional heat. The maximum permissible continuous current decreases at higher speeds.

The nominal current assigned to the rated torque is practically constant within the winding type of a motor type and is one of the characteristics of the motor type.

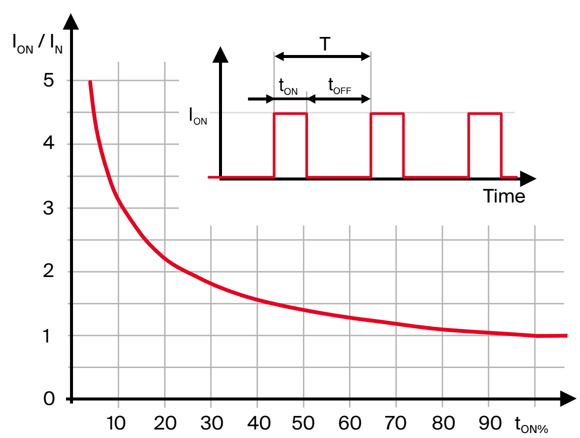
The maximum permissible speed
for DC motors is primarily limited by the commutation system. The commutator and brushes wear more rapidly at very high speeds. The reasons are:
– Increased mechanical wear because of the large traveled path of the commutator
– Increased electro-erosion because of brush vibration and spark formation.

A further reason for limiting the speed is the rotor’s residual mechanical imbalance which shortens the service life of the bearings. Higher speeds than the limit speed n_{max} (line 23) are possible, however, they are “paid for” by a reduced service life expectancy. The maximum permissible speed for the EC motor is calculated based on service life considerations of the ball bearings (at least 20 000 hours) at the maximum residual imbalance and bearing load.



Operating range diagram

Intermittent operation
Switch-on duration and current



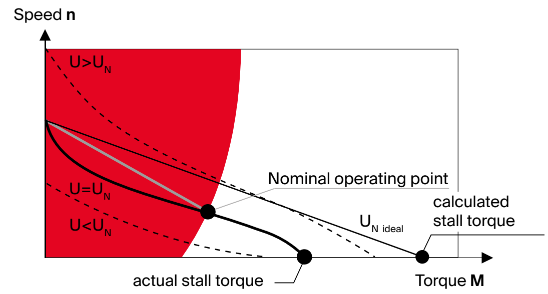
ON	Motor in operation
OFF	Motor stationary
I_{ON}	Max. peak current
I_N	Max. permissible continuous current (line 6)
t_{ON}	ON time *[s]*, should not exeed τ_w (line 19)
T	Cycle time $t_{ON} + t_{OFF}$ *[s]*
$t_{ON\%}$	Duty cycle as percentage of cycle time. The motor may be overloaded by the relationship I_{ON} / I_N at X % of the total cycle time.

$$I_{on} = I_N \sqrt{\frac{T}{t_{ON}}}$$

maxon EC flat and EC-i motors

Multi-pole maxon flat motors and EC-i motors require a greater number of commutation steps per revolution (6 x number of pole pairs). Due to their wound stator teeth, they have a higher terminal inductance than motors with an ironless winding. At high speeds, the current cannot fully develop due to the short commutation intervals. The torque is therefore less. In addition, some current is returned to the controller power stage. As a result, the behavior deviates from the ideal linear characteristic depending on voltage and speed: The apparent speed/torque gradient is steeper at higher speeds and flatter at very low speeds.
Mostly, flat motors are operated in the continuous operation range where the achievable speed-torque gradient at nominal voltage can be approximated by a straight line between no load speed and nominal operating point. The achievable speed-torque gradient is approximate.

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

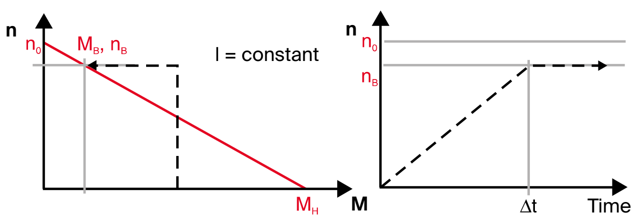


The stall torque specified on the product page is equal to the linearly calculated load torque (without magnetic saturation effect) which causes the shaft to stall at nominal voltage. With EC-flat and EC-i motors, this torque often cannot be achieved due to saturation effects.

Acceleration

In accordance with the electrical boundary conditions (power supply, control, battery), a distinction is primarily made between two different starting processes:
– Start at constant voltage (without current limitation)
– Start at constant current (with current limitation)

Start under constant current
A current limit always means that the motor can only deliver a limited torque. In the speed-torque diagram, the speed increases on a vertical line with a constant torque. Acceleration is also constant, thus simplifying the calculation. Start at constant current is usually found in applications with servo amplifiers, where acceleration torques are limited by the amplifier's peak current.



– Angular acceleration α (in rad/s²) at constant current I or constant torque M with an additional load of inertia J_L:

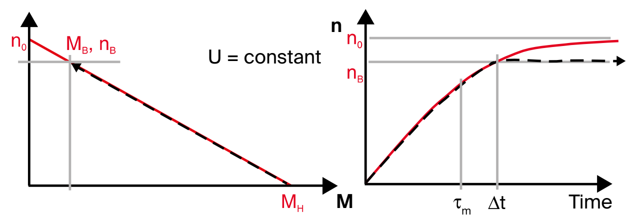
$$\alpha = 10^4 \cdot \frac{k_M \cdot I_{mot}}{J_R + J_L} = 10^4 \cdot \frac{M}{J_R + J_L}$$

– Run-up time Δt (in ms) at a speed change Δn with an additional load inertia J_L:

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

(all variables in units according to the catalog)

Start with constant terminal voltage
Here, the speed increases from the stall torque along the speed-torque line. The greatest torque and thus the greatest acceleration is effective at the start. The faster the motor turns, the lower the acceleration. The speed increases more slowly. This exponentially flattening increase is described by the mechanical time constant τ_m (line 15 of the motor data). After this time, the rotor at the free shaft end has attained 63% of the no load speed. After roughly three mechanical time constants, the rotor has almost reached the no load speed.



– Mechanical time constant τ_m (in ms) of the unloaded motor:

$$\tau_m = 100 \cdot \frac{J_R \cdot R}{k_M{}^2}$$

– Mechanical time constants τ_m' (in ms) with an additional load inertia J_L:

$$\tau_m' = 100 \cdot \frac{J_R \cdot R}{k_M{}^2} \left(1 + \frac{J_L}{J_R}\right)$$

– Maximum angular acceleration α_{max} (in rad/s²) of the unloaded motor:

$$\alpha_{max} = 10^4 \cdot \frac{M_H}{J_R}$$

– Maximum angular acceleration α_{max} (in rad/s²) with an additional load inertia J_L:

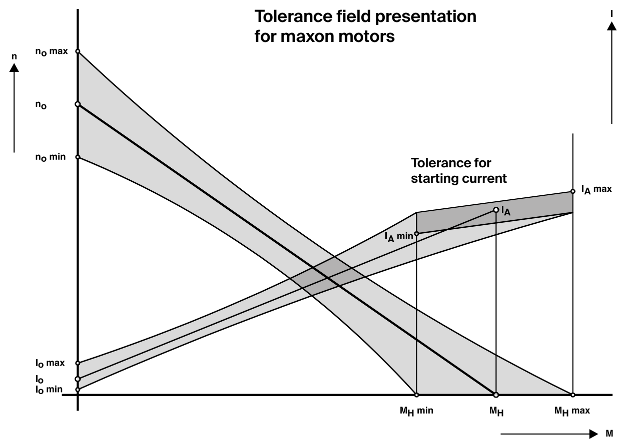
$$\alpha_{max} = 10^4 \cdot \frac{M_H}{J_R + J_L}$$

– Run-up time (in ms) at constant voltage up to the operating point (M_L, n_L):

$$\Delta t = \tau_m' \cdot \ln \left(\frac{\left(1 - \frac{M_L + M_R}{M_H}\right) \cdot n_0}{\left(1 - \frac{M_L + M_R}{M_H}\right) \cdot n_0 - n_L} \right)$$

Tolerances

Tolerances must be considered in critical ranges. The possible deviations of the mechanical dimensions can be found in the overview drawings. The motor data are average values: the adjacent diagram shows the effect of tolerances on the curve characteristics. They are mainly caused by differences in the magnetic field strength and in wire resistance, and not so much by mechanical influences. The changes are heavily exaggerated in the diagram and are simplified to improve understanding. It is clear, however, that in the motor's actual operating range, the tolerance range is more limited than at start or at no load. Our computer sheets contain all detailed specifications.



Thermal behavior

The Joule power losses P_J in the winding determine heating of the motor. This heat energy must be dissipated via the surfaces of the winding and motor. The increase ΔT_W of the winding temperature T_W with regard to the ambient temperature arises from heat losses P_J and thermal resistances R_{th1} and R_{th2}.

$$T_W - T_U = \Delta T_W = (R_{th1} + R_{th2}) \cdot P_J$$

Here, thermal resistance R_{th1} relates to the heat transfer between the winding and the stator (magnetic return and magnet), whereas R_{th2} describes the heat transfer from the housing to the environment. Mounting the motor on a heat dissipating chassis noticeably lowers thermal resistance R_{th2}. The values specified in the data sheets for thermal resistances and the maximum continuous current were determined in a series of tests, in which the motor was end-mounted onto a vertical plastic plate. The modified thermal resistance R_{th2} that occurs in a particular application must be determined using original installation and ambient conditions. Thermal resistance R_{th2} on motors with metal flanges decreases by up to 80% if the motor is coupled to a good heat-conducting (e.g. metallic) retainer.

The heating runs at different rates for the winding and stator due to the different masses. After switching on the current, the winding heats up first (with time constants from several seconds to half a minute). The stator reacts much slower, with time constants ranging from 1 to 30 minutes depending on motor size. A thermal balance is gradually established. The temperature difference of the winding compared to the ambient temperature can be determined with the value of the current I (or in intermittent operation with the effective value of the current $I = I_{RMS}$).

$$\Delta T_W \quad \frac{(R_{th1} + R_{th2}) \cdot R \cdot I_{mot}^{\ 2}}{1 - \alpha_{Cu} \cdot (R_{th1} + R_{th2}) \cdot R \cdot I_{mot}^{\ 2}}$$

Here, electrical resistance R must be applied at the actual ambient temperature.

Influence of temperature
An increased motor temperature affects winding resistance and magnetic characteristic values.

Winding resistance increases linearly according to the thermal resistance coefficient for copper (α_{Cu} = 0.0039):

$$R_T = R_{25} \cdot (1 + \alpha_{Cu} (T - 25°C))$$

Example: a winding temperature of 75°C causes the winding resistance to increase by nearly 20%.

The magnet becomes weaker at higher temperatures. The reduction is 0.5 to 5% at 75°C depending on the magnet material.

The most important consequence of increased motor temperature is that the speed curve becomes steeper which reduces the stall torque. The changed stall torque can be calculated in first approximation from the voltage and increased winding resistance:

$$M_H = k_M \cdot I_A = k_M \cdot \frac{U_{mot}}{R_T}$$

Motor selection

The drive requirements must be defined before proceeding to motor selection.
- How fast and at which torques does the load move?
- How long do the individual load phases last?
- What accelerations take place?
- How great are the mass inertias?

Often the drive is indirect, this means that there is a mechanical transformation of the motor output power using belts, gears, screws and the like. The drive parameters, therefore, are to be calculated to the motor shaft. Additional steps for gear selection are listed below.

Furthermore, the power supply requirements need to be checked.
- Which maximum voltage is available at the motor terminals?
- Which limitations apply with regard to current?

The current and voltage of motors supplied with batteries or solar cells are very limited. In the case of control of the unit via a servo amplifier, the amplifier's maximum current is often an important limit.

Selection of motor types
The possible motor types are selected using the required torque. On the one hand, the peak torque, M_{max}, is to be taken into consideration and on the other, the effective torque M_{RMS}. Continuous operation is characterized by a single operating or load point (M_L, n_L). The motor types in question must have a nominal torque M_N that is greater than load torque M_L.

$$M_N > M_L$$

In operating cycles, such as start/stop operation, the motor's nominal torque must be greater than the effective load torque (RMS). This prevents the motor from overheating.

$$M_N > M_{RMS}$$

The stall torque of the selected motor should usually exceed the emerging load peak torque.

$$M_H > M_{max}$$

Selection of the winding: electric requirement
In selecting the winding, it must be ensured that the voltage applied directly to the motor is sufficient for attaining the required speed in all operating points.

Uncontrolled operation
In applications with only one operating point, this is often achieved with a fixed voltage U. A winding is sought with a speed-torque line that passes through the operating point at the specified voltage. The calculation uses the fact that all motors of a type feature practically the same speed-torque gradient. A target no load speed $n_{0,theor}$ is calculated from operating point (n_L, M_L).

$$n_{0,\,theor} = n_L + \frac{\Delta n}{\Delta M} M_L$$

This target no load speed must be achieved with the existing voltage U, which defines the target speed constant.

$$k_{n,\,theor} = \frac{n_{0,\,theor}}{U_{mot}}$$

Those windings whose k_n is as close to $k_{n,\,theor}$ as possible, will approximate the operating point the best at the specified voltage. A somewhat larger speed constant results in a somewhat higher speed, a smaller speed constant results in a lower one. The variation of the voltage adjusts the speed to the required value, a principle that servo amplifiers also use.

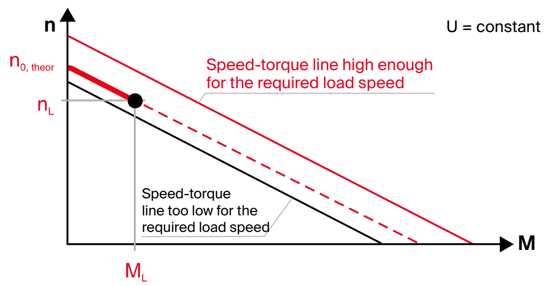
The motor current I_{mot} is calculated using the torque constant k_M of the selected winding and the load torque M_L.

$$I_{mot} = \frac{M_L}{k_M}$$

Advices for evaluating the requirements:
Often the load points (especially the torque) are not known or are difficult to determine. In such cases you can operate your device with a measuring motor roughly estimated according to size and power. Vary the voltage until the desired operating points and motion sequences have been achieved. Measure the voltage and current flow. Using these specifications and the part number of the measuring motor, our engineers can often specify the suitable motor for your application.

Additional optimization criteria are, for example:
- Mass to be accelerated (type, mass inertia)
- Type of operation (continuous, intermittent, reversing)
- Ambient conditions (temperature, humidity, medium)
- Power supply, battery

When selecting the motor type, other constraints also play a major role:
- What maximum length should the drive unit have, including gear and encoder diameter?
- What service life is expected from the motor and which commutation system should be used?
- Precious metal commutation for continuous operation at low currents (rule of thumb for longest service life: up to approx. 50% of I_N).
- Graphite commutation for high continuous currents (rule of thumb: 50% to approx. 75% of I_N) and frequent current peaks (start/stop operation, reversing operation).
- Electronic commutation for highest speeds and longest service life.
- How great are the forces on the shaft, do ball bearings have to be used or are less expensive sintered bearings sufficient?

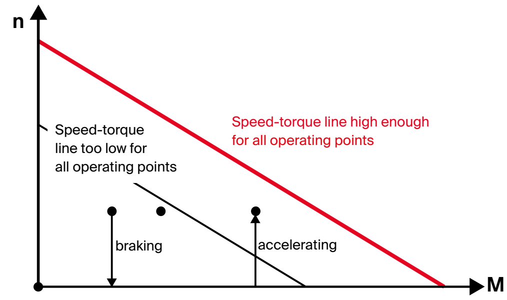


maxon

Regulated servo drives
In operating cycles, all operating points must lie beneath the curve at a maximum voltage U_{max}. Mathematically, this means that the following must apply for all operating points (n_L, M_L):

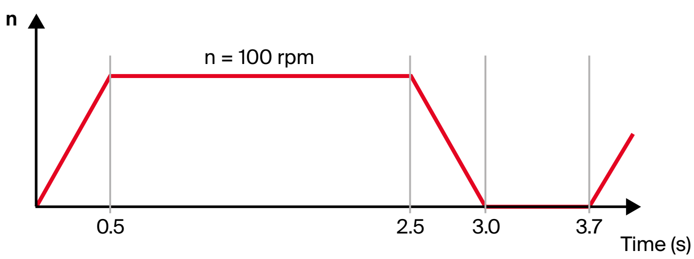
$$k_n \cdot U_{max} = n_0 > n_L + \frac{\Delta n}{\Delta M} M_L$$

When using servo amplifiers, a voltage drop occurs at the power stage, so that the effective voltage applied to the motor is lower. This must be taken into consideration when determining the maximum supply voltage U_{max}. It is recommended that a regulating reserve of some 20% be included, so that regulation is even ensured with an unfavorable tolerance situation of motor, load, amplifier and supply voltage. Finally, the average current load and peak current are calculated ensuring that the servo amplifier used can deliver these currents. In some cases, a higher resistance winding must be selected, so that the currents are lower. However, the required voltage is then increased.



Example for motor/gear selection

The following speed curve is to be repeated cyclically.



The accelerated load inertia J_L is 300 000 gcm^2 = 0.03 kgm^2. The friction torque is 400 mNm. The motor is driven with the 4-Q servo amplifier ESCON 36/2 DC for DC motors. The power supply has a maximum output of 3 A and 24 V.

Calculation of load data
The torque required for acceleration and braking are calculated as follows (motor and gearhead inertia omitted):

$$M_\alpha = J_L \cdot \frac{\pi}{30} \frac{\Delta n}{\Delta t} = 0.03 \cdot \frac{\pi}{30} \cdot \frac{100}{0.5} = 0.628 \text{ Nm} = 628 \text{ mNm}$$

Together with the friction torque, the following torques result for the different phases of motion.

– Acceleration phase	(duration 0.5 s)	1028 mNm
– Constant speed	(duration 2 s)	400 mNm
– Braking (friction brakes with 400 mNm)	(duration 0.5 s)	-228 mNm
– Standstill	(duration 0.7 s)	0 mNm

Peak torque occurs during acceleration.
The RMS determined torque of the entire operating cycle is

$$M_{RMS} = \sqrt{\frac{t_1 \cdot M^2{}_1 + t_2 \cdot M^2{}_2 + t_3 \cdot M^2{}_3 + t_4 \cdot M^2{}_4}{t_{tot}}}$$

$$= \sqrt{\frac{0.5 \cdot 1028^2 + 2 \cdot 400^2 + 0.5 \cdot (-228)^2 + 0.7 \cdot 0}{3.7}} \approx 486 \text{ mNm}$$

The maximum speed (100 rpm) occurs at the end of the acceleration phase at maximum torque (1028 mNm). Thus, the peak mechanical power is:

$$P_{max} = M_{max} \cdot \frac{\pi}{30} n_{max} = 1.028 \cdot \frac{\pi}{30} \cdot 100 \approx 11 \text{ W}$$

Physical variables		and their units SI	Catalog
i	Gear reduction*		
I_{mot}	Motor current	A	A, mA
I_A	Stall current*	A	A, mA
I_0	No load current*	A	mA
I_{RMS}	RMS determined current	A	A, mA
I_N	Nominal current*	A	A, mA
J_R	Moment of inertia of the rotor*	kgm^2	gcm^2
J_L	Moment of inertia of the load	kgm^2	gcm^2
k_M	Torque constant*	Nm/A	mNm/A
k_n	Speed constant*		rpm/V
M	(Motor) torque	Nm	mNm
M_L	Load torque	Nm	mNm
M_H	Stall torque*	Nm	mNm
M_{mot}	Motor torque	Nm	mNm
M_R	Moment of friction	Nm	mNm
M_{RMS}	RMS determined torque	Nm	mNm
M_N	Nominal torque*	Nm	mNm
$M_{N,G}$	Max. torque of gear*	Nm	Nm
n	Speed		rpm
n_L	Operating speed of the load		rpm
n_{max}	Limit speed of motor*		rpm
$n_{max,G}$	Limit speed of gear*		rpm
n_{mot}	Motor speed		rpm
n_0	No load speed*		rpm
P_{el}	Electrical power	W	W
P_J	Joule power loss	W	W
P_{mech}	Mechanical power	W	W
R	Terminal resistance	Ω	Ω
R_{25}	Resistance at 25°C*	Ω	Ω
R_T	Resistance at temperature T	Ω	Ω
R_{th1}	Heat resistance winding housing*		K/W
R_{th2}	Heat resistance housing/air*		K/W
t	Time	s	s
T	Temperature	K	°C
T_{max}	Max. winding temperature*	K	°C
T_U	Ambient temperature	K	°C
T_W	Winding temperature	K	°C
U_{mot}	Motor voltage	V	V
U_{ind}	Induced voltage (EMF)	V	V
U_{max}	Max. supplied voltage	V	V
U_N	Nominal voltage*	V	V
α_{Cu}	Resistance coefficient of Cu	= 0.0039	
α_{max}	Max. angle acceleration	rad/s^2	
$\Delta n/\Delta M$	Curve gradient*	rpm/mNm	
ΔT_W	Temperature difference winding/ambient	K	K
Δt	Run up time	s	ms
η	(Motor) efficiency		%
η_G	(Gear) efficiency*		%
η_{max}	Max. efficiency*		%
τ_m	Mechanical time constant*	s	ms
τ_S	Therm. time constant of the motor*	s	s
τ_W	Therm. time constant of the winding*	s	s

(*Specified in the motor or gear data)

Gear selection

We are looking for a gearhead with a maximum continuous torque of at least 0.486 Nm and a short-term torque of at least 1.028 Nm. This requirement can be fulfilled by the ceramic version of the configurable GPX 22 gearhead with 2 or 3 stages. With 2 stages, the maximum gearhead input speed of 10 000 rpm permits a maximum ratio of

$$i_{max} = \frac{n_{max,\,G}}{n_L} = \frac{10\,000}{100} = 100{:}1$$

Three-stage gearheads permit higher input speeds, and the maximum ratio is 120:1. Because of the shorter design, we decide to use the 2-stage gearhead. To keep the motor torque as small as possible, we select the highest possible ratio of 44:1. The 2-stage gearhead has an efficiency of 81%.

Motor type selection

Speed and torque are calculated to the motor shaft

$$n_{mot} = i \cdot n_L = 44 \cdot 100 = 4400 \text{ rpm}$$

$$M_{mot,\,RMS} = \frac{M_{RMS}}{i \cdot \eta} = \frac{486}{44 \cdot 0.81} \approx 13.6 \text{ mNm}$$

$$M_{mot,\,max} = \frac{M_{max}}{i \cdot \eta} = \frac{1028}{44 \cdot 0.81} \approx 28.8 \text{ mNm}$$

The possible motors, which match the selected gears in accordance with the maxon modular system, are summarized in the table opposite. The table shows only motors with graphite commutation because they are better suited for stop-and-go operation.

We select the DCX 22 S, which has sufficient continuous torque. The motor should have a torque reserve so that it will be able to function in slightly less favorable conditions.
The additional torque requirement during acceleration is no problem for the motor. The short-term peak torque is only slightly less than twice as high as the permissible continuous torque of the motor.

Selection of the winding

The DCX 22 S motor has a mean characteristic gradient of about 110 rpm/mNm. The desired idle speed is calculated as follows:

$$n_{0,\,theor} = n_{mot} + \frac{\Delta n}{\Delta M} \cdot M_{max} = 4400 + 110 \cdot 28.8 = 7570 \text{ rpm}$$

The extreme operating point should of course be used in the calculation (max. speed and max. torque), since the speed-torque line of the winding must run above all operating points in the speed / torque diagram.
This target no load speed must be achieved with the maximum voltage U = 24 V supplied by the control (ESCON 36/2), which defines the minimum target speed constant $k_{n,\,theor}$ of the motor.

$$k_{n,\,theor} = \frac{n_{0,\,theor}}{U_{mot}} = \frac{7570}{24} = 315 \frac{\text{rpm}}{V}$$

If one considers the speed constant of the windings, then the first choice would be the motor with a nominal speed of 36 V. At a speed constant of 342 rpm V^{-1} however, it has only a small speed control reserve. If the tolerances are insufficient, then the winding with the next higher speed constant (24 V nominal voltage) offers better safety.
The higher speed constant of the winding compared to the calculated value means that the motor runs faster at 24 V than required, which can be compensated with the speed controller. The motor can be equipped with an encoder to record the speed. The speed constant of the selected 24 V winding is 18.4 mNm/A. The maximum torque therefore corresponds to a peak current of

$$I_{max} = \frac{M_{max}}{k_M} + I_0 = \frac{28.8}{18.4} + 0.036 = 1.6\,A$$

This current is smaller than the maximum current (4 A) of the controller and the power supply unit (3 A).

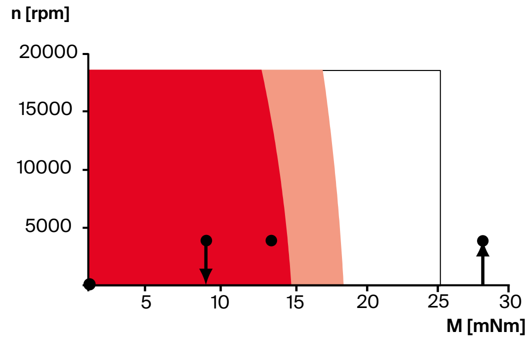
Thus, a gear motor has been found that fulfils the requirements (torque and speed) and can be operated by the controller provided.

Alternative solutions

GPX 19 ceramic gearhead
3 stages (138:1 reduction)
with motor type DCX 16 S (graphite brushes)

GPX 22 gearhead, standard configuration
3 stages (111:1 reduction)
with motor type DCX 19 S (graphite brushes)

Motor	M_N	Suitability
DCX 22 S	≈ 15 mNm	good
DCX 22 L	≈ 30 mNm	too strong, builds long
DC-max 22 S	≈ 11 mNm	too weak



maxon

General Information

Quantities and their basic units in the International System of Measurements (SI)

Quantity	Basic-unit	Sign
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electrical current	Ampere	A
Thermodynamic Temperature	Kelvin	K

Conversion Example

A known unit
B unit sought

known:	multiply by	sought:
oz-in	7.06	mNm

Factors used for ...

... conversions:

1 oz = $2.834952313 \cdot 10^{-2}$ kg
1 in = $2.54 \cdot 10^{-2}$ m

... gravitational acceleration:

g = 9.80665 m s^{-2}
= 386.08858 in s^{-2}

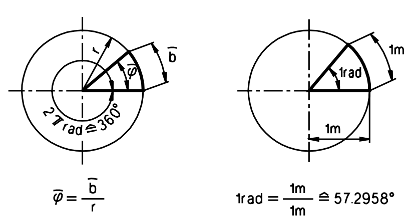
... derived units:

1 yd = 3 ft = 36 in
1 lb = 16 oz = 7000 gr (grains)
1 kp = 1 kg · 9.80665 ms^{-2}
1 N = 1 $kgms^{-2}$
1 W = 1 Nms^{-1} = 1 $kgm^2 s^{-3}$
1 J = 1 Nms^{-1} = 1 Ws

Decimal multiples and fractions of units

Prefix	Abbreviation	Multiply	Prefix	Abbreviation	Multiply
Deka . .	da	10^1	Dezi . .	d	10^{-1}
Hekto . .	h	10^2	Zenti . .	c	10^{-2}
Kilo . .	k	10^3	Milli . .	m	10^{-3}
Mega . .	M	10^6	Mikro . .	µ	10^{-6}
Giga . .	G	10^9	Nano . .	n	10^{-9}
Tera . .	T	10^{12}	Piko . .	p	10^{-12}

Arc definition



Units used in this brochure

Power P [W]

B \ A	oz-in-s^{-1}	oz-in-min^{-1}	in-lbf-s^{-1}	ft-lbf-s^{-1}	W = N · ms^{-1}	mW	kpm s^{-1}	mNm min^{-1}
W = N · ms^{-1}	$7.06 \cdot 10^{-3}$	$1.17 \cdot 10^{-4}$	0.113	1.356	1	$1 \cdot 10^{-3}$	9.807	$2\pi/60000$
mW	7.06	0.117	112.9	$1.356 \cdot 10^3$	$1 \cdot 10^3$	1	$9.807 \cdot 10^3$	$2\pi/60$
oz-in-s^{-1}	1	1/60	16	192	141.6	0.142	$1.39 \cdot 10^3$	$2.36 \cdot 10^{-3}$
ft-lbf-s^{-1}	$1/192$	$1/11520$	$1/12$	1	0.737	$0.737 \cdot 10^{-3}$	7.233	$1.23 \cdot 10^{-5}$
kpm s^{-1}	$7.20 \cdot 10^{-4}$	$1.2 \cdot 10^{-5}$	$1.15 \cdot 10^{-2}$	0.138	0.102	$0.102 \cdot 10^{-3}$	1	$1.70 \cdot 10^{-6}$

Torque M [Nm]

B \ A	oz-in	ft-lbf	Nm = Ws	Ncm	mNm	kpm	pcm	
Nm	$7.06 \cdot 10^{-3}$	1.356	1	$1 \cdot 10^{-2}$	$1 \cdot 10^{-3}$	9.807	$9.807 \cdot 10^{-5}$	
mNm	7.06	$1.356 \cdot 10^3$	$1 \cdot 10^3$	10	1	$9.807 \cdot 10^3$	$9.807 \cdot 10^{-2}$	
kpm	$7.20 \cdot 10^{-4}$	0.138	0.102	$0.102 \cdot 10^{-2}$	$0.102 \cdot 10^{-3}$	1	$1 \cdot 10^{-5}$	
oz-in	1	192	141.6	1.416	0.142	$1.39 \cdot 10^3$	$1.39 \cdot 10^{-2}$	
ft-lbf	$1/192$	1	0.737	$0.737 \cdot 10^{-2}$	$0.737 \cdot 10^{-3}$	7.233	$7.233 \cdot 10^{-5}$	

Moment of Inertia J [kg m^2]

B \ A	oz-in^2	oz-in-s^2	lb-in^2	lb-in-s^2	Nms^2=kgm^2	mNm s^2	gcm^2	kpm s^2
g cm^2	182.9	$7.06 \cdot 10^4$	$2.93 \cdot 10^3$	$1.13 \cdot 10^6$	$1 \cdot 10^7$	$1 \cdot 10^4$	1	$9.807 \cdot 10^7$
kgm^2=Nms^2	$1.83 \cdot 10^{-5}$	$7.06 \cdot 10^{-3}$	$2.93 \cdot 10^{-4}$	0.113	1	$1 \cdot 10^{-3}$	$1 \cdot 10^{-7}$	9.807
oz-in^2	1	386.08	16	$6.18 \cdot 10^3$	$5.46 \cdot 10^4$	54.6	$5.46 \cdot 10^{-3}$	$5.35 \cdot 10^5$
lb-in^2	$1/16$	24.130	1	386.08	$3.41 \cdot 10^3$	3.41	$3.41 \cdot 10^{-4}$	$3.35 \cdot 10^4$

Mass m [kg]

B \ A	oz	lb	gr (grain)	kg	g
kg	$28.35 \cdot 10^{-3}$	0.454	$64.79 \cdot 10^{-6}$	1	$1 \cdot 10^{-3}$
g	28.35	$0.454 \cdot 10^3$	$64.79 \cdot 10^{-3}$	$1 \cdot 10^3$	1
oz	1	16	$2.28 \cdot 10^{-3}$	35.27	$35.27 \cdot 10^3$
lb	$1/16$	1	$1/7000$	2.205	$2.205 \cdot 10^3$
gr (grain)	437.5	7000	1	$15.43 \cdot 10^3$	$15.43 \cdot 10^6$

Force F [N]

B \ A	oz	lbf	N	kp	p
N	0.278	4.448	1	9.807	$9.807 \cdot 10^{-3}$
kp	0.028	0.454	0.102	1	$1 \cdot 10^{-3}$
oz	1	16	3.600	35.27	$35.27 \cdot 10^{-3}$
lbf	$1/16$	1	0.225	2.205	$2.205 \cdot 10^{-3}$
pdl	2.011	32.17	7.233	70.93	$70.93 \cdot 10^{-3}$

Length l [m]

B \ A	in	ft	yd	Mil	m	cm	mm	µ
m	$25.4 \cdot 10^{-3}$	0.305	0.914	$25.4 \cdot 10^{-6}$	1	0.01	$1 \cdot 10^{-3}$	$1 \cdot 10^{-6}$
cm	2.54	30.5	91.4	$25.4 \cdot 10^{-4}$	$1 \cdot 10^2$	1	0.1	$1 \cdot 10^{-4}$
mm	25.4	305	914	$25.4 \cdot 10^{-3}$	$1 \cdot 10^3$	10	1	$1 \cdot 10^{-3}$
in	1	12	36	$1 \cdot 10^{-3}$	39.37	0.394	$3.94 \cdot 10^{-2}$	$3.94 \cdot 10^{-5}$
ft	$1/12$	1	3	$1/12 \cdot 10^{-3}$	3.281	$3.281 \cdot 10^{-2}$	$3.281 \cdot 10^{-3}$	$3.281 \cdot 10^{-6}$

Angular Velocity ω [s^{-1}]

B \ A	s^{-1} = Hz	rpm	rad s^{-1}
rad s^{-1}	2π	$\pi/30$	1
rpm	$1/60$	1	$30/\pi$

Angular Acceleration α [s^{-2}]

B \ A	min^{-2}	s^{-2}	rad s^{-2}	min^{-1} s^{-1}
s^{-2}	$1/3600$	1	$1/2\pi$	$1/60$
rad s^{-2}	$\pi/1800$	2π	1	$\pi/30$

Linear Velocity v [m s^{-1}]

B \ A	in-s^{-1}	in-min^{-1}	ft-s^{-1}	ft-min^{-1}	m s^{-1}	cm s^{-1}	mm s^{-1}	m min^{-1}
m s^{-1}	$2.54 \cdot 10^{-2}$	$4.23 \cdot 10^{-4}$	0.305	$5.08 \cdot 10^{-3}$	1	$1 \cdot 10^{-2}$	$1 \cdot 10^{-3}$	$1/60$
in-s^{-1}	1	60	12	720	39.37	$39.37 \cdot 10^{-2}$	$39.37 \cdot 10^{-3}$	0.656
ft-s^{-1}	$1/12$	5	1	60	3.281	$3.281 \cdot 10^{-2}$	$3.281 \cdot 10^{-3}$	$5.46 \cdot 10^{-2}$

Temperature T [K]

B \ A	° Fahrenheit	° Celsius = Centigrade	Kelvin
Kelvin	(°F -305.15) / 1.8	+ 273.15	1
° Celsius	(°F -32) / 1.8	1	-273.15
° Fahrenheit	1	1.8°C + 32	1.8 K + 305.15

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