maxon DC motor and maxon EC motor
Key information

See also: Technology – short and to the point, explanation of the motor

The motor as an energy converter

The electrical motor converts electrical power P_{el} (current I and voltage U) 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

$$U \cdot I = \frac{\pi}{30\,000} n \cdot M + R \cdot i^2$$

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.

$$M = k_M \cdot I$$

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.

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 42).

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)

$$P_{el} = U \cdot I \qquad P_J = R \cdot I^2 \qquad P_{mech} = \frac{\pi}{30\,000} M \cdot n$$

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, power output P_2 and efficiency η are applied as a function of torque M at constant voltage U.

Speed-torque line
This curve describes the mechanical behavior of the motor at a constant voltage U:
- Speed decreases linearly with increasing torque.
- The faster the motor turns, the less torque it can provide.

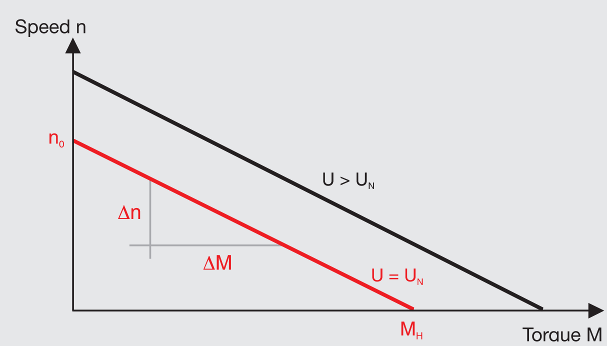
The curve can be described with the help of the two end points, no-load speed n_0 and stall torque M_H (cf. lines 2 and 7 in the motor data).
DC motors can be operated at any voltage. No-load speed and stall torque change proportionally to the applied voltage. This is equivalent to a parallel shift of the speed-torque line in the diagram. Between the no-load speed and voltage, the following proportionality applies in good approximation

$$n_0 \approx k_n \cdot U$$

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 with torque M using the torque constant in the detailed power balance:

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

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.

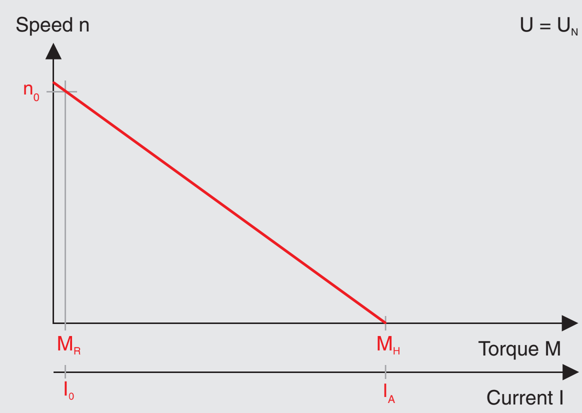
$$n = k_n \cdot U - \frac{30\,000}{\pi} \cdot \frac{R}{k_M^2} \cdot M$$

or with the gradient and the no-load speed n_0

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

May 2009 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.

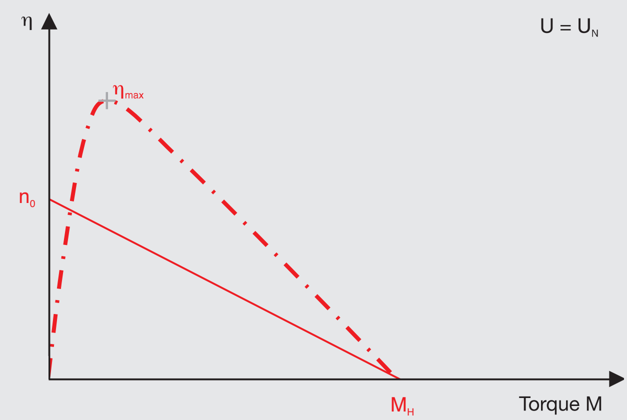
$$M_R = k_M \cdot I_0$$

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.



$$\eta = \frac{\pi}{30\,000} \cdot \frac{n \cdot (M - M_R)}{U \cdot I}$$

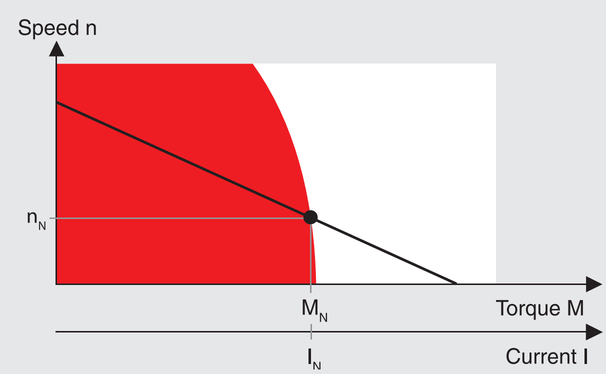
One can see that at constant applied voltage U and due to the proportionality of torque and current, the efficiency increases with increasing speed (decreasing torque). At low torques, friction losses become increasingly significant and efficiency rapidly approaches zero. Maximum efficiency (line 9 of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

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

A rule of thumb is that maximum efficiency occurs at roughly one seventh of the stall torque. This means that maximum efficiency and maximum output power do not occur at the same torque.

Rated working point

The rated working point is an ideal working 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 working point follows from the equivalence of torque and current, and 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 catalogue 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 permis- sible 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.

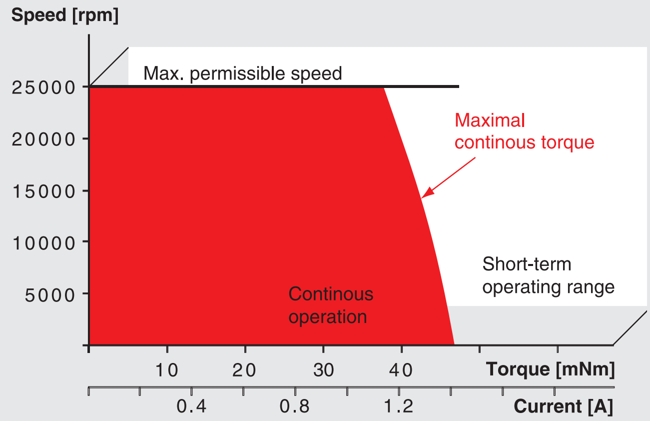
Short-term operating range
The motor may only be loaded with the maximum continuous current for thermal reasons. However, temporary higher currents (torques) are allowed. As long as the winding temperature is below the critical value, the winding will not be damaged. Phases with increased currents are time li- mited. 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 time is heavily dependent on the motor current and the rotor's starting temperature.

Maximum continuous current, maximum continuous torque
The Jule power losses heat up the winding. The heat produced must be able to dissipate and the maximum rotor temperature (line 22 of the motor data) should not be exceeded. This results in a maximum continuous current I_{cont}, at which the maximum winding temperature is attained under standard conditions (25°C ambient temperature, no heat dissipation via the flange, free air circulation). Higher motor currents cause excessive winding temperatures.
The nominal current is selected so that it corresponds to this maximum permissible constant current. It depends heavily on the winding. These thin wire windings have lower nominal current levels than thick ones. With very low resistive windings, the brush system's capacity can further limit the permissible constant current. With graphite brush motors, friction losses increase sharply at higher speeds. With EC motors, eddy current losses increase in the return as speed increases and produce additional heat. The maximum permissible continuous current decreases at faster speeds accordingly. The nominal torque allocated to the nominal current is almost constant within a motor type's winding range and represents a characteristic size of the motor type.

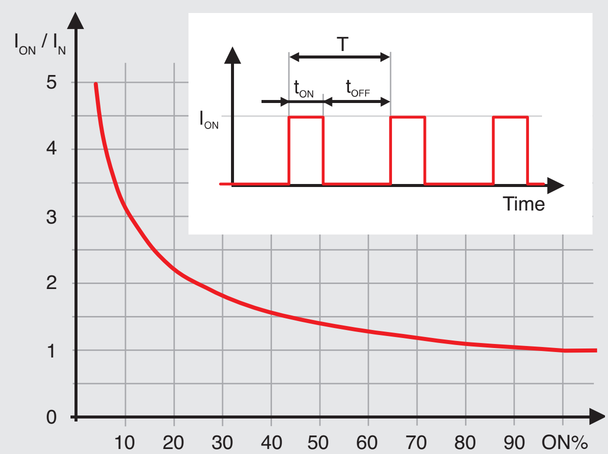
The maximum permissible speed
for DC motors is primarily limited by the commutation system. The commutator and brushes wear more rapidly at very high speeds.
The reasons are:
- Increased mechanical wear because of the large traveled path of the commutator
- Increased electro-erosion because of brush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

Maximum winding temperature
The motor current causes the winding to heat up due to the winding's re- sistance. To prevent the motor from overheating, this heat must dissipate to the environment via the stator. The coreless winding is the thermally critical point. The maximum rotor temperature must not be exceeded, even temporarily. With graphite brush motors and EC motors which tend to have higher current loads, the maximum rotor temperature is 125°C (in individual cases up to 155°C). Motors with precious metal commutators only allow lower current loads, so that the rotor temperatures must not exceed 85°C. Favourable mounting conditions, such as good air circulati- on or cooling plates, can significantly lower temperatures.



Operating range diagram



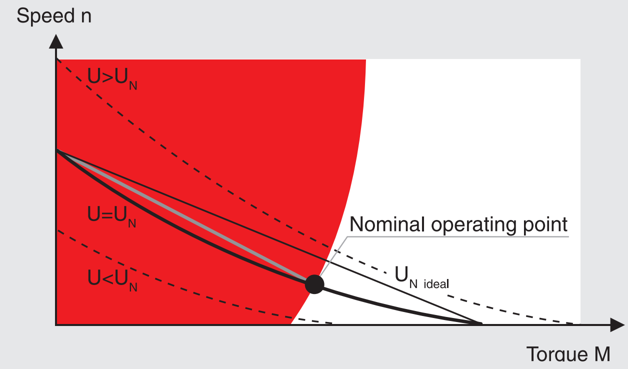
ON	Motor in operation
OFF	Motor stationary
I_{ON}	Max. peak current
I_N	Max. permissible continuous current (line 6)
t_{ON}	ON time *[s]*, should not exeed τ_w (line 19)
T	Cycle time $t_{ON} + t_{OFF}$ *[s]*
$t_{ON\%}$	Duty cycle as percentage of cycle time. The motor may be overloaded by the relationship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

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

maxon flat motor

Multipole EC motors, such as maxon flat motors, require a greater number of commutation steps for a motor revolution (6 x number of pole pairs). Due to the wound stator teeth they have a higher terminal inductance than motors with an ironless winding. As a result at higher speed, the current cannot develop fully during the correspondingly short commutation intervals. Therefore, the apparent torque produced is lower. Current is also fed back into the controller‘s power stage.
As a result, motor behaviour deviates from the ideal linear speed-torque gradient. The apparent speed-torque gradient depends on voltage and speed: The gradient is steeper at higher 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 working point. The achievable speed-torque gradient is approximately.

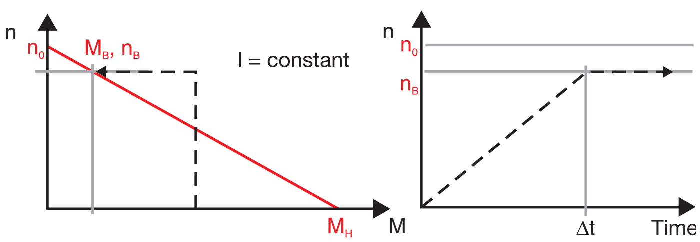
$$\frac{\Delta n}{\Delta M} \approx \frac{n_0 - n_N}{M_N}$$



Acceleration

In accordance with the electrical boundary conditions (power supply, control, battery), a distinction is principally 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:

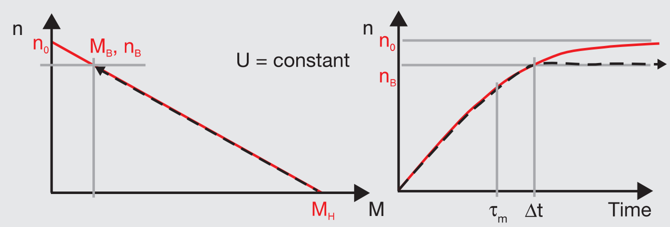
$$\alpha = 10^4 \cdot \frac{k_M \cdot I}{J_R + J_L} = 10^4 \cdot \frac{M}{J_R + J_L}$$

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

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

(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 tm (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:

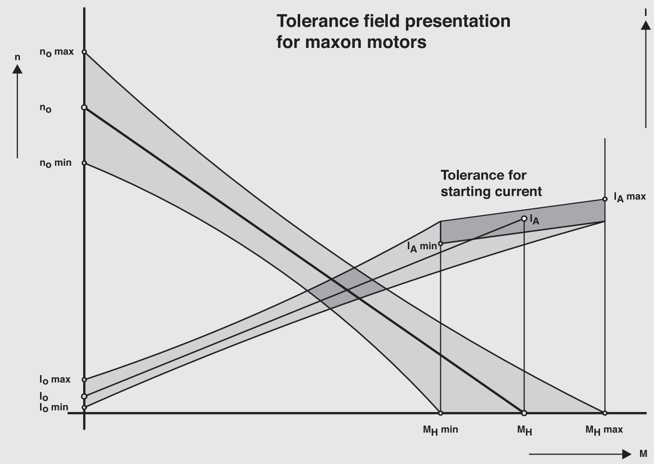
$$\alpha_{max} = 10^4 \cdot \frac{M_H}{J_R + J_L}$$

- Run-up time (in ms) at constant voltage up to the operating point (M_B, n_B):

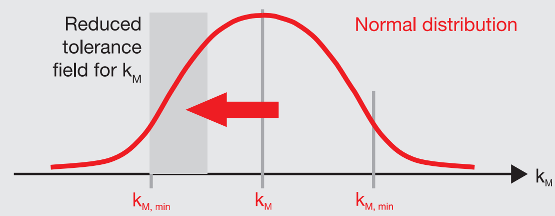
$$\Delta t = \tau_m' \cdot \ln \left(\frac{\left(1 - \frac{M_B + M_R}{M_H}\right) \cdot n_0}{\left(1 - \frac{M_B + M_R}{M_H}\right) \cdot n_0 - n_B} \right)$$

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.



Calibrating
The tolerances can be limited by controlled de-magnetization of the motors. Motor data can be accurately specified down to 1 to 3%. However, the motor characteristic values lie in the lower portion of the standard tolerance range.



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 50% 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 $I = I_{RMS}$).

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

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:

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

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

The magnet becomes weaker at higher temperatures. The reduction is 1 to 10% 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.

$$M_{HT} = k_M \cdot I_{AT} = k_M \cdot \frac{U}{R_T}$$

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 point (M_B, n_B). The motor types in question must have a nominal torque (= max. continuous torque) M_N that is greater than operating torque M_B.

$$M_N > M_B$$

In work cycles, such as start/stop operation, the motor's nominal torque must be greater than the effective load torque (quadratically averaged). 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.

Unregulated 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_B, M_B).

$$n_{0,theor} = n_B + \frac{\Delta n}{\Delta M} M_B$$

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

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

Those windings whose kn 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.

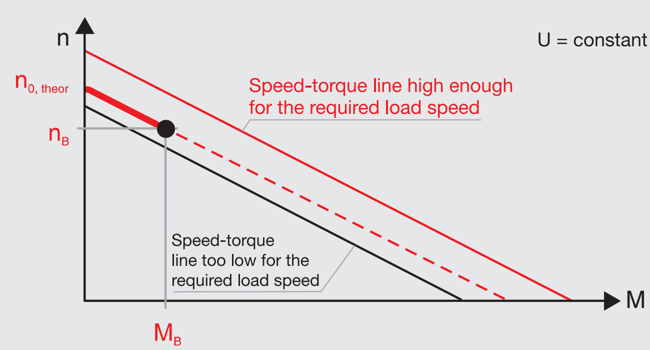
Motor current I is calculated from the torque constant k_M of the selected winding and the operating torque M_B.

$$I = \frac{M_B}{k_M}$$

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 order 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?
– What 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?

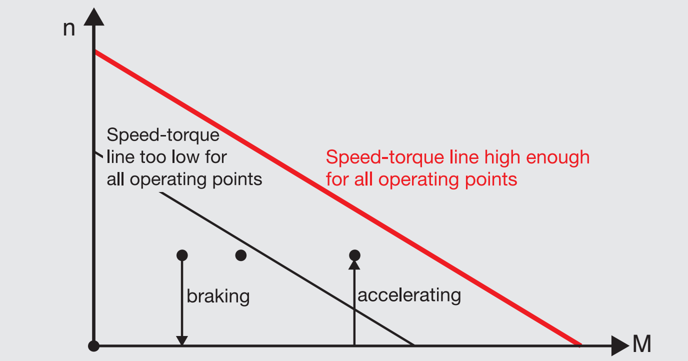


maxon motor

Regulated servo drives
In work 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_B, M_B):

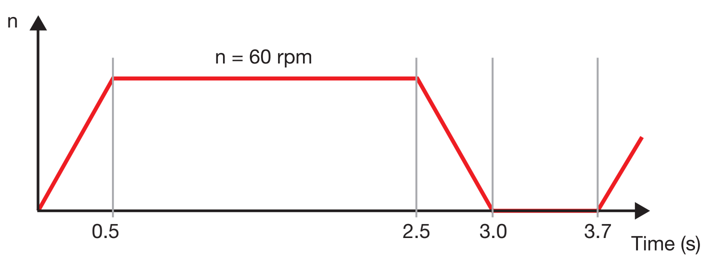
$$k_n \cdot U_{max} = n_0 > n_B + \frac{\Delta n}{\Delta M} M_B$$

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

A drive should move cyclically in accordance with the following speed diagram.



The inertia of load J_L to be accelerated is 130 000 gcm². The constant friction torque is 300 mNm. The motor is to be driven with the linear 4-Q servo amplifier from maxon (LSC). The power supply delivers max. 5 A and 24 V.

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

$$M_\alpha = J_L \cdot \alpha = J_L \cdot \frac{\pi}{30} \frac{\Delta n}{\Delta t} = 0.013 \cdot \frac{\pi}{30} \cdot \frac{60}{0.5} = 0.163 \text{ Nm} = 163 \text{ mNm}$$

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

– Acceleration phase	(duration 0.5 s)	463 mNm
– Constant speed	(duration 2 s)	300 mNm
– Braking (friction brakes with 300 mNm)	(duration 0.5 s)	137 mNm
– Standstill	(duration 0.7 s)	0 mNm

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

$$M_{RMS} = \sqrt{\frac{1}{t_{tot}} \left(t_1 M_1^2 + t_2 M_2^2 + t_3 M_3^2 + t_4 M_4^2 \right)}$$

$$= \sqrt{\frac{1}{3.7} \left(0.5 \cdot 463^2 + 2 \cdot 300^2 + 0.5 \cdot 137^2 + 0.7 \cdot 0^2 \right)} \approx 280 \text{ mNm}$$

The maximum speed (60 rpm) occurs at the end of the acceleration phase at maximum torque (463 mNm). Thus, the peak mechanical power is:

$$P_{max} = M_{max} \cdot n_{max} \frac{\pi}{30} = 0.46 \cdot 60 \frac{\pi}{30} \approx 2.9 \text{ W}$$

Physical variables		and their units SI	Catalog
i	Gear reduction*		
I	Motor current	A	A, mA
I_A	Starting 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*	kgm²	gcm²
J_L	Moment of inertia of the load	kgm²	gcm²
k_M	Torque constant*	Nm/A	mNm/A
k_n	Speed constant*		rpm/V
M	(Motor) torque	Nm	mNm
M_B	Operating 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_B	Operating speed		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	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		
α_{max}	Maximum angle acceleration		rad/s²
$\Delta n/\Delta M$	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}	Maximum efficiency*		%
τ_m	Mechanical time constant*	s	ms
τ_S	Therm. time constant of the stator*	s	s
τ_W	Therm. time constant of the winding*	s	s

(*Specified in the motor or gear data)

Gear selection
A gear is required with a maximum continuous torque of at least 0.28 Nm and an intermittent torque of at least 0.46 Nm. This requirement is fulfilled, for example, by a planetary gear with 22 mm diameter (metal version). The recommended input speed of 6000 rpm allows a maximum reduction of:

$$i_{max} = \frac{n_{max,G}}{n_B} = \frac{6000}{60} = 100:1$$

We select the three-stage gear with the next smallst reduction of 84 : 1 (stock program). Efficiency is max. 59%.

Motor type selection
Speed and torque are calculated to the motor shaft

$$n_{mot} = i \cdot n_B = 84 \cdot 60 = 5040 \text{ rpm}$$

$$M_{mot,RMS} = \frac{M_{RMS}}{i \cdot \eta} = \frac{280}{84 \cdot 0.59} \approx 5.7 \text{ mNm}$$

$$M_{mot,max} = \frac{M_{max}}{i \cdot \eta} = \frac{460}{84 \cdot 0.59} = 9.3 \text{ mNm}$$

The possible motors, which match the selected gears in accordance with the maxon modular system, are summarized **in the table opposite.** The table only contains motors with graphite commutation which are better suited to start/stop operation.

Selection falls on an A-max 22, 6 W, which demonstrates a sufficiently high continuous torque. The motor should have a torque reserve so that it can even function with a somewhat unfavorable gear efficiency. The additional torque requirement during acceleration can easily be delivered by the motor. The temporary peak torque is not even twice as high as the continuous torque of the motor.

Selection of the winding
The motor type A-max 22, 6 W has an average speed-torque gradient of some 450 rpm/mNm. However, it should be noted that the two lowest resistance windings have a somewhat steeper gradient. The desired no-load speed is calculated as follows:

$$n_{0,theor} = n_{max} + \frac{\Delta n}{\Delta M} M_{max} = 5040 + 450 \cdot 9.3 \approx 9200 \text{ rpm}$$

The extreme working 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 working points in the speed / torque diagram.
This target no-load speed must be achieved with the maximum voltage U = 19 V supplied by the control (LSC), (voltage drop of the power amplifier of the LSC 5 V), which defines the minimum target speed constant $k_{n,\,theor}$ of the motor.

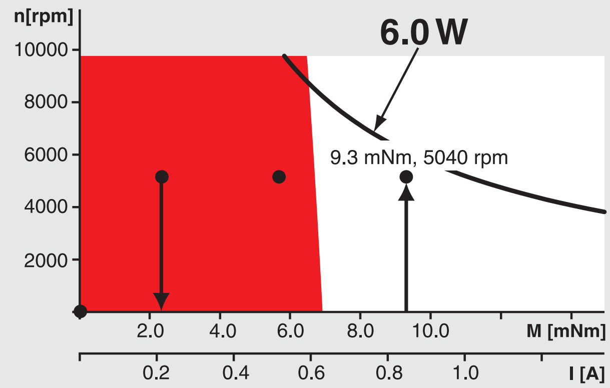
$$k_{n,theor} = \frac{n_{0,theor}}{U} = \frac{9200}{19} = 485 \frac{\text{rpm}}{\text{V}}$$

Based on the calculation, motor 110162 is chosen which corresponds to the winding with the next highest speed constant (689 rpm/V) and has a second shaft end for mounting the encoder. The winding's higher speed constant compared to the target value means that the motor runs faster than required at 19 V which, however, can be compensated for by the controller. This selection also ensures that there is a speed regulating reserve of more than 20%. Thus, even unfavorable tolerances are not a problem.
The torque constant of this winding is 13.9 mNm/A. The maximum torque corresponds to a peak current of:

$$I_{max} = \frac{M_{max}}{k_M} + I_0 = \frac{9.3}{13.9} + 0.036 \approx 0.7 \text{ A}$$

This current is lower than the maximum current (2 A) of the controller (LSC).

Therefore, a gear motor combination has been found that fulfills the requirements (torque and speed) and can be operated with the controller provided.



Motor	M_N	Suitability
A-max 22, 6 W	≈ 6.9 mNm	Good
A-max 19, 2.5 W	≈ 3.8 mNm	Too weak
RE-max 21, 6 W	≈ 6.8 mNm	Good