

## Motor Type Selection

Parameters that define a motor type are the mechanical output power, the shaft bearing system, the commutation system used, and the possible combinations with gearheads and sensors. The most important criteria include the speed and torque requirements, and the commutation system.

Some of the formulas used in this article use subscripts that need to be explained. The variables on the motor shaft (output) are identified with the subscripts *Mot*. For example,  $n_{Mot}$  stands for the required motor speed. Parameters that describe the characteristics of the motor have no special additional subscript. For example,  $n_o$  stands for the no-load speed of the motor.

We'll discuss speed and torque requirements first. The maximum speed that occurs on the motor shaft  $n_{maxMot}$  should be below the maximum permissible speed of the motor  $n_{max}$ , or  $n_{maxMot} \leq n_{max}$ .

As a rule, expected useful life decreases as motor speed increases because of the greater load on the bearings and the higher mechanical wear of the brush system on DC motors. Noise generation increases as well. These effects are particularly pronounced at speeds above the maximum permissible speed. The effective torque  $M_{rmsMot}$  that is required must be less than the rated torque of the motor  $M_N$ , or  $M_{rmsMot} \leq M_N$ .

Rated torque is derived from the rated current  $I_N$ , which is selected to equal the maximum continuous current of the motor (from a thermal point of view). Note that the low friction losses of maxon motors are included in the permissible continuous torques of the motors. The friction losses of the graphite brushes and the iron losses of brushless EC motors depend on speed. The result is a visible rounded boundary of their continuous operating range.

The motor must be able to produce the maximum torque for the application. This means that during startup the motor's stall torque at the rated voltage  $M_H$  should not be exceeded. On larger motors with a correspondingly higher stall torque, brief peak torques up to approximately four times the rated torque  $M_N$  can be handled without any problems:  $M_{maxMot} \leq 4 \cdot M_N$  or  $M_{axMot} \leq M_H$ .

A more detailed analysis would take into account the extent and duration of the overload, as well as the winding and ambient temperatures. In very dynamic applications, the additional torque needed for motor acceleration must be included in the calculation of the operating points:  $M_{Mot,\alpha} = J_{rot} \cdot \pi/30 \cdot \Delta n_{Mot}/\Delta t_\alpha$  (duration  $\Delta t_\alpha$ , rotor moment of inertia  $J_{rot}$ ). The effective load must then be recalculated.

There are influences on the rated torque. Take, for example, the rated torque in a maxon motor.  $M_N$  represents the maximum permissible continuous torque. Under standard conditions at 25°C the motor reaches the maximum permissible temperature. The rated torque varies as a function of the ambient



maxon's EC 4-pole brushless motors

temperature  $T_{Amb}$  and mounting conditions; a higher ambient temperature results in a less efficient dissipation of heat and consequently a lower continuous torque.



Similarly the details of the thermal coupling have an influence on the thermal resistance  $R_{th2}$  between housing and ambient and thus on the rated torque. As the heat dissipation improves, like at a lower  $R_{th2}$ , the rated torque of the motor increases. The thermal resistance  $R_{th2}$  can easily be reduced by one-half by forced cooling or thermal coupling to a heat conducting (metal) heat sink.

The selection of a suitable commutation system is an important issue. The first choice to be made is between mechanical commutation (DC motor with brushes) and electronic commutation (EC motor or brushless DC motor, BLDC). Considerations relating to life expectancy, reliability, simplicity of actuation, and maximum speed play a role in this process.

Furthermore, special environmental conditions such as operation in a vacuum or the ability to withstand sterilization must also be taken into consideration. The most important characteristics and differentiating features are presented in the comparative tables 1 and 2.

### Comparative Table 1:

*Comparison of the basic characteristics of DC and brushless (EC) motors.*

	DC motors	EC motors
Operating life	<ul style="list-style-type: none"> <li>• limited by brush system</li> <li>• typical: 1000-5000 hours</li> <li>• less than 100 hours under extreme loads</li> <li>• over 15,000 hours under favorable conditions</li> </ul>	<ul style="list-style-type: none"> <li>• limited only by bearing system (preloaded ball bearings)</li> <li>• preloaded ball bearings designed for 20,000 hours of operation</li> </ul>
High speeds of rotation	<ul style="list-style-type: none"> <li>• limited by commutation</li> <li>• typically up to approximately 10,000 <math>\text{min}^{-1}</math></li> <li>• in individual cases up to 20,000 <math>\text{min}^{-1}</math></li> </ul>	<ul style="list-style-type: none"> <li>• very high speeds possible on motors with 1 pole pair</li> <li>• typically up to 50,000 <math>\text{min}^{-1}</math>, in individual cases up to 100,000 <math>\text{min}^{-1}</math></li> </ul>
Actuation	<ul style="list-style-type: none"> <li>• simple, only DC voltage from battery</li> <li>• motor can be operated directly from battery</li> </ul>	<ul style="list-style-type: none"> <li>• electronic commutation system required</li> </ul>
Motor connections	<ul style="list-style-type: none"> <li>• 2 (DC voltage)</li> </ul>	<ul style="list-style-type: none"> <li>• 3 for winding and 5 for Hall sensors</li> <li>• 3 for winding (on sensorless motors)</li> </ul>
Maximum efficiency	<ul style="list-style-type: none"> <li>• very high</li> </ul>	<ul style="list-style-type: none"> <li>• high</li> </ul>
Loses	<ul style="list-style-type: none"> <li>• primarily resistance losses in the winding</li> <li>• brush friction with graphic brushes</li> <li>• negligible eddy current losses</li> </ul>	<ul style="list-style-type: none"> <li>• primarily resistance losses in the winding</li> <li>• increasing eddy current losses at high speeds of rotation</li> </ul>
Costs	<ul style="list-style-type: none"> <li>• dependent on the specific model, construction and control system</li> </ul>	

## Comparative Table 2:

Comparison between the characteristics of precious metal and graphite brushes.

	Precious metal brushes with CLL	Graphite brushes
Use for long operating life	<ul style="list-style-type: none"> <li>• for small motors</li> <li>• for very small currents and voltages in continuous operation</li> </ul>	<ul style="list-style-type: none"> <li>• for larger motors</li> <li>• for higher currents</li> <li>• for frequent peak currents in start-stop and reversing operation</li> </ul>
Applications	<ul style="list-style-type: none"> <li>• fans</li> <li>• simple pumps</li> </ul>	<ul style="list-style-type: none"> <li>• servo drives in operating equipment</li> <li>• feeder systems, robots</li> <li>• drills, screwdrivers</li> </ul>
Additional characteristics compared	<ul style="list-style-type: none"> <li>• lower costs</li> <li>• lower audible noise level</li> <li>• lower losses, lower no-load current</li> </ul>	<ul style="list-style-type: none"> <li>• higher costs</li> <li>• higher audible noise level</li> <li>• greater losses, higher no-load current</li> </ul>
Construction	<ul style="list-style-type: none"> <li>• few parts, simple construction</li> <li>• brushes preloaded</li> </ul>	<ul style="list-style-type: none"> <li>• more complex construction</li> <li>• lead wire for brush contacts</li> <li>• brushes mounted on shafts and pressed against the commutator with spring</li> </ul>
Brush material, brush resistance	<ul style="list-style-type: none"> <li>• carrier material: spring bronze</li> <li>• contact material: silver alloy (some gold alloy)</li> <li>• very low electrical resistance</li> </ul>	<ul style="list-style-type: none"> <li>• graphite with copper added (approximately 50%) to reduce brush resistance</li> <li>• maximum operating life with pure electrographic brushes</li> </ul>
Contact response	<ul style="list-style-type: none"> <li>• low, constant contact resistance</li> <li>• small contact surface</li> <li>• very sensitive to arcing, therefore capacitive damping by CLL</li> </ul>	<ul style="list-style-type: none"> <li>• depends on surface of the commutator (patina)</li> <li>• good electrical contact only at higher currents</li> <li>• less sensitive to moderate brush fire (no CLL disc required)</li> </ul>
Lubrication	<ul style="list-style-type: none"> <li>• lubrication with special commutator lubricant</li> </ul>	<ul style="list-style-type: none"> <li>• no lubrication</li> <li>• graphite and the moisture in the air act as lubricant</li> </ul>
Commutator	<ul style="list-style-type: none"> <li>• silver alloy</li> <li>• surface polished or coated</li> </ul>	<ul style="list-style-type: none"> <li>• copper alloy</li> <li>• surface turned on the lathe for perfect conditioning (concentricity, cleanliness, and surface texture)</li> </ul>

### Examples: Selection of motor type (commutation and bearing system)

#### Linear axis for positioning

Production appliances are generally equipped with brushless motors that guarantee a long operating life with minimum maintenance. Because these drives are precision-controlled, the additional costs for the electronic commutation has only marginal significance in the selection process. Typical operating conditions are start-stop motions in both directions of rotation with cycle times of a few seconds and round-the-clock duty.

Evaluation, selection of commutation, and bearing system:

- Very long life expectancy required in operating hours and number of duty cycles
- Cyclical motion in both directions of rotation
- Operating life can be achieved only with brushless EC motor and preloaded ball bearings – generally in combination with feedback sensor

#### Billboard drives

Billboards where ads rotate and change at specified intervals attract attention and make it possible to display several ads in a single space. Typical operating requirements are: around the clock start-stop operation with a cycle time of 10 seconds (e.g. 2 seconds on, 8 seconds off). Over an operating life of 10 years, this comes to approximately 30 million duty cycles and a total on-time of 17,500 hours.

Evaluation, selection of commutation, and bearing system:

- Required operating life very long
- Cyclical motion in both directions of rotation
- Life expectancy can probably be achieved only with brushless commutation (EC motors) and preloaded ball bearings
- A combination with a ceramic gearhead must be considered for the low speeds of the load
- Note on the control system: The motor Hall sensors feedback used for commutation might be sufficient for positioning, given a high enough gear reduction ratio

## Motor winding selection

Finding the appropriate winding for a selected motor type means understanding the electrical characteristics, which vary within the winding series. The objective of the winding selection process is to achieve an optimum match between the electrical and mechanical power aspects.

The speed-torque line describes the possible operating states (working points) of a motor at a given applied motor voltage  $U_{Mot}$ . On DC and EC motors, this characteristic line is represented in the standard diagram (speed vs. torque) as a linear relationship that runs from the no-load speed  $n_0$  (torque 0) to the stall torque  $M_H$  (speed 0). It follows the equation:  $n = k_n \cdot U_{Mot} - \Delta n / \Delta M \cdot M$ , where  $\Delta n / \Delta M$  is the slope of the speed-torque line and  $k_n$  is the speed constant of the motor.

The speed-torque line describes how the motor becomes progressively slower as the load increases, until it ultimately comes to a stop at the stall torque. From a torque point of view the motor exhibits the maximum torque at stall, and the faster it turns the less torque it produces.

In motor catalogs, voltage-dependent values are often given at the rated voltage  $U_N$  (understood as a reference voltage), which is not necessarily the voltage the motor must operate at. The influence of the applied motor voltage  $U_{Mot}$  on the speed-torque line is a parallel shift: upwards at higher voltages and downwards at lower voltages. Slope remains the same. The no-load speed and stall torque shift accordingly. The no-load speed is easily calculated using the applied motor voltage and the speed constant:  $n_0 = k_n \cdot U_{Mot}$ . Note that this simple relationship between motor speed and applied voltage is valid only at no-load operation.

The characteristic lines of the various windings of a maxon motor, for instance, are represented at their specific rated voltage. Rated voltages are chosen to give a resulting no-load speed that is similar for all the different windings. If we plot all these characteristic lines at the same motor voltage, we get a diagram that shows a group of parallel straight lines. This result is because all the characteristic lines of the windings of a given motor type have approximately the same value of slope or gradient, even at different speed constants ( $k_n$ ).

The slope or gradient of the speed torque line is a measure of motor performance. A flat speed-torque line with a low value for the slope corresponds to a powerful motor where speed varies only slightly as the load increases. Less powerful motors have a steeper speed-torque line with a correspondingly higher value for the slope.

The slope of the speed-torque line is a constant determined solely on the basis of design variables: the geometric arrangement and dimensions of the winding and magnetic circuit and the resulting magnetic flux density in the air gap. The number of windings and the resistance of the winding also enter the calculation, however, their influence cancels over a series of windings if the total copper cross section in the air gap is equal. Therefore, the slope of the speed-torque line may be considered a mechanical constant. Motors with the same speed-torque line slope will exhibit the same speed response under load.

On larger motors, we find the constant  $k$  as a comparative measurement for motor performance, which is given  $Nm/W^{1/2}$ . A higher  $k$  value indicates a more powerful motor. The slope of the characteristic line has the same meaning as  $k$ , and they are related by  $\Delta n/\Delta M \propto 1/k^2$ , although  $\Delta n/\Delta M$  is more practical for the calculations.

For example, a speed-torque line slope of 5 rpm/ $mNm$  means that at constant applied voltage an increase in the required torque by 10  $mNm$  results in a speed drop by 10  $mNm \cdot 5 \text{ rpm}/mNm = 50$  rpm.

The slope of the speed-torque line of a motor can be calculated from the no-load speed  $n_0$  and the stall torque  $M_H$  values listed in the motor data sheets. The following equation applies:  $\Delta n/\Delta M = n_0/M_H$ . If the motor data sheet is unavailable, the slope of the speed-torque line can be calculated from a measurement of the no-load speed  $n_0$  at the motor voltage  $U$  and from the motor resistance  $R$ :  $\Delta n/\Delta M = \pi/30 \cdot R \cdot n_0^2/U$ . The electrical resistance  $R$  of the motor should thereby be determined by means of a current measurement with the motor shaft locked (starting current  $I_A$ ):  $R = U/I_A$ .

The objective of winding selection is to find a motor with the speed-torque line that covers all the working points dictated by the load at a given voltage – the extreme working point. The speed-torque line must extend above this point at the maximum available voltage. All other working points can then be reached by reducing the motor voltage. This extreme working point falls at the end of the acceleration process, where both the torque and speed are at maximum.

For a methodical determination of the appropriate windings, assume that the optimum winding for an application has a speed-torque line that runs directly through the extreme working point ( $M_{maxMot}$ ,  $n_{maxMot}$ ) at the maximum possible motor voltage  $U_{Mot}$ . On the assumption of an average speed-torque line slope for the motor type, we can calculate a no-load speed  $n_{0,theor}$  as an auxiliary variable:  $n_{0,theor} = n_{maxMot} + (\Delta n/\Delta M)_{avg} \cdot M_{maxMot}$ .

Note that a more conservative approach takes the slope of the least powerful winding of the motor type being considered (i.e. the steepest slope). Accordingly,  $n_{0,theor}$  becomes greater. This theoretical no-load speed must be achieved with the maximum voltage  $U_{Mot}$  available to the motor. This is equivalent to saying that the speed constant  $k_n$  of the selected motor must be greater than the ratio of the no-load speed to the motor voltage:  $k_n \geq n_{0,theor}/U_{Mot}$ .

To this point, no tolerances have been explicitly taken into consideration in the load, drive, motor, controller and power supply. We can now make up for this lack of consideration by selecting a winding with a speed constant that is higher by approximately 20%:  $k_n \geq 1.2 \cdot n_{0,theor}/U_{Mot} = 1.2/U_{Mot} (n_{maxMot} + (\Delta n/\Delta M)_{avg} \cdot M_{maxMot})$ .

The final step is to verify whether the available current for the selected motor winding can produce the required output torque for both intermittent and continuous operation. On maxon motors, the torque produced is proportional to the motor current which can easily be calculated by means of the torque constant  $k_M$ . Losses that occur in the motor must also be taken into consideration. These are expressed by the no-load current  $I_0$ , which depends slightly on speed. To estimate whether the current available is sufficient, however, this dependency can be ignored. The resulting selection criterion is therefore that in each time cycle the available current  $I_{Mot}$  must be greater than that current required for the production of the load torque (including the no-load current of the motor):  $I_{Mot} \geq M_{maxMot}/k_M + I_0$ . The current  $I_{Mot}$  available at the motor is specified by the characteristics of the power supply and the controller.

Motor type selection, including winding selection, in the end, doesn't take as much calculating as one might think. Having motor specifications handy and knowing a few key motor characteristics in relation to a specific application often provides all the necessary data needed to come up with a useable solution.

Try maxon precision motors easy-to-use motor selection program at:  
<http://www.maxonmotorusa.com/downloads.asp>

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