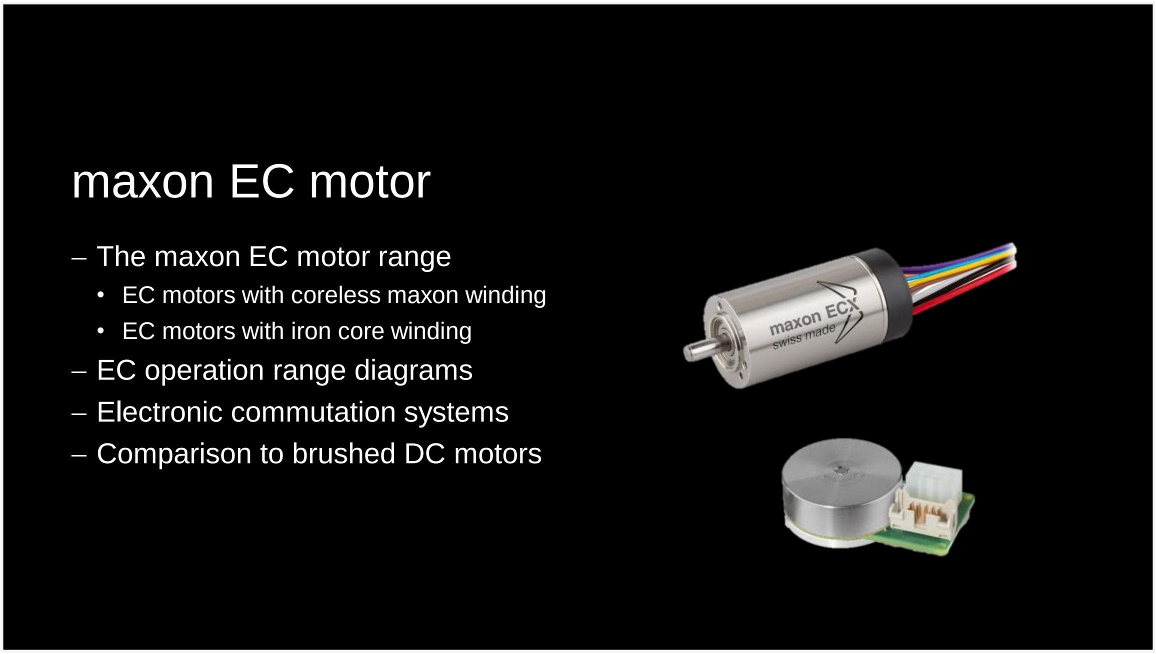


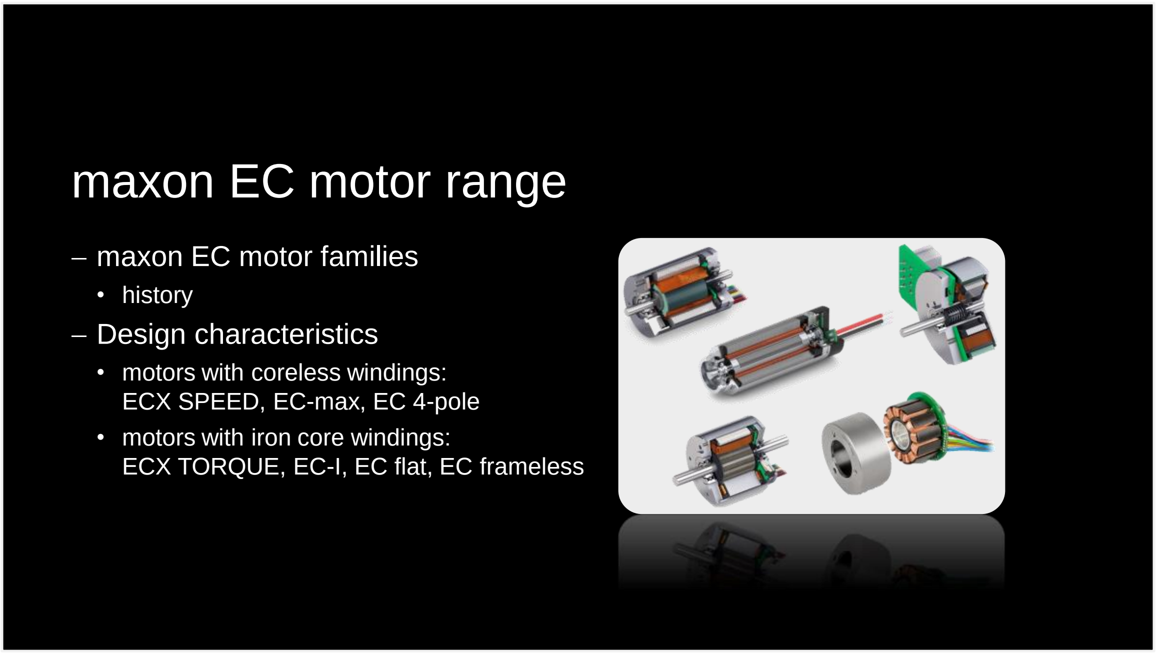
This presentation introduces the design and operation principle of the brushless maxon EC motors. EC motors are also called brushless DC (BLDC) motors.
At first, we show the basic designs principles of brushless maxon motors. Mainly we have to distinguish between motors with coreless maxon winding and motors with classical iron core winding.
Motor data and operation range diagrams of brushless motors show some particularities that we have to look at next
In the third part we have a closer look at the different electronic commutation systems, i.e. how the electronics switches the current on the three phases.
At the end we compare these brushless motor designs to maxon DC motors with mechanical commutation.

maxon EC motor - Objectives

What you should know at the end ...

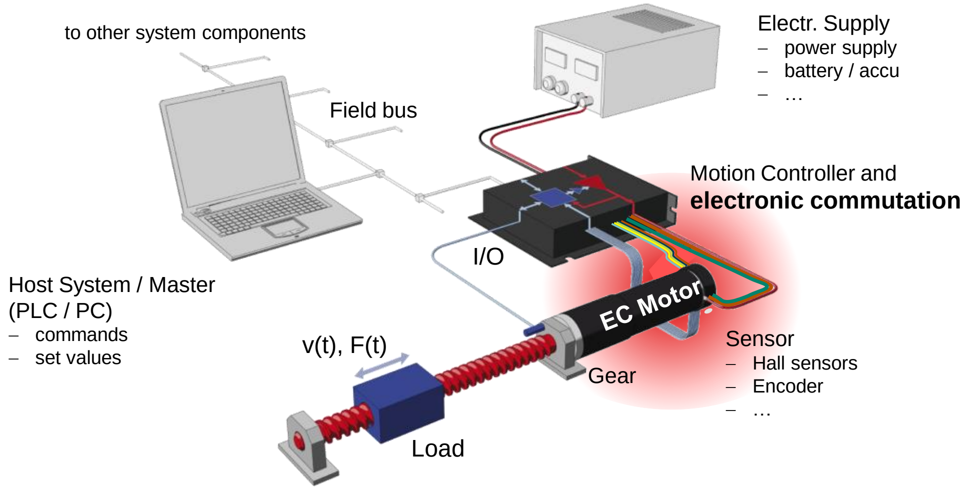
– What are the main benefits of brushless DC motors?
– What is the difference between the maxon EC motor families?
– How does electronic commutation work?
– How are operation range diagrams and motor behavior to be interpreted?

There are some practical aspects that you will learn.
What are the advantages of brushless DC motors compared to brushed DC motors?
Brushless motors come in different flavours, each with special characteristics.
There are different ways to operate brushless motors, i.e. different commutation systems.
How to interprete motor data and operation range diagrams.



The first section gives an overview on the maxon EC motor product range.
It enlightens the different designs and their characteristics.

Components of a EC motor drive system



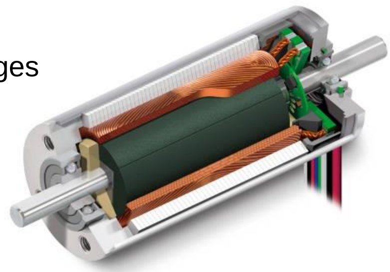
Let's first look at an EC drive system in general.
The three phases of the EC motor cannot be connected directly to a DC power supply. The voltage needs to be switched in a sequence. This is done by the electronic commutation. Electronic commutation is in almost all cases integral part of the power stage of the motion controller. Hence, the electronics often not only performs the commutation but at the same time can be used to control speed or position.
For the correct powering of the three motor phases, the rotor position needs to be known. This information is often provided by Hall sensors. For more sophisticated commutation and precise motor control, e.g. at very low speeds, the use of an encoder feedback might be necessary.

An EC motor cannot operate on its own: It's always the combination of motor and electronics commutation that makes the full drive.

Brushless DC motor

– Main advantages
  - higher life
  - higher speeds

– Designation
  - EC motor
  - BLDC motor

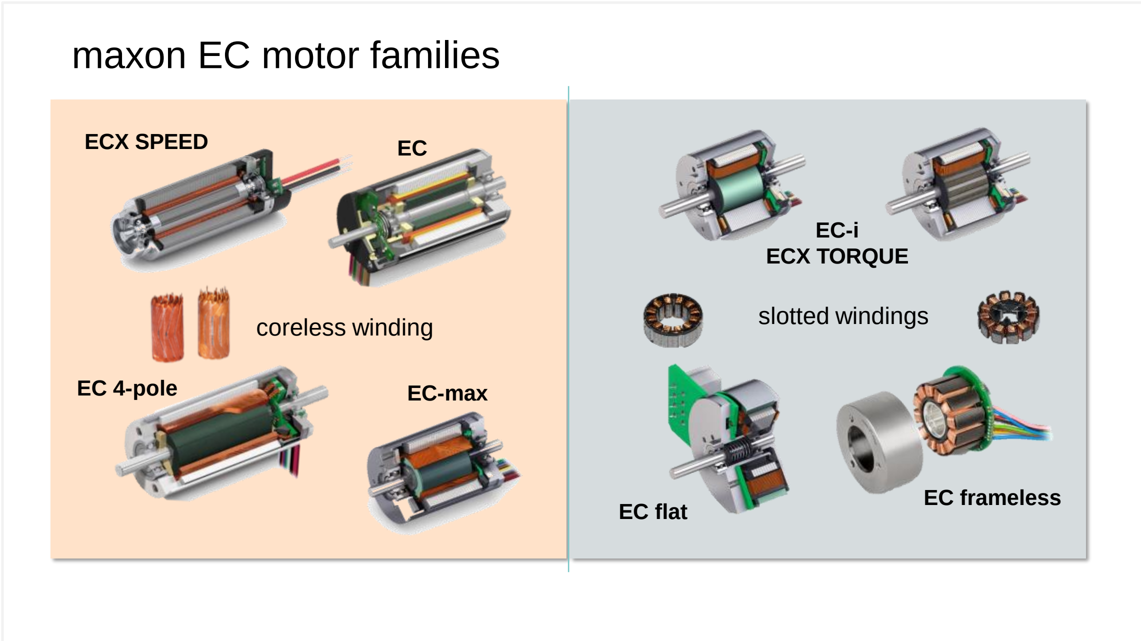


Features in common
- 3 phase winding in the stator (3 winding connections)
- rotating permanent magnet made of NdFeB
- preloaded ball bearings
- electronic commutation

– EC motor behaves like DC motor
  - design similar to synchronous motor (3 phase stator winding, rotating magnet)
  - the powering of the 3 phases according to rotor position

maxon EC motors are brushless DC motors. The EC stands for electronic commutation to distinguish these motors from DC motors with mechanical commutation by a brush system. The main advantages of a brushless DC motors are the longer motor life and the higher motor speed. They are not limited by the brushes.
The windings of an EC motor are powered similarly as in a brushed DC motor – the electronic commutation mimicking the brush system. Therefore, there is the same speed-torque behavior as with any DC motor. In particular the high starting torque and the resulting high dynamics are obtained as well.
(The arrangement of rotor and stator in brushless DC motors reminds strongly of synchronous or stepper motors. However, there is a big difference to these motor types: The powering of the 3 phases is not imposed from outside (step commands or frequency) but is done according to the internal rotor position.)

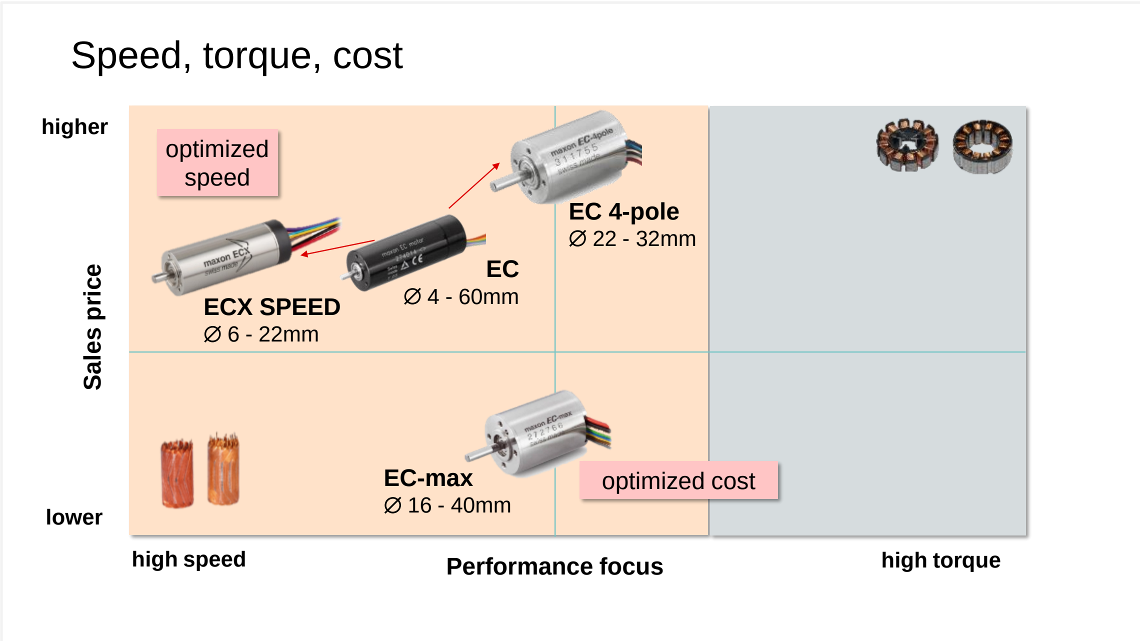
There are many different maxon EC motor designs. However, some features all these designs have in common
The winding consists essentially of 3 parts with 3 connections (called phases). It must be fixed in the stator and cannot rotate because there are no brushes to transmit the current onto a rotating winding.
It's always the magnet that is rotating. The permanent magnet being made of NdFeB in most cases.
In order to achieve high bearing life and low noise at high speeds preloaded ball bearings are used.
Brushless DC motors need electronics to run.



There are different maxon EC motor designs

Coreless designs exhibit typically a long cylindric shape with a limited number of 1 or 2 magnetic pole pairs well suited for high speeds, however at rather low torque. The coreless winding shows no magnetic detent torque or cogging, resulting in low vibration.

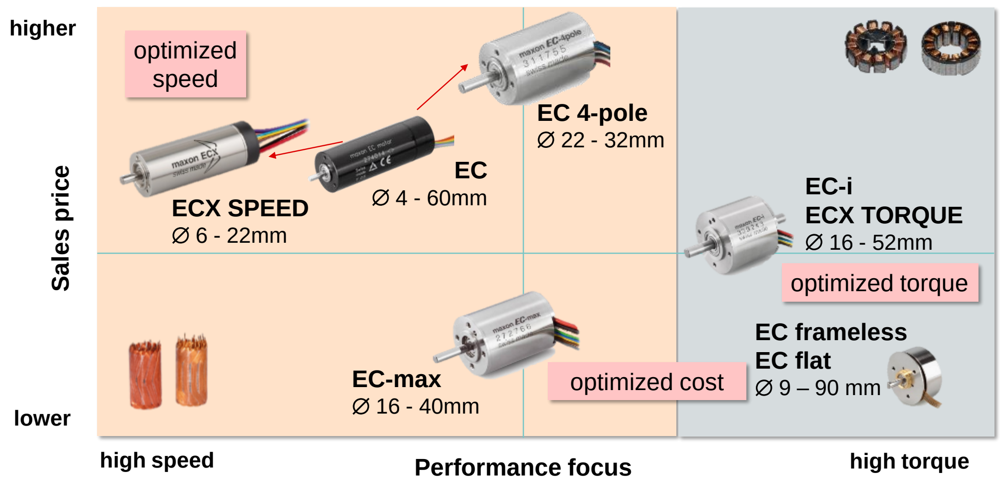
Slotted designs are based upon windings with iron core. They are typically made with many magnetic poles resulting in quite a high produced torque. However, the maximum speed is limited due to the higher magnetization frequencies and the resulting higher losses. The interaction of the permanent magnet with the iron core is responsible for cogging.



The different EC motor series in the maxon product range exhibit different characteristics according to their respective design objectives.

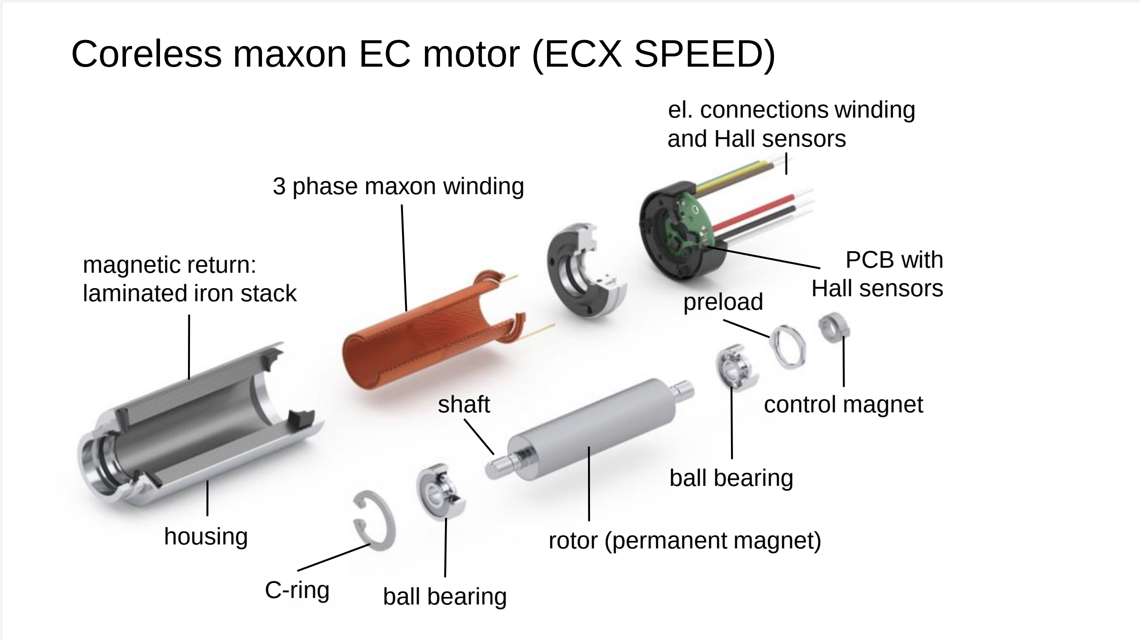
maxon EC motor with coreless windings:
maxon EC motor: These first generation motors exhibit a permanent magnet with 1 pole pair and a relatively high speed (several 10'000 rpm). Now being replaced by newer designs ….
maxon ECX SPEED motor are specially made for high speed applications of several 10’000 rpm. The 1 pole pair design builds upon the classical coreless maxon EC motor. From a commercial point of view, the big advantage is the “Configure to Order” concept: the mechanical and electrical interfaces, as well as possible combinations can be configured online. This results in the shortest delivery times.
maxon EC-max: The "max" refers to maximum performance to price ratio. This motor is not optimized for high power – be it high speed or high torque - but for reasonable low cost. in combination with gearheads this reliable motor is just perfect.
maxon EC-4pole: The philosophy of these motors with 2 magnetic pole pairs is to provide the highest power. Besides the 4-pole design this is achieved by a special winding arrangement and highest quality magnetic materials.

Speed, torque, cost (continued)

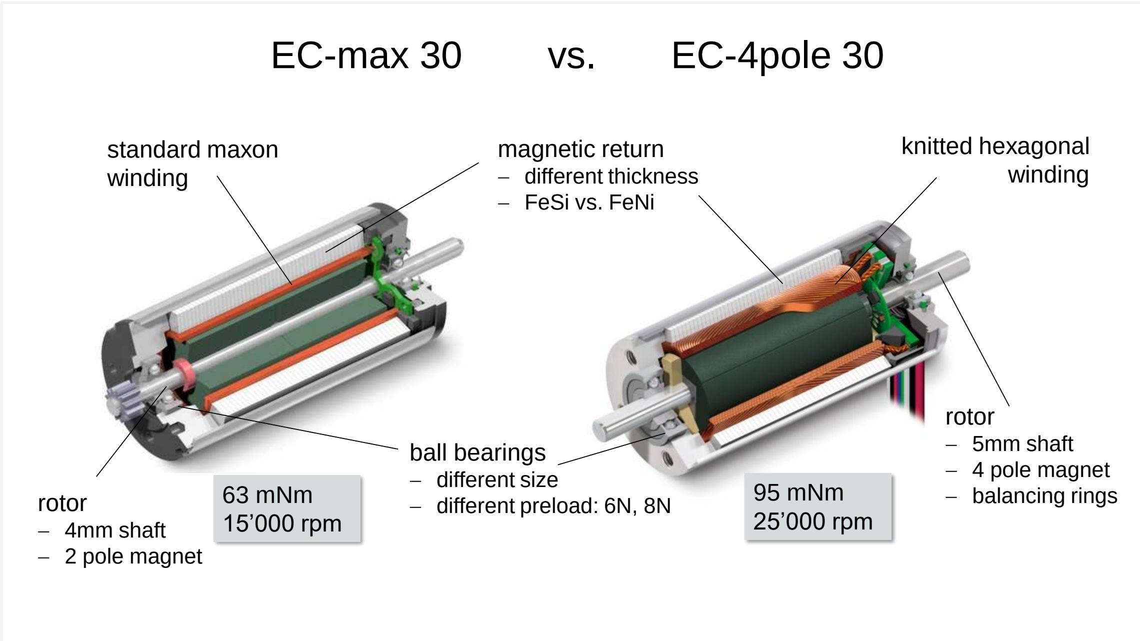


continued

maxon EC motors with slotted winding:
The EC-i (ECX TORQUE) with the external winding and the multi-pole magnet close to the center exhibits a high torque per mass inertia of the rotor. This results in a very dynamic motor with fast acceleration. There are different versions available: Standard, High Torque, Sterilizable.
The external rotor of the EC-flat produces the force far from the rotating axis. This gives a very high torque. But the large rotor diameter causes the rotor mass inertia to be high as well. Therefore, the dynamics is limited. The flat design can be an advantage in certain applications with limited space available. Flat motors are cost optimized.
Frameless EC motors are thought do be integrated into the application mechanical system. They consist of separate stator and rotor without bearings. Frameless motors are based upon the EC flat or EC-i design providing a high torque.



On the coreless maxon ECX SPEED motor we can distinguish the following main subassemblies:
The rotor (in the lower line) with the permanent magnet mounted on the shaft at the center. The rotor is dynamically balanced which is important for reducing vibration and noise and for increasing bearing life, particularly at the high speeds obtainable with brushless motors.
The stator (in the upper line) includes the housing with the magnetic return. The magnetic return is made of an laminated iron stack in order to reduce the iron losses due to the rotating permanent magnet. Inside the iron stack we have the coreless maxon winding, the three phases are contacted via the printed circuit board (PCB) to the electrical winding connections.
Rotor position feedback is often achieved by a system of three Hall sensor mounted on the PCB. The Hall sensors detect the magnetic field of a control magnet which is attached to the shaft. In some cases the magnetic field of the main permanent magnet is monitored directly. The Hall sensors have 5 additional electrical connections: 2 for the supply voltage and 3 for the Hall sensor signals.
The ball bearings are preloaded.

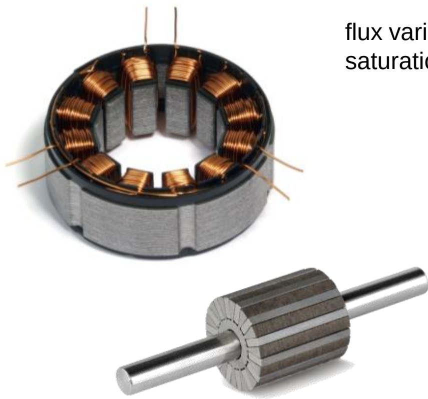


What are the main differences between a cost optimized EC-max and a power optimized EC-4pole motor? We make this comparison on motors with 30 mm diameter.

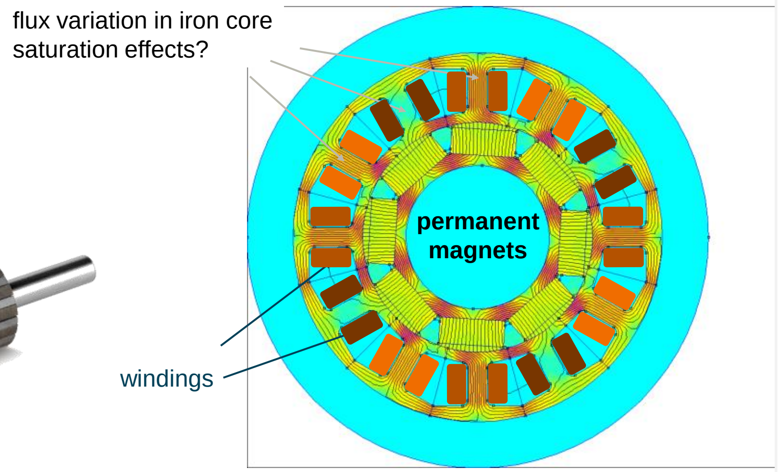
Enhancing the power density on the EC-4pole is achieved by
4 permanent magnetic poles, i.e. 2 pole pairs instead of 1. This results in a higher total magnetic flux in the air gap. The assembly of the rotor, however, is more complicated; there are 4 magnetized segments that need to be mounted on the shaft.
A high grade iron-nickel magnetic return order to keep the eddy current losses small . The magnetization frequency in the magnetic return is twice as high as on a motor with 1 pole pair. The maximum magnetic flux density, however, is smaller allowing a thinner magnetic return. This gives more space for the winding and the rotor diameter can be made slightly larger. Both factors have a positive effect on the produced torque.
A hexagonally shaped knitted maxon winding resulting in a higher motor torque. Further increased by a sophisticated connection of the winding segments.
The higher power of this motor needs a stronger shaft and larger bearings.

Reducing the cost on the EC-max 30 is achieved by
A simpler rotor design, with no balancing. Therefore, the motors should not be used at very high speeds.
A standard maxon winding instead of a knitted winding. This reduces performance.
Hall sensors monitoring directly the power magnet, i.e. without extra control magnet.
Interestingly, the lack of balancing rings and control magnet allow a longer magnetic system. Even though this motor is not optimized with respect to power there is quite a lot of torque generated.

EC-i (EC TORQUE) animation

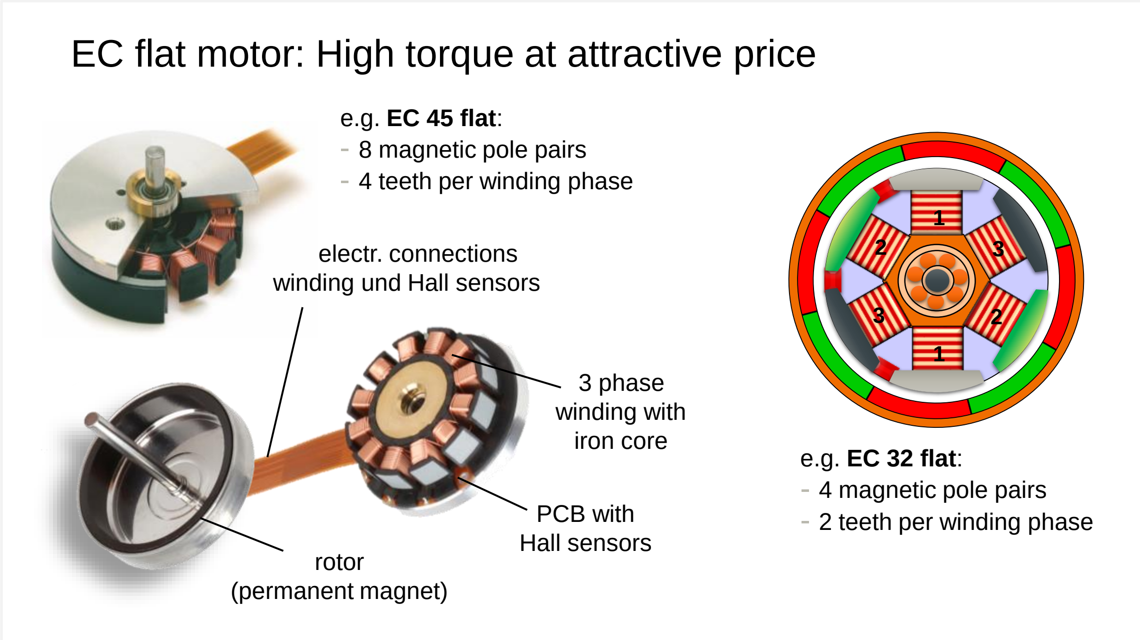


internal rotor motor



Slotted maxon EC motor design versions are the EC-i and ECX TORQUE motors.
As with the coreless versions, the permanent magnets are mounted on the rotor while the winding at the outside contains a slotted iron core.
The multi-pole design enhances the torque capabilities compared to the slotless maxon motors. In combination with the low inertia rotor, this results in a short mechanical time constant; i.e. in a very dynamic motor.

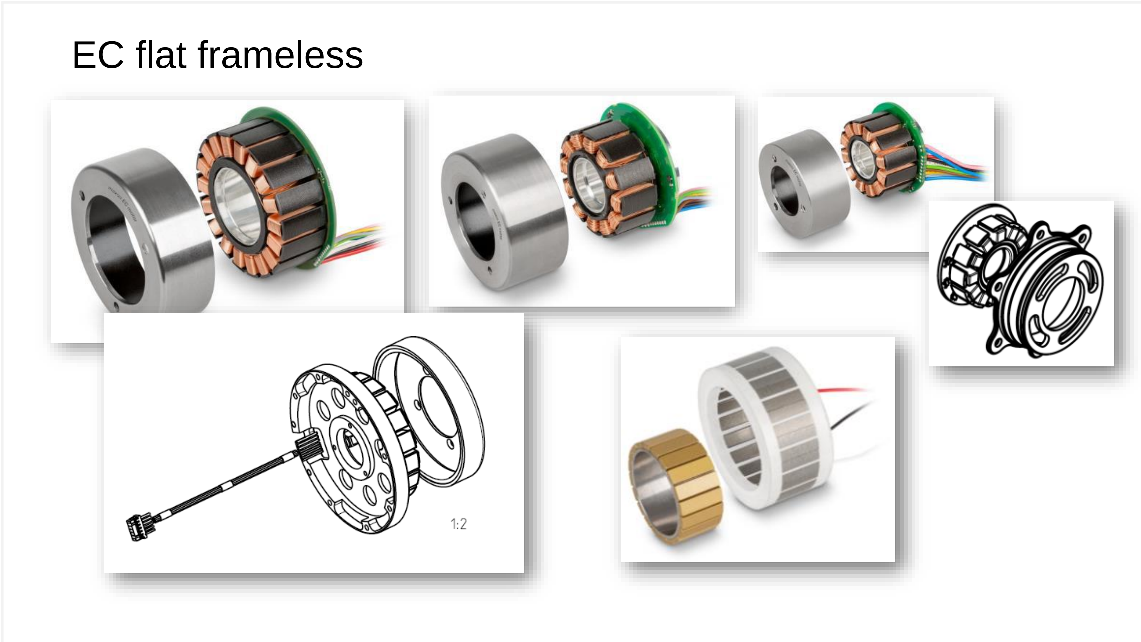
Drawbacks of slotted designs are
the increased iron losses leading to additional heating.
the limited the maximum speed due to the higher commutation frequency and the growing iron losses.
saturation effects in the iron core resulting in deviation from the linear motor behavior and lower maximum torque.
cogging because of the magnetic interaction of iron teeth and permanent magnetic poles.



The philosophy of flat motors: a flat design at attractive price.
The external rotor produces a high torque. However the multi-pole magnetic ring results in a high commutation frequency, and, hence, a limited speed range.

This slide shows - on the left – a view into an EC 45 flat motor

On the right a schematic cross section of an EC 32 flat motor.
We can see the external rotor magnet ring with 8 magnetic poles (4 pole pairs in green and red).
Each winding phase is made of two stator teeth lying opposite.
The Hall sensors (dark and bright blue) are located between the stator teeth and monitor directly the poles of the magnetic ring.



At the moment (2018) maxon offers three different diameters of frameless motors (top row pictures) based on the larger catalog flat motors
45 mm (3 different lengths)
60 mm
90 mm (2 different lengths)
There are other designs with magnetic inner rotor in preparation at maxon.

The idea of frameless motors is to save space by allowing design engineers to integrate the motor into the mechanics of an application. Think of a robotic joint, a pump mechanism, a valve or a wheel. The motors are delivered as separate stator and rotor without bearing assembly. The large central hole can serve to take up large bearings, or for feeding through cables and vacuum lines, or for mounting special shaft materials.

Frameless motors are most of the time direct drives that need a high torque. Therefore, flat and multipole motor designs are preferred. The high degree of integration requires often a special flange design as can be seen from the 2 drawings.

maxon EC motor summary

– ECX SPEED
- High speed design
- Long, small diameter

– EC-4pole
- Rather high torque
- Medium speed

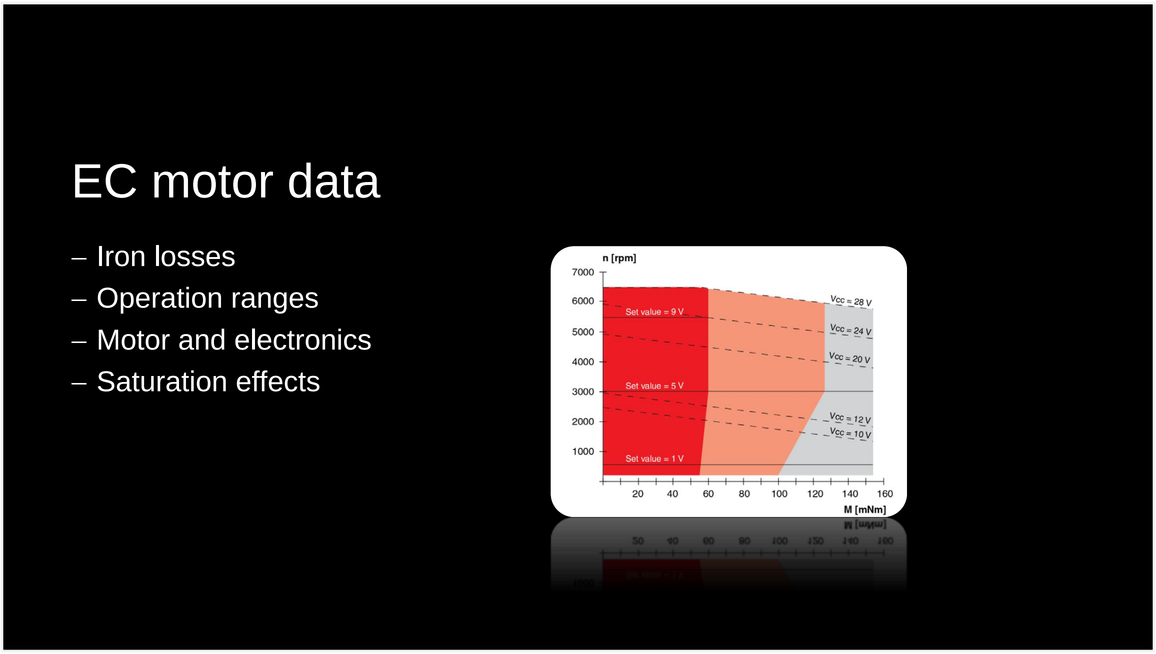
– EC-max
- Lower cost design, limited speed and torque
- Perfect for combination with ceramic gears

– EC-i, ECX TORQUE
- High torque, high dynamics
- Multipole design
- Cogging
- Medium length

– EC flat
- High torque, low dynamics
- Multipole «open» design
- Cost effective
- Short length

– EC frameless

And here as a summary, the charcteristic snapshot of the maxon EC motor families.



This second part highlights two particularities of the brushless design and their effects on motor data.

The first are iron losses, that occur in most motor types. These are power losses in the iron parts that guide the magnetic flux, namely the magnetic return path and the iron core of slotted windings. Iron losses provide an additional heating of the motor.

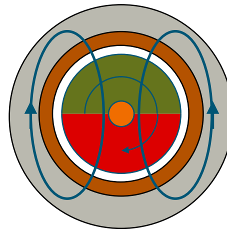
The second effect is also related to the iron. It’s the saturation in the iron core of the windings.

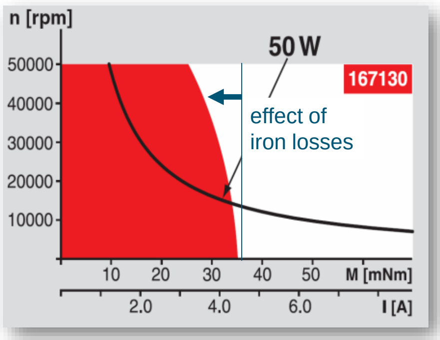
Iron losses

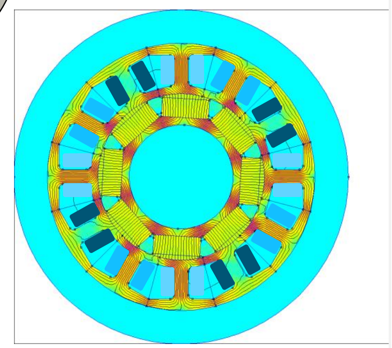
Changing magnetization

➔ hysteresis losses:

➔ induced eddy current



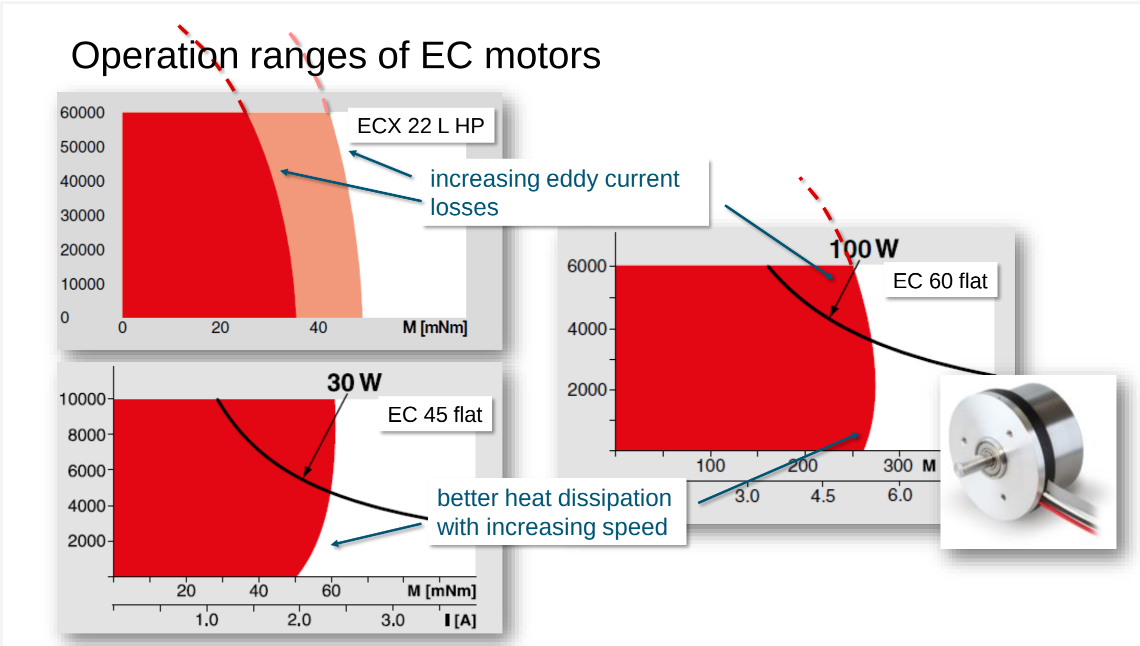




Effect: additional motor heating at high speeds
(less current for torque generation is allowed)

Iron losses are caused by two mechanisms, both relying on the fact that the flux in the iron changes its direction or intensity.
Hysteresis losses describe the fact that changing the magnetization of the iron consumes energy. It's similar to running through the magnetization loop (hysteresis) of the material. Hysteresis losses can be minimized by selecting appropriate materials that can easily be magnetized (with a narrow hysteresis) and by lowering the flux density (i.e. selecting a large diameter of the material).
The changing magnetic flux induces voltages in the material. These voltages produce eddy currents in the iron which will be heated. Eddy currents can be minimized by selecting a laminated iron return made of thin iron foil which are electrically isolated. One can show that the more confined the eddy currents are the lower the losses.

Iron losses and speed
Hysteresis losses increase proportional to motor speed. Each hysteresis cycle adds a certain amount of energy loss: The higher the speed, the higher the number of magnetization cycles per time, the higher the power losses. Therefore, hysteresis losses can be treated like an additional constant friction torque.
Eddy current losses increase with the square of the speed. This can be understood from a simple argument: The faster the speed the higher the induced voltage and the higher the eddy current. Power losses go with the square of the current, hence, with the square of the speed. In short, eddy current losses can be treated like a speed dependent additional friction torque.
If the speed is sufficiently high it's the eddy current losses that dominate.

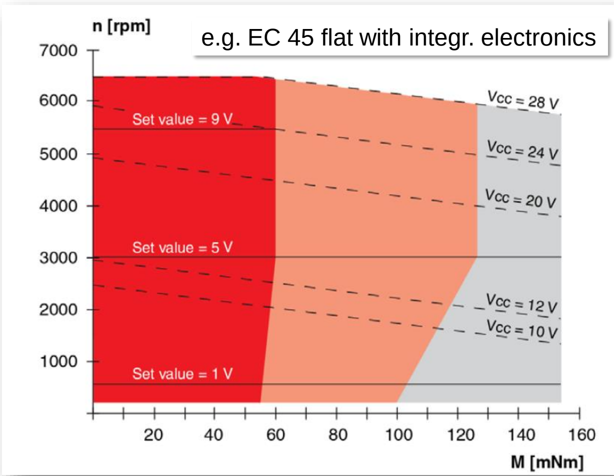


This additional heating can be seen in the operating range diagram. At high speeds the limit of the continuous operating range moves towards lower torques. The additional heating by the eddy current allows less current in the winding and, hence less torque.
Therefore, on most EC motors the border of the continuous operation range is curved. Extrapolating this effect to even higher speeds, the motor would heat up solely due to speed, even without a considerable torque load.

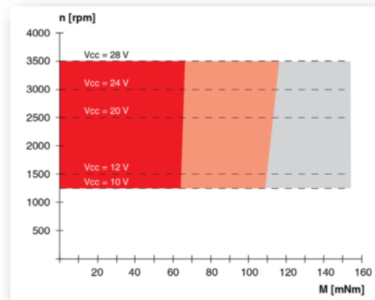
On some flat motors, the border of the continuous operating range just looks the opposite. More current is allowed at higher speeds generating more torque. The reason for this behavior lies in the open motor design, where with increasing speed the air flow through the motor grows stronger improving heat dissipation.

A nice example to show both effects is the operation range diagram of the EC 60 flat motor. When going to lower speeds the heat dissipation is reduced. Hence, less heating is permitted, i.e. less current and, therefore, less torque.
At higher speeds, however, the eddy current losses become more important than the gain in heat dissipation. As a result the maximum permissible current is reduced and hence the maximum permissible torque.

Motor and electronics: operation range



- limited supply voltage range
  ➔ limited speed range
- limited controller current
  ➔ limited torque range



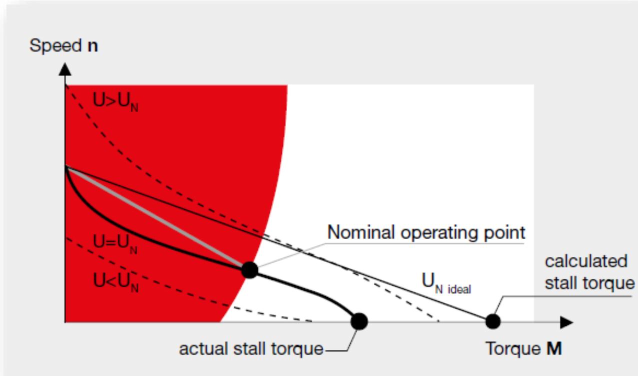
As we mentioned earlier: EC motors need electronics to run and therefore they should always be looked at in combination with the specific drive electronics.
This slide shows as an example an EC flat 45 motor with integrated electronics. However, the following reasoning apply to any electronics, be it integrated or external. (And by the way to any motor in combination with a motion controller)

Electronics has supply voltage limits.
Accordingly, the maximum speed is limited by the maximum voltage that the electronics is capable to apply to the motor. In the diagram above this can be seen by the dotted speed-torque-lines at different supply voltages. At given voltage only the area below these lines is accessible.
Electronics has current limits.
Limited current results in limited motor torque. Very often the stall torque and starting current indications in the motor specification are purely calculation values and cannot be reached in practice due to the limited current capabilities of the electronics or the power supply.
Simpler and cost-effective electronics can have functional restrictions, such as limited set value options, or one direction operation only.

EC motor data slotted designs

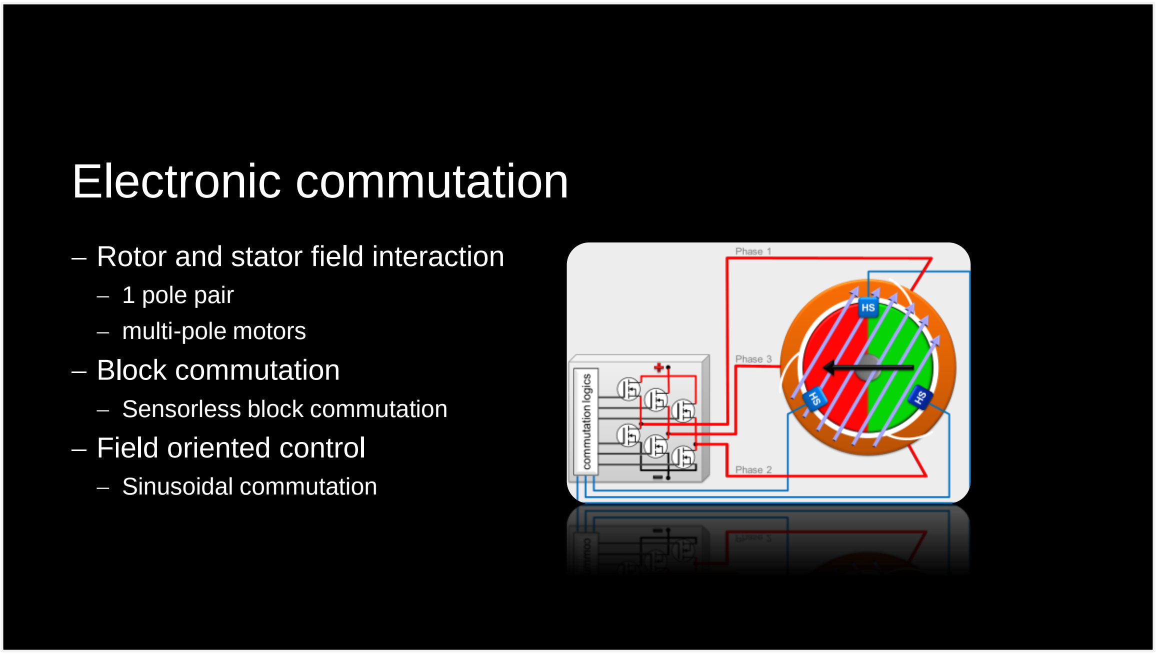
– Motor data defined for
  - block commutation
  - infinitely powerful amplifier (current and voltage not limited)
  - no saturation effects in iron

Motor behavior of motors with slotted iron core winding



maxon gives EC motor data for block commutation assuming an infinitively powerful amplifier with no current limitations. As we have seen this is usually not the case. Additionally, saturation effects in the iron core are not taken into account at the time being (2018).

The simple and in essence linear motor characteristics of slotless motors will not hold for motors with slotted windings, in particular if they exhibit multiple permanent magnetic poles. There are two main effects:
First, at high speed the commutation frequency is very high due to the multipole design. As a result, the current has difficulty to build up during the short commutation intervals. The effect is further aggravated by the large inductance of the iron core winding and current being back driven into the power stage. As a net result the motor becomes weaker at high speeds as can be seen from the steeper speed-torque-lines (dotted lines in the diagram). The linear speed-torque line (black straight line), which is at the basis of motor data representation in the maxon catalog, is not realistic anymore. In the continuous operation range, a linear interpolation between no-load and nominal operation point can be a reasonable approximation of real motor behavior (grey line in the diagram).
Second, at higher currents the iron core saturates resulting in less torque per current (or a lower torque constant). Accordingly the achievable stall torque can be much lower than the specified value for the given starting current. Fortunately, this effect does not occur very often, due to the fact that on larger motors the supply current is limited by the electronics anyway.



This part of the presentation considers the interaction between rotor and stator, which is the basis for understanding electronic commutation.

Electronic commutations systems

Commutation type	Block		Sinusoidal Field oriented control	
Maxon controller families	ESCON	ESCON ESCON	EPOS4 EPOS2 EPOS4 MAXPOS	HPSC
Rotor position feedback	Sensorless	Hall sensors	Encoder + Hall sensors	Sensorless
	block shaped phase currents ➔ torque ripple		sinusoidal phase currents ➔ smooth torque	
Application types	Continuous operation at high speeds ➔ fans, drills, grinder	Speed control Position control	Position control Speed control	Sensorless speed control from speed zero. Needs customization ➔ for larger volumes
Remarks	Starting procedure similar to stepper motor	maxon standard commutation		

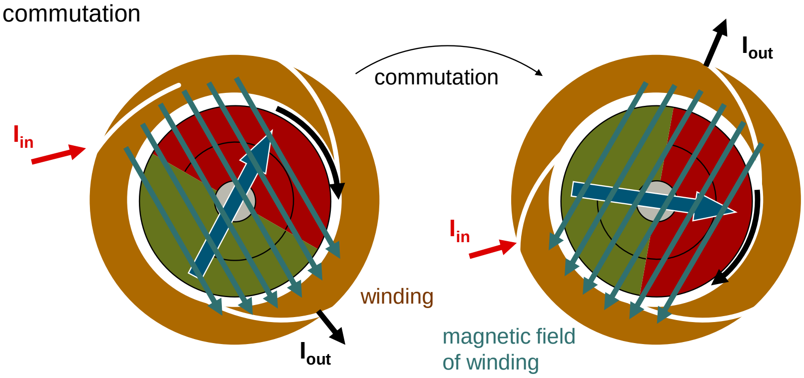
There are different systems. maxon uses the following:
Block commutation with or without Hall sensors
Sinusoidal commutation with encoder feedback.
The HPSC (High performance sensorless control) is a highly customized version of sensorless control by FOC. It is beyond the scope of this presentation and we will not further treat it here.
As you can see the different maxon controller families perform different commutation types.

Common to all these systems is that they should apply the current in a way, that the generated torque is as high as possible. This is achieved by a perpendicular orientation of the magnetic fields of permanent magnet and winding. In order to achieve this it is important to know the orientation of the permanent magnet.

The standard commutation type is block commutation with Hall sensor position feedback. Once this is understood this the two other commutation schemes are easily derived from it.

Interaction of rotor and stator

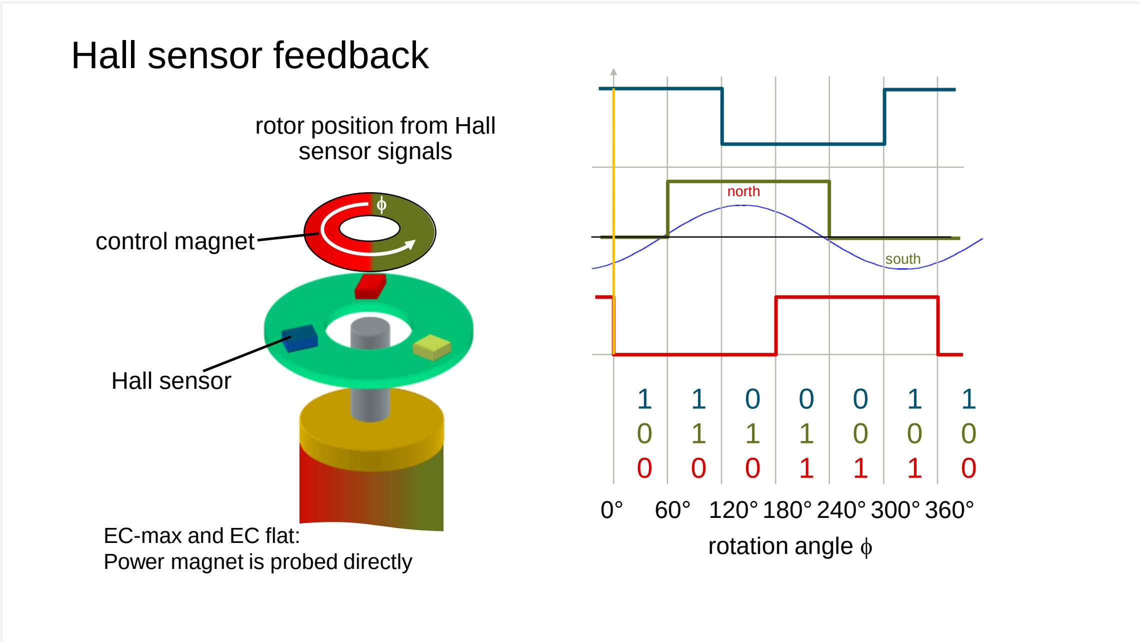
– current distribution in phases
  - 3 phases: 6 possible current distributions
  - 6 winding magnetic field directions rotated by 60°
  - 60° commutation



Let us start with the interaction between the magnetic fields of rotor and stator, i.e. the principle of how a permanent uniform torque is generated. We do this in a simplified way on the maxon EC motor with one pole pair. We will later see what changes occur if the number of pole pair is enhanced.
First we observe that the three phases allow 6 different ways of how current can flow through the motor. (Here we make the assumption that the supply voltage is applied to two of the winding connections at a time.)
For one current distribution the winding produces a magnetic field which points diagonally across the motor. According to the 6 current possibilities there are 6 magnetic field directions separated by 60°.

Comments on the animation:
The permanent magnet of the rotor tries to align with this field produced by the winding. However, we do not allow this. The torque has a maximum at the perpendicular orientation of the two fields. Thus, we switch the current 30° before and after the perpendicular positions. In this way the generated torque is always close to the maximum.
The angle between two consecutive switching (or commutation) is 60°.

The big question that arises is: How do we know when to commutate?
We need to know the angular rotor position. A traditional way is to use the Hall sensor signals.

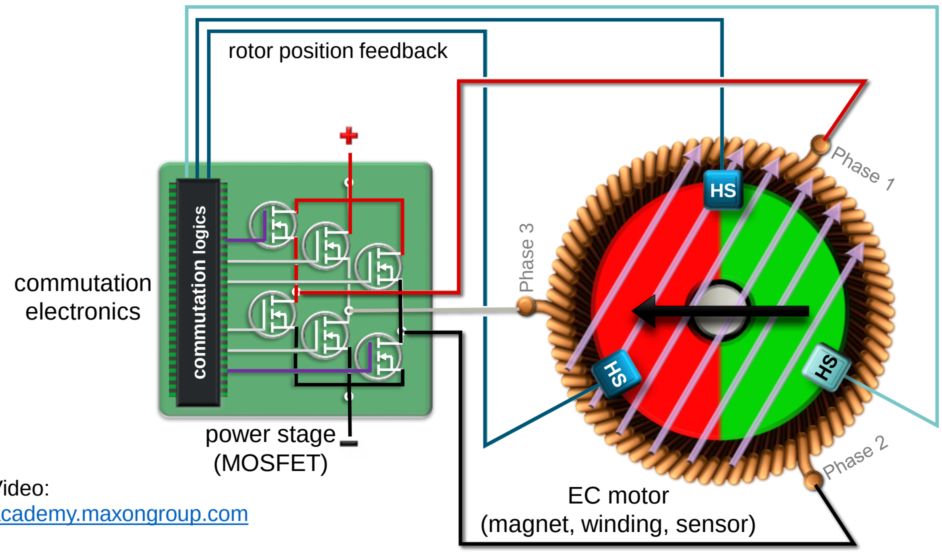


We examine the Hall sensor feedback signals based on the simplest design, the slotless maxon EC motor with 1 pole pair.
There are three Hall sensor mounted on the PCB at an angle of 120° and monitoring the magnetic poles of the control magnet which is mounted on the shaft. The control magnet exhibits the same two magnetic poles in the same orientation as the power magnet. (Basically the Hall sensors could monitor the power magnet directly but the control magnet offers two advantages: The magnetic transitions between north and south pole are more precisely defined. And an angular misalignment and tolerances between the relative position of winding and Hall sensors can be adjusted.)
The digital Hall sensors generate a signal depending on the direction of the magnetic field: a high output signal (5V) for the north pole, a low level (Gnd) for the south pole .

The starting position of the control magnet in the diagram generates the following signals: The blue Hall sensor sees the north pole. Thus, the signal output level is high and will remain high for the next 180°. The green Hall sensor is close to the south pole. The output level is low for the next 60°. Then the north pole approaches and the output signal will switch to a high state. The red Hall sensor has just switched from high to low where the signal level will stay for the next half a turn.

The combination of the three Hall sensor signals is unique for each 60° of rotation allowing to know the rotor position within 60°. That is exactly what we need for commutation since there are 6 different ways of how the voltage can be applied to the 3 phase winding.
The next slide shows how the complete block commutation system works.

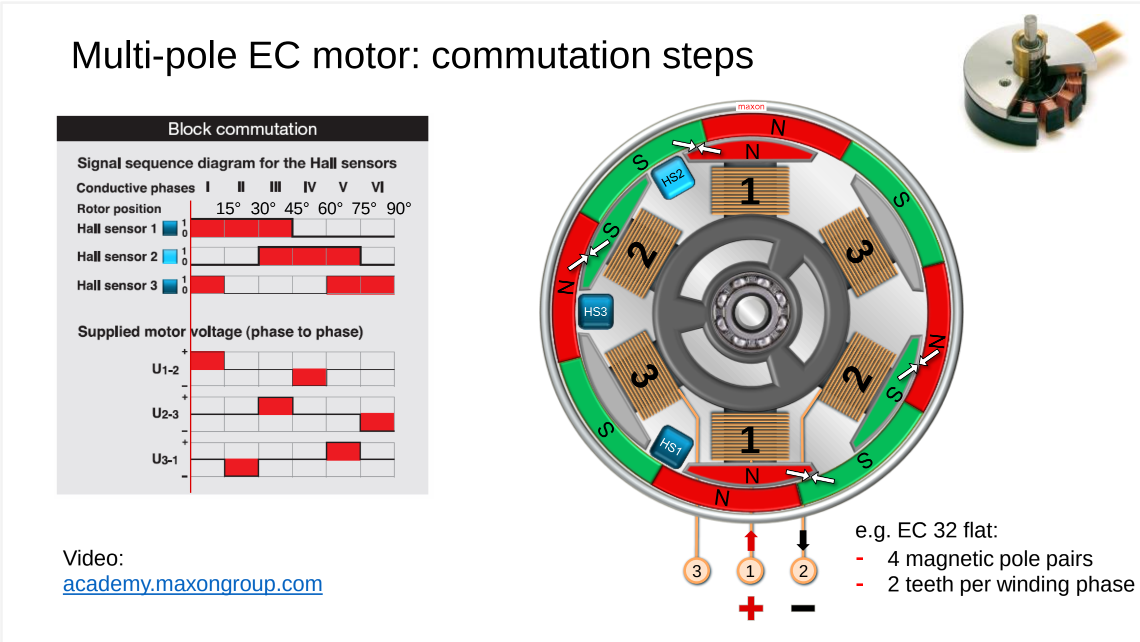
Block commutation - steps



Video:
academy.maxongroup.com

On the right we have a schematic cross section of a maxon EC motor with 2 pole permanent magnet in the center, the three phase winding and the three Hall sensors placed at 120°. For simplicity we assume the Hall sensors to probe the power magnet directly.
On the left we have the commutation electronics which is fed with a DC supply voltage. There is a power bridge made of 6 MOSFETs. Three of them are needed to contact the motor phases to the positive supply voltage. The lower three MOSFETs make the contact to the supply ground. The power bridge is controlled by a commutation logic that evaluates the Hall sensor signals and, accordingly, switches the power on the three motor phases.

Comments on the animation:
In this starting position the Hall sensors give the following signal: HS1 has just switched to a high state, HS2 is low and HS3 is high. The commutation logic knows that for this signal combination and clockwise motor rotation the current must flow from phase 1 to 2 and powers the respective two MOSFETs. Accordingly, the winding produces a diametrical magnetic field and the magnetic rotor tries to align with it.
After 60° the HS3 starts seeing the south pole. Its output switches to low and the commutation logic switches the current from phase 1 to 3. The field of the winding advances by 60° and the rotor continues to rotate.
Again after 60° the Hall sensor pattern changes, HS2 switches to a high output level. Accordingly the electronics commutates the current to flow from phase 2 to 3. Again the field of the winding advances by another 60° and the rotor continues.
And so on … . After 6 commutation intervals we are back at the initial configuration and the rotor has accomplished one turn.



Let's now look at the same block commutation sequence of a multi-pole motor.
The magnetic interaction is shown in a simplified picture that considers just the attraction of opposite and repulsion of similar magnetic poles.
We take the example of EC 32 flat. This motor has 4 magnetic pole pairs in the rotor. The winding has 3 phases, each with 2 stator teeth lying opposite. The Hall sensors are located between the stator teeth. (A high output level is indicated by a bright blue color.)
On the left is the block commutation diagram that can be found in the maxon catalog. The rotor position angles are adjusted to the actual example of the EC 32 rotor.

In this starting position the Hall sensors give the following signal: HS1 has just switched to a high state, HS2 is low and HS3 is high.
The commutation logic knows that for this signal combination and clockwise motor rotation the current must flow from phase 1 to 2 and powers the corresponding two MOSFETs.
The stator teeth become north poles at phase 1 and south poles at phase 2. These poles attract the opposite poles of the permanent magnetic rotor (and repel the poles with the same polarity). The rotor starts to turn. After 15° the HS3 starts seeing the south pole. Its output switches to low and the commutation logic applies the current between phases 1 and 3. Accordingly the south poles of the winding appear on phase 3. The rotor continues to rotate. Again after 15° the Hall sensor pattern changes, the electronics commutates the current and the rotor continues, and so on … .
After 6 commutation intervals we are back at the initial electrical configuration, but the rotor has only travelled 6*15° = 90°. On a multi-pole motor the commutation angle equals 60° divided by the number of pole pairs (P) on the rotor.

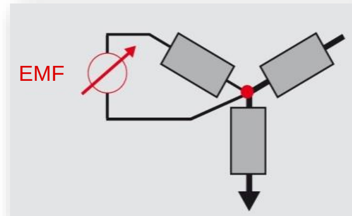
Sensorless block commutation

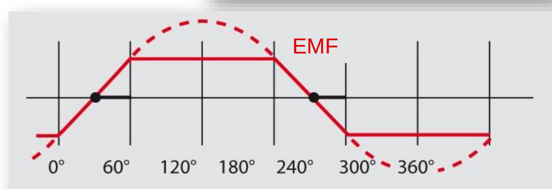
– rotor position detection without (Hall) sensors

– measuring the back EMF
- star point
- zero crossing of back EMF
- time delay 30°e

– difficult at low speeds
- special starting procedure similar to stepper motor

sensorless commutation for continuous operation at high speeds only



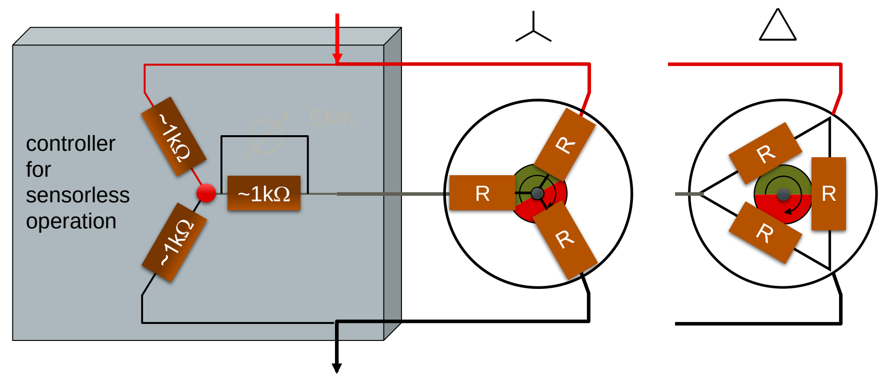


Up to this point we have considered "Block commutation with Hall sensors".
But if you look in the maxon catalog you find sensorless motors with just the three winding connections and no Hall sensors at all. How can these motors be operated when there is no position information from the Hall sensors?
There is another way of getting the necessary position information from the motor. Let's consider a motor with one pole pair and a winding in star configuration. The phase which is not powered sees the rotating permanent magnet which induces a sinusoidal voltage in this phase – the back EMF. One can show that exactly in the middle of the 60° of block commutation the induced voltage crosses zero. This voltage crossing can be detected if the star point of the winding is accessible as well. Then wait until 30° of rotation have passed and do the next switching of block commutation. (The tricky thing is to have speed information as well in order to know when the 30° have passed). During the next commutation interval one looks at the next phase that is not powered, and so on.

There is one problem. When the speed is low the amplitude of the EMF becomes small, the slope of the EMF voltage becomes flat and zero crossing is difficult to determine. Even worse, at zero speed there is no back EMF at all! This means that sensorless commutation does not work well at low speeds (typically below approx. 1000 rpm for motors with 1 pole pair) and it needs a special starting procedure which is done similar to a stepper motor. I.e. the windings are powered according to the block commutation sequence without taking note of the EMF. The commutation frequency is gradually enhanced and if anything goes well the rotor will accelerate as well. Once a certain minimum speed is reached the real sensorless block commutation is established. The parameters of the start-up procedure must be selected carefully depending on motor characteristics and load (friction, mass inertia, …).

Sensorless commutation: virtual star point

- virtual star point in the electronics
  - star or delta configuration



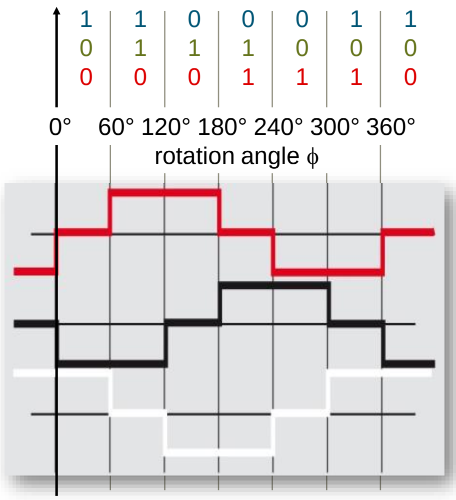
We have seen that sensorless block commutation needs the star point of the winding. But on many sensorless motors this point is not accessible; there are just the connections to the three phases.

However there is a way of getting the potential of the star point without physical access to it. In the electronics three resistances are set up in star configuration in parallel to the motor winding. The resistances in the electronics are much higher in order to have the current still flowing through the motor. But the voltage levels are the same. And now it is easy to measure the back EMF on each phase individually with the help of the virtual star point in the electronics.

The nice thing is: It even works for motors in delta configuration where there is no star point at all. (Again this shows that it is not necessary to know whether a winding is in star or delta configuration.)

Block commutation: Phase currents

- motor with 1 pole pair
  - position known within 60°
  - commutation every 60°
- motor with P pole pairs
  - position known within 60°/ P
  - commutation every 60°/ P
- block shaped phase currents
  - theoretical torque ripple 14%
  - vibrations, humming



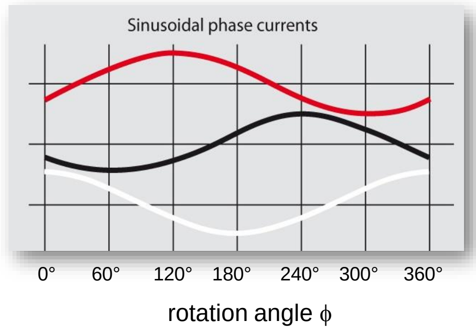
Block commutation with or without Hall sensors is characterized by the abrupt switching of the current every 60°, or every 60° divided by the number of pole pairs, respectively. The term "block commutation" is derived from these block shaped phase currents.
The torque within one commutation interval is not uniform, it will vary theoretically by 14%. This can cause excitations that can be seen as vibration or audible noise. Very low speeds might not be uniform.

The motor data in the maxon catalog are given for block commutation with Hall sensors.

Field oriented control (FOC)

– Sinusoidal phase currents
  - 120° phase shifted
  - Rotor position must be known very accurately ➔ encoder feedback
  - Hall sensors for absolute rotor position at start

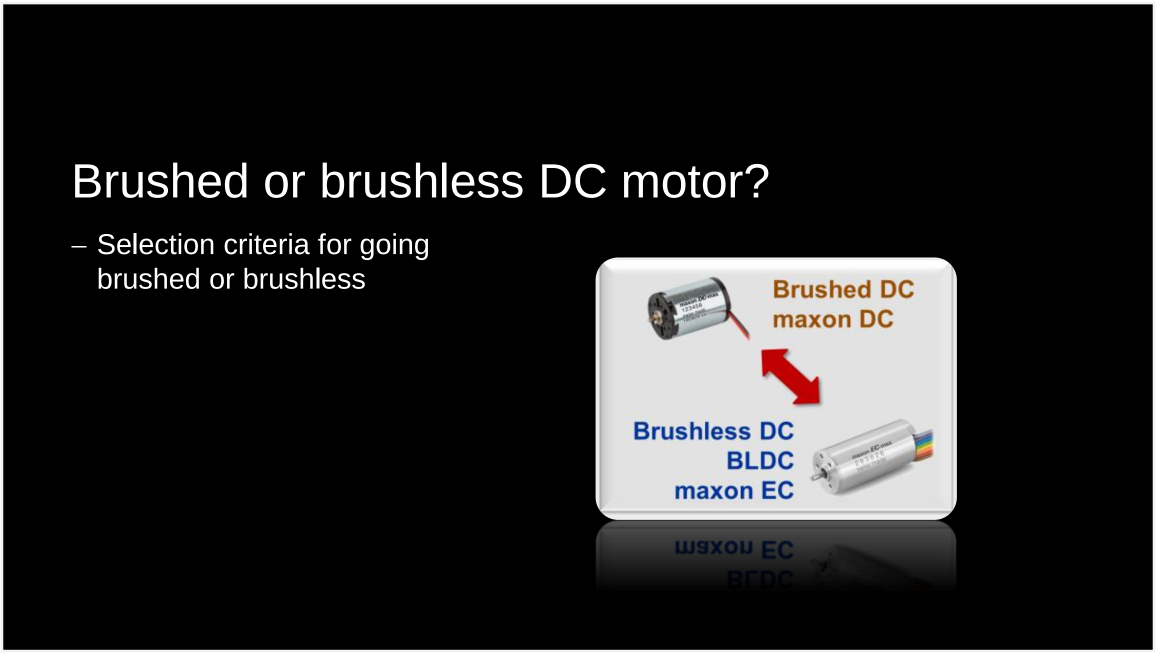
  - theoretically no torque ripple
  - lower power losses, less heating



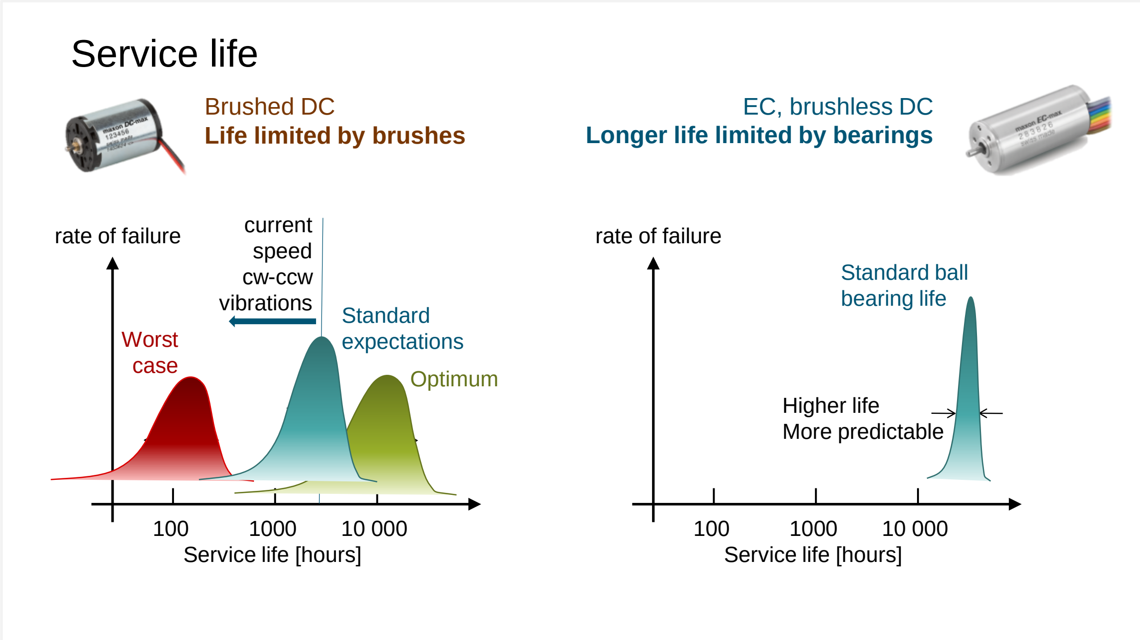
Sinusoidal commutation for smooth running even at the lowest speeds

Very smooth operation can be achieved by adjusting the phase current more gradually. One can show that the best solution is a sinusoidal current flow. The generated torque is constant.
However, mimicking a sinusoidal current needs a better position resolution than can be achieved by the Hall sensors. The motor current in the 3 phases needs to be adjusted more often. Thus, sinusoidal commutation needs typically an encoder for accurate position feedback.
The result of sinusoidal commutation is a very smooth motor operation and even a better motor performance. You can get about 5% more torque at the same power losses (heating) of the motor.

Remark: Sinusoidal commutation reminds of a tri-phase synchronous motor, but there is one big difference. On a synchronous AC motor the frequency is set externally by the AC supply. The relative field position of rotor and stator depend on the load and are hardly ever at 90°. This results in the typical speed-torque behavior. On the EC motor the information for powering the phases comes from within the motor. The relative field position is always perpendicular producing the maximum torque. This is exactly what the brush system in a mechanically commutated DC motor does: Applying the current to the winding in order to get the maximum torque all the time. Therefore, the EC motor shows the same speed-torque behavior as a DC motor with brushes.



For answering this question, you have to look at all aspects of your application. The choice between brushed and brushless is dictated by technical considerations, as well as environmental conditions and service life, and in the end commercial aspects.

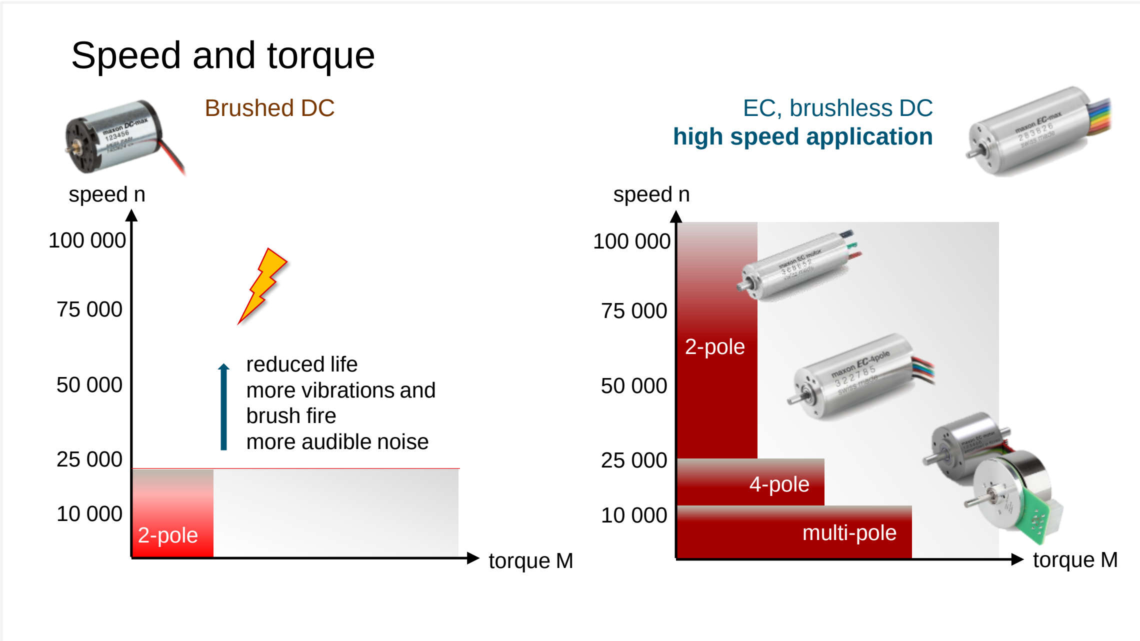


The most important difference between brushed and brushless motors is service life.

Brushed motors suffer from a limited service life of the brushes.
Usually you can achieve a few 1000hrs, in best cases up to 10.000 hrs, in worst case less than 100 hrs. Brush life is difficult to predict and there is no secure way to calculate it.
A lot depends on the use: High current, high speed, left-right operation and high vibration reduce life. All you can do is make some guessing by comparison to similar applications and operating conditions.

A few 1000 hrs of service life are sufficient for many applications. However, some applications with constant operation need several 10.000 hrs and the use of brushes should be avoided.
In brushless motors, the expected life of the ball bearings essentially limits the service life. Ball bearing life is much better understood than brush life and can be estimated quite accurately. Typically, they are made for several 10.000hrs.

But still, there are many applications that don’t need the high service life of a brushless motor.



What are the differences between brushed and brushless motors concerning speed and torque.

As a starting point, let’s take a brushed DC motor of a given size. Typically, maximum speeds of DC motors can go as high as 20’000 rpm, but in most cases they are limited to values below 10’000rpm. At higher speeds service life is strongly reduced due to increased electrical and mechanical wear.

A brushless EC motor of similar size and magnetic design can be operated at much higher speeds, reaching 100’000 rpm in some cases. These are perfect motors for applications running at high speeds such as grinders, cutters and some blowers.
Since the torque reaches about the same level, the power rating is higher than on the brushed motor.
It’s interesting to note, that the brushless motors are often made “multi-pole”. This enhances the torque at the cost of speed. In many application, extremely high speed is not needed, but more torque would be nice to have.

But clearly speaking: One of the main advantages of brushless DC motors is, that they can reach higher speeds. Multi-pole designs have the advantages rather on the torque side. Please note that these are trends only. You will have to look at the specific data sheet to get the information about maximum speed and torque capabilities.

Special Ambient Conditions

Brushed DC
More difficult to adapt

Brushfire
- electromagnetic noise
- explosive environments

Graphite brushes
- clean room applications
- use in optical systems
- high and ultra-high vacuum

Lubricant of metal brushes
- high and ultra-high vacuum

EC, brushless DC
Easier to adapt

Sterilizable (autoclavable) motors

Sterilization with steam	
Temperature	+134°C ± 4°C
Compression pressure up to	2.3 bar
Rel. humidity	100 %
Cycle length	18 minutes

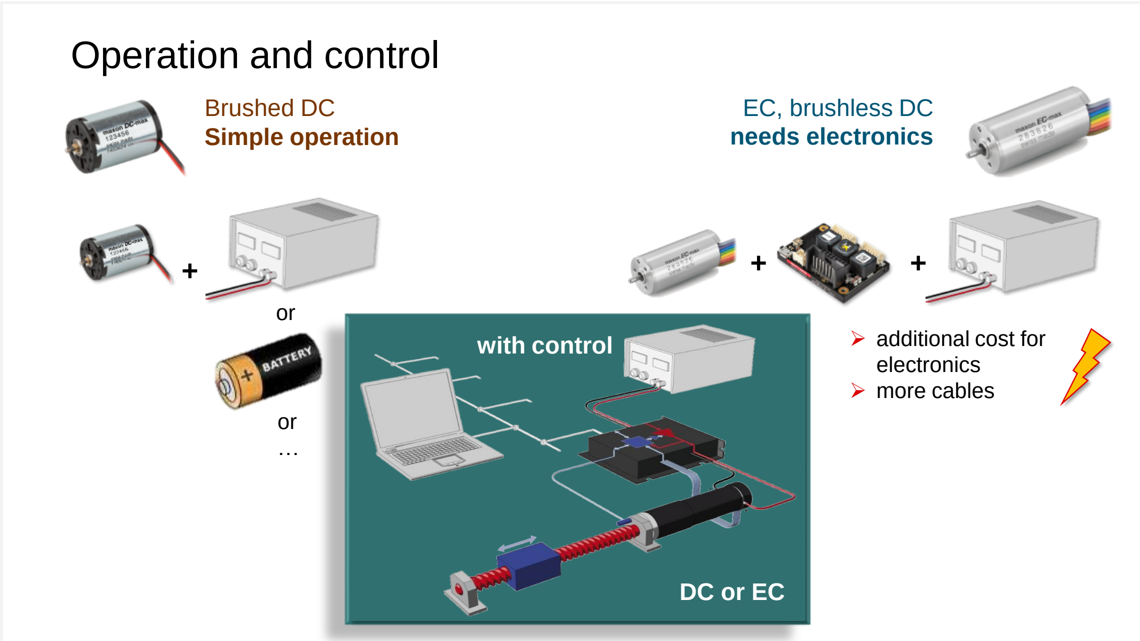
Vacuum, clean room
- low outgassing level
- high temperature
- no graphite dust

Down-hole drilling:
Heavy duty motors
- high temperature/pressure
- high vibration / shocks

Mercury	167°C
Venus	464°C
Earth	15°C
Mars	-63°C
Jupiter	-108°C
Saturn	-138°C
Uranus	-197°C
Neptune	-200°C
Pluto	-229°C

Brushed motors can cause complications in special ambient conditions.
Brushfire is at the origin of electromagnetic noise which might require additional damping. In explosive gas ambient, the sparks might also not be too welcome. However note that a brushless motor is not explosion proof per se without further modifications.
Graphite brushes produce graphite dust that might pollute clean rooms or high vacuum or optical devices.
Graphite Brushes need some humidity (but not too much) and oxygen in the atmosphere to work properly.
Precious metal brushes are lubricated. As a result, both brush types show limited suitability for the use in vacuum applications.

Therefore, most motors for special ambient conditions are brushless. Think of motors that can be sterilized or motors for ultra-high vacuum applications that need previous heating, or motors for space applications. Or motors for down-hole drilling that have to support high levels of vibrations and temperature,



When it comes to motor operation: There is no other motor as simple to operate as a brushed DC motor. All you need is applying a voltage and the motor turns.

For operating a brushless DC motor, an additional piece of electronic is needed for the commutation. Cabling is more complex; there are up to 8 connections to be made just for running the motor, compared to the 2 connections for a brushed motor

The situation changes in applications with higher levels of control:
Usually, controllers for motor speed, position or torque can be used with both type of motors, brushed or brushless. In such cases the additional costs for the electronics, feedback, and the additional cabling effort are very similar.