maxon EC motor
An introduction to
brushless DC motors

- **Design variants: maxon EC motor families**
- **Common features**
  – operating principle
  – winding connections, iron losses
- **Electronic commutation systems**
  – block commutation with and without Hall sensors
  – sinusoidal commutation
- **Comparison to DC motors with brushes**

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This presentation introduces the design and operation principle of the brushless maxon EC motors. EC motors are also called brushless DC (BLDC) motors.

- In a first part we show the basic designs of brushless maxon motors

- The second part treats some common features: the operating principle which is based on the interaction between the magnetic fields of permanent magnet and winding. Additionally we give information about the winding connection of three phase motors and iron losses.

- 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.

Components of an EC drive system
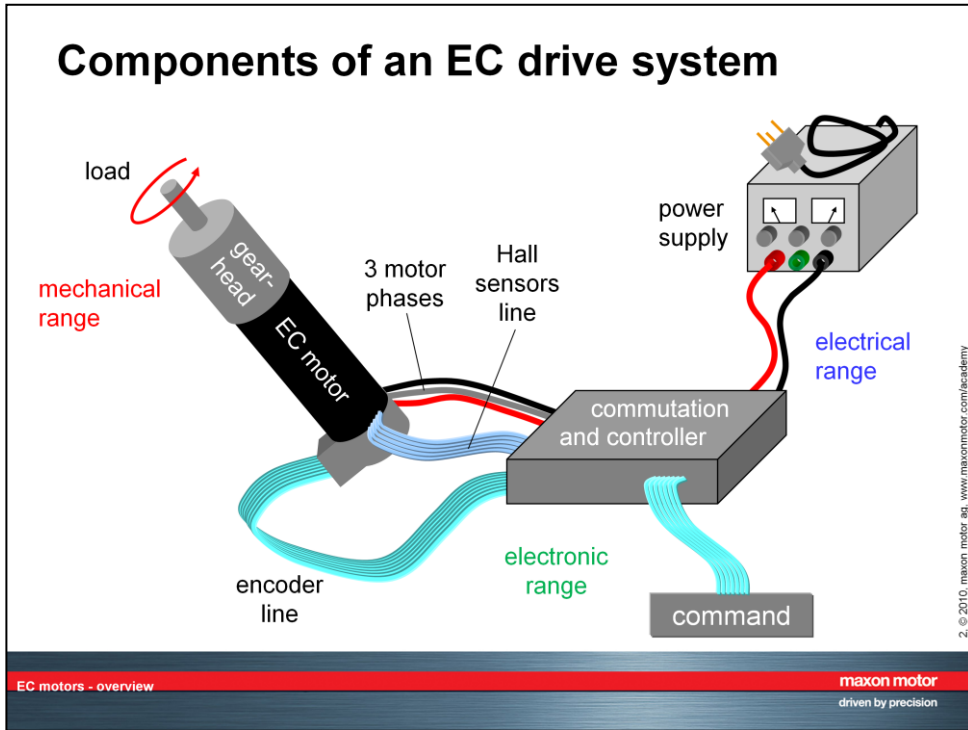
Let's first look at an EC drive system in general.

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. For the correct switching the electronics needs rotor position information from the motor. This information is usually provided by the Hall sensors.

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

For more sophisticated commutation and precise motor control, e.g. at very low speeds, the use of an encoder feedback might be necessary. Often the electronics not only performs the commutation but at the same time can be used to control speed or position.

Brushless DC motor

- names: EC motor, BLDC motor
- motor behavior similar to DC motor
  - design similar to synchronous motor (3 phase stator winding, rotating magnet)
  - the powering of the 3 phases according to rotor position

- main advantages: higher life, higher speeds
- slotless windings
  - similar advantages as coreless DC motors
  - no magnetic detent, less vibrations

- becomes more attractive: costs, size, magnets

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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 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: It's the powering of the 3 phases which is done according to the internal rotor position and not imposed from outside.
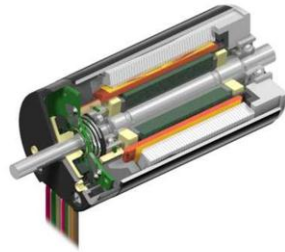
The windings of an EC motor are powered similarly as in a brushed DC motor – the electronic commutation mimicking the brush system. Therefore, there is the **same speed-torque behavior** as with any DC motor. In particular the high starting torque and the resulting high dynamics are obtained as well.

The **main advantage** of a brushless design is the longer motor life and the higher motor speed. They are not limited by the mechanical commutation system.
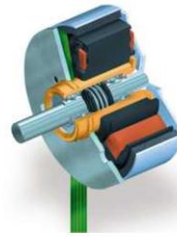
maxon EC motors come in slotted and slotless design. Slotless winding design with the traditional maxon winding system have similar advantages as the coreless maxon DC motors: There is no magnetic detent and, therefore, less vibration and noise.

Brushless motors have become more and more attractive over the last 2 decades. Mainly because the electronics necessary for operation became less expensive and smaller in size.

Furthermore the development of high power Neodymium magnets allowed the rotor mass inertia to be reduced and, hence, the dynamics to be increased.
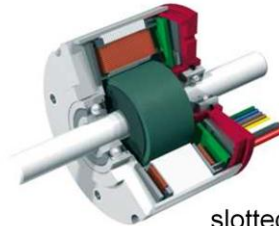
maxon EC motors come in different designs.

First, there are the **slotless design** variants based on the rhombic maxon winding.

Then there are designs where the winding is wound on a **slotted iron core**.

However there are some **common features** of all these EC motors.

- The winding has **3 phases**. The winding must be on the stator, because there is no brush system that could transmit the current on a rotating winding. (And the motor connections should not be wound up at 10'000rpm!)

- Consequently, it's the **permanent magnet that rotates**. Usually the magnetic material is **NdFeB** to get a high power density.

- maxon brushless motors are equipped with **preloaded ball bearings**. In the absence of brushes it's the bearing system that limits motor life. Preloaded ball bearing are one of the most promising system to achieve a high service life.

- And of course all EC motors need **commutation electronics** to operate.

maxon EC motor: Coreless design

- **design with coreless maxon winding**
  - internal rotor with 1 or 2 pole pair

- **maxon EC motor**
  - many types: e.g. short – long, sterilisable, integrated electronics, …
  - typically for high speeds
- **maxon EC-max**
  - Philosophy: reliable EC motor at reasonable price
- **maxon EC-4pole**
  - Philosophy: the strongest possible motor
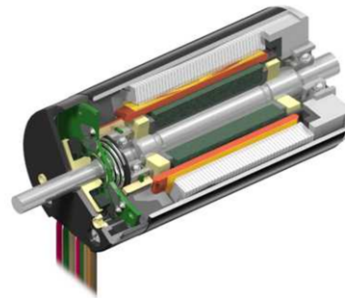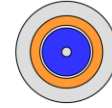
The first design variant that we want to look at is the classical maxon EC motor design based on the **coreless maxon winding**.

Three motor families in the maxon catalog comply with this design.

- **maxon EC motor:** These motors have a permanent magnet with 1 pole pair. Their speed is quite high (up to 100'000 rpm). maxon EC motors come in many different types: The diameter ranges from 6 to 60 mm. Often there are a short and a long version per diameter. Some motors are sterilisable, some have the electronics integrated.

- **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. For many applications that don't need very high speeds or torque (e.g. in combination with gearheads) this reliable motor is just perfect. The diameters range from 16 to 40 mm.

- **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.

In the following let's look at some details.
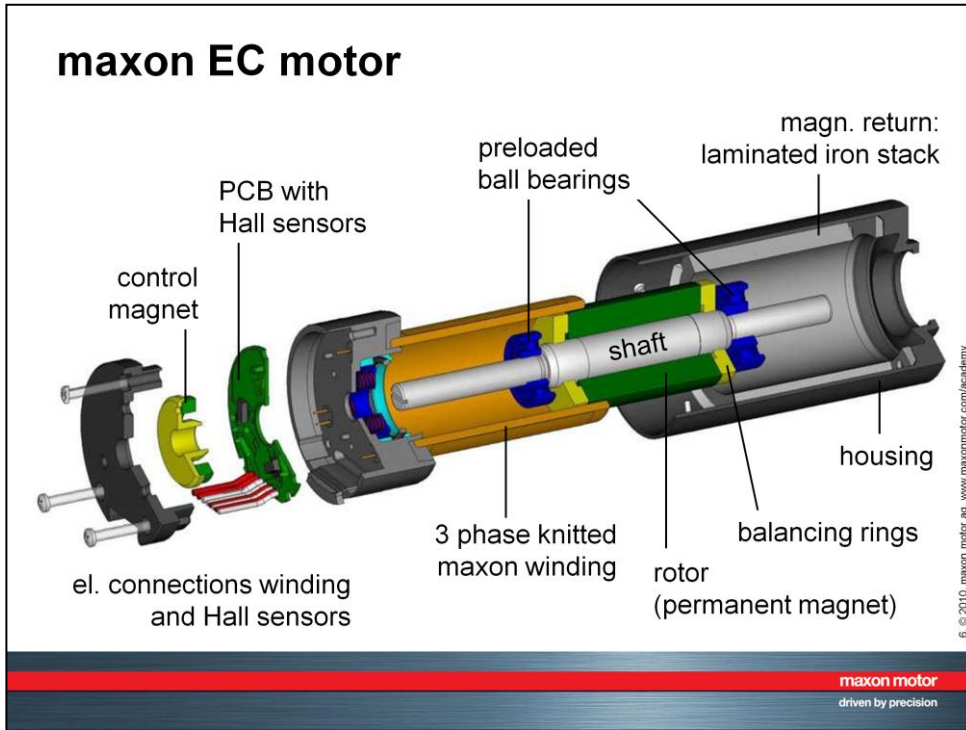
maxon EC motor

On the maxon EC motor we can distinguish the following main subassemblies:

- The **rotor** with the permanent magnet mounted on the shaft at the center. Dynamic balancing is achieved by removing material from the two balancing rings made of brass. Balancing is important for reducing vibration and noise and for increasing bearing life, particularly at the high speeds obtainable with brushless motors.

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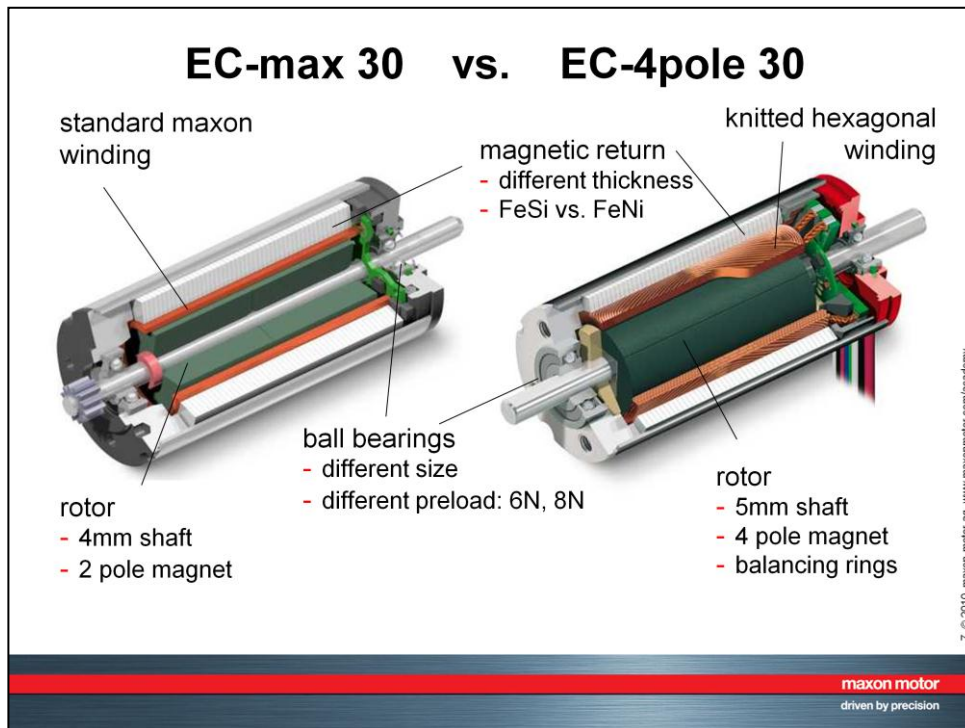
What are the main differences between a cost optimized EC-max and a power optimized EC-4pole motor? We make this comparison on motors with 30 mm diameter.

Enhancing the power density on the EC-4pole is achieved by

- **4 permanent magnetic poles** instead of 2, 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**. The magnetization frequency in the magnetic return is twice as high as on a motor with 1 pole pair. In order to keep the eddy current losses small this high performance material is used. 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**. The hexagonal winding can result in a higher motor torque. A further torque increase is achieved 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**, with no balancing. However, this requires low tolerances and a precise mounting of the magnets. There is some unbalance left; thus, 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 if this motor is not optimized with respect to power there is quite a lot of torque generated.

EC-max: design characteristics

Philosophy: reliable EC motor at reasonable price

- **standard maxon winding**
  - only star circuit possible
  - not optimized with respect to performance (power)
- **Hall sensors monitor directly the power magnet**
  - no control magnet
  - special orientation process of Hall sensors to winding
- **no balancing rings**
  - very high speeds are not possible (up to 12 - 20'000 rpm)
- **preloaded ball bearings**
- **long and short versions per diameter**

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Here again the most important design characteristics of the EC-max product range.

EC-4pole: design characteristics

Philosophy: the strongest possible EC motor

- very high torque and acceleration
  - knitted maxon winding
  - hexagonal winding on long versions
  - 4-pole permanent magnet
- moderate speeds up to 25'000 rpm
  - higher commutation frequency
  - higher iron losses
- special orientation process of Hall sensors to winding
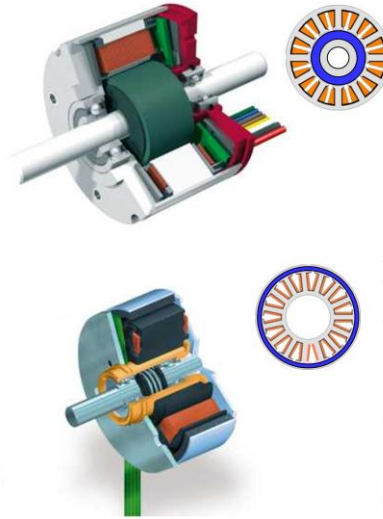- preloaded ball bearings

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And here we have the characteristics of the EC-4pole product range.

Let's now turn to the **slotted maxon EC motors**.

These motors have some common features which makes them **commercially attractive**.

- The slotted windings can be produced at lower cost than the coreless maxon winding.
- The multi-pole magnet are made from isotropic Neodymium magnets instead of the anisotropic ones in the slotless designs.

There are some other **technical features** which are similar on both designs.

- The high number of magnetic poles results in quite a **high produced torque**, though it **limits the maximum speed** due to the higher magnetization frequencies.
- The slotted design results in a slight **cogging torque**.

The **behavior** however is quite different, because of the different arrangement of winding and rotor.

- The **EC-i** with the external winding and the 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.
- 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.

EC flat motor: design characteristics

Philosophy: flat design with attractive price

rotor:
- external rotor => high torque
- multi-pole magnetic ring of NdFeB
  => higher commutation frequency,
  => not very high speeds

stator:
- 3 phases, several teeth per phase

further characteristics:
- Hall sensors detect magnetic ring
- but also often sensorless
- preloaded ball bearings
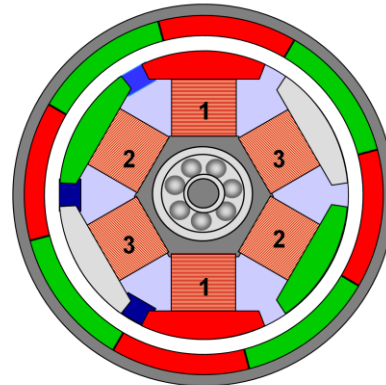
e.g. EC 32 flat:
- 8 magnetic poles
- 2 teeth per winding phase

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This slide shows a 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.

Part 2: 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

commutation

I_{out}

I_{in}

I_{in}

winding

I_{out}

magnetic field
of winding

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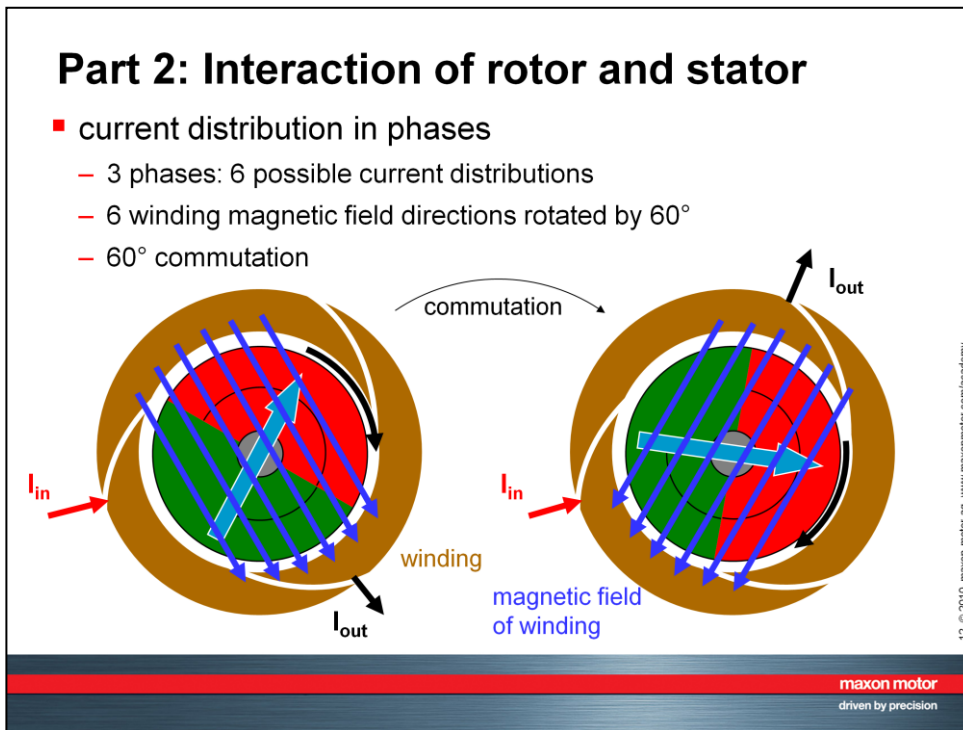
In this second part we would like to have a closer look at three features.

The first feature is 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. This will be explained later in the part 3 of this presentation.

Winding connections

"Y-circuit"

W$_1$
U$_{3-1}$ U$_{1-2}$
W$_3$ W$_2$
U$_{2-3}$

"Δ-circuit"

W$_1$
U$_{3-1}$ U$_{1-2}$
W$_3$ W$_2$
U$_{2-3}$

- high resistance
- low currents
- higher torque constant

$$R_Y = 3 \cdot R_\Delta$$

$$k_{M,Y} = \sqrt{3} \cdot k_{M,\Delta}$$

$$k_{n,Y} = \frac{1}{\sqrt{3}} \cdot k_{n,\Delta}$$

- low resistance
- low voltages
- higher speed constant
- possibility of induced circular winding currents

internal connection of the 3 phases: no practical consequences

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A second feature we would like to discuss shortly is the **internal winding connection**.

Basically, a three phase winding can be considered as made up of three equal parts represented here as resistances R. There are two ways of arranging these resistances in a symmetric manner: The well known **Star** (or Wye) and **Delta** connections.

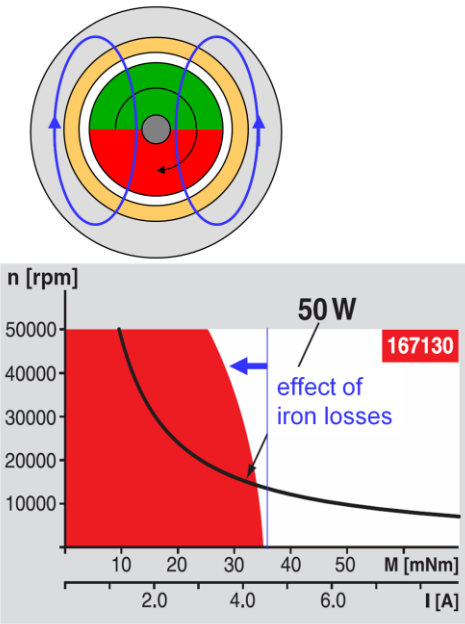What is the difference of the two arrangements?

- Although the star circuit has a higher terminal resistance (by a factor of three) the **power losses are the same** for the same operating point (torque, speed).

- The **star circuit** has the **higher torque constant**. This means that with the same amount of current more torque is generated than in a delta configuration.

- The **delta circuit** has the **higher speed constant**. Hence less voltage is needed to reach the same speed, or with a given voltage a higher speed can be reached.

These findings could be summarized as: Two motors with the same winding once in star once in delta configuration behave like two motors with windings made of different wire diameter. One needs a higher current but a lower voltage than the other to reach the same torque and speed.

For maxon motors the arrangement star or delta is fixed. For motor operation and commutation this information is not needed. The only practical consequence of a delta circuit could be that in unfavorable conditions circular winding currents might be induced.

Iron losses

- origin: rotating magnet
- hysteresis losses
  - changing the direction of magnetization needs energy
- eddy current losses
  - rotating magnetic field causes eddy currents
- effects: additional motor heating
  - at high speeds less current for torque generation is allowed
  - see operation range diagram

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Iron losses 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.

Iron losses are caused by **two mechanisms**, both relying on the fact that the flux in the iron changes its direction or intensity.
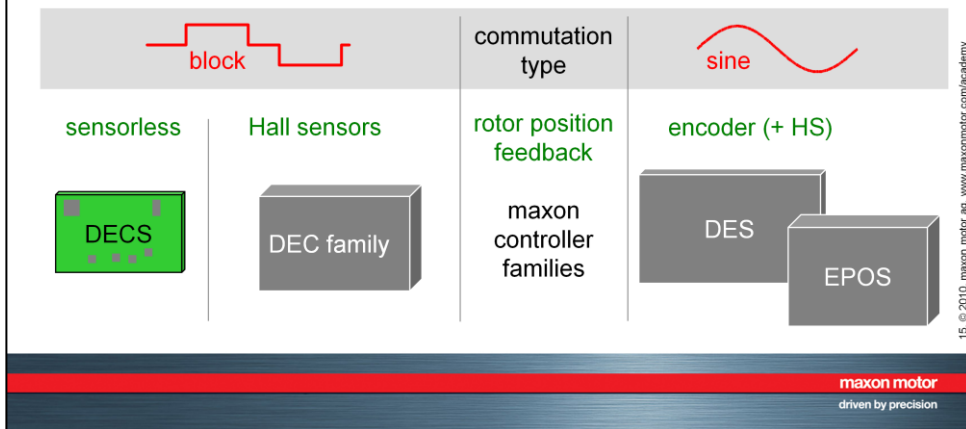
- **Hysteresis losses** describe the fact that changing the magnetization of the iron consumes energy. It's similar to running through the magnetization loop (hysteresis) of the material. Hysteresis losses can be minimized by selecting appropriate materials that can easily be magnetized (with a narrow 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.

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Part 3: Electronic commutations systems

- common goal: applying the current to get the maximum torque
- perpendicular magnetic field orientation of
  - rotor (permanent magnet)
  - and stator (winding)
- knowledge of rotor position with respect to winding

block	commutation type	sine
sensorless	**Hall sensors**	**rotor position feedback**	**encoder (+ HS)**
DECS	DEC family	maxon controller families	DES / EPOS

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In this third part of the presentation we would like to understand the **electronic commutation**.

There are different systems. maxon uses the following three:

- **Block commutation with or without Hall sensors**
- **Sinusoidal commutation**.

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**. As we have learned this is achieved by a perpendicular orientation of the magnetic fields of permanent magnet and winding. We have seen as well that we need to know the orientation of the permanent magnet to achieve this.

We start with block commutation with Hall sensor position feedback. That's the standard commutation type. Once we have understood this the two other commutation schemes are easily derived from it.
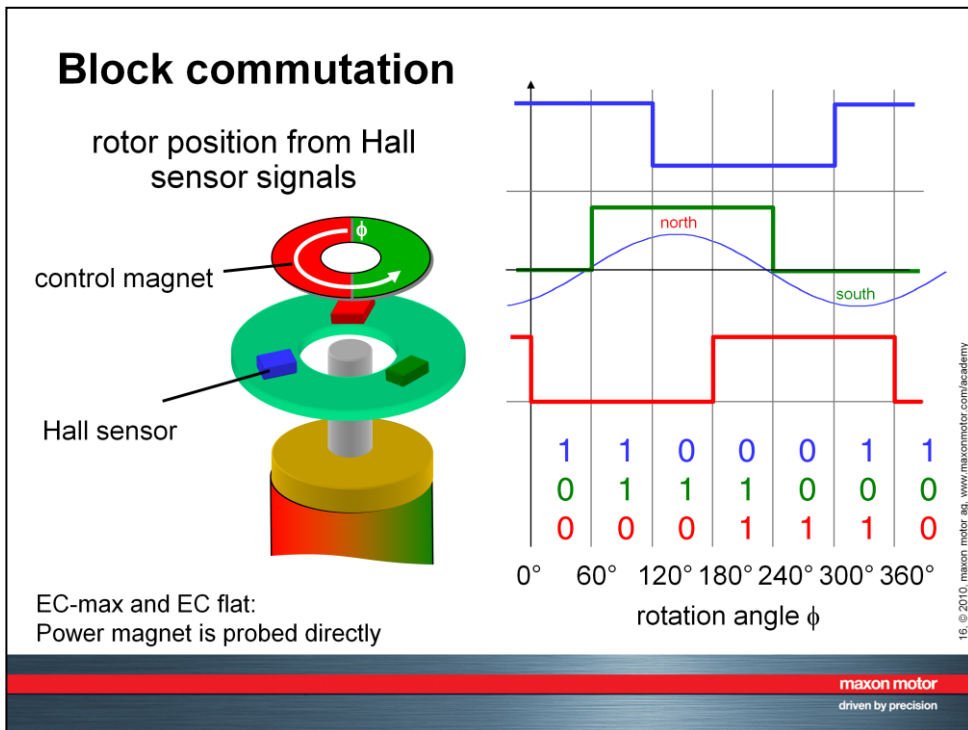
First we have to look at the **Hall sensor feedback signals**. Again we do this based on the simplest design, the slotless maxon EC motor with 1 pole pair.

In the back of the motor there are three Hall sensor mounted on the PCB at an angle of 120°. The Hall sensor detect 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 used probe the direction of the magnetic field. They generates a high output signal (5V) if the north pole of the control magnet is close to them. A south pole produces a low level (Gnd).

The actual 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 120°.
- 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. Looking at these signals allows to know the rotor position within 60°. That exactly what we need for commutation. Remember there were 6 different ways of current flow through the motor at a commutation angle of 60°.

The next slide shows how the complete block commutation system works.
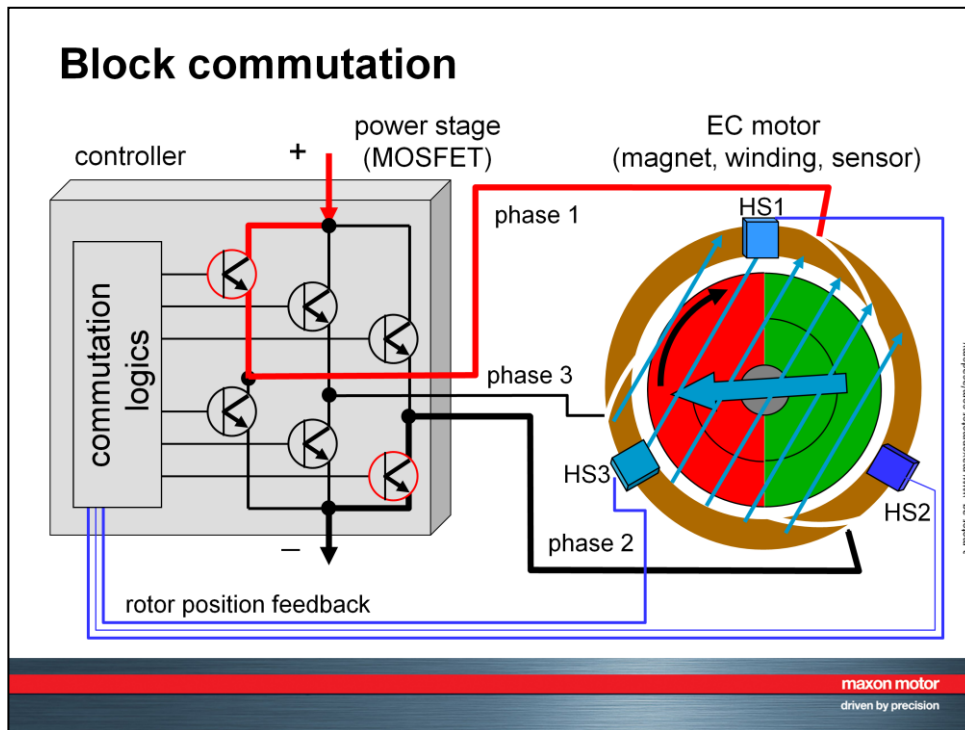
On the right we have a schematic **cross section of a maxon EC motor** with 2 pole permanent magnet in the center, the three phase winding and the three Hall sensors placed at 120°. For simplicity we assume the Hall sensors to probe the power magnet directly.

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.
- The winding produces a magnetic field and the magnetic rotor tries to align.
- 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.
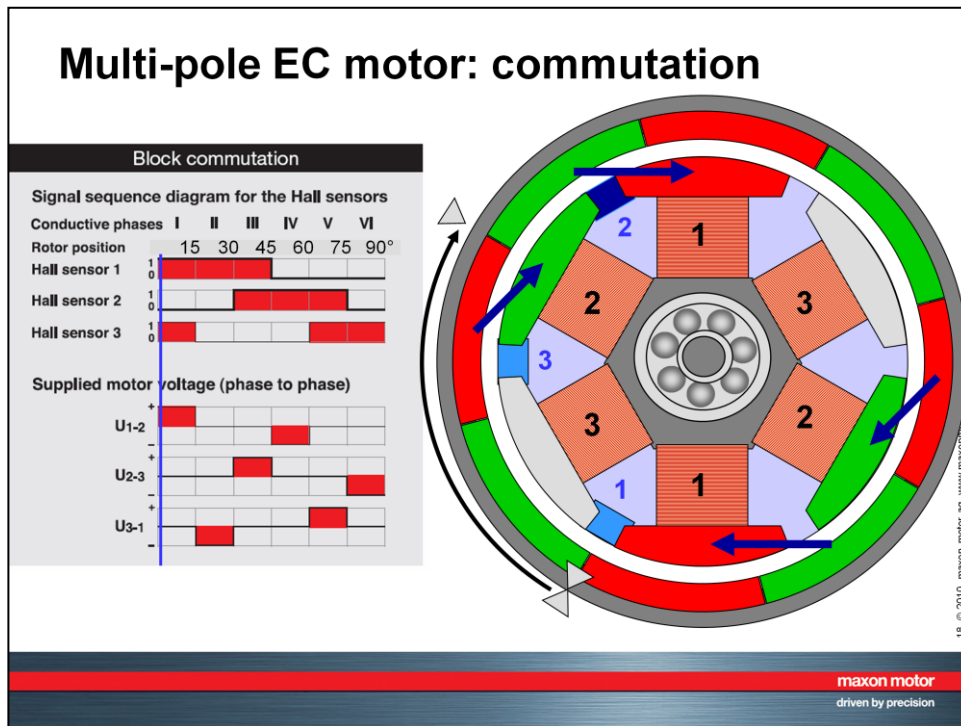
Let's now look at the same block **commutation sequence of a multi-pole motor**.

The magnetic interaction is shown in a simplified picture that considers just the attraction of opposite and repulsion of similar magnetic poles.

Again we take the **example of EC 32 flat.** We remember that 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 scale is adapted to the actual example of the EC 32 rotor.

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 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.

- Remark: In order to achieve a high torque it is necessary that the opposite poles of rotor and stator do not approach each other too much. Because this produces forces that point towards the rotating axis and not in a tangential direction and the generated torque will be smaller.

- The rotor continues to rotate. Again after 15° the Hall sensor pattern changes, HS2 switches to a high output level. Accordingly the electronics commutates the current to flow from phase 2 to phase 3. Phase 1 is switched off and the north poles can now be found on the teeth of phase 2.

- The rotor continues, and so on … . After 6 commutation intervals we are back at the initial configuration, but this time the rotor has only travelled 6*15° = 90°. This is the major difference for a multi-pole motor: The commutation angle equals 60° divided by the number of pole pairs (P) on the rotor. Or, for the same speed the commutation frequency must be P times higher.

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 with a winding in star configuration.

There is always one phase of the winding which is not powered. But this phase will see 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 (when the phase is not powered) the induced voltage **crosses zero**. This voltage crossing can be detected if the star point of the winding is accessible as well.
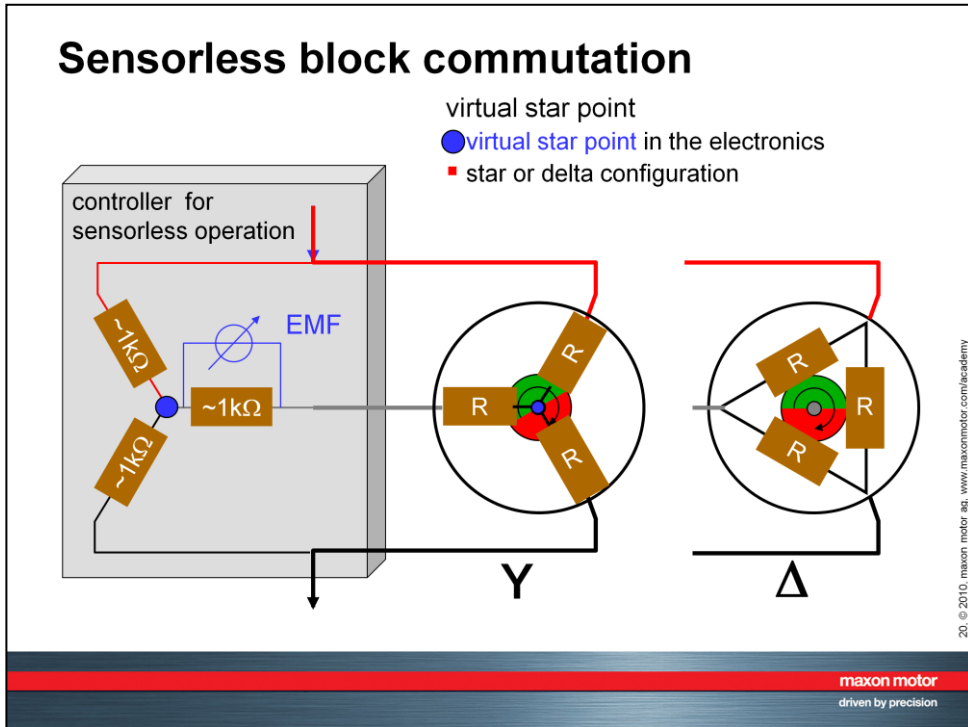
Then one has to **wait until 30° of rotation** have passed and do the next switching of block commutation. (The tricky thing is to have speed information as well in order to know when the 30° have passed. But this can be done more or less precisely, e.g. from the time distance of the previous zero-crossings).

During the next commutation interval one looks at the next phase that is not powered and so on.

There is one problem. When **speed is low** the amplitude of the EMF becomes smaller and smaller. The slope of the EMF voltage becomes flatter and flatter and it is difficult to determine exactly the zero crossing. Even worse, at zero speed (e.g. **during start-up**) 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 enhanced and if anything goes well the rotor will speed up. Once a certain minimum speed is reached the back EMF is taken into consideration and the real sensorless block commutation is established.

In order to get a reliable starting up the parameters of the start-up procedure must be selected carefully depending on motor characteristics and load (friction, mass inertia, …).

Sensorless block commutation

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

controller for sensorless operation

~1kΩ

~1kΩ

~1kΩ

EMF

Y

Δ

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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 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 a little. 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.
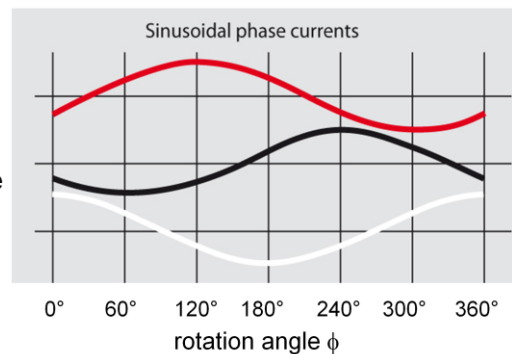
Sinusoidal commutation

rotor position
- must be known very accurately
- typical 2'000 points per rev.
- 500 pulse encoder
  (Hall sensors for start: absolute rotor position)
- resolver as an alternative

phase currents
- sinusoidal
- 120° phase shift
- similar to synchronous motor with variable frequency

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.

Part 4: DC and EC motor: Comparison

DC motor

- simple operation and control, even without electronics
- no electronic parts in the motor

- brush commutation system limits motor life
- max. speed limited by commutation system

EC motor

- long life, high speeds
  – preloaded ball bearings
- no brush fire

- iron losses in the magnetic return
- needs electronics to run
  – more cables
  – more expensive
- electronic parts in the motor (Hall Sensor)

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In this last part let's review the properties of the maxon EC motors.

This first slide shows in short the **advantages and disadvantages** of brushless EC motors compared to brushed DC motors.

DC motors are simpler to operate. All you need is to apply a DC voltage and the motor turns. There is no need for electronics in simple applications. There are no Hall sensors in the motor which can be an advantage in difficult operation conditions such as radiation or chemically aggressive environments. However, the brush system limits motor life and motor speed.

The higher motor life – basically limited by the bearing life – is the big asset of **brushless EC motors**. Very high speeds can be achieved if the rotor is well balanced the bearing system is dimensioned accordingly and iron losses can be kept low. There is no brush fire in brushless motors, generating less elctromagnetic interferences (EMI). EC motors need electronics to run. In application using a controller anyway this is not a big disadavantage. Just select a motion or speed controller that can do the electronic commutation as well!
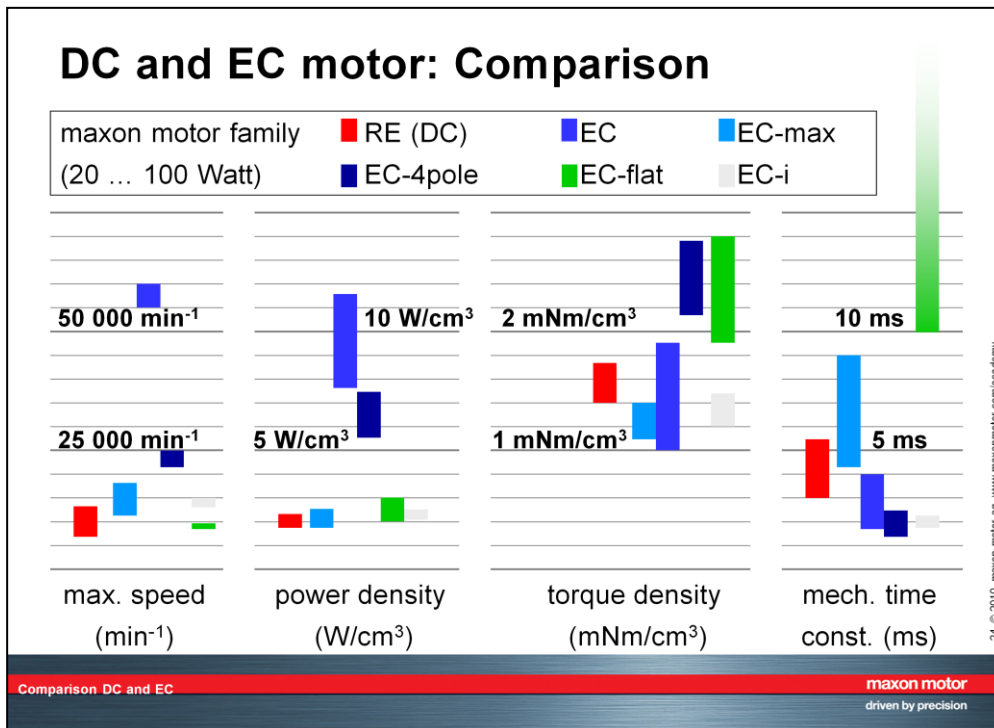
This slides sums up the properties of the different **maxon EC motor families** and of the **RE motor**, the maxon DC motor with the same Neodymium magnet as the EC motors. In order to have a relatively fair comparison only motors with the same magnet are selected and with similar power range (20 … 100W)

- Looking at the **maximum speed** we can clearly see the advantage of the **maxon EC motor**. It's the design with 1 pole pair and coreless maxon winding. In contrast to this, the multi-pole EC designs do not show a big advantage over the brushed RE motor. That's because of the iron losses at the high switching frequency necessary with the high number of pole pairs.
- The very high speed of the maxon EC motor results in a high power density of these motors. The second **highest power density**, however, is achieved with the **4-pole EC motor**. As we have learned these motor are specially designed for this feature. In particular, they exhibit the highest torque density resulting in the **most dynamic** motor with the lowest mechanical time constant.
- Still very dynamic are the **EC-i motors**.
- The **EC-flat design** generates quite a high torque, but the dynamics is poor due to the high mass inertia.
- Finally, the cost effective **EC-max motor** has quite a similar performance as the brushed RE motor, but a much higher life can be expected.

In short, the design and the properties of EC motors can be very different and they have to be selected **according to the individual requirements of the particular application**.