This presentation shows the design and operation principle of the maxon DC motor. These are small DC motors with permanent magnets and winding without iron core.
We start with the differences to the conventional DC motor with iron core and the advantages of such a coreless design, and give a short introduction to the maxon DC motor product range.
We have a closer look at the stator and the rotor and the interaction between current through the winding and the stator magnetic field.
Then we present the commutation process and the different properties of graphite and precious metal brushes.
At the end some remarks about service life and bearings.

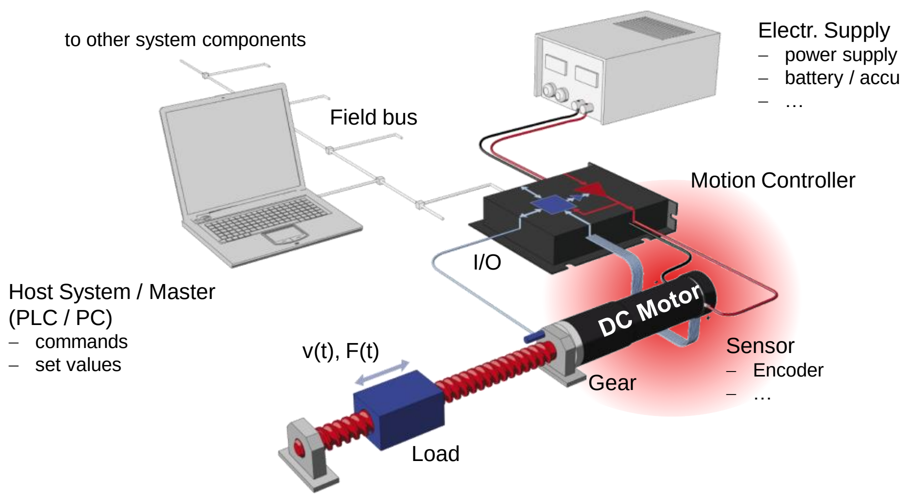
maxon DC motor - Objectives

What you should know at the end ...

- What are the main advantages of DC motors with ironless winding?
- What are the differences between the maxon DC motor families?
- What is the CLL disc used for?
- Which bearings and brushes are best suited for particular operation conditions and applications?

What is in this presentation for you?
Of course, it is about maxon specific topics. What is special about the maxon ironless DC motors? How can CLL improve service life?
But also when to use graphite or metal brushes? Or when to select sleeve bearings instead of ball bearings?

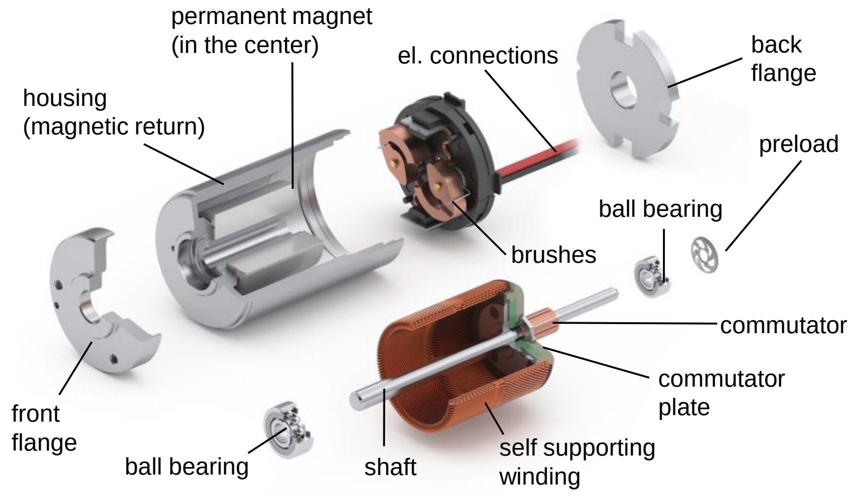
Components of a DC motor drive system



DC motors are just one components of a complete drive system. Motors transform electrical into mechanical energy.
In our case, they are powered by a DC supply.
Very often a controlled motion is required. This adds the need of a speed or position controller and a matching feedback sensor.
A higher level master delivers the necessary commands. However, commands can also be very simple digital and analog signals.
The motor output drives a gear or some mechanical system.

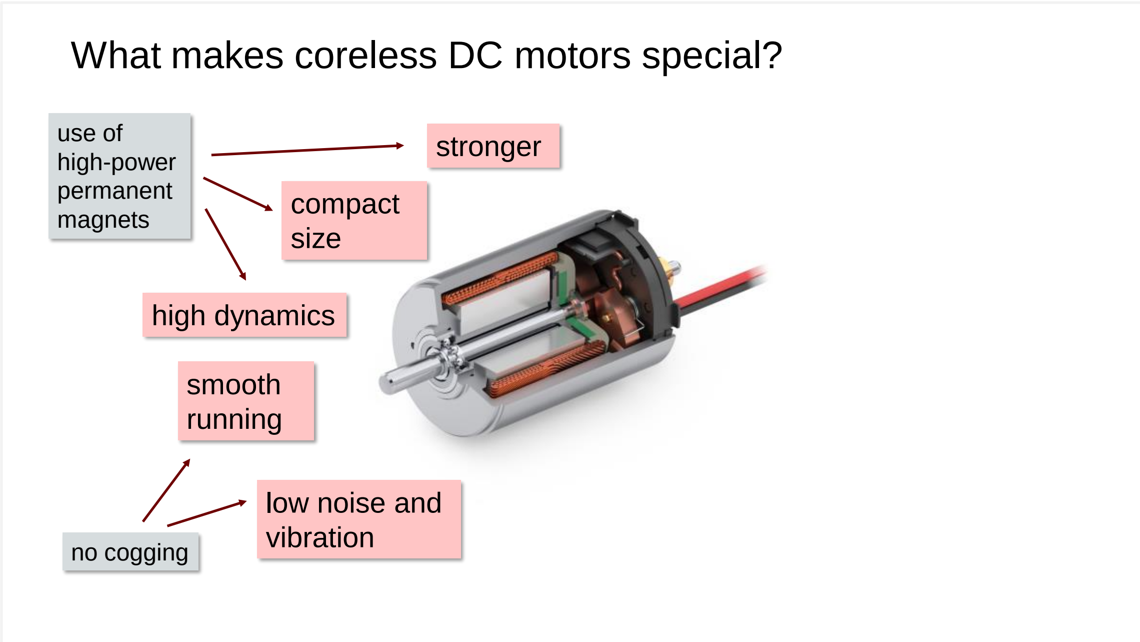
Low power conventional DC motors (below approx. 1 kW) mostly use permanent magnets to produce the stator magnetic field. The winding is on the rotor side. It's wound around an slotted iron core for flow concentration and enhancement.
DC motors with a so called coreless winding don't use the iron core. That's the system maxon uses and which is to be presented here in more detail.

Coreless maxon DC motor (DCX 22)



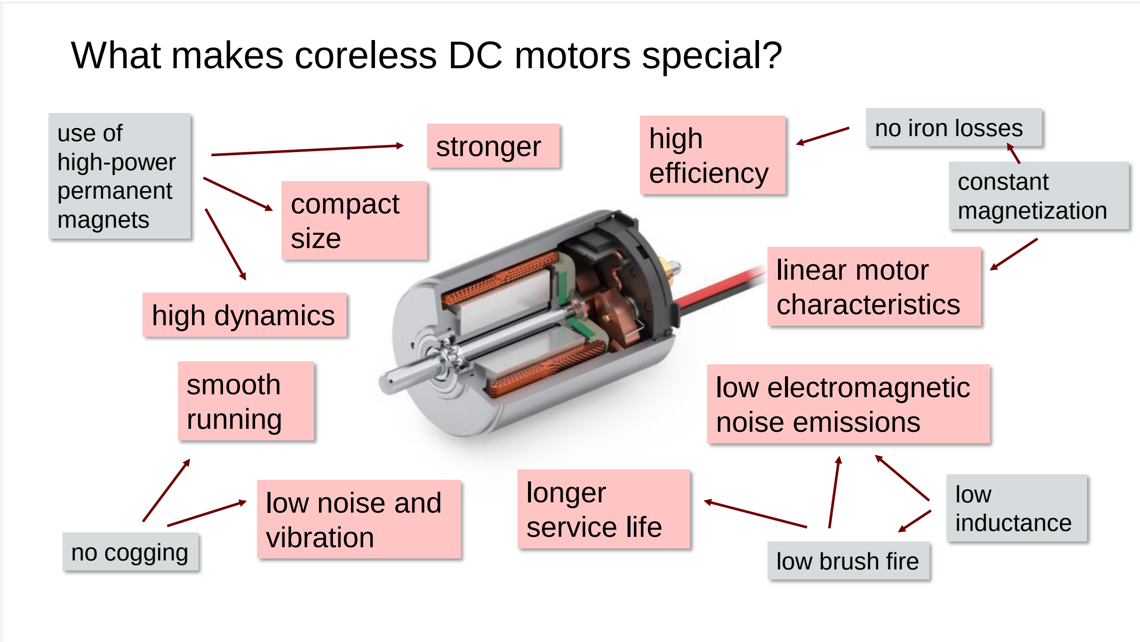
This picture shows a coreless maxon DCX motor. We recognize the same three subassemblies as can be found on conventional motors.
The stator consists of the permanent magnet located at the center, the housing (serving as the magnetic return path), and the mounting flange.
The rotor with winding and commutator: The winding is connected to the shaft by the "commutator plate". In this example the shaft is supported in the stator by ball bearings. The shape of the rotor reminds of a Xmas bell; that's why it is sometimes called "bell shaped" armature. The winding moves in the narrow air gap between magnet and housing.
The brush system in this case is made with graphite brushes. Cables serve as electrical motor connections.

The next slide shows the advantages of such a coreless motor design.



The use of high performance magnetic materials gives compact motors with high power density.
The central magnet position allows the use of the strongest available magnets leading to the highest magnetic flux density in the air gap. There is no iron core that limits the maximum possible magnetic flux. Accordingly the produced torque is much higher than on a conventional design.
Without iron core, the rotor is a hollow cylinder with a considerably lower mass inertia. In combination with the high torque this results in very dynamic drives with mechanical time constants of a few milliseconds. The strongest maxon motors have time constants (and hence acceleration times) even as low as 1 ms.

Coreless motors have no cogging; there are no soft magnetic teeth. The produced torque is uniform and results in a jerk-free and smooth operation even at low speeds. At higher speeds the motor excites less vibrations reducing the audible noise.
From a control point of view there are some advantages as well. The uniform torque is simpler to control and the motor doesn't show the tendency to stop at preferred positions.



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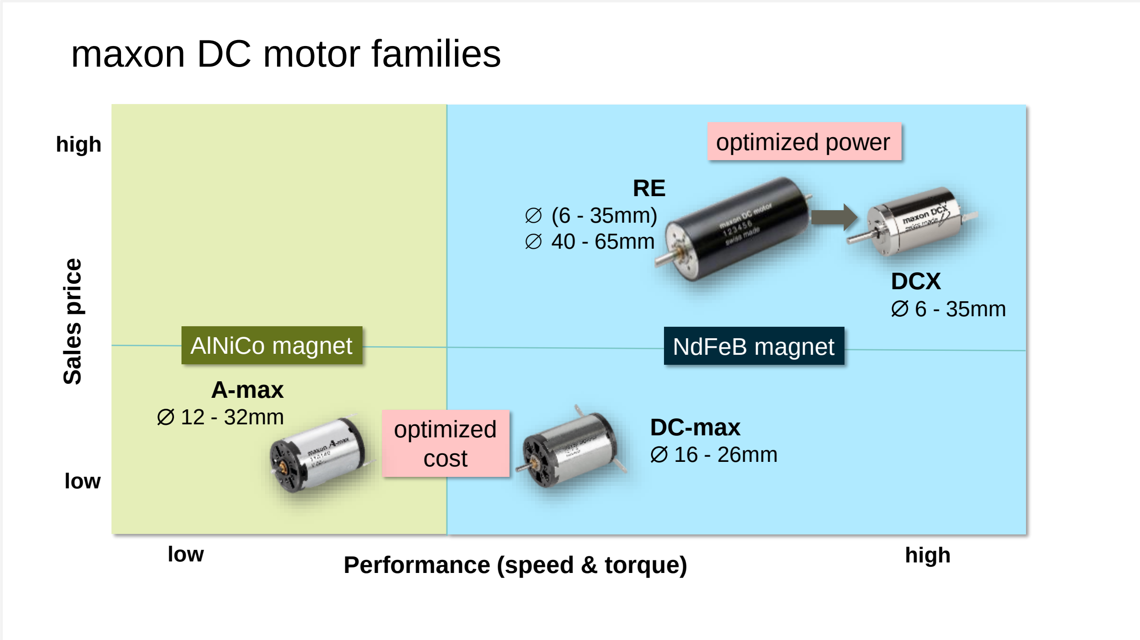
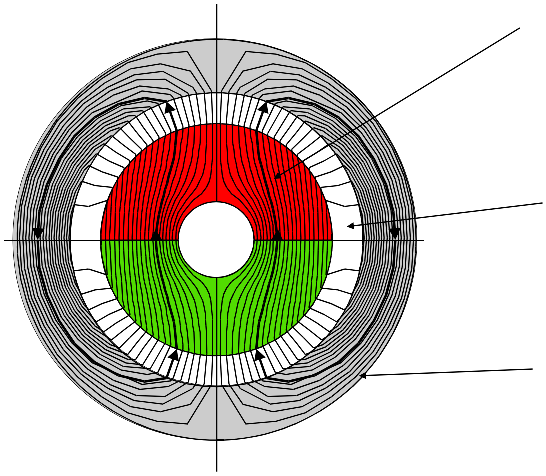
From an electrical point of view, the winding inductance is much smaller. There is less magnetic energy involved in the commutation process. This reduces the brush fire - the typical discharges that occur when the contact on an inductive load is broken up. The commutator-brush system is less affected and has a higher service life.
The reduced brush fire also creates less electromagnetic interferences which are easy to suppress. For instance, a simple capacitor between the motor connections might be all that is needed or a ferrite core on the motor cable.
However, the low inductance causes the motor current to react very fast. With pulsed supply (e.g. by pulse width modulation, PWM) there might by a current ripple that can strongly heat up the motor and affect the stability of the current control loop. Therefore, maxon controller which are specially designed for the low inductance maxon motors have motor chokes already built-in.

Coreless DC motors have no iron losses. In a conventional design the iron core permanently changes its magnetization. This consumes energy. Additionally, these flux variations induce Eddy currents in the iron core resulting in power losses that grow with the square of the motor speed.
In a coreless motor the magnetization is permanently impressed and constant. The power losses are smaller, the efficiency is higher and the no-load current is lower. Furthermore, no saturation in the narrow parts of the iron core (at the base of the teeth) can occur. Hence the produced torque remains exactly proportional to the motor current.



This slide gives a summary of the actual maxon DC motor families.
The DCX and RE motors are equipped with the high power Neodymium magnets. The motors are designed for high performance. These are the motors with the highest power density (combination of speed and torque) on the market. Further characteristics are: A robust design (metal flange), reliability and a comparably high service live for a brushed motor.
On the DCX motors the mechanical and electrical interfaces, as well as possible combinations can be configured online.
The philosophy behind the A-max motor is a good price-performance ratio. The motors are equipped with AlNiCo magnets with a lower power density. The flange is made of plastic and production is automated to a high degree. A-max motors are typically used in OEM appliances.
The DC-max motor combines the high power of NdFeB magnets with the efficient production and design of A-max motors. The result is a motor with a performance between A-max and RE motors.
Besides these three actual motor families there are older designs, called S A or F motors.

Stator - the magnetic circuit



Permanent magnet:
produces the magnetic field with north and south pole on opposite sides.

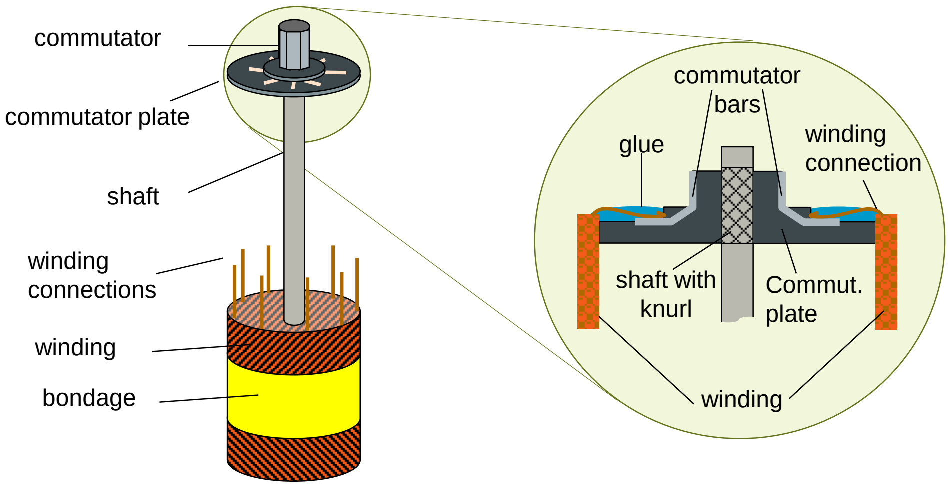
Air gap:
the larger the air gap
the weaker the magnetic field

Housing:
magnetic return path guides magnetic field lines
made of magn. steel (iron)

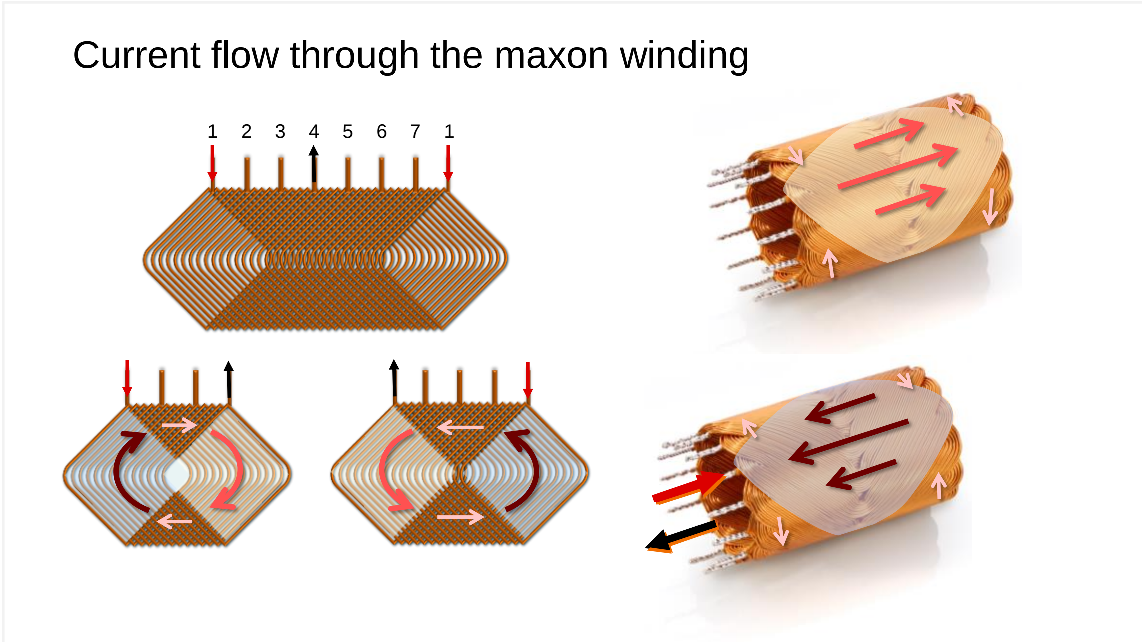
This slides shows a cross section of the stator.
In the center we have the permanent magnet. It is diametrically magnetized, the north pole being colored in red, the south pole in green. The bore in the middle serves for the motor shaft.
The magnetic field lines leave the magnet at the north pole and enter the magnet at the south pole. Magnetic field lines - more exactly the magnetic induction B - are closed lines and must be guided back from the north to the south pole. That's the duty of the housing (or magnetic return path) which is made of a magnetically conducting material.
In the air gap between the permanent magnet and the magnetic return the field lines point in radial direction. The goal of this arrangement is to create an magnetic field as strong as possible in the air gap in order for the winding to produce as much force as possible. Air is a bad magnetic conductor and the larger the air gap the smaller the magnetic flux that can be built. Therefore, the air gap should be as narrow as possible. However, in a narrow air gap there is not much room for the winding. The current density is small and so is the produced force. Finding the right dimensions for the air gap is a classic optimization problem depending strongly on the properties of the permanent magnet.

In short: We have a configuration producing a magnetic field in the air gap which points from bottom to top in this representation.

Rotor and winding



Have now a closer look at the rotor.
In the center, there is the shaft made of hardened steel. The commutator plate is fixed on the shaft and it contains the commutator bars.
At the outside of the commutator plate the self supporting winding is fixed. The contacts of the windings are welded to the commutator bars.
The final step of rotor production consists of covering the commutator plate by a glue. This arrangement protects the contacts and welding points and transmits the produced torque from the winding to the shaft.

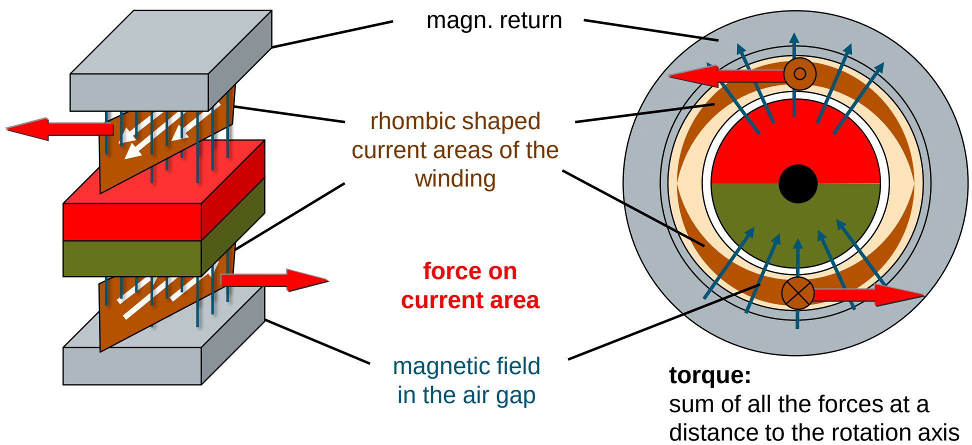


This slide explains the distribution of the current flow in a maxon winding.

Start with the picture on top left showing a maxon winding unrolled. Let's consider current entering the winding at the first and last connection and leaving it in the middle. The current splits up, half of the current flows through the left part of the winding, the other half of the current through the right part as shown in the two winding halves below. At the opposite side (contact no. 4), the two current reunite and leave the winding through the other brush.
Looking separately at the two parts of the winding we can see that the current flows in a circular way in opposite directions in the two halves. A detailed analysis of the average current gives two rhombic shaped areas on the left and right with a current flow which is essentially directed in axial direction. Adding the two halves of the winding, we even get an exactly axial average current in the motor.
Besides there are two triangular shaped areas on top and at the bottom where the average current flows to the left or right. (On the winding cylinder these currents point in a tangential direction and don't add to the motor torque.)

In summary we get two rhombic shaped current areas on opposite side of the winding cylinder. The current is in axial and opposite direction. The angle of the rhombuses lie at the winding connection that carry the current.

Force and torque generation



Hence, we have now all ingredients to understand how the torque is generated. All we have is to remember the Lorentz force from physics classes. It describes that a current conductor in an external magnetic field experiences a force. The force is perpendicular to the current and the magnetic induction field and the "right hand rule" applies.
In our arrangement with the magnetic induction pointing from bottom to top and the current pointing backwards or to the front this results in forces to the left or right. In the motor these forces add to a torque in one and the same direction.

In summary, the torque is generated by the interaction of the electrical current and the field of the permanent magnet.

(An alternative way of looking at the situation: The current in the winding can be considered as a circular current, generating a magnetic field similar to the one of a solenoid. The field of the winding is perpendicular to the one of the permanent magnet. The torque comes from the fact, that the permanent magnet wants to align with the winding field.)

Commutation with brushes

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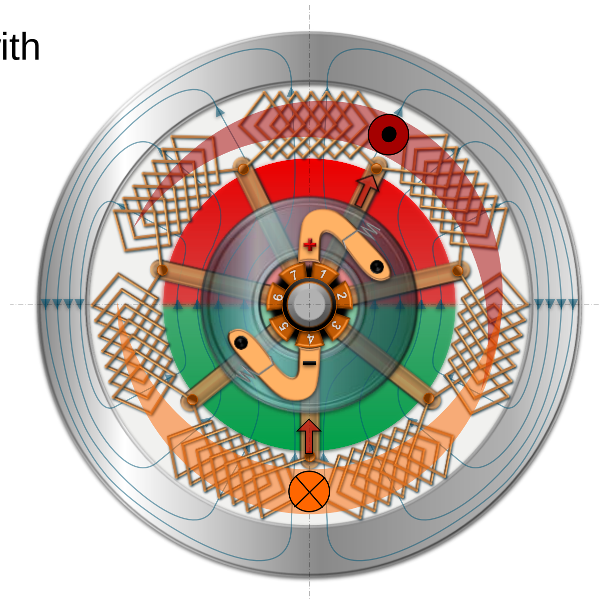
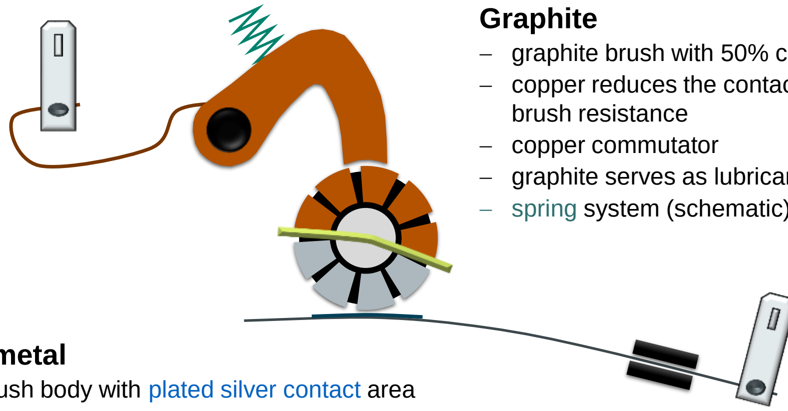


⊕	⊖
1	4
1	5
2	5
2	6
3	6
3	7
4	7
4	1
5	1
5	2
6	2
6	3
7	3
7	4
1	4

We know now how the torque is generated. The next step is to see how a continuous motion is achieved. For this we need the commutation system.
The generated torque causes the rotor to turn and, hence, the current rhombuses move away from the magnetic poles. The torque decreases and after a quarter turn it even vanishes and points then in the opposite direction.
Fortunately, the winding has many connections, all connected to the commutator. Upon rotation the brushes automatically contact a new commutator bar and the current rhombus jumps back one winding segment and is relocated near the pole of the permanent magnet where the torque is highest. With a high number of commutator and winding segments an almost constant torque can be achieved.

maxon motors have an odd number of commutator bars; the commutation takes place at one brush at a time and the current changes direction in one winding segment only. A relative high and odd number of commutator bars reduces the inherent torque variations and it has the advantage that only a small amount of energy must be switched during commutation reducing the brush fire at the commutator. This is good for service life and the motor shows less electromagnetic interferences (EMI). Furthermore, the torque ripple due to the finite commutation angle is small.

DC commutation systems



Graphite

- graphite brush with 50% copper
- copper reduces the contact and brush resistance
- copper commutator
- graphite serves as lubricant
- spring system (schematic)

Precious metal

- bronze brush body with plated silver contact area
- silver alloy commutator
- smallest contact and brush resistance (50 mΩ)
- CLL for high service life

On small DC motors one finds two types of brush systems which are presented here for comparison. (In one motor there is only one type! Just to make sure that this diagram is not misunderstood.)

Graphite brushes

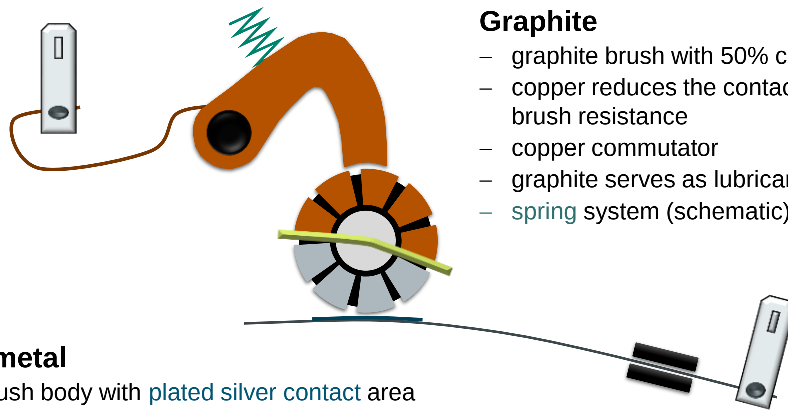
Graphite brushes are often made as lever brushes, i.e. they rotate around an axis and are pressed against the commutator by a spring. There is a lot of labor involved in the production of this system with brush, bearing, spring and strand.

The brush of small DC motors is made with a graphite content of approx. 50%. The rest is copper to enhance the conductance of the brush. Otherwise a large portion of the applied voltage would be lost over the brushes.

The commutator is made of a copper alloy. The commutator surface is turned on the lathe to ascertain roundness and to produce a certain roughness. This surface roughness is important for the building of the patina, the brownish layer made from copper oxide, water, graphite, ...

Graphite brushes on copper commutator is a well-proven gliding contact used in many areas and in many motors. It is particularly well suited for high current densities because this allows to penetrate the oxide layer at the commutator surface more easily. In these cases the contact resistance is small. Graphite brushes are not very sensitive to brush fire.

DC commutation systems



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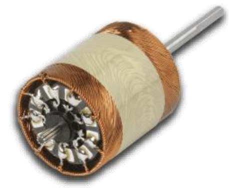
continued

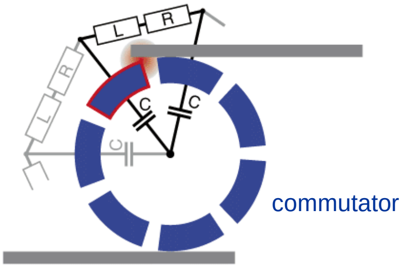
Precious metal brushes
Precious metal brushes are better suited for small currents and voltages. The gliding contact is directly between metal and metal and exhibits an extremely small contact resistance.
Precious metals (mostly silver, rarely gold) are used to prevent oxidation.
The brush body is made of a spring bronze with a plated silver contact area. The brush serves as a spring itself simplifying the design and reducing costs.
The commutator is made of a silver alloy. The surface is finished by grinding and polishing.
Precious metal brushes are not suited for high currents and voltages. Brush fire reduces the service life dramatically. (The reason for this is in the low melting temperature of the silver alloys and the tiny contact dimensions and layer thickness). Brush fire is suppressed by capacitors which are contained in the CLL disk. To enhance service life even more, the precious metal commutation is lubricated.

Precious metal commutation: CLL

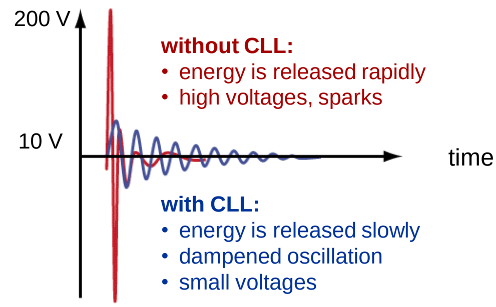


Problem

– Brush fire => Reduced life



voltage between commutator bars



Solution

– capacitors and resistors between neighboring commutator segments

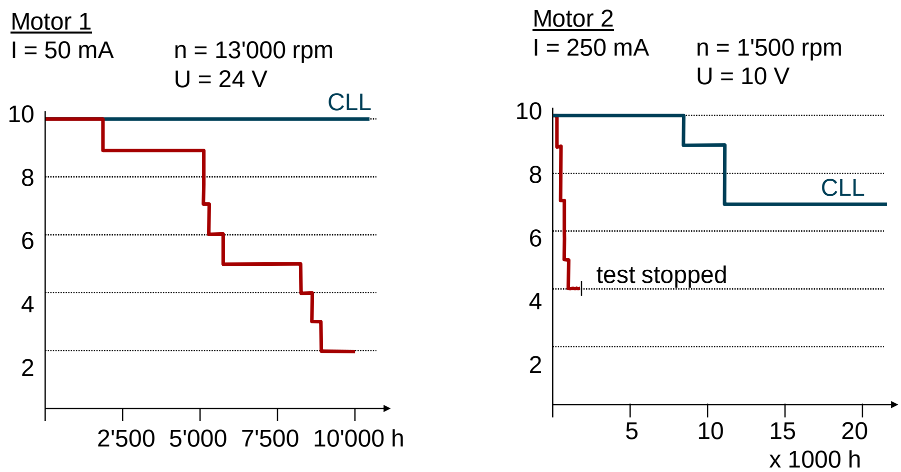
– energy is deviated into capacitor: no arcs produced

As we've heard already precious metal commutation is very sensitive to brush fire. These sparks are produced during commutation when the contact between brush and commutator bar is opened. The winding represents an inductive load and the current wants to continue to flow. Brush fire is produced as well when the brush starts to vibrate and looses contact at higher speeds.

A solution for this problem is the capacitive spark quenching. A capacitor is mounted in parallel to the contact to open taking up the excess energy. Later this switching energy is dissipated in the resistance.
That's in short the CLL concept which is realized as a disk mounted on the commutator plate and electrically contacted to the winding connections.

The schematic diagram at the right shows the voltages that occur at the commutator. It's based on simulations.
The brush short-circuits two adjacent commutator bars. Very often the current cannot fully vanish during this phase and when the contact is opened a high voltage pulse is generated which might be as high as several 100 V (red curve) leading to a discharge.
With the CLL disk the energy is deviated into the capacitor and then slowly dissipated in a dampened oscillation (blue curve). The voltages that can occur are below 12 V (in the ideal case) where no discharge can occur.

Service life and CLL (examples)



CLL stands for "Capacitor Long Life".
That motor life is longer indeed can be seen from these comparative life testing results.
The red curve refers to the number of surviving motors without CLL.
Blue is the number of motors with CLL

On the left there is the case of a low current load:
Many motors without CLL fail around 5000 hours of service. One even much earlier.
With CLL all the 10 motors still worked after 10'000 hours.

On the right there is the case of a higher current load:
First thing we see is that motor current is an important parameter influencing motor life.
Without CLL the service life was very short, less than about 1000 hours.
With CLL it took approx. 8000 hours for the first motor to fail.

DC commutation: Characteristics

Graphite

✓high and peak currents
✓continuous, start-stop and reversing operation
✓larger motors (>approx. 10 W)

– not suited for small currents
– higher friction, higher no-load current

Precious metal

✓smallest currents and voltages
✓continuous operation
✓smaller motors
✓very low friction
✓low audible noise and electromagnetic interference
✓cost effective

– not suited for high current, peak currents, start-stop operation

Let's summarize the properties of the two commutation systems.

Graphite commutation better suits high currents and peak currents that occur during start-stop operation. Larger motors usually have higher currents; that's why motors with a power higher than about 10 W are equipped with graphite brushes only.
Precious metal brushes can be found on the smallest motors. They are well suited for smallest currents and voltages. They exhibit a very small friction, generate almost no noise and - grace to the CLL - almost no electromagnetic interference.

The choice between graphite and precious metal brushes can only be made in the motor diameter range from 13 to 26 mm. Larger motors only have graphite brushes, smaller motors only precious metal brushes.

Ball and sleeve bearings: characteristics

Ball bearing

- ✓ well suited for high radial and axial loads
- ✓ well suited for all operating modes, for start-stop and reversing operation
- ✓ on larger motors
- ✓ high speed ceramic option

- – more audible noise if not preloaded
- – when preloaded higher friction
- – more expensive

Sintered sleeve bearings

- ✓ suited for low radial and axial loads
- ✓ suited for continuous operation at higher speeds
- ✓ smaller motors
- ✓ low friction and noise
- ✓ cost effective

- – not suited for start-stop operation

At the end some remarks about the bearings that often can be selected as well.
As a general rule, for higher loads and requirements ball bearings are better. On high speed EC motors ball bearings with ceramic balls are used in certain applications.
Sintered sleeve bearings are much more cost effective, but work best at higher speeds and low radial shaft load.

Often sintered sleeve bearings can be used in the same applications as precious metal brushes.
The same holds for the combination of ball bearings and graphite brushes.

Service life brushed DC motors

no general statement possible

- average conditions
  ➔ 1'000 - 3'000 hours
- extreme conditions
  ➔ less than 100 hours
- favorable conditions
  ➔ more than 20'000 hours

➔ Use graphite brushes and ball bearing for extreme requirements.

Influencing factors

- electrical load:
  - higher currents = higher electro erosion (brush fire)
- speed:
  - higher speed = higher mechanical wear
- operation mode:
  - continuous operation vs. start-stop operation
  - reverse operation = reduced service life
- humidity of the air
- temperature
- load on the shaft (bearing)

Remarks about the service life of the maxon DC motor

In most cases it's the brush system that limits motor life. In rare cases it's the bearings.
Each application is different and service life can vary a lot. That's why no general statement can be made or even guaranteed.
Experience shows however, that for average conditions several 1000 hours can be reached..
Under favorable conditions (e.g. continuous operation at low load) more than 20'000 hours or more have been reached.
Extreme conditions such as high vibration, extreme start-stop and reverse operation can limit motor service life to less than 100 hours.

The most important point is to find out what really the needed life is for the given application, expressed in hours or number of working cycles. An interesting remark: With graphite brushes several million working cycles could be reached in several applications.

