Crystal Clear Electronics

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Contact http://crystalclearelectronics.eu/en/
info@kristalytisztaelektronika.hu

13 - DC Motors

Written by Dániel Csapó

English translation by Xtalin Engineering Ltd.

Revised by Szabolcs Veréb

By the end of this chapter you will understand the basics of direct current motors, their structure, main areas of application and you will be able to use them with confidence in engineering and everyday life.

Introduction

I'm sure all of you, who have been drawn to the world of science and technology as a child, dismantled their remote-controlled car to see what they could find under the hood. The part shown below must be familiar to everybody and it may also bring back some pleasant childhood memories.

Figure 1 - Small DC motor
Author: Dcaldero8983 [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]
https://commons.wikimedia.org/wiki/File:DC_Motor.jpg

Now it's time to dismantle our model car even further and understand what made our childhood toys move.

Principle of Operation

The operation of every electric motor is based on the interaction of two magnetic fields. This is the same effect which everyone has already experienced by moving two magnets close together. If the magnetic poles are the same, the magnets repelled each other, while different poles attracted each other.

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Let's stop for a short moment to clarify some basic definitions in the area of magnetism. A magnet's most fundamental property is that it creates a magnetic field. A magnetic field can be created by combining different materials found in nature (permanent magnets), or by constructing and powering a device (electromagnets). The magnetic field is polar, which means it always has two opposite magnetic poles: north, and south. A single magnetic pole by itself (called a monopole) does not exists. Our Earth also has a magnetic field, but we cannot see it, in the same way we cannot see the fields of our magnets, we can only know about their existence by observing their effect on other things. Magnetic fields are represented with magnetic field lines or in other words flux lines, which are always closed curves, starting from a pole and closing on the other pole.

We can think of the strength of a magnetic field in terms of how strongly a compass orients itself in the north-south direction. In physics the strength of a magnetic field is described by the quantity of magnetic induction, which has the SI unit of Tesla (T) in remembrance of the great inventor and physicist of the XIX. century Nikola Tesla (1856-1943).

Everybody knows that certain materials are affected by our magnets, while on certain other materials our magnets seem to have no effect whatsoever. In reality, magnetic fields affect every material, however the strength of the effect can be strong, or even barely measurable.

We call those materials that have strong reactions to magnetic fields ferromagnetic materials. We can imagine ferromagnetic materials as there are a lot of small elemental magnets inside them, which are arranged in the same direction when an external magnetic field is present. When the small magnets are oriented the same way, the material shows magnetic properties, and has a magnetic field on its own. The so-called soft magnetic materials only show these properties while an external field is present, and they lose their magnetic characteristics when the field disappears, whereas the so-called hard magnetic materials, or permanent magnets retain them even without external excitation.

Ferromagnetism

Although, the Latin word ferrum means iron, ferromagnetic characteristics aren't showed only by iron. The source of magnetism in materials can be traced back to quantum physical properties. Movement of electrons around the nucleus (orbital angular momentum) and the rotation around their centerline (spin angular momentum) determine the basic magnetic characteristics, thus, elements of the periodic table with a certain electron structure are ferromagnetic elements. Iron, cobalt, nickel, their alloys, and certain rare earth metals, like the neodymium or samarium, are the most commonly used permanent magnetic materials in the industry.

It's worth to mention another important definition of electromagnetism and electricity: inductivity. Current flowing through a coil generates (induces) a magnetic field with a strength that is dependent on the strength of the current. As the magnetic field changes, it induces voltage in the conductor, which is called EMF (Electromotive Force). The electromotive force creates current in the conductor (if the conductor forms a closed circuit) which in turn creates a magnetic field again, but with opposite polarity so that it tries to weaken the effect that caused it. This is **Lenz's law**.

In a circuit that contains a coil, the current cannot change instantaneously. The resistance of the coil to current change is characterized by the coil's **inductivity**. We use the letter L, after Heinrich Lenz, to mark

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it. Its SI unit is the H (Henry). The higher the inductivity of a circuit, the harder it is to suddenly change the current flowing in the circuit. The inductivity of a coil is primarily defined by its geometric parameters (such as number of turns), and characteristics of the material inside the coil (iron core, air core coil).

It was necessary to define inductivity before discussing electric motors since our motors contain coils and behave like inductive circuits.

Let's examine how the magnetic field was created in our small electric race car that made the motor spin.

First let's recall Ampére's law (**André-Marie Ampére 1775-1836**), which states that, if current flows in a conductor, it creates magnetic field around the conductor. If the conductor is then placed into another magnetic field, a force is exerted on the conductor proportional to the strength of the current and the external magnetic field. This was discovered by the Dutch physicist **Hendrik Antoon Lorentz**, and the law was named after him. The **Lorentz law** states:

$$F = B \cdot I \cdot l$$

where B is the magnetic induction, I is the current and l is the length of conductor (if the conductor is perpendicular to the magnetic force lines).

The direction of the force can be determined with the use of left hand rule (Fleming's left hand rule), where our middle finger shows the direction of the current, our index finger shows the direction of the magnetic field and our thumb shows the direction of the force exerted.

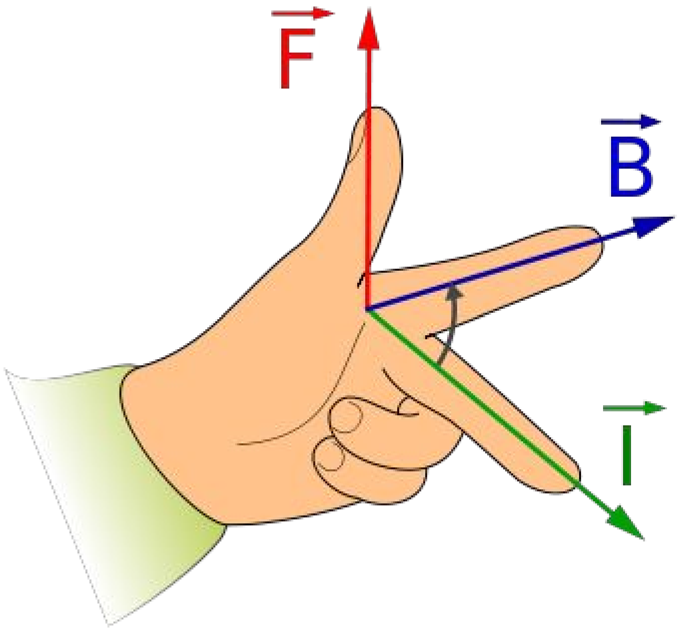

Figure 2 - Left hand rule
Author: Jfmelero [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]
https://commons.wikimedia.org/wiki/File:LeftHandRule.svg

Inside a DC motor, which is the simplest structure we're examining right now, there is a stationary magnetic field created by permanent magnets (PM – Permanent Magnet).

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Imagine what happens if a loop with a current flowing through it is placed inside magnetic field, as shown in the figure below.

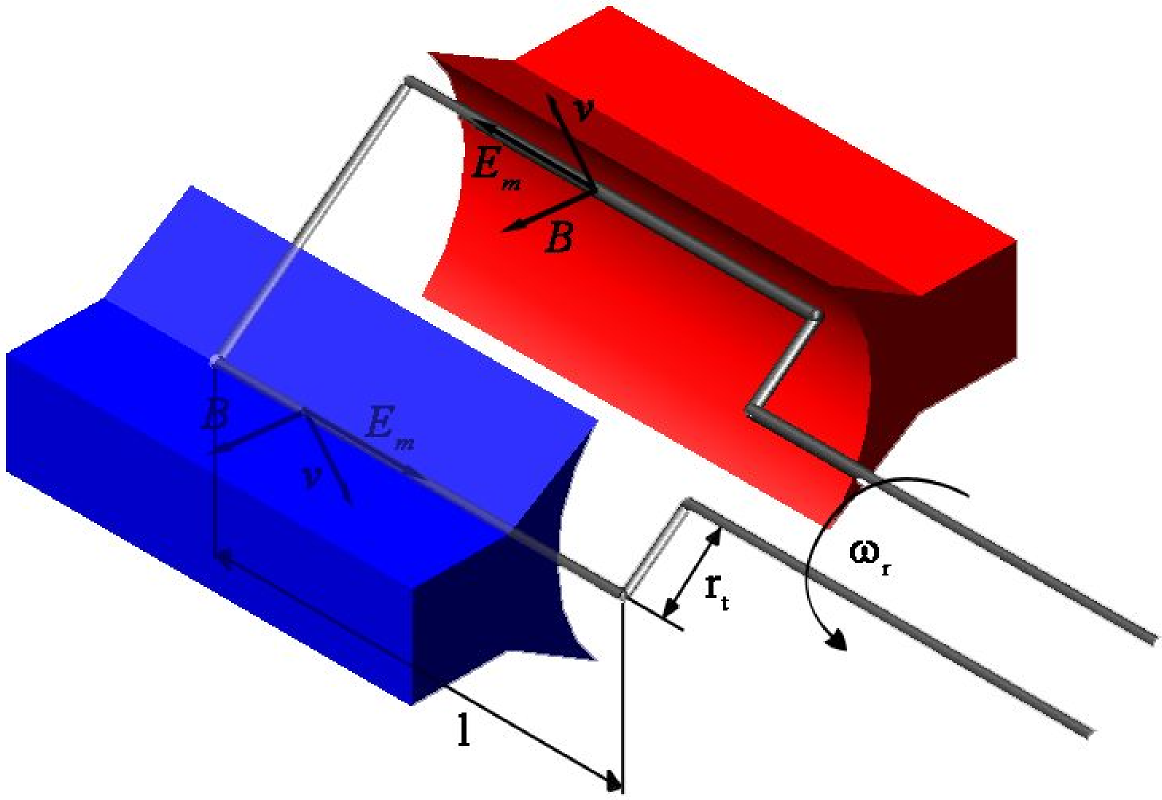

Figure 3 - Force on moving electrons in a moving frame in a magnetic field

Since we have a current flowing in a magnetic field according to Lorentz's law a force will be exerted on the loop. You can see the direction of the force in the picture above, and it is clear that it creates torque making the loop rotate. Torque is a physical quantity that describes a force rotating an object around an axis and is measured in Nm (Newton-meters). When we spin the carousel at the playground, we make it rotate by applying torque to it. The Lorentz force has a similar effect on the conductor loop until a point, where the forces on the two branches of the loop are aligned but acting in the opposite direction (they have a common axis). When that happens, the system reaches steady state, since the two forces cancel each other out. No torque is created, the conductor loop does not rotate anymore. What do we have to do to get over this point, and force our device to keep spinning?

Ányos Jedlik, one of the greatest inventors of the 19th century, has also experienced this problem. He realized that, if we change the direction of the current using a clever trick just before the steady state happens, then the forces will change in way that keeps the loop spinning. If we think about it, we can see, that the force, that affects the upper conductor, will now point to the opposite direction and it will try to move the upper branch into the lower position, while in the other branch the same thing happens the other way round. If you change the direction of the current after every 180 degrees of rotation, your motor can keep on spinning. This task is performed by a device called the current switcher or the commutator.

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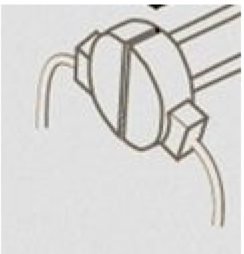

Figure 4 - Commutator

Early types of commutators

Jedlik used two mercury channels in order to change the direction of the current, which were isolated from each other and connected to a rudimentary galvanic battery's positive and negative poles. The two terminals of the rotating conductor immersed into the mercury and after a 180-degree turn, it touched an inverse polarity mercury, which changed the direction of the current in the conductor, so it created rotation.

The exerted force is the largest on the conductive loop when it is perpendicular to the permanent magnet, if we imagine the loop's magnetic field as another magnet (two similar magnets want to rotate to the same direction).

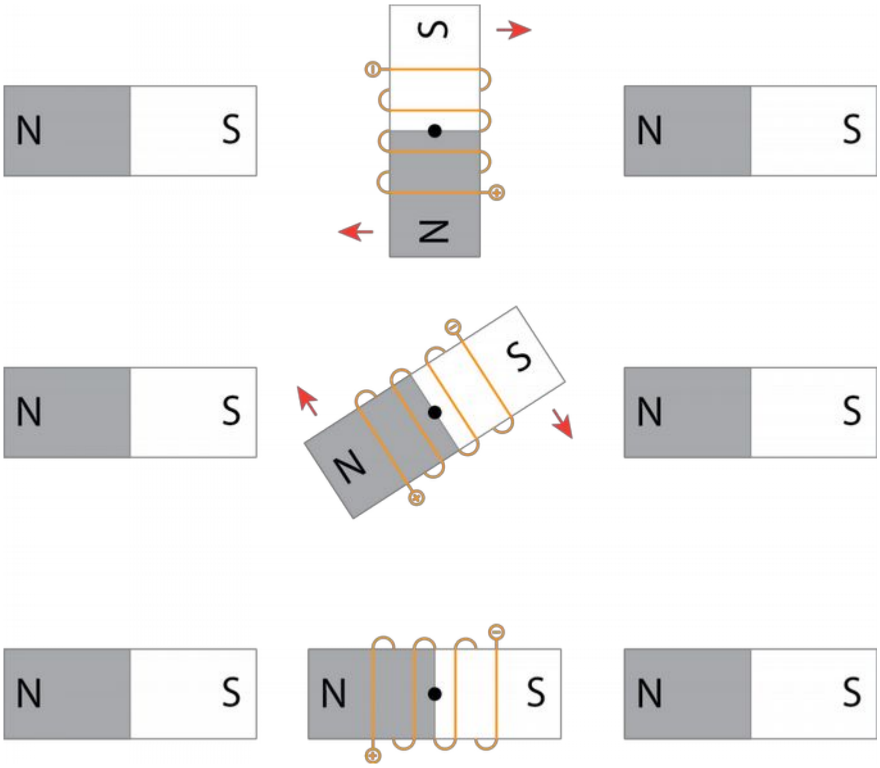

Figure 5 – Force on a magnet/coil

As the loop rotates, the torque decreases. Our theoretic machine wouldn't produce consistent rotation like this, it would „jump" after every half turn. If we place a second conductor perpendicular to the first

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loop, which is connected to our direct current source through the commutator at every quarter turn, the „pulsation” of the torque will be smaller. If we increase the number of loops, we'll get a smooth rotation.

The machine constructed by Jedlik in 1829, was the world's first operational electric motor and it contained the three basic elements of a DC motor:

- stationary part (called stator), which creates the stationary magnetic field (with permanent magnets)
- rotating part (called rotor)
- and the commutator, responsible for changing the direction of the current flowing in the rotor (this process is called commutation)

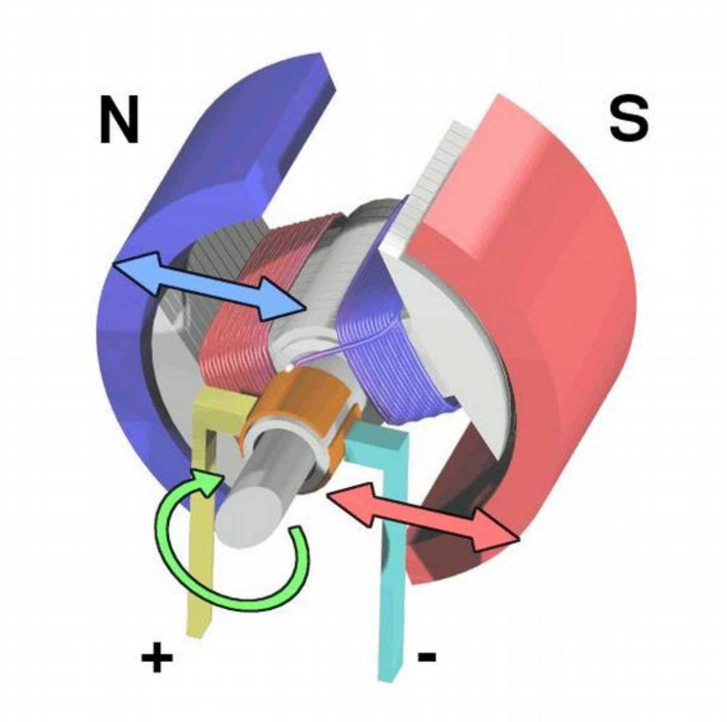

Figure 6 - with the commutator and voltage source. The figure is only for demonstration purposes, in case of this layout, the commutator would short circuit the source by turning
Author: Wapcaplet [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]
http://en.wikipedia.org/wiki/Image:Electric_motor_cycle_3.png

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STRUCTURE

A DC motor can be taken apart to the three main parts we mentioned:

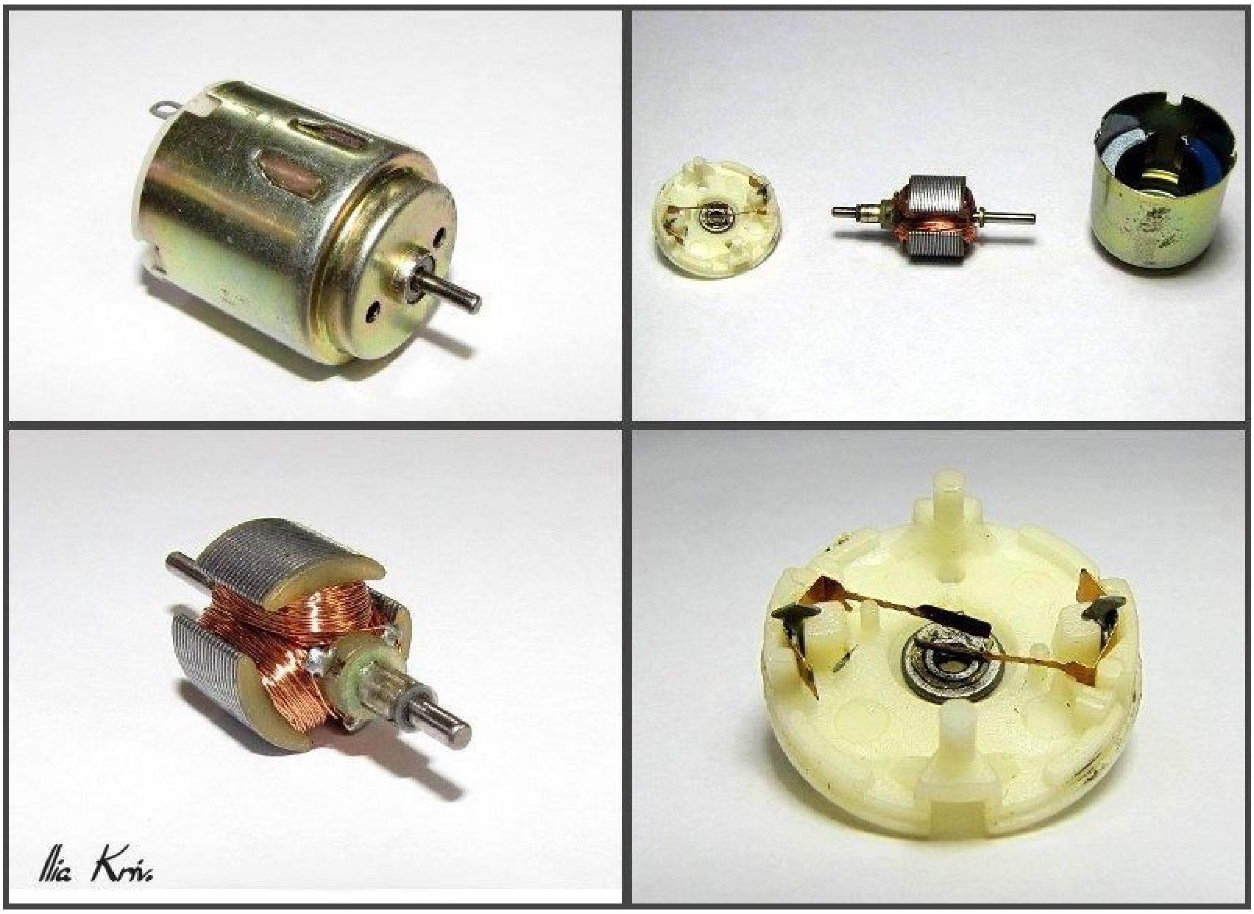

Figure 7 - The main parts of a DC motor
Author: Ilia Krivoruk [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]
https://commons.wikimedia.org/wiki/File:Brushed_dc_motor_assembly.jpg

STATOR

The stator is the part of our machine that is stationary, it does not move. It creates a stationary magnetic field. Until now we have assumed that this part is made with permanent magnets, but in many DC motors the stator is made with electromagnets that create the stationary magnetic field only when power is applied.

Electromagnets vs. permanent magnets

An advantage of using electromagnets is that we can adjust the strength of the magnetic field, while in the case of permanent magnets – especially when using rare earth magnets - the strength of the magnetic field depends on the material used.

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The ferromagnetic materials (such as iron) used in the stationary part shape the magnetic flux lines and provide mechanical strength and protection.

Rotor or Armature

The rotating part of the DC motor is typically made from ferromagnetic material. Copper conductors are wound in the grooves of the rotor. Again, iron has a role in concentrating the flux lines and making sure the conductors stay in place. The coils are connected to the commutator.

Commutator and Brushes

The commutator is a cylinder mounted on the axle of the rotor on one end. The rotor consists of copper segments, which are isolated from each other. Stationary brushes made of carbon or graphite are pushed against the commutator by springs, allowing current from the external DC voltage source to flow through the rotor. The disadvantage of this solution is that the brushes are subject to mechanical wear over time and need replacement, and the coal dust produced where the brushes contact the rotating axle can short circuit the isolated segments of the commutator.

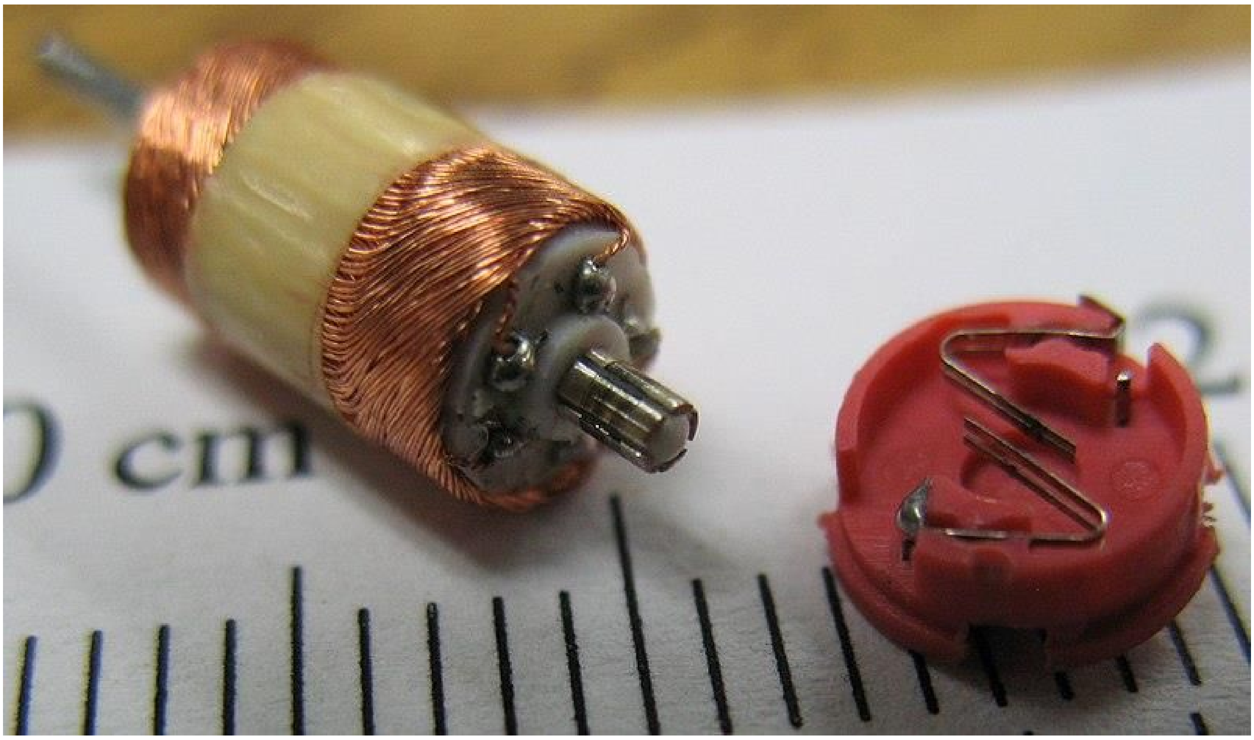

Figure 8 - Commutator

Author: Dale Mahaiko [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]

https://en.wikipedia.org/wiki/File:Tiny_motor_windings_-_commutator_-_brushes_in_Zip_Zaps_toy_R-C_car.jpg

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Figure 9 - Commutator
Author: Jjmontero9 [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]
https://commons.wikimedia.org/wiki/File:Small_DC_Motor_Rotor.JPG

CONTROLLING DC MOTORS

The speed of a permanent magnet DC motor is proportional to the applied voltage and the torque is proportional to the flowing current.

The direction of rotation can be changed by switching the polarity of the supply voltage.

Motor parameters

In the datasheet of a DC motor, the most important electrical information usually indicated, such as the voltage, current, torque, power, and speed ratings of the motor.

The maximum current a motor can handle is limited by overheating. The maximum current also determines the maximum torque, as the two are directly related. Generally speaking, if a motor can handle higher current, it can output more torques as well.

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The maximum voltage a motor can handle is usually determined by the type of insulation used between the coil windings. If the voltage is too high, the insulation can arc over, and short windings together. The maximum speed of a motor is related to the maximum voltage; higher voltage means faster rotation of a specific motor.

The rated power of the motor can be calculated from its current and voltage rating. The power rating means that the motor can safely operate on that power level for a long time. Exceeding the rated voltage or current can cause damage to the motor. In certain cases, the manufacturer indicates maximum values, which can be exceeded for a short amount of time without damage.

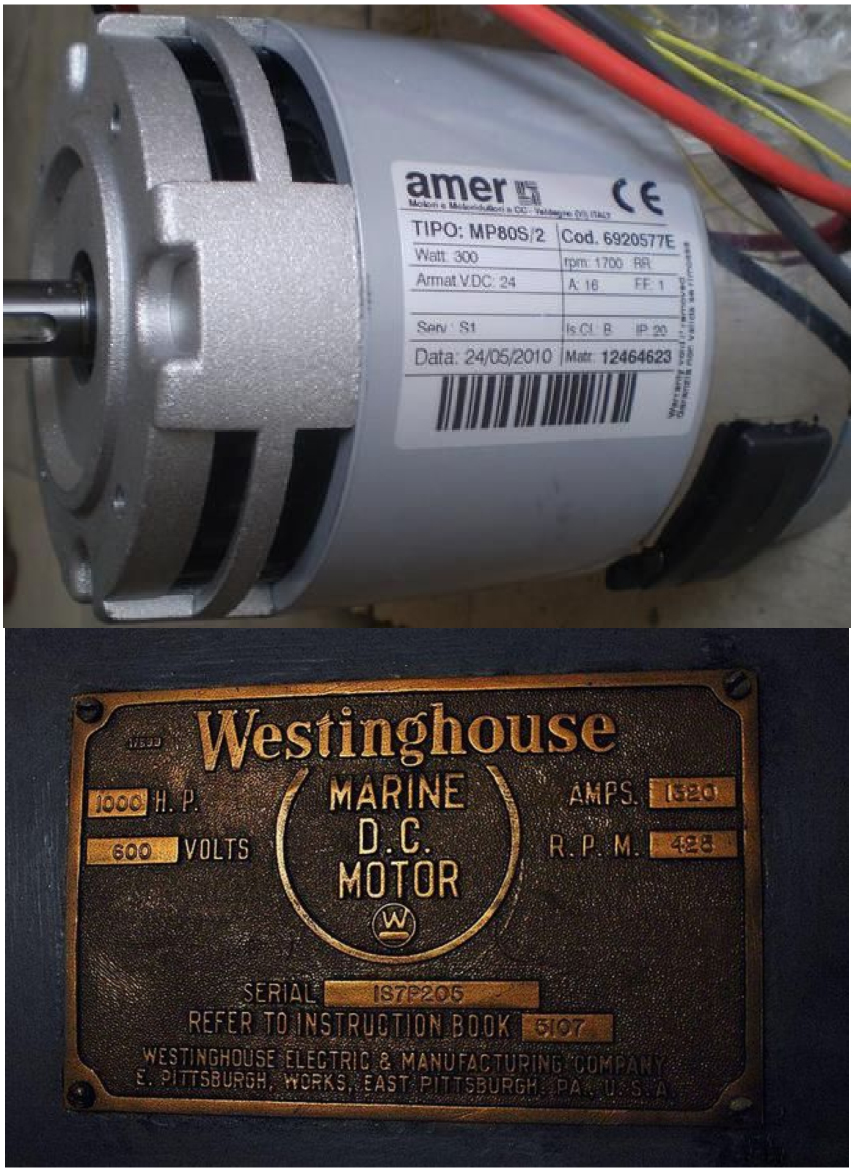

Figure 10 – Parameters of DC motors

Author: Kaylee La Spisa [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]

https://commons.wikimedia.org/wiki/File:Wuxi_TECO_Electric_%26_Machinery_3-phase_induction_motor_plate_20160319.jpg

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Universal Motor

What about electric motors that are in our everyday household items such as a kitchen blender or a drill, that are powered from the wall plug? Maybe you have already heard that these devices also contain DC motors. How is it possible for the DC motor we have learned about to operate from AC voltage?

First, think about what would happen if we have connected a simple, permanent magnet DC motor to the 50 Hz AC electric grid? Assuming the motor is rated for the higher voltage because it is AC the current would change direction in the coil windings hundred times every second. As a result, the force that should spin the motor would also jump back and forth, trying to move the rotor in the opposite direction every time. This means that the rotor cannot turn, and our motor won't spin, only the coils will get hot from the AC current.

However, if we changed the polarity of the stationary magnetic field (made by our permanent magnets in this case) at the same time the AC current changes direction in the rotor windings, the resulting force would still point towards the same direction, allowing the motor to turn (you can verify this for yourself using the left-hand rule). To achieve this, we must use electromagnets in the stator instead of permanent magnets and connect their windings in series to the rotor windings through the commutator. This way, the current changes at the same time in both the stator and the rotor, ensuring that the torque has a constant direction.

If we switched the polarity of the permanent magnets at the same time when the direction of the conductor rotor current changes, then the direction of the appearing torque (force) wouldn't change (it can be checked using the left hand rule). In order to achieve this, let's change the permanent magnets on the stator to electromagnets and connect their windings serial to the rotor's coils, through the commutator. In this case, the current changes at the same time in both the stationary and rotary parts, ensuring a torque which has constant direction.

Bigger universal motors

Most of our hand tools use universal motors, of which power is typically under 1 kW, but universal motors can even be found in electric trains as well.

Why does my drill spark?

If you observe some of your hand tools you can see sparking while the motor rotates. We can explain this phenomenon using what we've learnt so far. On the rotor windings the current cannot change instantaneously since they are inductive elements. When commutation happens, the commutator breaks the circuit to interrupt current flow and connects the power supply to the next winding. However, when the circuit is broken, the current cannot drop to zero immediately because that would violate the laws of physics. Instead, the voltage starts to rapidly rise inside the winding until the point where it is high enough to create an arc over air and connect the winding again so that current can flow just a little longer, until it decreases. This is what causes the sparks you can see.

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BLDC MOTOR

What if we reversed our construction and build a motor where stator had electromagnets like in a universal motor, but the rotor would be made out of permanent magnets. Something like a reversed DC motor. In such a motor we couldn't use mechanical commutation, since current only flows in the stationary parts, but we can use electronic switches to turn on and off each part of the stator coils separately to achieve the same result.

This is what we call a brushless direct current motor (BLDC – Brushless DC), which has permanent magnets on the rotor and electromagnets in the stator, with commutation done by an external control circuit.

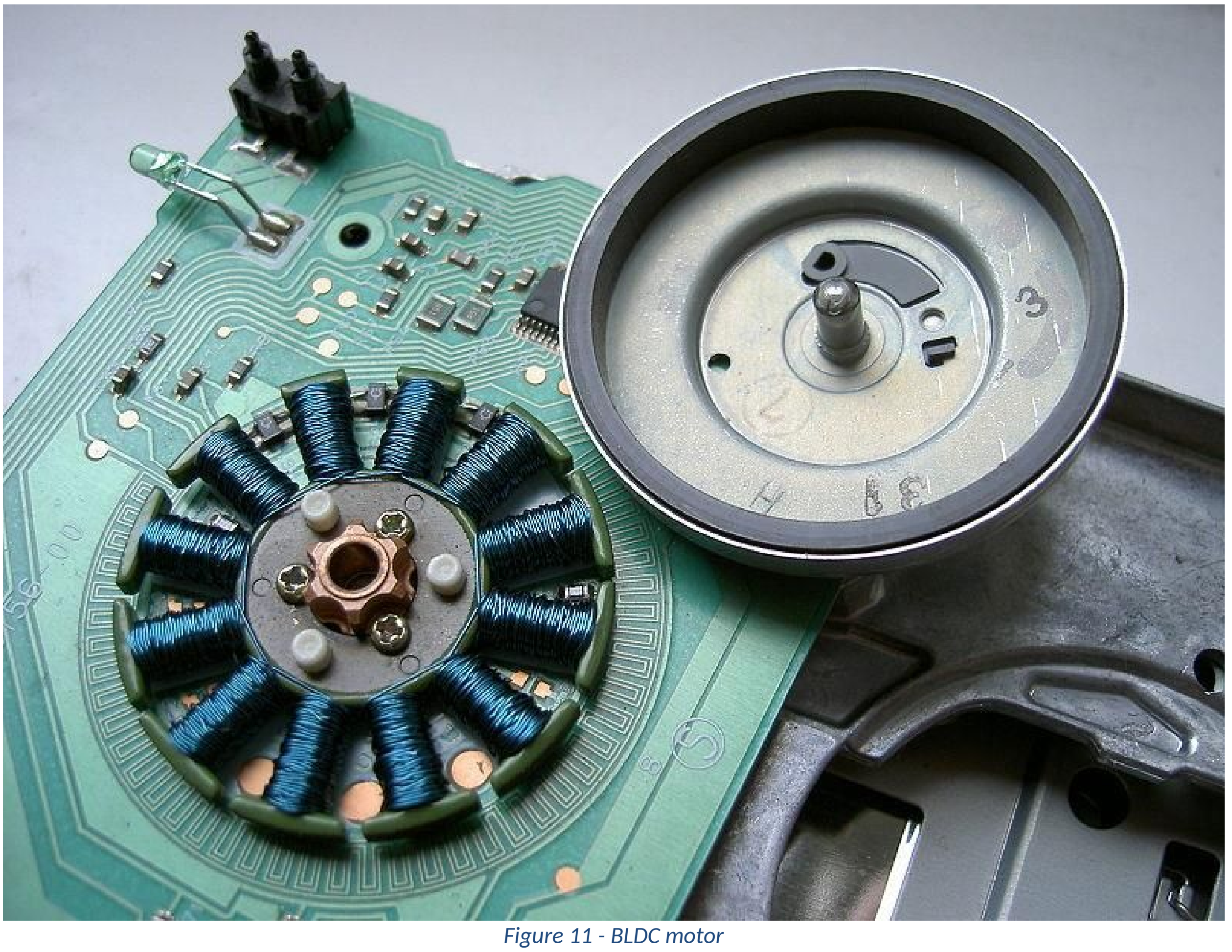

Figure 11 - BLDC motor
Author: Sebastian Koppehel [CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)]
https://commons.wikimedia.org/wiki/File:Floppy_drive_spindle_motor_open.jpg

The commutator circuit connects the DC voltage source to the stator coils in order, which creates a rotating magnetic field inside the motor. If we simply put a permanent magnet in such a field, it will always try to align itself with the field exactly the way a compass aligns with the Earth's magnetic field. But, just before the alignment could happen, the commutator circuit switches to the next set of electromagnets, causing the rotor to turn further trying to align again. This means, in a BLDC motor the rotor always lags behind the rotating magnetic field created by the stator.

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But, in order to do this, the commutator circuit must know the current position of the rotor, or it couldn't know which coils to switch on. Therefore, BLDC motors always need a position sensor to work.

The physical design of a BLDC motor can be various, you can find both outrunner and inrunner designs, meaning which part of the motor actually turns, and which is bolted down to something. Where the available space is limited, a flat design is used with a disc-shaped stator and rotor placed against each other.

Permanent magnet synchronous motors

It's important to clarify that the structure of a BLDC motor and a permanent magnet synchronous motor (PMSM) is very similar, the only difference is the power supply and controlling mode.

Alternating current motors can be controlled electronically as well. Such an example is the permanent magnet synchronous motor, which uses permanent magnets on the rotor similarly to the BLDC motors, however its operation is fundamentally different.

APPLICATION

Traditional DC motors have many applications. You can find them in toys, servo mechanisms, valves, robots, or automotive electronics.

To find BLDC motors it's enough if you think of computer peripherals and accessories. They drive our computer's fans, and hard disks, but high-power BLDC motors are used in electric vehicles and industrial applications as well.

A BLDC motor with a controller, is usually more expensive than a traditional DC-motor with brush, however its lifetime is longer (there isn't any mechanical wear on brushes), its reliability and efficiency is greater, and it can be controlled more precisely because of the lack of mechanical commutation. They are commonly used in high speed applications where precise actuation is an important aspect (microcontroller programmability).

BLDC in vehicles

In electric hybrid vehicles, we can find BLDC motors used to supplement the internal combustion engine. Several electric scooters and bicycles use BLDC motors as well, which are usually built into the wheel hub.

Now that we finally understand how our electric race car from our childhood worked, we can go and replace the disposable batteries with rechargeable ones, the remote to electronic motor control, the DC motor to a high powered one, and design our own electric race car!

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