G4. Continuous Current Electric Motors

GOAL

The goal of this experiment is to better understand the processes used in electric generators and motors, using “simple” models, that are close to actual machines. We suggest the students first focus on the practical aspect of the experiment (different setups, measuring of key characteristics, etc.), before going deeper into the theoretical aspect.

I. INTRODUCTION.

Continuous current motors are defined by a large number of different characteristics, that makes them appropriate for nearly every task. They are primarily used when the energy comes from batteries (e.g. cars, toys, …). There exist two main types of machines: synchronous motors (alternators) and asynchronous motors (induction). The first are used in systems at constant speed and low starting torque, whereas the latter are used for high power applications ($10^{-1} - 10^{-3}$ kW).

Any transportation system that requires a hovering technology in order to get rid of material contacts requires a special kind of propulsion mechanism: motors that work as well for accelerating and braking, without using any kind of friction. For safety reasons, in the case of the propulsion of high-speed vehicles, these motors must have better performance in braking than in traction. There are two families of thrusters which comply with these specifications: reactors used in aeronautics and linear electric motors.

II. OPERATION PRINCIPLE

Ampere Law and Lorentz Force

Let us consider a random conductor under a current I and place it in a magnetic field $\vec{B}$. Each length element $d\vec{l}$ of the wire is subject to a force (fig. 1a):

$$d\vec{F} = Id\vec{l} \times \vec{B} \qquad (1)$$

In particular, if the wire is straight, and the field uniform (i.e. $\vec{B} = cst$) the resulting force acting of a length of wire L is:

$$\vec{F}_L = \int_L Id\vec{l} \times \vec{B} = I\vec{L} \times \vec{B} \qquad (2)$$

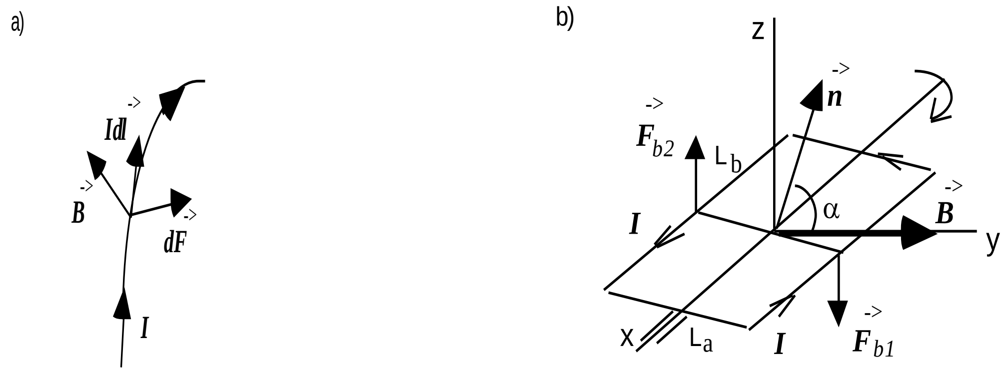

Fig.1: a) Electrical conductor in a magnetic field
b) Torque acting on a rectangular coil

Let us now consider a rectangular frame (of length L_a and width L_b) with a current I and capable of rotating about an axis going through the center of two opposite sides (fig. 1b). This frame is placed in a uniform magnetic field $\vec{B}$, perpendicular to the axis. Suppose that the normal to the frame forms an angle α with respect to the field $\vec{B}$. We can easily verify that the forces acting on the sides of length $\mathrm{L_a}$ cancel, since they are of same magnitude, but opposite direction. However, the forces $\vec{F}_{b1}$ and $\vec{F}_{b2}$ generate a torque.

$$\left|\vec{F}_{b1}\right| = \left|\vec{F}_{b2}\right| = IL_b B \sin\alpha \qquad (3)$$

$$Couple = C = IBL_a L_b \sin\alpha \qquad (4)$$

In vector notation:

$$\vec{C} = I \cdot S \cdot \vec{n} \times \vec{B} \qquad (5)$$

With $S = L_a L_b$, the frame's surface, and $\vec{n}$ the normal unit vector of the frame. (direction is defined by the right-hand rule with respect to the direction of the conventional current).

We notice that for:

- $\alpha = 0$ the torque is zero
- $\alpha = \frac{\pi}{2}$ the torque is maximal in the direction indicated by the diagram
- $\alpha = \pi$ the torque is zero
- $\alpha = \pi + \Delta\alpha$ the torque switches directions compared to that of the diagram

In order to maintain the torque in one given direction, the current must switch directions every time α equals $0, \pi, 2\pi, 3\pi$ etc.

Motors

For continuous motors, it is easy to reverse the direction of the current, by using a system of brushes and commutators (fig. 2). Every half-period, the current going through the frame is reversed. The magnetic field is generated by a permanent magnets or a set of coils connected directly to the power supply..

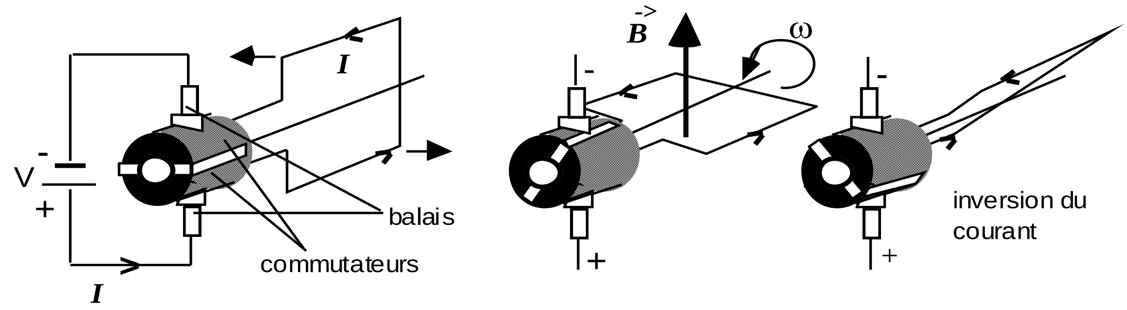

Fig. 2: Continuous current motors. The commutators are attached to the shaft of the motor, and rotate with it. Electrical contact is achieved using a set of brushes.

Faraday's Law of Induction

In fig. 2, and for no power supply, if a mechanical force rotates the shaft at a constant angular velocity ω, an induce electromotive force appears

$$E_i = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int \vec{B} \bullet d\vec{S} = \frac{d}{dt}(\mathrm{BS}\cos\alpha) \qquad (6)$$

where α is the angle between $\vec{B}$ the normal unit vector $\vec{n}$. Also, $\omega = \frac{d\alpha}{dt}$, so we can deduce:

$$E_i = BA\omega \sin \omega t \qquad (7)$$

Therefore, a spinning coil inside a constant magnetic field $\vec{B}$ produces an alternative current. This is the basic principle of electric generators

III. ROTOR AND STATOR

In practice, the mobile frame is made of more complex coils and systems of coils around a metallic body (cylindrical Fe core for a larger torque). This part is called a **rotor** (fig. 3).

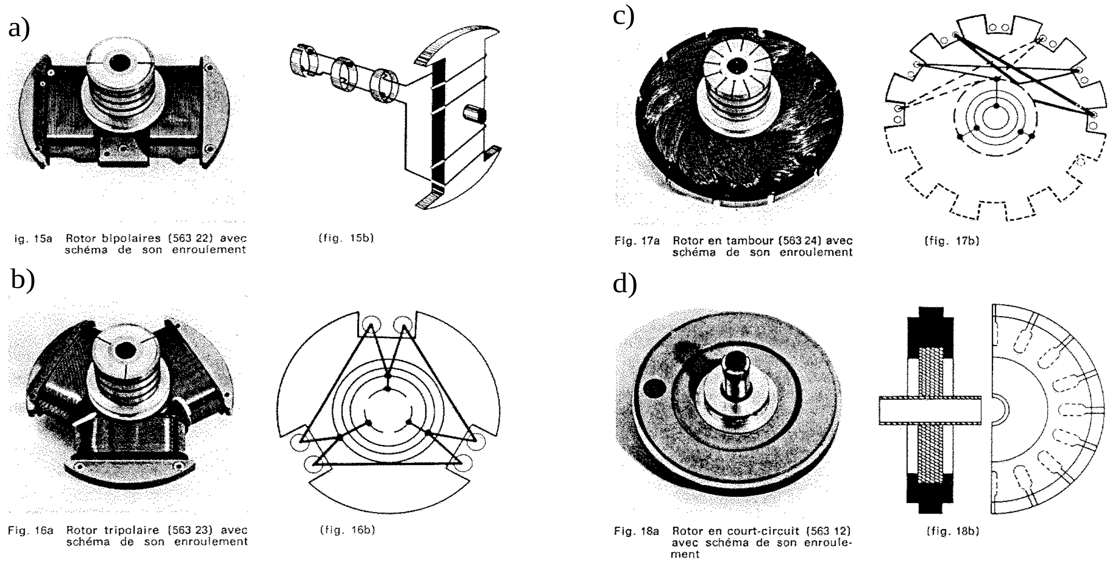

Fig. 3: Different rotors. To avoid eddy currents, the rotors have cores made of pressed sheets of iron, assembled using rivets.

The rotor is connected to a shaft, and spins between two pieces of a permanent magnet inductor. This part is called **stator**. The $\vec{B}$ field can be created using an electromagnet connected directly to the power supply of the rotor, or another source.

The **bipolar rotor** (Fig. 3 a) is a double T with a continuous winding, whose extremities are connected to the collector rings. It's made of 2x380 turns. For the **tripolar rotor**. (Fig. 3 b), the extremities of two neighboring coils are connected together to a collector ring and a collector bridge (in this case, 340 turns per coil). The **drum rotor** in figure 3c is made of 80 coils of 80 turns each, connected in series. The connections to the collector rings and bridges are indicated in the diagram, The **short circuit rotor** (Fig. 3d) is made of iron sheet in which a lighter metal was cast.

IV. DIFFERENT TYPES OF CONTINUOUS MOTORS

The continuous motor using permanent magnets is not the only possibility. Often, the magnets are replaced by electromagnets (coils and continuous current). The coils are called *excitation coils*, or *inductive coils*. We can distinguish 4 different types of motors, differing by their electrical setup

Independent excitation motor: The inductor can either be a permanent magnet, or an electromagnet connected to a different power source than the rotor.

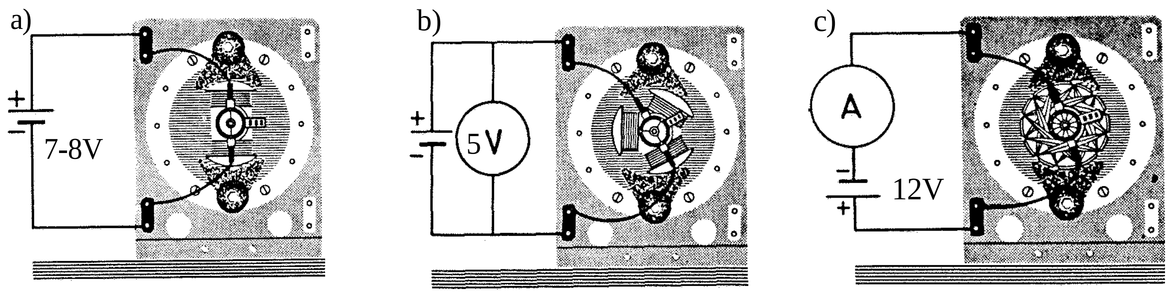

Fig. 4: Independent excitation motor: a) bipolar rotor b) tripolar rotor, c) drum rotor

Series motor (Fig. 5a): Rotor and inductive coils (250 turns) are connected in series. The voltage must remain below 15 V.

Shunt motor (Fig. 5b): Rotor and inductive coils (250 turns) are connected in parallel. The voltage must remain below 10 V.

Compound motor (Fig. 5c): One inductive coil is connected directly to the power supply, whereas the other is connected in series to the rotor. The applied voltage must remain under 10 V.

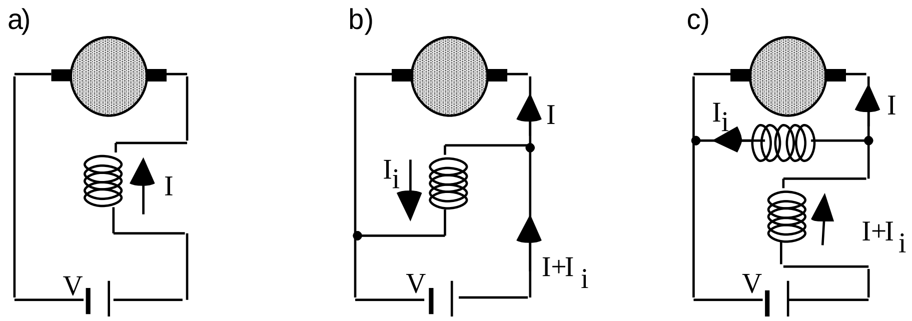

Fig. 5: Motors excited using inductive coils. Connections: a) series, b) shunt, and c) compound

V. A FEW CHARACTERISTICS OF MOTORS

a) Motor torque (see page 36, Leybold instruction)

The force applied by an inductive field on the coil supporting the current depends on the intensity of the field, and the intensity of the current. A tangential force dF is applied to every length element dl on the circumference of a shaft. The motor's torque will be:

$$\vec{M} = \oint_{poulie} \vec{r} \times d\vec{F} = \vec{k} \oint r dF \qquad (8)$$

r is the shaft's radius and $\vec{k}$ a unit vector in the direction of the axis.
Motor torque can be measured using a configuration with two dynamometers and a wire.
A wire is passed around the pulley, the two ends of which are each attached to a dynamometer (Fig. 6). The dynamometers are attached to support material. Using the latter, different braking forces are applied to the motor. The tangential force is the difference $F_2 - F_1$, from which we can determine the torques for different loads. By varying the traction force F_2, the braking force acting on the rotor is modified in stages.

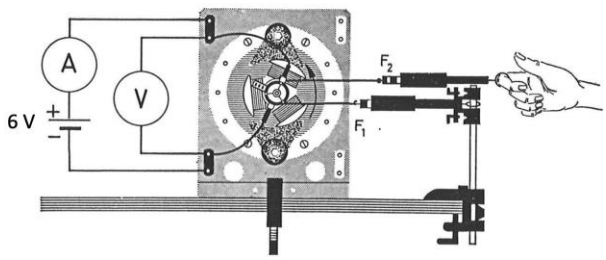

Fig. 6 : Scheme of tangential force measurement

b) Motor efficiency

Electric motors absorb electrical energy and supply mechanical energy. In that sense, they work a energy transformers. By efficiency η, we mean the ratio:

$$\eta = \frac{P_m}{P_e} \qquad (10)$$

P_m is the developed mechanical power, and P_e the absorbed electrical power. P_e is the total supplied electric power. It is calculated by measuring the output current and voltage. The supplied mechanical power can be determined using a setup with two dynamometers and a string. It is expressed as

$$P_m = F \cdot 2r\pi \cdot f_r \qquad (11)$$

where r = 12 mm is the radius of the pulley and f_r the number of rotations per second.

c) Induced counter-voltage in the rotor (see page 33, Leybold instruction)

The effective voltage U_R at the terminals of the rotor depends on the voltage U_G applied minus the voltage U_M induced in the opposite direction:

$$U_R = U_G - U_M = RI_R \qquad (12)$$

The setup on figure 6 allows us to measure U_G and the induced current I_R once the motor reaches its stationary rotation speed. Knowing the rotor's resistance, we can calculate U_M. We can calculate with Ohm's law the value of the resistance of the rotor when the rotor is not rotating and U_M = 0 V.

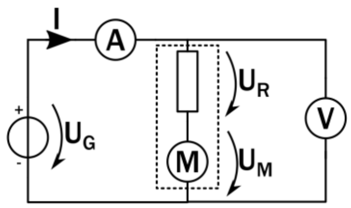

Fig.7: Measurement of the counter-voltage

d) Starting current (see page 33, Leybold instruction)

For a constant excitation field, the voltage in the rotor varies with its rotation speed. An motor starts a 0 turns/min, to reach 5000 turns/min shortly after (depending on the applied voltage).

Therefore, the supplied current can quickly rise while the rotor is starting, and getting from zero to a constant rotational speed. Therefore, the starting current can be 4 to 5 times greater than the current while the motor is running. The risk of overheating the rotor is present.

e) The rotational speed of the motor depends on the intensity of the current and the intensity of the inductive field (see page 36 Leybold instruction)

The force with which a conductor with a current is moved in a magnetic field depends on the length of the conductor, the intensity of the current going through said conductor, and the intensity of the field. The speed of the rotor is therefore determined by the number of turns it has, as well as the intensity of the current flowing through it and the electromagnets

f) Electric braking (pages 44 et 45, notice Leybold)

If we switch the direction of the current in the rotor without inverting the polarization of the field, the rotor switches directions. If we turn off the current at the exact moment it switches directions, the rotor stops. *Inverting the current* constitutes an easy way of achieving electric braking.

Resistive electric braking. While it's running, all motor acts simultaneously as a generator. It produces a counter voltage in the opposite direction than the one supplying it. When the rotor's power supply is cut, the only voltage left is the counter voltage, which will slow the rotor down.

VI. SUGGESTED EXPERIMENTS

VI.1. Simple bipolar and multipolar models with permanent magnets.

Mount the setup shown in figure 8.
Start by mounting the stator. It's made of two permanent magnets, and iron cores. The direction of the magnets is important! Make sure the magnets attract one another.

Put some oil on the axis, than place the rotor. Oil strongly decreases friction, and allows the motor to run much more efficiently. A thin layer is sufficient.
Attach the brushes on the axis, pushing against the commutators. The orientation of the brushes is very important. With the available rotor, the motor is most efficient when the brushes are at a small angle with the magnetic field.
Connect the rotor to the power supply. Measure the current and tension of the rotor with the multimeters in DC mode.

When starting the rotor, apply a voltage gradually. The bipolar rotor needs to be started by hand. The tripolar and drum rotor start on their own.

Sparks can be well observed at every switch of commutator. The magnitude of these sparks varies with the orientation of the brushes. The motor is most efficient when these sparks are smallest and when its rotation speed is maximal. Find this position for each rotor.

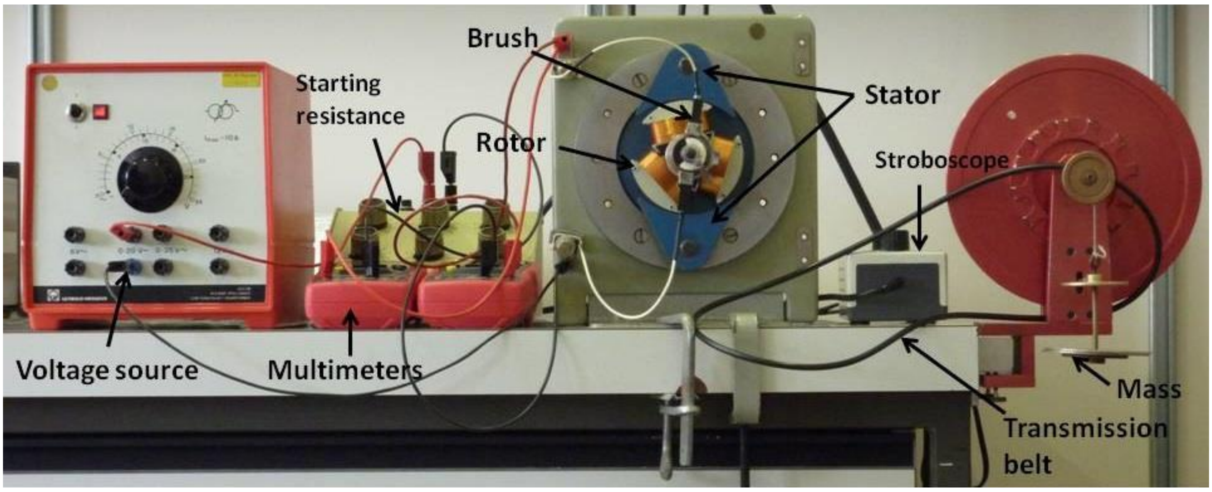

Fig. 8 : Image of the setup using permanent magnets

Measurements to be made

Induced counter-voltage: Vary voltage applied to the system, and measure the angular velocity, as well as the current and voltage of the rotor.
The speed of rotation is measured using a revolution counter. To know the resistance of the rotor, it is necessary to measure the voltage and the current also when the motor is not running.
Make measurements for bipolar and tripolar rotors. Discuss the evolution of the induced counter-voltage as a function of the speed of rotation and the number of turns in the rotor.

Efficiency and torque: Assemble the setup in Fig. 9.
Determine the mechanical power supplied by the motor, and divide it by the electrical power supplied to the motor to obtain the efficiency. Also determine the torque supplied by the motor.
Establish measurements for bipolar, tripolar and drum rotors. Discuss the evolution of efficiency and torque as a function of the speed of rotation.

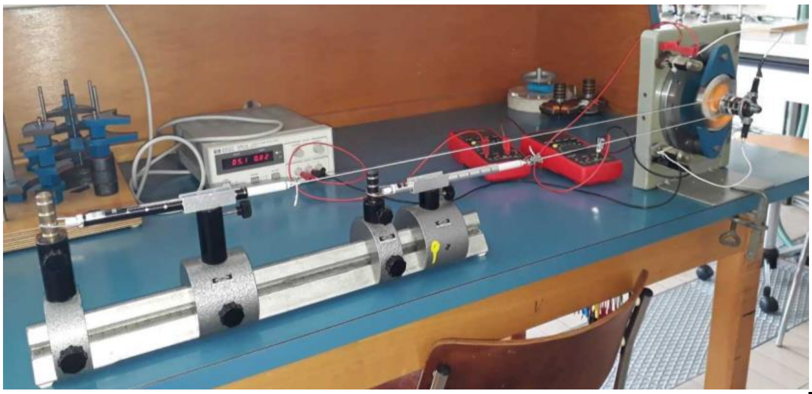

Fig. 9 : Photo of the assembly with two dynamometers and a wire for measuring the tangential force

VI.2. For a bonus

If the measurements described above are of a good quality, you can discuss with your assistant and make additional experiments. For example:
- Generator: Use the crank to impose a rotational speed on the motor. Study the voltage and the power available as a function of the speed of rotation. For a precise rotation frequency, you can use “pause (0.5); beep ”on matlab or an application (“ Natural Metronome ”on Android).

- Setup with coils to induce the magnetic field and measures related to this assembly
- Study of the voltage at the motor terminals using the oscilloscope.