SZÉCHENYI ISTVÁN EGYETEM
AUDI HUNGÁRI JÁRMŰMÉRNÖKI
KAR

MAGNETIC BASICS AND EXPERIMENTS

Measurement practice I.

FOR VEHICLE ENGINEER STUDENTS

Version: 1.0

Széchényi István University
Department of Power Electronics and Drives

1. Introduction

The imaginary lines which represent the direction of magnetic field, are known as magnetic lines of force. Magnetic lines of force are closed curves. Outside the magnet their direction is from north (N) pole to south (S) pole.

1.1 Objectives

- Illustration of magnetic force lines;
- Investigate permanent magnets;
- Investigating and illustrating induced voltage;

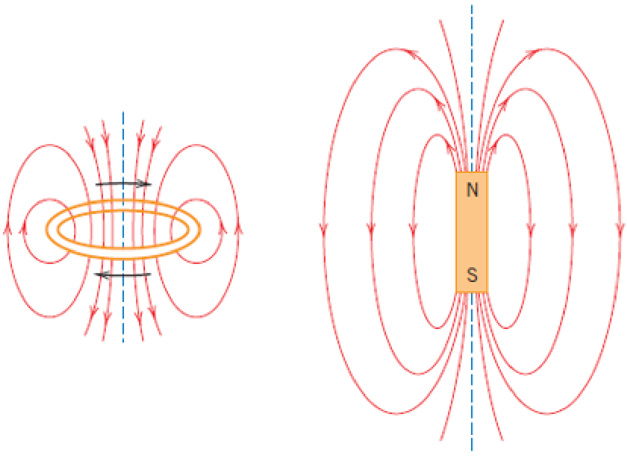
2. Literature review

2.1 Magnetic basics

The magnetic field cannot be detected by human senses, it can be detected by its effects:

- Force (attraction/ repulsion);
- Current-carrying conductor;
- Induction effect.

Experimentally, it can be demonstrated that a magnetic field can be created by a permanent magnet or by a conductor with a current carrying it (see Fig. 1.).



a. **b.**

Fig.1. The current carrying wire (loop) and the magnetic field of the permanent magnet

Fig. 1. shows that in all cases the magnetic lines of force are closed, and in all cases they point from the north pole (N) towards the south pole (S). The magnetic field is represented by lines of force. One way of illustrating this is to put an iron filling near a permanent magnet (it works the same way for a conductor with current flowing through it) (see Fig. x.).

The permanent magnet or the field around the conductor through which the current flows can be described by the magnetic field strength. Its symbol is **H** and its unit is [*A/m*]. If created by current, the magnetic field can be described as follows:

$$H = \frac{Ni}{l}, \text{ where} \tag{1}$$

- H – magnetic field strength [A/m];
- N – number of turns [-];
- i – current [A];
- l - distance from conductor [m].

From the (1) equation, it is clear that the higher the excitation current, or the higher the number of turns in the coil, the greater the magnetic field strength, and the further away from the conductor the smaller the magnetic field strength. The magnetic field strength is a vector quantity, so its direction is not indifferent. Its direction can be determined by the right-hand rule (see Fig. 2.).

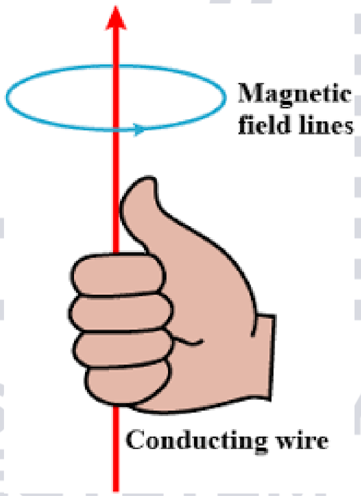


Fig.2. Right hand rule in current carrying wires

The first equation included an important parameter, the number of turns. We could see that if the space is not created with one conductor but with several, the resulting magnetic field will be larger. So,

$$Ni = Hl \tag{2}$$

The second equation is called Ampère's law in magnetostatics.
Different materials behave differently when placed in a magnetic field. This depends on whether there are so-called domains (elementary magnets) inside the material. These can be thought of as tiny "dominoes" (Figure 3/a). They are normally disordered in the material (Figure 3/b). If you place the material in a magnetic field, they will start to arrange themselves Figure 3/c). After the alignment, the magnetic field of the domains is added to the external field, so the magnetic field is multiplied. This property of the materials is the relative permeability. (μ_r).
In this regard, materials can be divided into 3 groups:

Table 1. Relative permeability of materials

Group	**Material (example)**	μ_r
Ferromagnetic	Iron	300 – 6000
	Permalloy	500 – 300 000
Paramagnetic	Aluminum	1,000022
	Tin	1,0000043
Diamagnetic	Water	0,9999901
	Gold	0,99997

From the first table, ferromagnetic materials greatly increase the magnetic field, while paramagnetic materials increase it very slightly and diamagnetic materials decrease it.

Relative permeability determines how the magnetic induction changes when the space is filled not with air (vacuum) but with some other material. The symbol of magnetic induction is **B** and its unit is [T] or [Vs/m^2] (in honor of Nikola Tesla.) So,

$$B = \mu H \tag{3}$$

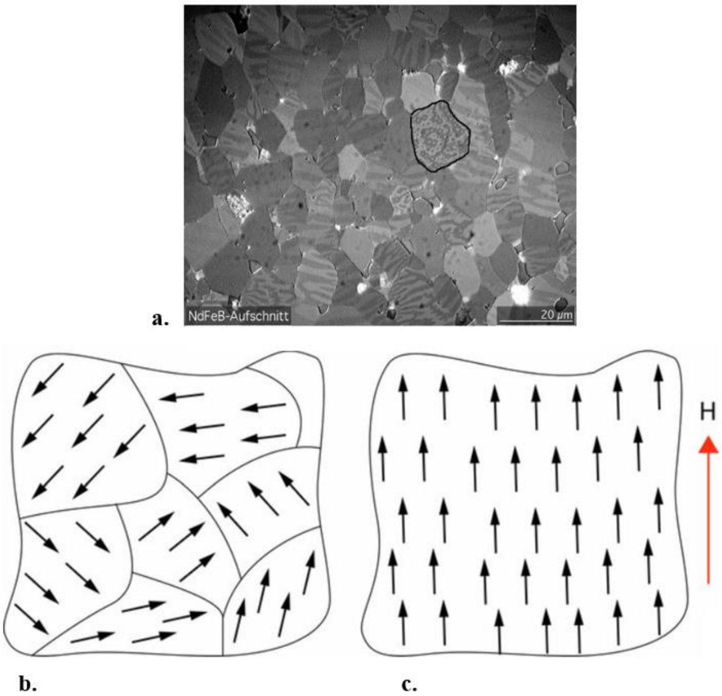


Fig.3. Magnetic domains

Accordingly, two types of magnetic circuit can be defined:

- $B = \mu_0 H$ (magnetic force lines in the air);
- $B = \mu_0 \mu_r H$ (magnetic lines of force in some material), where

μ_0 – is the permeability of vacuum: $4\pi 10^{-7}$ [Vs/Am].

What is the practical significance of this? If we know that $H = Ni/l$, then we can achieve a much higher magnetic induction with a much lower excitation current ("stronger magnet").
Magnetic induction (**B**) is also known as magnetic flux density: the measure of **B** is the density of lines of force passing through a closed surface. The symbol of flux is **Φ** and its unit is [Vs].
The total flux that passes through a given surface can be calculated from

$$\Phi = BA, \text{ where} \qquad (4)$$

A - the surface perpendicular to the induction lines.

It follows that if the flux (the number of magnetic lines of force) is constant, the smaller the surface area, the greater the magnetic induction. This is similar to a current flowing through a wire. In both cases, heating occurs.

Let's summarise the basic magnetic quantities (not exhaustive):

Table 2. Basic magnetic quantities (not exhaustive)

Quantity	Sign	Unit
Magnetic field strength	**H**	*A/m*
Magnetic induction	**B**	*T* or *Vs/m*^{2}
Magnetic flux	**Φ**	*Vs* or *Wb*
Permeability	**μ**	*Vs/Am*

2.2 Force in magnetic field

Personal experience shows that the magnetic field also manifests itself as a force (see Fig. 4.).
We use this in many applications, e.g. magnetic cranes, electric motors.
Experiments show that identical magnetic fields repel each other and different magnetic fields attract each other. These phenomena manifest themselves as a force effect.

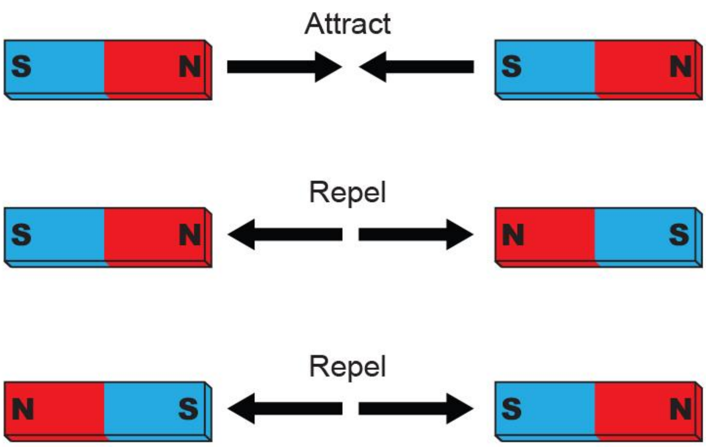


Fig.4. Magnetic forces

If one of the magnetic fields is created with a current instead of a permanent magnet, the magnitude and direction of the resulting force can be controlled.

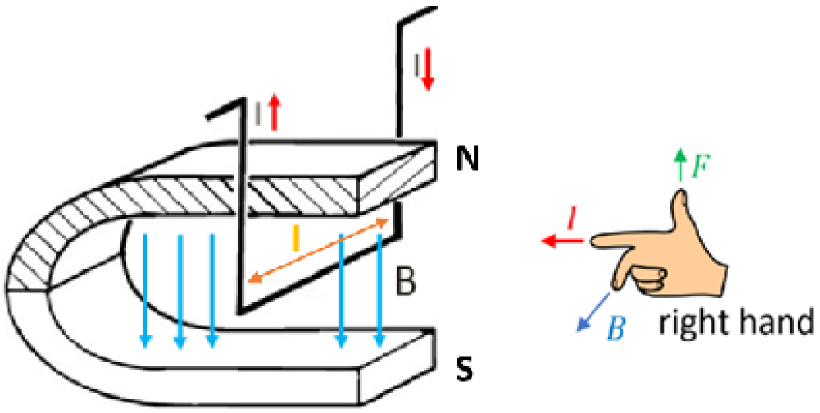


Fig.4. Magnetic forces – experiment- and the “right hand rule”

As shown in Fig. 5., a conductor (single-ended coil) is placed inside a horseshoe magnet. The magnetic lines of force of the horseshoe magnet point from pole N to pole S. When current flows in the conductor, the conductor moves depending on the direction of the current. The displacement depends on the magnitude of the current (since the magnetic field of the magnet is assumed to be constant). Depending on the direction of the magnetic field and current, the direction of the force generated can be determined by the right-hand rule. The resulting force is:

$$F = Bil, \text{ where} \qquad (5)$$

B – magnetic induction vector;
i – excitation current;
l - length of the wire (which is in a magnetic field).

The force will be highest when the magnetic field is perpendicular to the conductor. If not, then

$$F = Bil \sin(\propto), \text{ where} \qquad (6)$$

$\propto$ - The angle closed by the perpendicular.

From this point of view, it's not hard to imagine that if you use several parallel lead frames and are able to change the direction of the current in the wire, you've already built your electric motor (see. Fig. 5.).

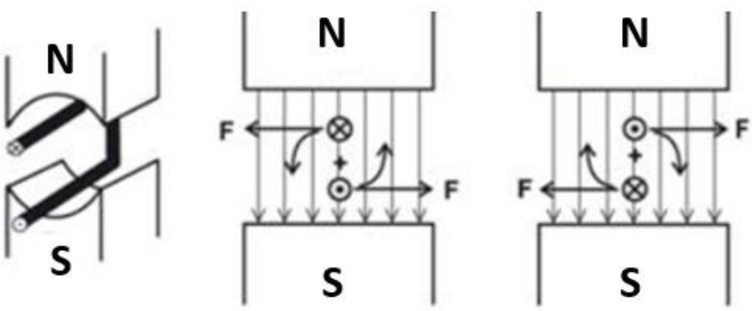


Fig.5. Electric motor basics

2.3 Magnetic coil

The magnetic field of the current-carrying conductor has been discussed several times. It was found that the magnetic field generated depends on the magnitude of the current flowing through the conductor. As can be seen in Fig. 2., the direction of the resulting magnetic field can be determined by the right-hand rule. Examining equation (2), the magnetic field can be increased if the magnetic field is created by multiple turns rather than a single "turns" conductor, i.e:

$$H = \frac{Ni}{l} \tag{7}$$

Fig. 6. shows that the right-hand rule still applies for each round. At point “A” the current flows into the plane and at point “B” the current flows out of the plane. The magnetic field inside the coil is the sum of the magnetic fields of the number of turns. This kind of arrangement is called a solenoid coil. The iron core and iron core-less solenoid coil physical design and circuit diagram are shown in Fig. 7.

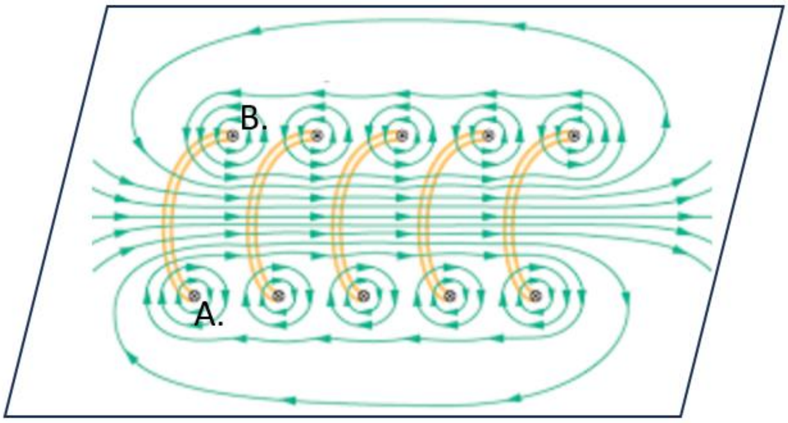


Fig.6. Magnetic field of solenoid coil

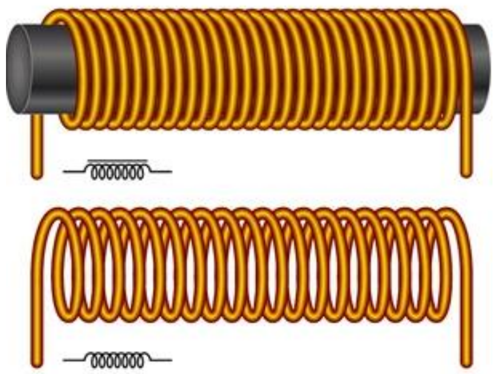


Fig.7. Iron core and iron coreless solenoid coil design and circuit symbol

2.3 Types of magnetic induction

The phenomena associated with changes in the magnetic field are called electromagnetic induction. The study of this is associated with Faraday (1831). There are several forms of electromagnetic induction:

- Motion (or Dynamic) induction;
- Rest (or Static) induction;
    - Self-induction;
    - Mutual induction.

Motion or dynamic induction occurs when a conductor moves through a magnetic field, cutting through magnetic flux lines, which induces an electromotive force (EMF) in the conductor. The key factor here is motion between the conductor and the magnetic field. This principle is used in generators, where mechanical motion is converted into electrical energy.

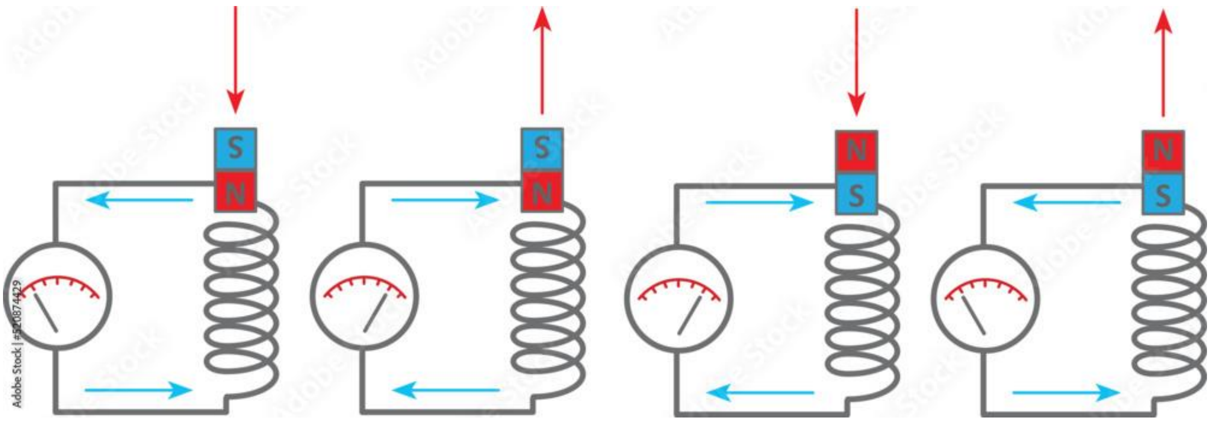


Fig.8. Motion (or Dynamic) induction

As can be seen in Fig. 8., the magnetic field and the direction of motion are not indifferent to the direction of the induced voltage (current). It can therefore be seen that the direction of the induced voltage changes if the induction (magnetic field (**B**)) or the direction of motion changes.

Resting (or static) induction occurs when the magnetic flux through a stationary conductor changes over time. A changing magnetic field without physical motion induces EMF in the conductor. In slightly simpler terms, the elements or components that create the magnetic field (induced voltage) do not move, but the magnetic flux changes. That is, the change in magnetic flux over time generates an induced voltage:

$$u_i = -\frac{d\Phi}{dt} \tag{8}$$

This is a key principle in transformers, where alternating current in the primary winding creates a varying magnetic field (magnetic flux) that induces voltage in the secondary winding. As shown in Fig. 9. The transformer will be discussed in more detail in the second measurement lab.

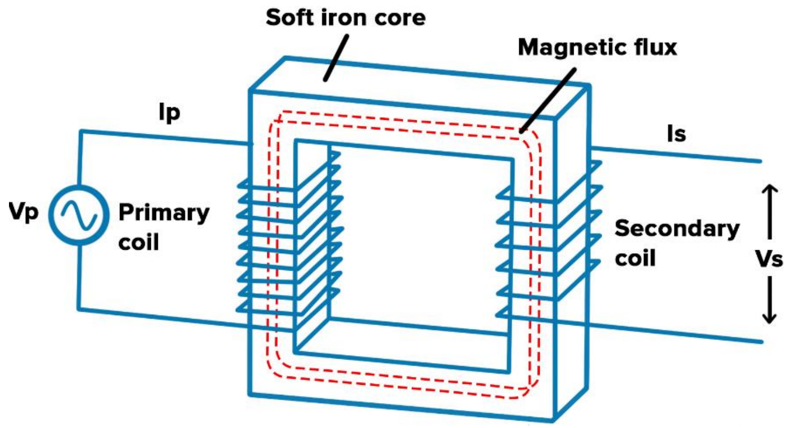


Fig.9. Construction and operating principle of transformer

To take the idea further: since the magnetic field is generated by the current, if the current in a coil is changed, an induced voltage is generated in the coil, i.e.:

$$u_i = -\frac{d\Phi}{dt} = -L\frac{di}{dt}, \text{ where} \tag{9}$$

L - is the self-inductance of the coil.

Self-inductance is the property of the current-carrying coil that resists or opposes the change of current flowing through it. The symbol of self-inductance is L and its unit is [H] -Henry-. The self-inductance is the coil's own parameter. The self-inductances of real coils are of the order of μH, mH and nH.

Mutual inductance is defined as the ratio between the EMF induced in one loop or coil by the rate of change of current in another loop or coil. Mutual inductance is given the symbol M. Very good examples are electric toothbrush chargers or wireless phone chargers (see Fig. 11.).

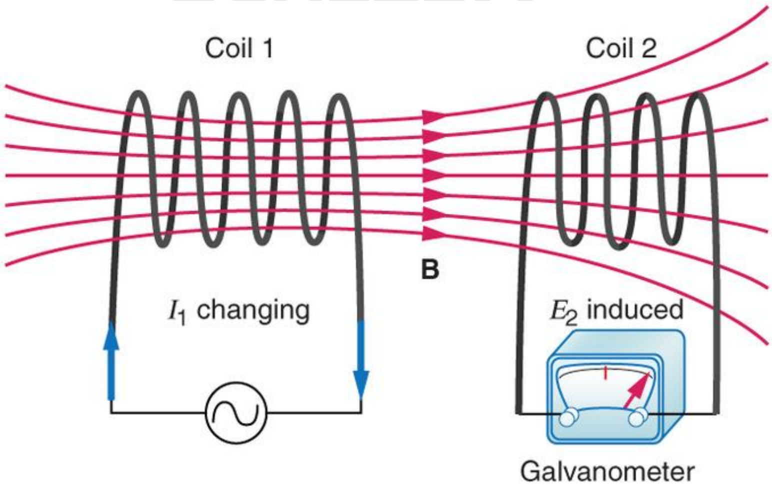


Fig.10. Mutual induction

Fig.11. Demonstrating mutual induction: toothbrush and wireless phone charger

2.4. Magnetic hysteresis

Remember: the current flowing through a resistor and the voltage across it are directly proportional. In other words, for a higher voltage, the current will be higher.

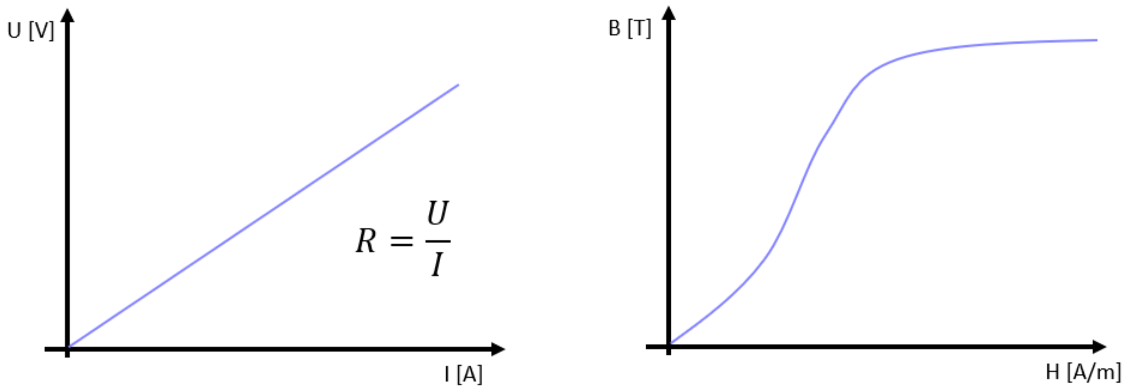


Fig.12. Resistor V-I characteristic vs. magnetic cores B-H characteristic

For magnetic cores, higher field strength (**H**) does not necessarily result in higher magnetic induction (**B**) in the magnetic core. Moreover, the magnetic core "saturates" after a given magnetic field strength (see Fig. 12. right graph and Fig. 13.). The reason for this is that the magnetic domains are already fully "aligned" with the magnetic field, they can no longer "align better". It can be seen and felt that mathematically this process is more difficult to describe using equations, such as Ohm's law.

If the magnetic core is examined in both directions, the hysteresis characteristics of the magnetic core are obtained (see Fig. 13.). The characteristics of different types of magnetic cores are different. However, the loss of iron core hysteresis is proportional to the area of the BH curve. It is interesting that this is frequency dependent: the "shape" of the curve depends on the frequency of the excitation current.

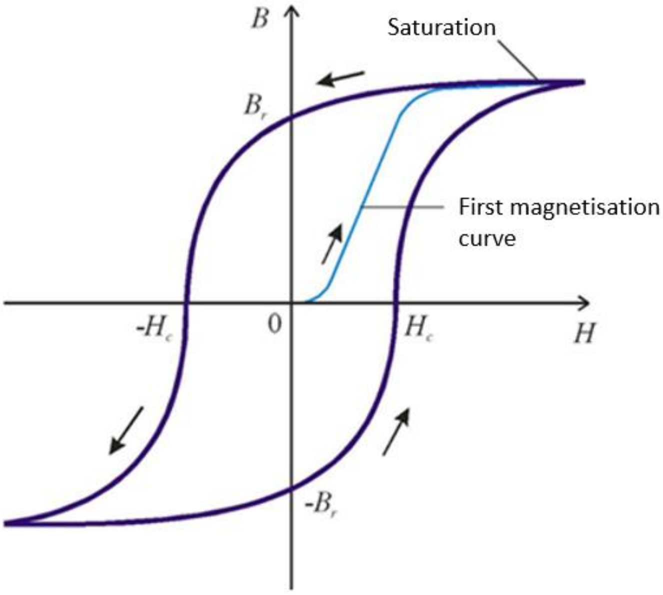


Fig.13. Hysteresis curve of magnetic core

3. Experiments

kísérletel:
tekercs belsejébe mágnes (mozgási indukció) + eltérő menetszámú tekercsek

3.1 Illustration of magnetic force lines

3.1.1 Magnetic field of bar (permanent) magnet

In this experiment we will investigate and detect the magnetic field of a permanent (bar) magnet using iron filings (see Fig. 14.).

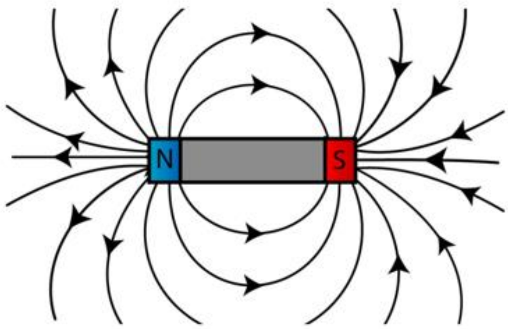


Fig.14. Magnetic field of permanent (bar) magnet

3.1.2 Magnetic field of current carrying wire

In this experiment, we investigate the magnetic field of current carrying wire: a magnetic field of a multiturn-conductor. To illustrate the magnetic field, we use iron filings, in the same way, like in case of permanent magnets. (see Fig. 15.).

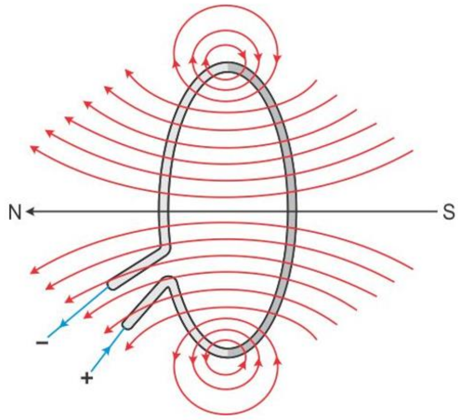
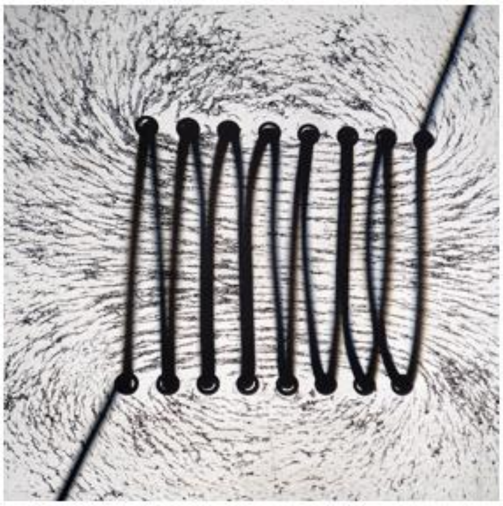


Fig.15. Magnetic field of a multiturn conductor

3.1.3 Magnetic field of solenoid coil

In this experiment, we investigate the magnetic field of a solenoidal coil. Iron filings are also used to detect the magnetic field. During the experiment we will vary the excitation current of the coil (see Fig. 16.).



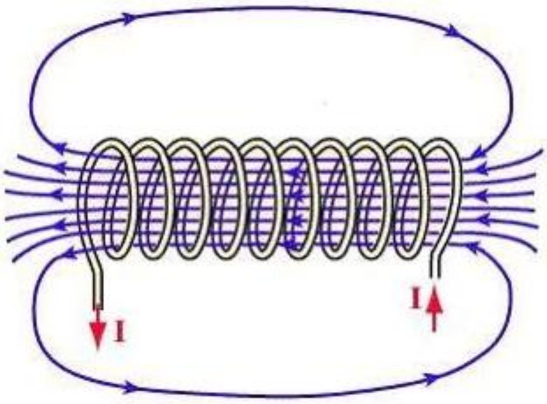


Fig.16. Magnetic field of a multiturn conductor

Conclusion, questions:

- How can the magnetic field be detected?
- Are the magnetic lines of force open or closed?
- Where do the magnetic lines of force point from and to?
- Is there any difference between a permanent magnet and the magnetic field of a wire (coil)?

3.2 Investigate and illustrating of induced voltage

3.1.1 Motion (or Dynamic) induction

In this experiment, we will investigate motion induction, i.e. how we can "create" induced voltage by motion. To do this, we need the experimental tool shown in Fig. 17.

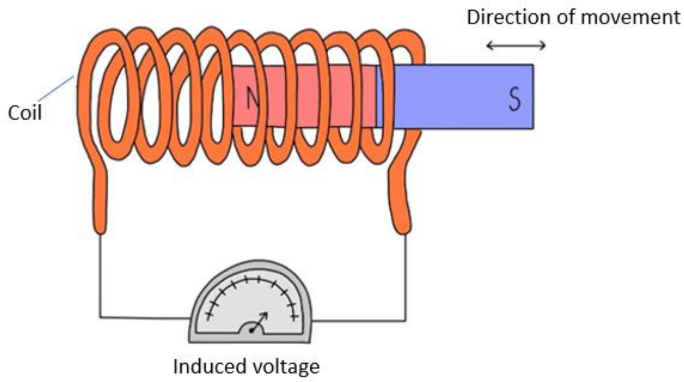


Fig.17. Induced voltage experiment

The experiment is run with three different numbers of turns (1200, 600 and 300) and the permanent (bar) magnet is moved forward in the coil, first with the north (N) pole and then with the south (S) pole.

Conclusion, questions:

- How does the direction of the induced voltage depend on the pole of the permanent magnet?
- How does the magnitude of the induced voltage depend on the number of turns? Is the higher induced voltage generated in the smaller or the higher number of turns?
- How does the magnitude of the induced voltage depend on the speed of movement?

3.1.2 Motion induction in rotating frame

The experiment will show that when a coil is rotated in a magnetic field, a voltage is induced in it. In this experiment we will investigate the principle of DC generators. The experimental setup (equipment) is shown in Figure 18. In its operation we have to examine an important component, the so-called commutator. For its operation, follow Figure 19. The commutator is responsible for the DC current at the output (points x and y). In other words commutator is a mechanical rectifier. Looking at the Fig. 19., in both cases, point x will be the negative output and point y the positive one.

Looking at the diagram on the left: if the frame is rotated from left to right, and the magnetic field is from left to right (from N to D), the current flows (in a closed circuit, of course) from point B to point A, and further from D to point C. The force is therefore upwards on the left side of the frame and downwards on the right side (due to rotation).

In the figure on the right, rotation causes edge AB to move to the right, while edge CD moves to the left. Accordingly, the force is down on the right and up on the left (due to rotation). Since we are talking about a DC generator, the current should flow in the same direction.

Accordingly, commutator segment C1 is connected to the + point and C2 to the negative point (In the figure on the left it was the other way round.).

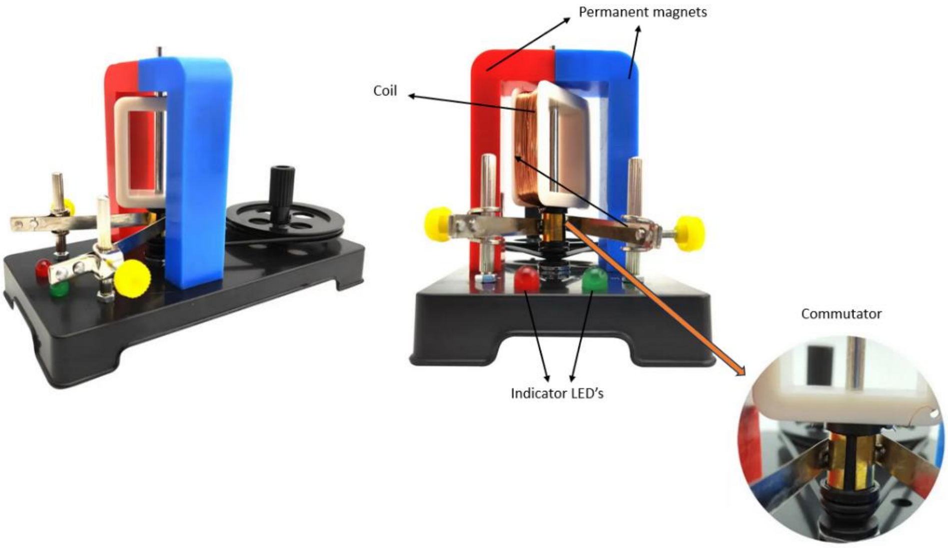


Fig.18. An experimental tool for motion induction

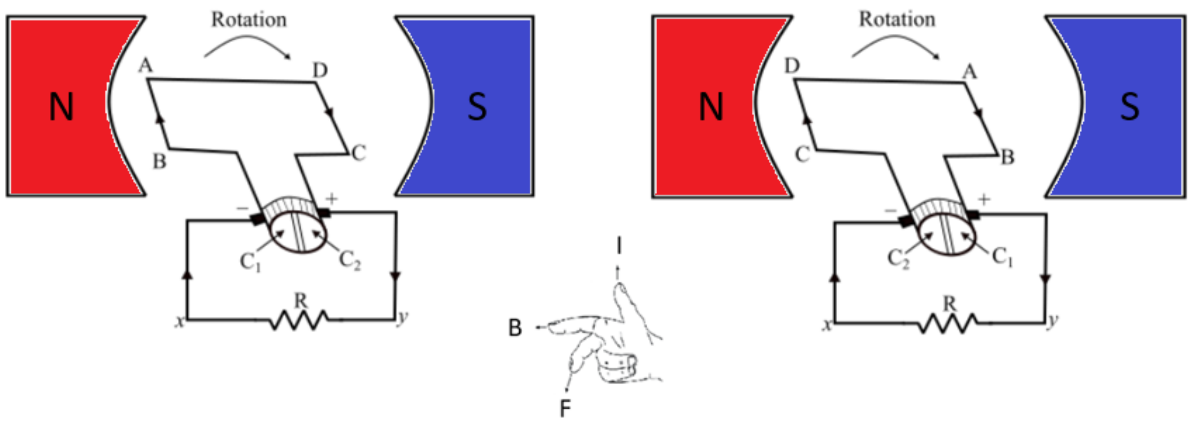


Fig.19. Working principle of commutator

5. Conclusions

6. Homework

7. References

[1] Electrical Engineering for Technical Secondary Schools, Student's book, Form Three.
[2] https://www.tutorialspoint.com/action-of-commutator-in-dc-generator