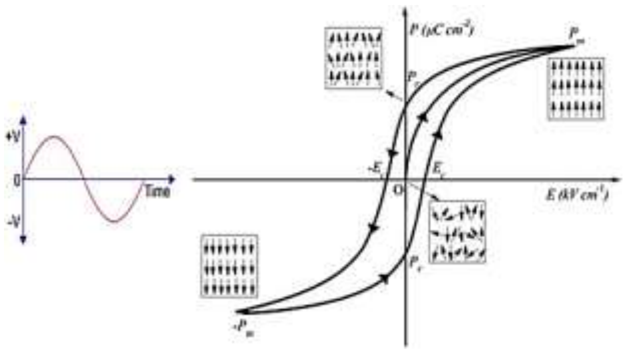
الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research
Mohamed Boudiaf University of M'sila
Faculty of Technology
Department of Electrical Engineering

وزارة التعليم العالي والبحث العلمي
جامعة محمد بوضياف – المسيلة
كلية التكنولوجيا
قسم الهندسة الكهربائية

Course Handout: Electrotechnical Materials
3rd Year Bachelor's Degree:
Electromechanics



Prepared by Dr. Khaled BELHOUCHET

Academic Year: 2025/2026

Chapter I. Magnetic materials

1.1. *Introduction:*

Certain substances subject to magnetic induction begin to produce themselves, in the volume they occupy and outside, a magnetic induction. They are said to magnetize *or* polarize magnetically. They are called *magnetic materials*. Electric machines operate in useful zone “2” (slightly saturated). In saturated zone “3”, the current I creating B is too high (heating of the machine). In linear zone “1”, field B is too weak.

The slope of the B-H curve at some location on its curve is its incremental permeability at that location. However, sometimes the permeability is measured from the origin to the location of interest, and that slope is called its apparent permeability, μ.

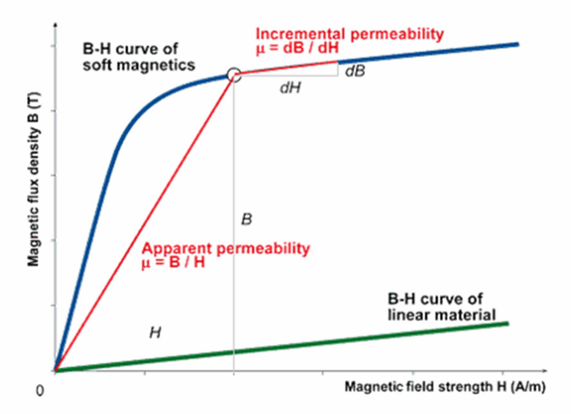


Fig. 1.1. Magnetization curve and permeability

For non-magnetic materials that do not saturate, the curve has a fixed slope approximately equal to μ_0. For Diamagnetic materials have a slightly smaller slope. And for Paramagnetic materials have a slightly greater slope

1.2. *Magnetic Field Theory:*

1.2.1. *Magnetic induction B and magnetic field H in vacuum:*

In a vacuum, Induction$\vec{B}$ is created by an electric circuit traversed by a current **I.** At a given point M in space, we always have a relation of the type:

$$\|\vec{B}\| = B_M = \mu_0 . K . I \qquad \text{(IV.1)}$$

and we thus define the magnetic excitation vector $\overrightarrow{H}$ which verifies the relationship:

$$\vec{B} = \mu_0 . \vec{H} \qquad \text{(IV.2)}$$

B in Tesla and **H** in A/m

The constant of proportionality $\mu_0 = 4\pi * 10^{-7}$ H/m, we call μ_o the magnetic permeability of the vacuum.

4.2.2. *Atomic magnetic moment. Instrument for studying magnetic materials:*

The magnetic moment of an atom is represented by two models:

- The magnetic dipole m_d

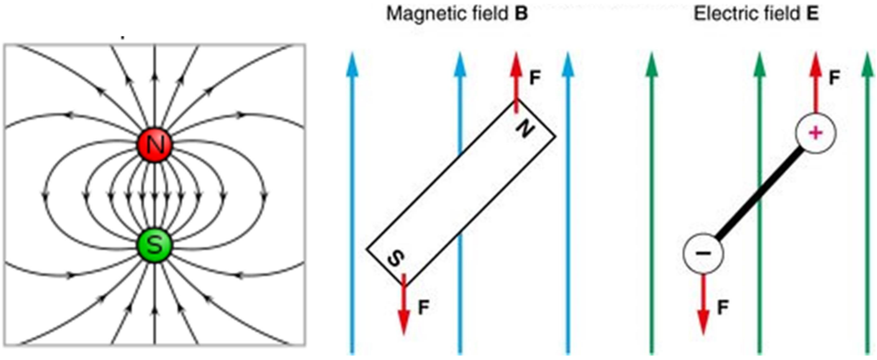


Fig.1.2. The magnetic dipole and Analogy with electric dipoles

- The amperian current m_A.

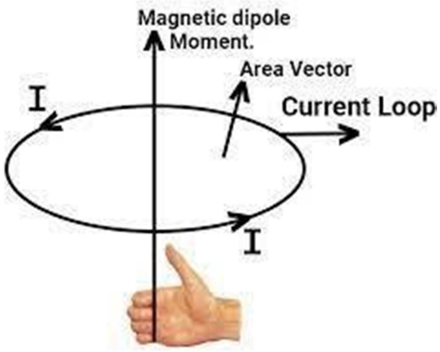


Fig.4.3. The Amperian current

Which are defined respectively by:

$$\boldsymbol{m}_d = m\,\boldsymbol{l}\ [\text{ Wb.m }] \qquad \text{(IV.3)}$$

$$\boldsymbol{m}_A = i\,\boldsymbol{a}\ [\text{ Am}^2\ ] \qquad \text{(IV.4)}$$

A is the vector representing the surface delimited by the circular current *i* .

1.2.3. Magnetization vector and magnetic polarization vector :

The magnetic induction in matter can be expressed by the equation

$$\boldsymbol{B} = \mu_o\,(\,\boldsymbol{H} + \boldsymbol{M}\,) \qquad \text{(IV.5)}$$

$$\boldsymbol{B} = \mu_o\,(\,\boldsymbol{H} + \boldsymbol{I}\,) \qquad \text{(IV.6)}$$

With: the *magnetization vector* ***M***, measurement of the volume density of amperian magnetic moment. The unit of ***M*** is ampere per meter. THE *magnetic polarization vector I*, measurement of the volume density of the dipole magnetic moment. The unit of I is the Tesla.

1.2.4. Magnetic permeability:

We call *absolute magnetic permeability* µ the magnitude

$$\mu = \mu_o + X = \mu_o\,(1 + X_r\,)\ \text{H/m} \qquad \text{(IV.7)}$$

Relative magnetic permeability

$$\mu_r = \mu/\,\mu_o \qquad \text{(IV.8)}$$

1.2.5. Magnetic susceptibility:

The magnetization M is proportional to the applied magnetics excitation H: the proportionality coefficient, noted χ, defines the magnetic susceptibility of the medium or material considered.

M= xH (IV.9)

In the general case, we define susceptibility by:

$$X_m = \frac{\partial M_{m,H}}{\partial H}\Big|_{H=0} \quad \text{(VI.10)}$$

There are several types of magnetism:

- When X is negative, we say that the body in which the magnetization appears is diamagnetic.
- When X is zero, we have a vacuum.
- When X is positive, the body is said to be paramagnetic.
- When X is positive and very high, the paramagnetic body is said to be ferromagnetic.

Certain ferromagnetic materials, in addition to their high permeability, exhibit remanence: they retain their magnetization in the absence of excitation. The main materials used are iron, cobalt and nickel.

1.3. The B-H Diagram :

The *BH diagram*, also called magnetization curve or hysteresis cycle, is the response curve of magnetic materials. The BH relationship is not linear since the permeability µ depends on *H,* hence the need for a representation of the function B(H).

The shape of the B-H diagram is based on the magnetic domain theory and it depends on the mobility of the **Bloch walls**, the internal energy of the material and the applied *H field.*

1.3.1. Polarization process and Magnetic Domains:

Magnetic polarization is a physical quantity. It relates to the electrodynamics of macroscopic matter and characterizes the magnetic flux density of a magnetic material in a vacuum when the proportion of the magnetic field is subtracted. And to explain this phenomenon, we consider a single crystal of iron, practically without defects, in which the magnetic domains appear as in the following figure.

As soon as we apply an increasing field H as indicated, the energy of the magnetic moments is increased in the different domains to create a single domain oriented along H which will remain, which causes a displacement of the **Bloch walls**. By cutting H, we therefore find ourselves in the initial state (a), the polarization process is reversible. The shape of the BH diagram can vary depending on the conditions of use and more particularly depending on the amplitude of the magnetic field.

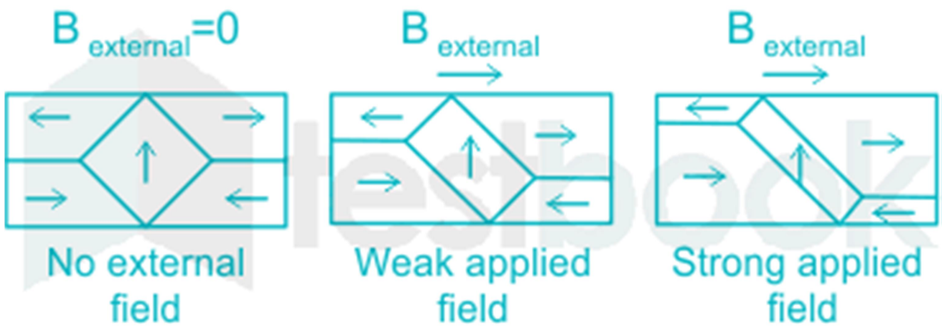


Fig.4.4. The magnetic domains

BH diagram is divided into three zones (Fig. 1.5):

- The *weak field zone:* characterized by a quasi-linear behavior of the material, as well as moderate permeabilities.
- The *zone of average fields:* in which the nonlinear effects are strongly accentuated, while the permeability does not pass its maximum value.
- The *strong field zone:* or *saturation zone where* the permeability decreases and tends asymptotically towards the permeability of the vacuum.

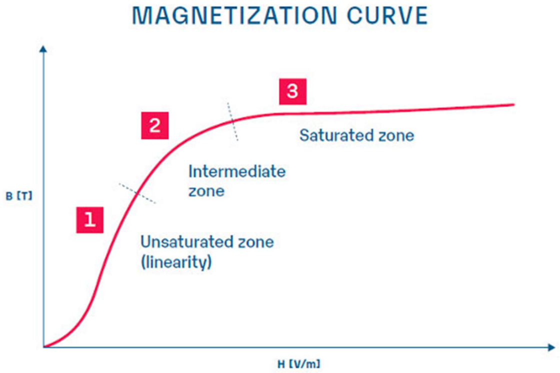


Fig.1.5. Magnetization curve

1.3.2. Polarization process and B-H Loops (hysteresis):

The function *B(H)* observed with increasing field on a sample that has never been polarized (on a macroscopic scale) is called the *first magnetization curve.* With decreasing field, the function *B(H)* deviates from the first magnetization curve, due to the irreversible nature of the polarization.

In the periodic regime, the function *B(H)* takes the form of a hysteresis cycle. Only the temperature (above the Curie point) makes it possible to describe the first magnetization curve once again.

To explain the polarization phenomenon and the hysteresis cycle, i.e. a sample that has never been polarized. That's to say, we consider a magnetic material in the demagnetized state ($B = 0$, $H = 0$ in Fig.1.6). Even though the local magnetic moments show long-range order (typically over several microns), the demagnetized state can be achieved by the formation of magnetic domains. Domains are regions of homogeneous magnetization separated by domain walls, surfaces over which the orientation of the atomic moments changes relatively abruptly (Section II.C). The vector magnetizations of the domains sum to zero in the demagnetized state. Application of a field to a demagnetized sample results in the motion of domain walls so as to expand the volume of those domains having the largest component of *M* along *H*.

The initial flux density, $B = \mu_o(H + M) = \varphi$/area, produced in response to a small field, *H*, defines the initial permeability, $\mu_i = B/H$ H≈ 0. At stronger fields, the permeability increases to its maximum value μ_{max}.

The relative initial permeability, μr, can be as great as 10^5 or $\mu_r\mu_o \approx 10^{-1}$ in some materials.

When most domain wall motion has been completed, there often remain domains with nonzero components of magnetization at right angles to the applied field direction. The

magnetization in these domains must be rotated into the field direction to minimize the potential energy *M-B*.
This process generally costs more energy than wall motion.

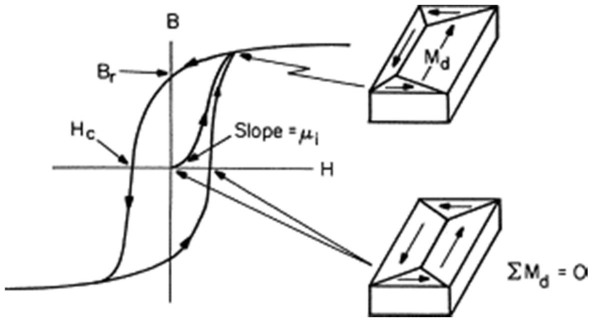


Fig.4.6. Hysteresis loop of a magnetic material showing the variation of B with changing H.

Upon decreasing the magnitude of the applied field from saturation, the magnetization rotates back toward its "easy" directions, generally without hysteresis. As the applied field decreases further, new domains may nucleate and domain walls begin moving back across the sample. Because energy is lost when a domain wall jumps abruptly from one local energy minimum to the next (Barkhausen jumps), wall motion is an hysteretic or lossy process.
The flux density and magnetization remaining in the sample when the applied field is zero are called the residual flux density, *Br*, and remanence, *Mr*, respectively. The reverse field needed to restore *B* to zero is called the coercivity, *Hc*. (The field needed to restore *M* to zero is called the intrinsic coercivity, *iHc*. The distinction between *Hc* and *iHc* is important only in permanent magnets, because in a soft magnetic material $Hc \ll M$ so that $M = 0$ for essentially the same field that gives $B = 0$). H_c is a good measure of the ease or difficulty of magnetizing a material.
In some soft magnetic materials, domain walls can be moved with fields of order 0.1 A/m. In general, defects such as grain boundaries and precipitates cause the wall energy to depend on position, so in most soft magnetic materials, higher fields (of order 10–1000 A/m) are required to move domain walls or rotate the magnetization vector.

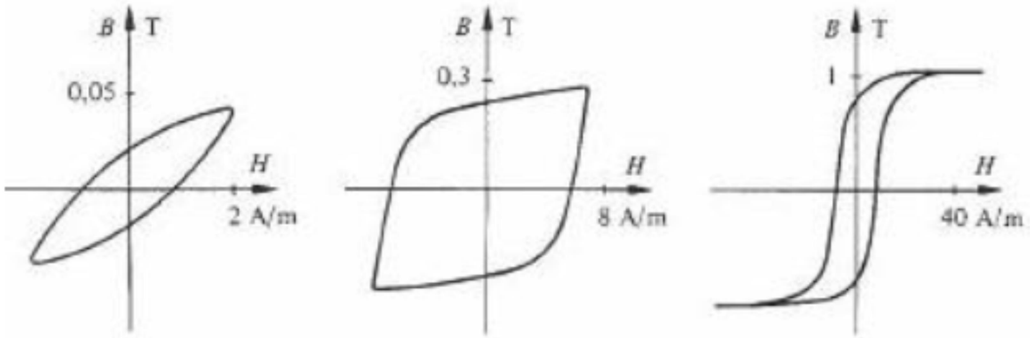


Fig.1.7. Effects of field amplitude on the BH diagram of an iron-nickel alloy.

1.3.3. Remanent induction:

Consider a sample polarized at saturation, that is to say subjected to a magnetic field ***H*** greater than ***H*$_{sat}$**. *Remanent induction **B$_r$*** (***Retentivity)*** *is* called the induction which remains in the sample after H has been reduced to zero.

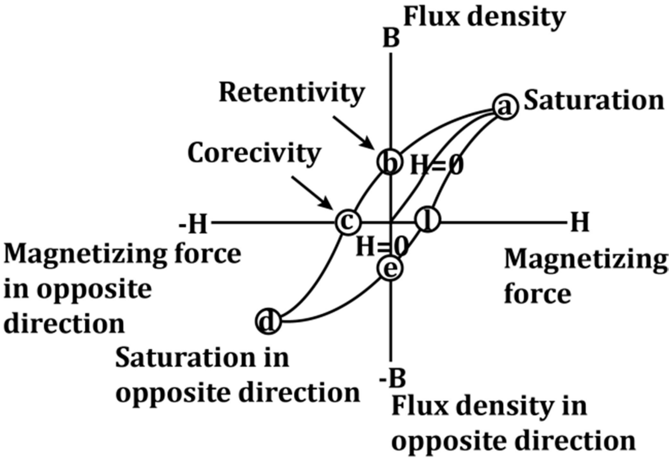


Fig.1.8. Remanent induction

1.3.4. Magnetic losses :

Any variation in induction in a magnetic material causes, within it, a dissipation of energy. This energy most often appears in the form of heat and is generally not recoverable, hence the expression magnetic losses used to designate the phenomenon. There are three types of magnetic losses

1.3.4.1. Hysteresis losses:

The hysteresis loss instead is the energy entrapped in magnetic materials exposed to a magnetic field in the form of residual magnetization -a typical behavior of FM materialswhich is then lost as heat during the demagnetization step.

this losses are due to the work of the braking forces acting on the moving Bloch walls. They are therefore maximum when the pinning forces are greatest, that is to say in hard magnetic materials. Hysteresis losses correspond to the work required to slowly traverse the BH diagram.

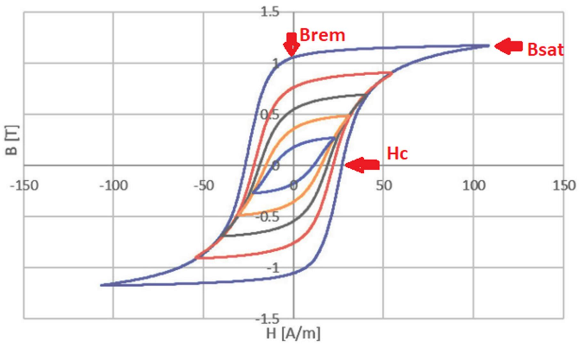


Fig.1.9. Hysteresis losses

Hysteresis of the magnetic circuit: The induction B present in a ferromagnetic material depends on the previous magnetic states:

- After a first “OM” magnetization, the magnetic circuit remains magnetized: remanent induction B_R).

- It is necessary to apply a negative excitation H C to cancel B again: H C = coercive excitement.
- Hysteresis cycle -- hysteresis losses

If we apply an alternating H excitation to a magnetic material, we obtain a hysteresis cycle in the "B,H " plane .

The surface of the cycle accounts for the difficulty in re-magnetizing the magnetic circuit. This results in losses proportional to the frequency f of the excitation H:

$$ph = k_1 f B_{2\ max} \qquad \text{(IV.11)}$$

K_1 depends on the material and is proportional to the surface of the cycle: to reduce losses, the surface of the cycle must be reduced:

Use of soft materials e.g. silicon steel

In permanent magnets, we look for high values of B_R and H_C : it is therefore necessary to increase the surface of the cycle:

Use of hard materials: The magnets are not subject to variable excitation H, the operating point M is fixed (the useful characteristic is in strong lines).

The point M does not move following the hysteresis cycle, and although the surface of the latter is large, the hysteresis losses are zero.

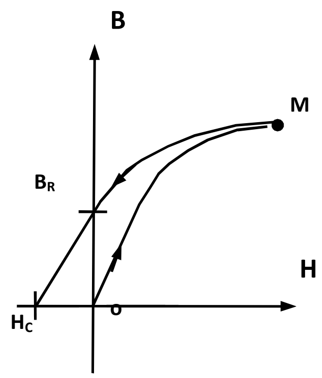


Fig.1.10. Remanent induction

1.3.4.2. Eddy current losses:

Eddy current loss is the Joule effect loss resulting from currents created in any conductive material (magnetic or not), by a flow varying over time. These losses can be significant in materials with low electrical resistivity such as magnetic alloys; they remain at a low level in ferrites.

Induced currents (eddy current losses): The magnetic circuit of most electrical machines "sees" a variable (alternative) induction B. The materials used, very often metallic (mainly iron), also conduct electricity. Thus, according to Faraday's law, induced currents i_F, called eddy currents, arise and generate losses in the material by Joule effect :

$$p_C = k_2 \times \frac{(e.f.B_{MAX})^2}{\rho} \qquad \text{(IV.12)}$$

So to reduce losses by eddy currents, we can:

Reduce the thickness e by using an assembly of thin sheets (35/100 or 50/100) insulated from each other: laminated magnetic circuit

Use magnetic materials with higher resistivity such as silicon steel sheets or ferrites (high frequency)

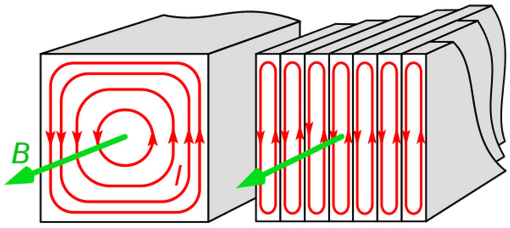


Fig.1.11. Eddy current losses

1.3.4.3. Residual losses or trailing losses:

Trailing losses are due to the delay of induction relative to the field, described in the following figure.

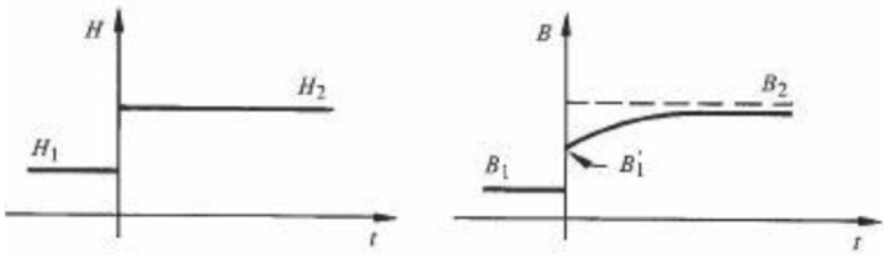


Fig.1.12. Residual losses.

When the field H varies suddenly from H_1 at H_2 , induction immediately follows from B_1 to B_1' then tends asymptotically towards the value of B_2 corresponding to H_2 .

- **Magnetic losses or iron losses**

Hysteresis and eddy current losses originate inside the material.

They are very often combined and called "magnetic losses or iron losses" :

$$pertes\ \ fer = C_{FER} \times \left(\frac{f}{f_0}\right)^k \times \left(\frac{\hat{B}}{\hat{B}_0}\right)^2 \times \mathrm{M} \qquad \text{(IV.13)}$$

C_{FER} : iron loss coefficient in W/kg (manufacturer data)

M : circuit ground, f_0 = 50Hz, B_0 = 1T, 1.5 < k < 2

1.4. Classification Of Types Of Magnetism :

1.4.1. Diamagnetism :

This type of magnetism is characterized by a negative relative susceptibility of low amplitude.

A diamagnetic material will magnetize weakly in the direction opposite to the magnetic field and will lose its magnetization when the magnetic field ceases.

Diamagnetism is due to an orbital movement of electrons, caused by the applied magnetic field cdr "diamagnetism is due to the fact that the electronic orbits each act like small turns of current". This movement can be compared to a microscopic current whose behavior would be comparable to that of a current induced in a solenode. By virtue of Lenz's law, the induced current opposes the field that produces it, which is consistent with the fact that Xr is negative.

Diamagnetism requires an even number of electrons, regardless of whether all electrons are paired. diamagnetism does not depend on temperature. Noble gases, some metals, most metallodes, and a large number of organic compound are diamagnetic.

Table 1.1 Some value of magnetic susceptibility

Matter	X_r	Matter	X_r
If	$-1.2*10^{-6}$	Se	$-4.0*10^{-6}$
Cu	$-1.08*10^{-6}$	Ag	$-2.4*10^{-6}$
Zn	$-1.9*10^{-6}$	Pb	$-1.4*10^{-6}$
Ge	$-1.5*10^{-6}$	Al_2O_3	$-3.5*10^{-6}$

1.4.2. Paramagnetism:

Paramagnetism is characterized by a positive relative susceptibility, of low amplitude, Car between 10^{-6} and 10^{-3}. It is found in substances whose atoms have their own magnetic moment. When the atoms and ions of these substances are not subjected to a magnetic field $\vec{H}$, their magnetic moment are randomly oriented and therefore they do not produce macroscopically observable magnetization. On the other hand, if we subject them to a magnetic field $\vec{H}$, the magnetic moments will orient themselves in the direction of $\vec{H}$ thus causing a macroscopic magnetic moment to appear $\vec{M}$ not bad.

But this macroscopic magnetic moment disappears with the magnetic field and this is because of the thermal agitation of the medium which breaks the preferential orientation that the specific magnetic moments had taken. This effect, this phenomenon therefore depends on the temperature and It follows Curie's law : $\chi = C/T$ (IV.14)

is called paramagnetism.

1.4.3. Ferromagnetism:

Ferromagnetic materials (e.g. iron, cobalt, nickel) have magnetic susceptibility X_m positive and large, and These materials all have an incomplete 3d or 4d under layer.
Ferromagnetism is the type of magnetism resulting from the alignment of specific magnetic moments, these magnetic moments which are locally oriented in the same direction by a mutual interaction called *ferromagnetic coupling*.
Ferromagnetic materials therefore also exhibit spontaneous polarization. The magnetization decreases as the temperature increases. Above the Curie temperature Tc = 768 °C, the iron becomes paramagnetic.

1.4.4. Antiferromagnetism:

Antiferromagnetism is distinguished by a variation in susceptibility as a function of temperature in a very particular way. This type of material does not exhibit magnetism because the electron spins of neighboring atoms are opposite.

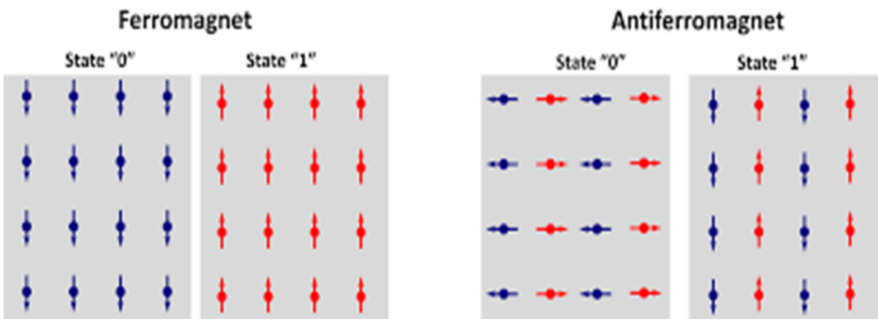


Fig.1.13. Differnce betwin ferromagnetism and Antiferromagnetism

As in paramagnetic materials, the atoms carry a permanent magnetic moment, however these moments are no longer independent of each other but on the contrary strongly linked. This interaction, which is called *antiferromagnetic coupling,* results in an antiparallel arrangement of moments.

As the temperature increases, this arrangement deteriorates. The concomitant reduction in the effect of alignment forces makes the action of an external field more

sensitive. This explains the decrease of $1/\chi_r$ as a function of temperature, up to a temperature ON called the Neel temperature, at which the antiferromagnetic coupling disappears.

Beyond .ON, the behavior of antiferromagnetic materials becomes comparable to that of paramagnetic materials.

1.4.5. Ferrimagnetism:

Ferrimagnetism is the magnetism of a class of oxides called ferrites. In the crystal structure of these materials, we can distinguish two families of sites A and B, occupied by ions having magnetic moments *mA* and *mB* respectively.

The number of A sites differs from the number of B sites and most often *mA* differs from *mB*. The strong antiferromagnetic coupling existing between sites A and B therefore causes a spontaneous polarization ***I*** S, that is to say, a polarization existing *in the absence of an applied magnetic field* (Fig.1.13).

This spontaneous polarization varies as a function of temperature. Thermal agitation increasing with temperature tends to randomly redistribute *mA* and *mB.* This results in a decrease in I_S, which vanishes for the Curie temperature.

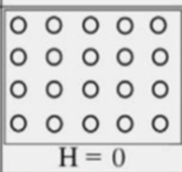
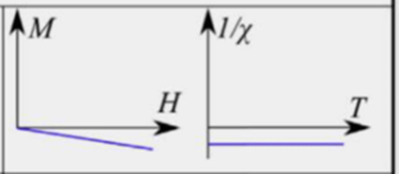
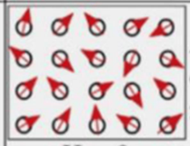
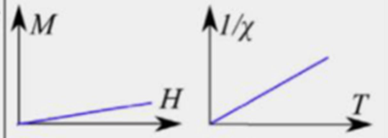
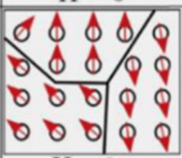
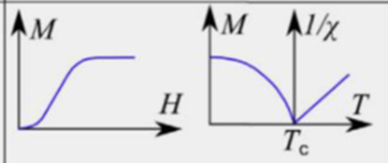
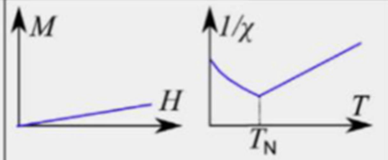
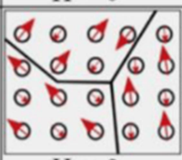
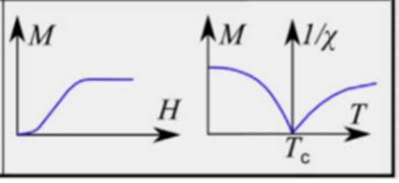
Magnetism	Examples	Magnetic behaviour
Diamagnetism	Bi, Si, Cu, inert gases Susceptibility small and negative (-10^{-6} to -10^{-5})	 H = 0 Atoms have no magnetic moments. 
Paramagnetism	Al, O_2, MnBi Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0 Atoms have randomly oriented magnetic moments. 
Ferromagnetism	Fe, Ni, Co, Gd Susceptibility large (generally > 100)	 H = 0 Atoms are organized in domains which have parallel aligned magnetic moments. 
Antiferromagnetism	Cr, MnO, FeO Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0 Atoms are organized in domains which have antiparallel aligned moments. 
Ferrimagnetism	Fe_3O_4, $MnFe_2O_4$, $NiFe_2O_4$ Susceptibility large (generally > 100)	 H = 0 Atoms are organized in domains which have a mixture of unequal antiparallel aligned moments. 

Fig.1.14: Recap of the Types Of Magnetic Materials With Examples And Their Behavior.

1.4.6. Critical points on the curve :

✓ For ferromagnetic materials that are non-linear, they have a μ_r that is much greater than 1, but when they saturate their μ_r approaches 1.

✓ The residual magnetism, Br, or remanence (or retentivity), is the flux density that is left within the material after it has been magnetize.

✓ A material with a high Br is desired for permanent magnets.

✓ The coercivity, Hc, is the magnetic field intensity that is required to demagnetize the material after it has been magnetized.

✓ A material with a high Hc is desired for permanent magnets to prevent them from being easily demagnetized.

✓ Rare earth magnets have a much higher Hc than Alnico magnets.

✓ The saturation effect of the material occurs when all of the magnetic domains within the material have become aligned with the external magnetic field that surrounds it.

1.5. Soft And Hard Magnetic Materials:

The magnetic materials that can retain their magnetism even after removal of external magnetic field, and are difficult to magnetized and demagnetized are known as hard magnetic materials. The magnetic materials that can be easily magnetized and demagnetized are known as soft magnetic materials.

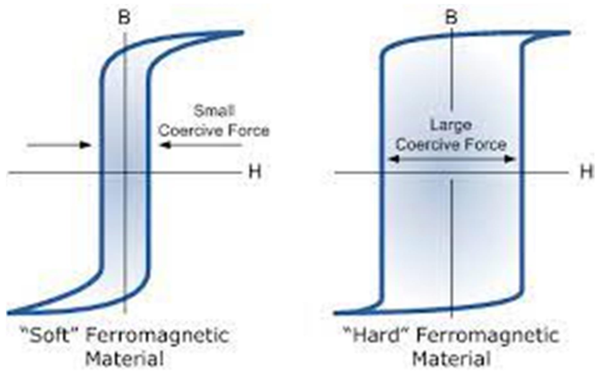


Fig.1.15: Magnetic Behaviors of Soft And Hard Magnetic Materials

1.5.1. Soft magnetic materials:

Materials with a narrow hysteresis cycle to minimize hysteresis losses, they are generally laminated and iron-based (pure iron has too high a resistivity). We essentially distinguish:

1.5.1.1. Electrical steels

They are mainly used in electrical machines working at industrial frequencies (transformers and rotating machines).

They are made of steel sheets alloyed with silicon (1to 5%), which has the advantage of increasing the resistivity but the disadvantage of making the sheets brittle. We distinguish:

- *Classic non-grain oriented sheets. CFER≈ 5W/kg*

They are obtained by hot rolling followed by chemical pickling, a final cold rolling and heat treatment. They are mainly used in rotating machines and low power transformers (< 100 kW).

- *Grain-oriented sheets. CFER≈ 1W/kg*

The manufacturing process is more complex and involves hot rolling followed by several cold rollings and intermediate heat treatments.

Optimal magnetic properties are obtained, but only in the rolling direction: high permeability, high saturation induction, very low iron losses.

They are mainly used in high power transformers (>1MW).

1.5.1.2. Fe/Ni or Fe/Co alloys :

Nickel and especially cobalt are expensive metals and are alloyed with iron in significant proportions (30 to 80%), which makes these alloys much more expensive than electrical steels. They are mainly used at medium frequency (<100kHz) and generally in areas where the power involved is rather low:

- ✓ Miniaturized electrical engineering (measuring devices, tachometers, certain relays, etc.)
- ✓ Telephony.
- ✓ Safety devices (differential circuit breakers, magnetic shielding).

1.5.1.3. Soft ferrites :

They are widely used in Power Electronics and more particularly in switching power supplies where the operating frequency is high (f>100 kHz)
These are ferromagnetic ceramics based on iron oxides (X.Fe12O19-- X=Mn or Ni, Zn)
They are manufactured under an inert atmosphere: After mixing and grinding the components, the powders are assembled by sintering at high temperature (≈1200°C). We thus obtain a material of high resistivity, massive, but unfortunately very brittle.

1.5.1.4. Characteristics of soft magnetic material :

- ✓ A material with a very low Br and Hc.
- ✓ It does not retain a strong magnetic field (does not make a good permanent magnet), and is easy to demagnetize.
- ✓ The area enclosed by the B-H curve is small, so it has low hysteresis losses or core losses.
- ✓ This material is desired for use in transformers, motors and electromagnets where the magnetic field is always changing. ✓ Electrical steels, which contain about 1-2% Si, is a soft magnetic material.

Table 1.2. Guide To Choosing Soft Materials

Induction form	Choice objectives	material						Economic data	uses
		examples	B_{max} (T)	Coercive field H_C (A/m)	μR for B=1 T	Resistivity (Ω.mx10^{-8})	Losses (W/kg)	*Production t/year* Price in F/kg	
constant	Seek maximum induction B with the lowest possible H field, hence high permeability	Pure Fe Mild steel (0.1% C)	1.6 1.2	4	10,000 1,500	10 10	B=1.5 T f= 50 Hz **≈10**	*5,000,000* **4 to 8**	Inductor poles of direct current machines. Electromagnet for contactors powered by direct current High power turbo alternator forged steel rotor
Variable f=50 or 60 Hz	Look for low eddy current and hysteresis losses while maintaining very good permeability, hence a narrow cycle material	Rolled sheet with non-grain oriented steel +1 to 4%Si	1.7	24 has 72	6,000 has 9,000	15 has 60	B=1.5 T f= 50 Hz ep. 35/100 : **2.3** th. 65/100 : **9.5**		Magnetic circuits of alternating current machines: transformers asynchronous motor, synchronous Electromagnet of contactors powered by alternating current
		Grain oriented steel sheet +3.5%Si	2	5.6	65,000	48	B=1.5 T f= 50 Hz ep. 27/100: **0.89** th. 35/100: **1.11**	*1,000,000* **8 to 16**	
Variable f>60 Hz	Look for significant permeability at high frequencies with low eddy current and hysteresis losses	Ferrites MFe_2O_3	0.4	? has ?	7000	Insulation: 10^{16}	B=0.2 T f= 100 kHz **100**	*150,000* **30 to 300**	M=Zn and/or Mn (f<1.5MHz) M=Zn and/or Ni (f<200MHz) Switching power supply, high frequency filter
		Iron - nickel alloy	0.8 has 1.6	0.4 has 55	6000 has 220000	35 has 60	B=0.2 T f= 100 kHz **100**	*10,000* **150 to 400**	Magnetic circuits of components used at medium and high frequency: - transformers - coupling coils - inductors - filters - shields
		Iron-cobalt alloy	0.6 has 1.2	35 has 150	5000 has 12,000	15 has 40	B=0.2 T f= 100 kHz **40**	*Weak* **800 to 2000**	

1.5.2. Hard magnetic materials:

They are generally massive and based on iron or rare earths (Sm: samarium, Nd: Neodymium) (Fig. 4.16).

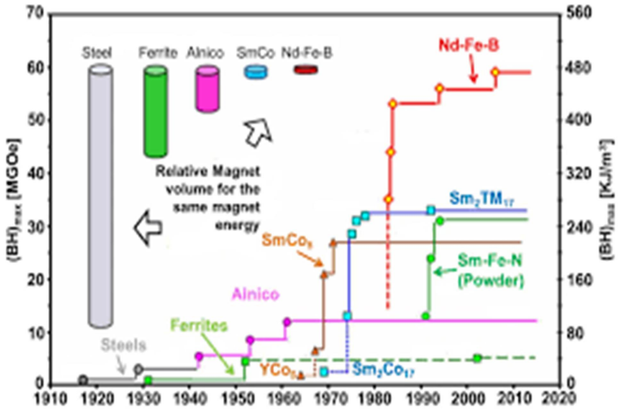


Fig. 1.16: Historical evolution of magnets

These materials are used to make permanent magnets. They have significant residual induction and a high coercive field (Fig. 1.17).

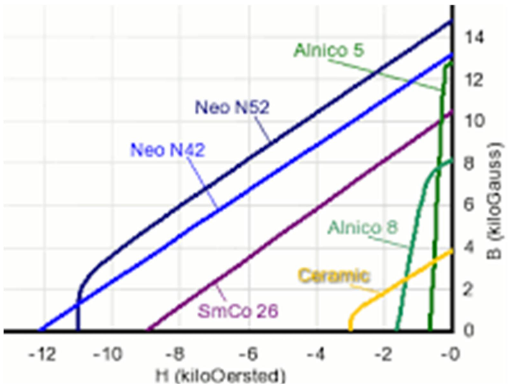


Fig. 1.17: Demagnetization Curves For Large Families Of Hard Magnetic Materials (Permanent Magnets Demagnetization curves).

They are often combined with soft iron which channels the induction lines and is magnetized during the manufacturing process. Today we essentially distinguish:

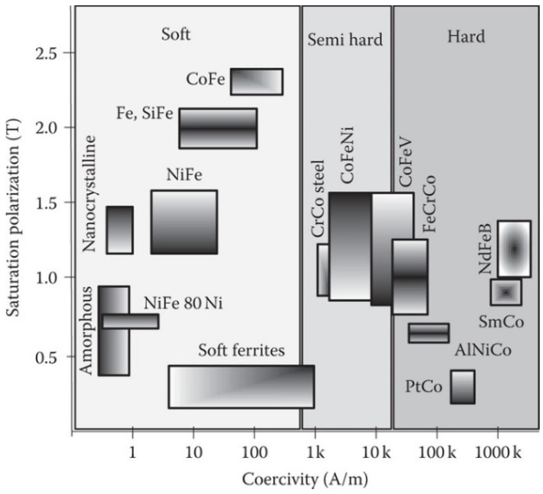


Fig. 1.18. Comparison of soft/hard materials

1.5.2.1. Alnico:

Alnico were the first artificially made magnets. They are now losing ground behind ferrites and rare earth magnets. These are alloys of iron, aluminum, nickel and cobalt (the best performance is obtained for alloys rich in cobalt).

They are obtained by molding at high temperature, followed by various thermal and magnetic treatments, or by sintering followed by grinding and cutting. They have very good temperature resistance (maintaining magnetic performance), as well as good mechanical strength. Their remanent induction is quite high (1.2T), but their magnetization falls very quickly and irreversibly in the presence of a demagnetizing H field (sudden increase in the air gap).

They are mainly used in metrology or in applications where magnets are exposed to mechanical stress.

1.5.2.2. Hard ferrites:

These are ceramics based on ferric oxides (Fe_2O_3) associated with Barium (Ba) or Strontium (Sr).

They are obtained after several steps:

Grinding of the different constituents then mixing at 1200°C to form ferrite.

Grinding of the ferrite in the presence of water to obtain a very fine powder (0.5µ).

Compression with a binder in molds of suitable shape, in the presence of a magnetic field.

Sintering (1200°C), followed by controlled cooling. They offer the best quality/ price ratio. On the other hand, their remanent induction is quite modest (<0.5T), and their magnetization also falls quickly and irreversibly in the presence of a demagnetizing H field (same as alnico). In addition, the ceramics obtained are very hard and brittle, which prohibits the machining of finished products.

1.5.2.3. Rare earth magnets:

Fairly recently, rare earth alloys have appeared. They have excellent magnetic properties: Specific energy density of 350kJ/m^3 (50kJ/m^3 for alnico), which allows a significant reduction in weight and volume at given induction and air gap. Field with almost constant magnetization which makes demagnetization of the magnet very difficult.

There are 2 alloys: Samarium-cobalt or Neodymium-iron-boron. As with ferrites, they are obtained by sintering powders.

These products are relatively expensive and do not have good temperature resistance. They are reserved for specific applications where size is the major parameter.

- **Areas of application of permanent magnets:**
  - ✓ Inductor of low power rotating machines (<10kW) (direct current, synchronous, permanent magnet machine).
  - ✓ Speaker and microphone
  - ✓ Magnetic detector
  - ✓ EDF meter -- magnetic brakes – tachometer
  - ✓ Measuring device.

1.5.3. Characteristics of hard magnetic material :

- ✓ A material with a very high Br and Hc.

- ✓ It retains a strong magnetic field (makes a good permanent magnet), and is difficult to demagnetize. ✓ The area enclosed by the B-H curve is large, so it has high hysteresis losses or core losses.
- ✓ This material is desired for use in permanent magnets.
- ✓ Alloys such as AlNiCo and NdFeB are hard magnetic materials.

Table 1.3. Guide To Choosing Hard Materials (Properties):

		Features					Economic data in 1995 (subject to all reservations)	Uses
Material		B_r (T)	Coercive field H_C(kA/m)	$(BH)_{max}$ kJ/m ^{3}	Curie temperature T_C (°C)	Max operating temperature (°C)	*Production t/year* **Price in F/kg**	
AlNiCo		0.7 has 1.4	50 has 60	13 has 60	860	450	*12,000* **250**	Measuring devices Sensors Parts exposed to shock
Ferrites		0.4	250	27	460	400	*320,000* **35**	Motors, couplings Repulsion, thin magnets
Rare earth	**$SmCo_5$**	1	750	190	730	200	*1,300* **2,500**	Embedded hardware Microelectronics Synchronous motor Repulsion, thin magnets Couplings
	Nd -Fe-B	1.3	950	360	310	150	*1,900* **1,500**	

Selection criteria: Each family of magnets has a defect:

- ✓ lNiCo : low coercive field (be careful of demagnetization)
- ✓ ***Ferrites***: low remanent induction
- ✓ ***Sm -Co***: expensive technology
- ✓ ***Nd -Fe-B***: low operating temperature due to thermal instability of thermal properties.

We will choose this or that family according to the following imperatives:

- ✓ ***Ferrites***: low cost price
- ✓ ***Rare earths***: reduced volume and weight
- ✓ AlNiCo: mechanical strength and good temperature resistance.

1.6. Application of magnetic materials

Magnetic materials play a crucial role in various applications, They are mainly classified based on their magnetic properties, On site

1.6.1. and medical applications:

1.6.1.1. Induction hobs :

Coils powered by alternating current generate an oscillating magnetic field on the ferromagnetic bottom of the pans. Since any temporal variation of the magnetic flux passing through a ferromagnetic material induces eddy currents , a current is established at the bottom of the pan. This setting in motion of the electrons by the Lorentz force causes energy dissipation by the Joule effect , and therefore heats the pan.

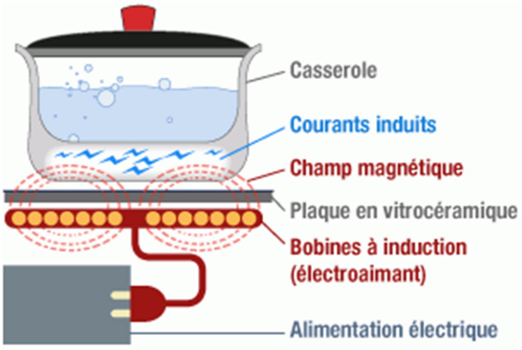


Fig. 1.19. Induction hobs

1.6.1.2. Hard drives

Information is stored using the orientation of magnetic domains of a thin ferromagnetic film deposited on a disk. The size of the latter is of the order of 20 nm. The reading head and the writing head are arranged on the same mechanical arm. This allows them to position themselves anywhere on the rotating disk so that they can carry out their actions.

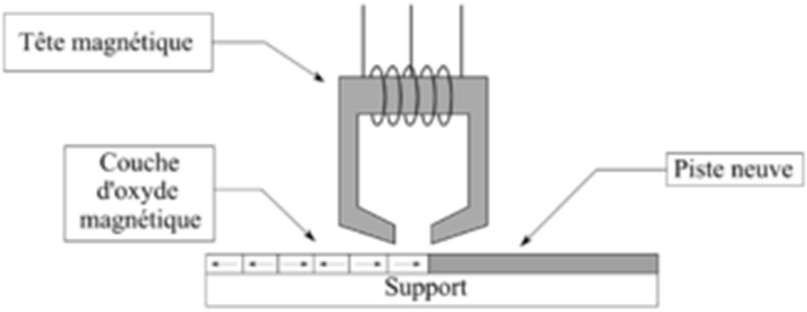


Fig. 1.20. Hard drives

1.6.1.3. Medical imaging :

Nuclear magnetic resonance imaging (MRI) is the most widely known application of nuclear magnetic resonance (NMR) in medical imaging. It allows you to have a 2D or 3D view of a part of the body, particularly the brain.

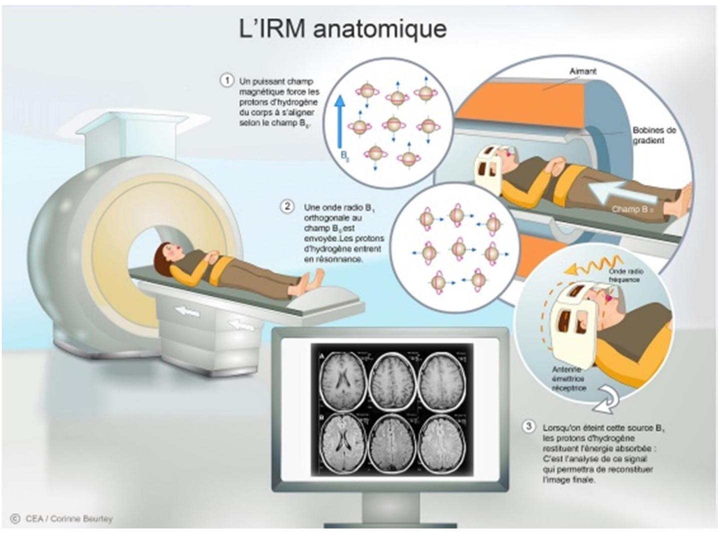


Fig. 4.21. IRM model

NMR is associated with a property of certain atoms when placed in a magnetic field. This effect is primarily used as a spectroscopic method of analyzing matter. NMR involves very low energy electromagnetic radiation, allowing extremely detailed and non-destructive examination of the sample. Atoms whose nucleus has an odd number of protons and neutrons have a nuclear spin , that is to say a non-zero spin quantum number . Placed under a magnetic field, these atomic isotopes can have two distinct states. By applying suitable radiation, a pulsed photon will cause the nucleus to oscillate from one energy state to another: this is called resonance. Returning to its equilibrium level, the nucleus emits a photon. This radiation, in addition to indicating the presence of the nucleus, can also give information about the environment of the molecule. In the case of MRI, we use the hydrogen atom present in the water of organic cells.

1.6.1.4. Magnetic levitation train:

Since the very first railway, little has changed in terms of basic technical concepts: trains are still supported, guided and powered by the wheels. But a new train system has appeared: magnetic levitation trains, which are supported, propelled and guided by electromagnetic force alone . This new concept has many advantages thanks to its

revolutionary “non-contact” technology. magnetic levitation train is a monorail train that uses magnetic forces to move. Two main types of lift trains exist.

Fig. 1.22. Maglev magnetic levitation train

electrodynamically supported (or EDS) type uses superconducting electromagnets (in) . The most successful project is the Japanese Maglev . Superconducting coils are placed in the train and electromagnets along the track. These figure 8 coils are in opposite directions, so they repel each other. Guidance is carried out by the same coils as those which provide levitation. The electric current passing through the coils is created by the passage of superconducting magnets, in accordance with the principle of electromagnetic induction. Thus the lower part of the 8 of the coil ensures levitation by repulsion and the upper part of the 8 the guidance, also by repulsion. When the train moves, a current is induced in the track. The resulting Laplace force levitates the train about ten centimeters above the ground. The movement of the train generates very significant electromagnetic drag, resulting in high energy consumption.

The electromagnetic levitation (or EMS) type, using conventional electromagnets . The electromagnetic drag here is very low, if any. The German Transrapid. The "carrying" rail contains magnets or electromagnets. The interaction between magnets on board the train and magnets arranged along the track creates an induced magnetic force that counteracts gravity and allows levitation . These magnets attract the train upwards and ensure sufficient distance between the rail and the train which prevents any loss due to friction. Furthermore, at high speeds, it is the aerodynamic resistance which represents by far the main resistance to advancement. The train is guided parallel to the track by electromagnetic forces, without contact. The track guide coils are located on the sides of the track, opposite the train guide coils.

1.6.2. Applications in Electrical Engineering:

1.6.2.1. Applications of the electromagnet :

Many applications use electromagnets: magnetic separators, movement of ferrous materials in the recycling or railway maintenance industry, etc. A simple example: the electromagnet door latch.

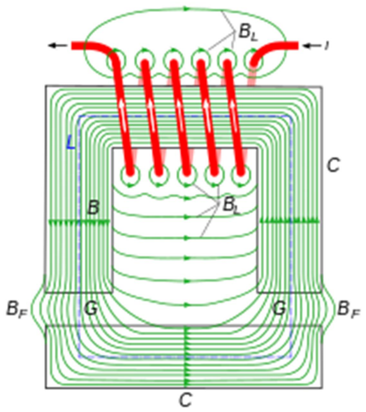


Fig. 1.23. Magnetic field of an electromagnet

1.6.2.2. Magnetic braking:

The magnetic brake is used as an additional brake in several areas. This system is only activated for emergency braking, when it is necessary to brake over the shortest possible distance . And this using the principle of eddy current .

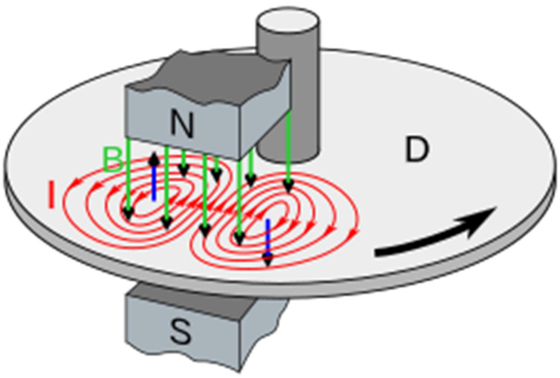


Fig. 1.24. Diagram of an eddy brake disc

1.6.2.3. Magnetic sensors:

Magnetic sensors are installed in a large number of objects. There are approximately fifteen types of sensors. Among them, we cite field sensors, position and angle sensors, current sensors, magnetoresistive sensors , flux sensors , etc.

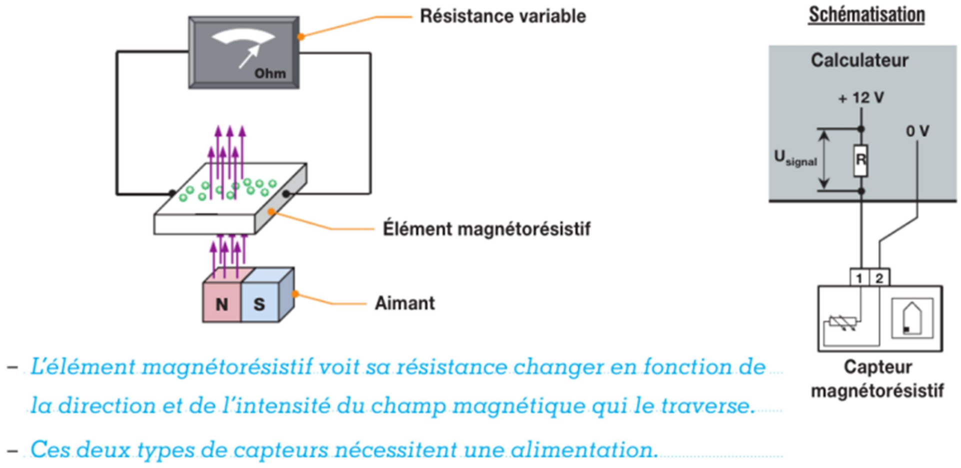


Fig.1.25. Principle of magnetoresistive sensor

1.6.2.4. Transformers:

It is an electrotechnical component which converts high alternating voltages into low alternating voltages and vice versa. The frequencies are preserved during the transformation.

Fig.1.26. Transformer

1.6.2.5. Electromechanical relays:

It is an electronic component controlled by low powers (low voltages and low currents) which can act as a switch on high power electronic circuits (high voltages and high currents).

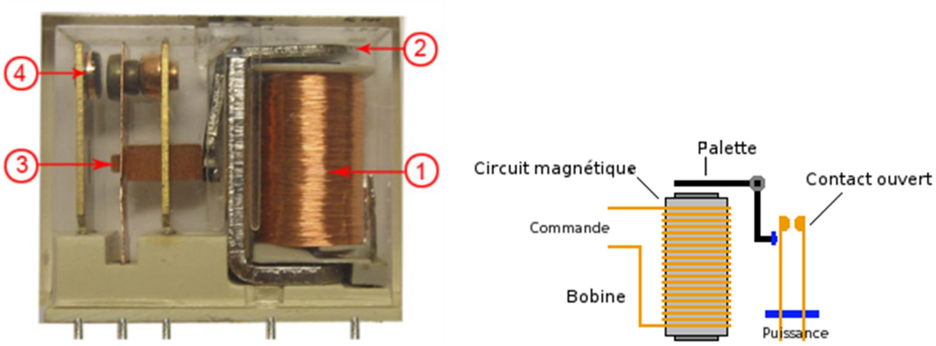


Fig.1.27. Principle of electromechanical relays.