MEE210 Electrical Machines

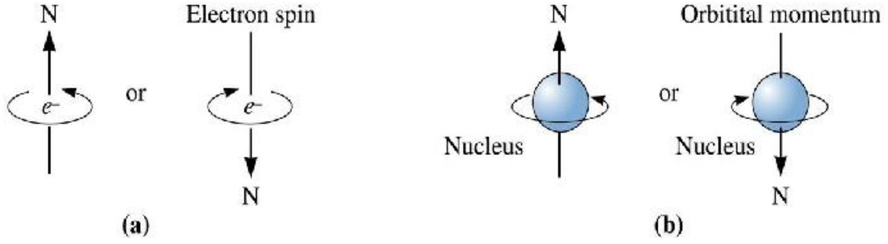
Magnetic circuits

Physical Basis of Magnetism

As mentioned before, the motion of an electric charge results in the production of a magnetic field.

For example, an electric current loop of area A and current I produces a magnetic dipole with strength m=IA

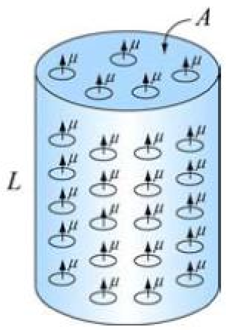
The physical basis of the magnetic properties of engineering materials is the current loops produced by the motion of electrons.

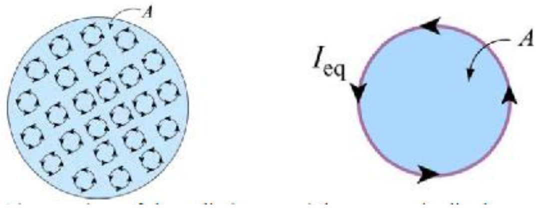


Magnetization

The magnetization of a material is expressed in terms of density of net magnetic dipole moments m in the material.

We define a vector quantity called the magnetization:





$$\vec{M} = \frac{\sum m}{V}\left[\frac{Am^2}{m^3} = \frac{A}{m}\right]$$

Two Magnetic Fields

when the generated fields pass through magnetic materials which themselves contribute internal magnetic fields, ambiguities can arise about what part of the field comes from the external currents and what comes from the material itself.

$$\vec{B} = \mu_o(\vec{M} + \vec{H})$$

The total magnetic induction is the sum of the contributions from the external magnetic field and internal field.

$$\vec{H} = \frac{\vec{B}}{\mu_o} - \vec{M}$$

H: magnetic field strength

It has been common practice to define another magnetic field quantity, usually called the "magnetic field strength" designated by H.

Magnetic Field Strength H

H has the value of unambiguously designating the driving magnetic influence from external currents in a material, independent of the material's magnetic response.

$$\vec{H} = \frac{\vec{B}}{\mu_o} - \vec{M}$$

H and **M** have the same units, amperes/meter.
The relationship for **B** and **H** above can be written in the equivalent form

$$\vec{B} = \mu_o(\vec{M} + \vec{H}) = \mu_o\left(1 + \frac{\vec{M}}{\vec{H}}\right)\vec{H} = \mu_o\mu_r\vec{H}$$

$$\mu_r = \left(1 + \frac{\vec{M}}{\vec{H}}\right)$$ μ_r : The relative permeability

Magnetic Permability

As seen in previous slide, The Magnetic induction B is proportional to the applied Magnetic field intensity H.

$$\vec{B} = \mu\vec{H}$$

In electromagnetism, ”μ” permeability is the measure of the ability of a material to support the formation of a magnetic field within itself.

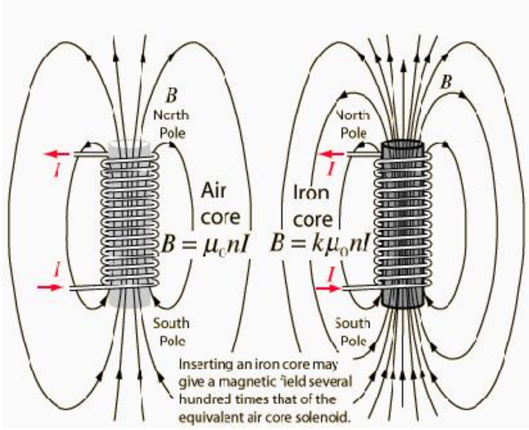
In other words, it is the degree of magnetization that a material obtains in response to an applied magnetic field.

Permeability of a material is defined realtive to permability of the space.

$$\mu = \mu_o\mu_r$$ $\mu_0 = 4\pi \times 10^{-7}$ T m/A is called the permeability of space.

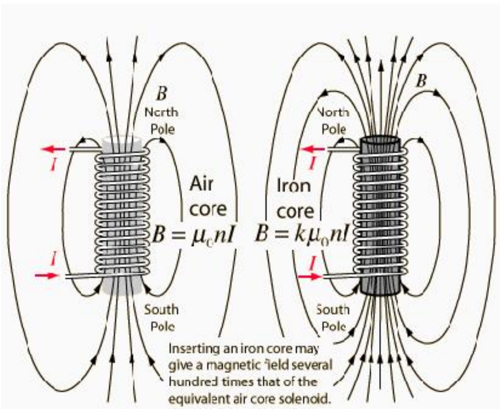
Relative Permability

The relative permeability μ_r can be viewed as the amplification factor for the internal field **B** due to an external field **H.**



$K« = «_r«_0$

Relative Permability



When ferromagnetic materials are used in applications like an iron-core solenoid, it might be expected that a magnification of about 200 compared to the magnetic field produced by the solenoid current with just an air core.

Magnetic susceptibility

The magnetic susceptibility is a dimensionless proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field.

$$\vec{M} = \chi \vec{H}$$

$$\vec{B} = \mu_o(\vec{M} + \vec{H}) = \mu_o(1 + \chi)\vec{H} = \mu_o \mu_r \vec{H}$$

$$\mu_r = (1 + \chi)$$

Magnetic Properties of Solids

Materials may be classified by their response to externally applied magnetic fields as diamagnetic, paramagnetic, or ferromagnetic.

- **Diamagnetism** is a property of all materials and opposes applied magnetic fields, but is very weak.
- **Paramagnetism** is stronger than diamagnetism and produces magnetization in the direction of the applied field, and proportional to the applied field.
- **Ferromagnetic** effects are very large, producing magnetizations sometimes orders of magnitude greater than the applied field and as such are much larger than either diamagnetic or paramagnetic effects.

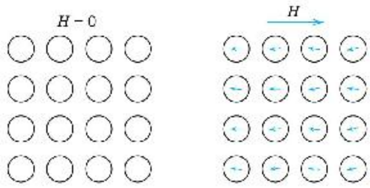
Diamagnetism $B \approx \mu_r\mu_o H$

The orbital motion of electrons creates tiny atomic current loops, which produce magnetic fields.

When an external magnetic field is applied to a material, these current loops will tend to align in such a way as to oppose the applied field.

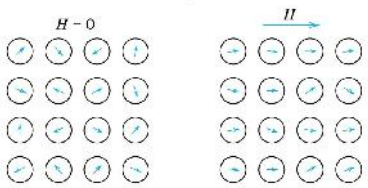
This may be viewed as an atomic version of Lenz's law: induced magnetic fields tend to oppose the change which created them.

Materials in which this effect is the only magnetic response are called diamagnetic.



Paramagnetism $B \approx \mu_r\mu_o H$

All atoms have inherent sources of magnetism because electron spin contributes a magnetic moment and electron orbits act as current loops which produce a magnetic field.



In most materials the magnetic moments of the electrons cancel, but in materials which are classified as paramagnetic, the cancelation is incomplete.

Paramagnetic materials exhibit a magnetization which is proportional to the applied magnetic field in which the material is placed.

Diamagnetism&Paramagnetism

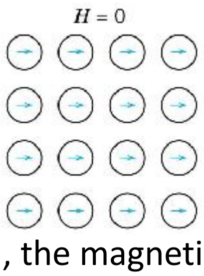
In diamagnetic materials, even in an external magnetic field, very weak form of magnetism occurs opposite to external field.Their Relative permeability is about (≈0.99)

Diamagnetism is found in all materials, but it is so weak that only noticed if no other form of magnetism exists.

Paramagnetic materials, in an external field, the magnetic dipole moments align with the field, thus enhancing it only a very small amount.Permeability (μ_r) barely, ≈ 1.00001 to 1.01.

Ferromagnetism

Ferromagnetic materials exhibit a long-range ordering phenomenon at the atomic level which causes the unpaired electron spins to line up parallel with each other in a region called a domain.



Within the domain, the magnetic field is intense, but in a bulk sample the material will usually be unmagnetized because the many domains will themselves be randomly oriented with respect to one another.

Ferromagnetism

Ferromagnetism manifests itself in the fact that a small externally imposed magnetic field, say from a solenoid, can cause the magnetic domains to line up with each other and the material is said to be magnetized.

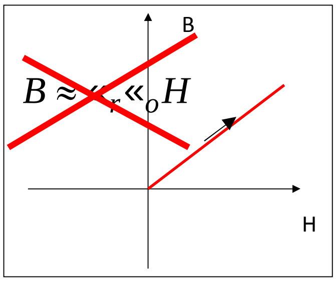
The driving magnetic field will then be increased by a large factor which is usually expressed as a relative permeability for the material.

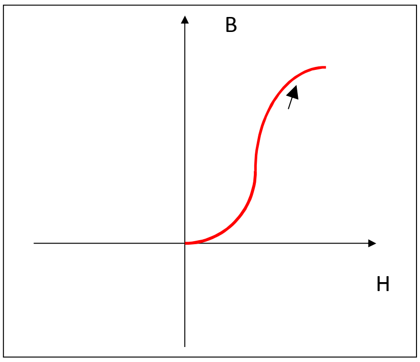
Ferromagnets will tend to stay magnetized to some extent after being subjected to an external magnetic field.

This tendency to "remember their magnetic history" is called hysteresis.

$$\cancel{B \approx «_r «_o H}$$

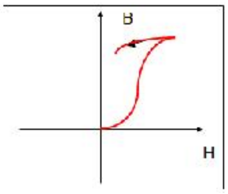
Ferromagnetism-Hysteresis





The relation between magnetic field B to the applied field Strength H for the ferromagnetic curve is non-linear

Ferromagnetism-Hysteresis

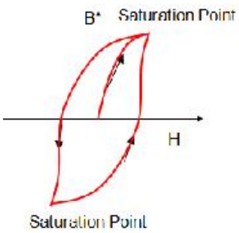


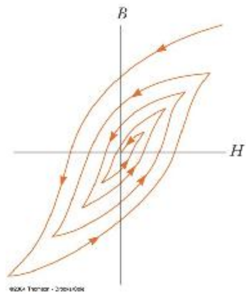
In addition, if you decrease H for the ferromagnetic sample, the B field will not decrease in the same way, it increased

Because of the domains, ferromagnetic substances will retain a permanent B-field after magnetization.

This property, where the response to magnetization depends on the previous magnetizations is called hysteresis

Ferromagnetism-Hysteresis



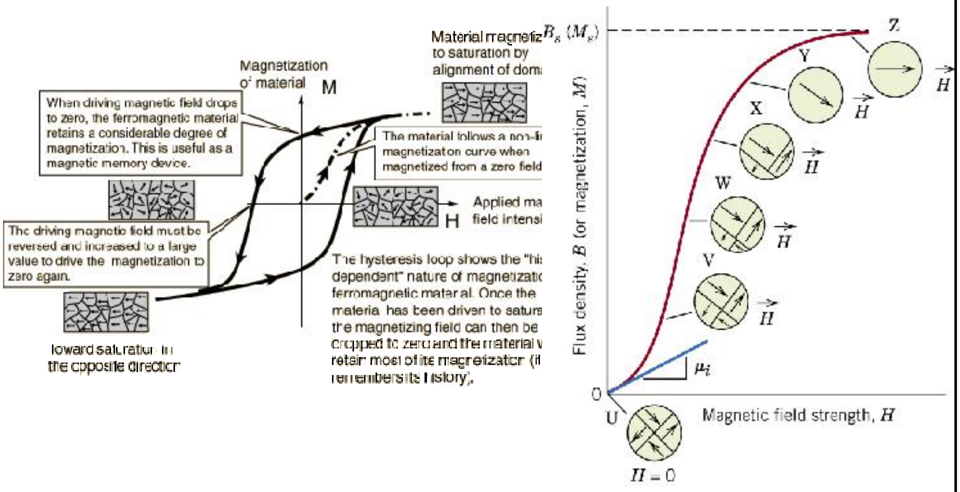


The figure above shows a hysterisis curve between the two saturation points of a particular ferromagnetic material

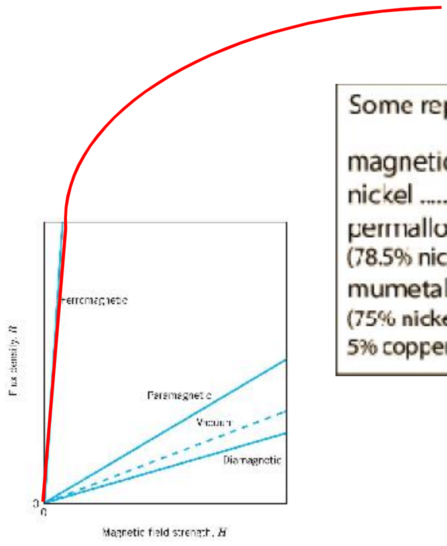
The saturation point corresponds to the maximum magnetization that a material can achieve

To ***reverse*** the process of magnetizing a ferromagnetic material, one would have to follow this hysteresis curve

Ferromagnetism-Hysteresis



Ferromagnetism-Relative permability



Some representative relative permeabilities:

magnetic iron 200
nickel 100
permalloy...............................8,000
(78.5% nickel, 21.5% iron)
mumetal..............................20,000
(75% nickel, 2% chromium,
5% copper, 18% iron)

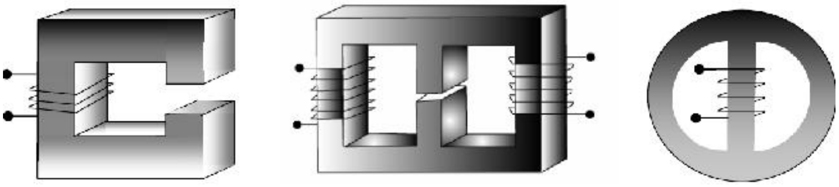
at a magnetic flux density of 0.002 W/m^2

Magnetic circuits-structure

Magnetic fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators and transformers.

All of which have

a magnetic material of regular geometric shape called core.



an exciting coil having a number of turns (= N) of conducting material are wound over the core.

Magnetic circuits- Ampere's Law

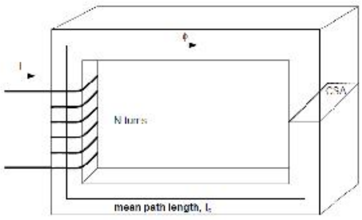
Ampere's Law is the basic law governing the production of a magnetic field by a current:

$$\oint H dl = I_{net}$$

where H is the magnetic field intensity produced by the current I_{net} and dl is a differential element of length along the path of integration. H is measured in Ampere-turns per meter.

Magnetic circuits- Ampere's Law

Consider a current currying conductor is wrapped around a ferromagnetic core;

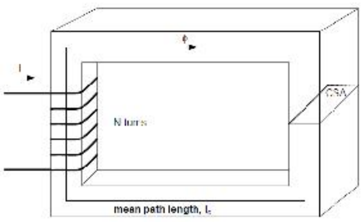


Applying Ampere's law, the total amount of magnetic field induced will be proportional to the amount of current flowing through the conductor wound with N turns around the ferromagnetic material as shown.

Since the core is made of ferromagnetic material, it is assume that a majority of the magnetic field will be confined to the core

Magnetic circuits- Ampere's Law

The path of integration in Ampere's law is the mean path length of the core, l_c. The current passing within the path of integration I_{net} is then Ni, since the coil of wires cuts the path of integration N times while carrying the current i.



Hence Ampere's Law becomes

$$Hl_c = Ni$$

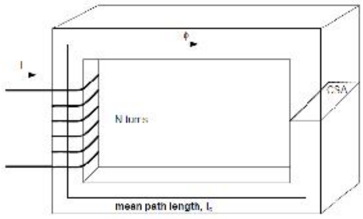
Magnetic circuits- Magnetic Flux

The magnetic flux density due to exciting coil is:

$$H = \frac{Ni}{l_c}$$

$$B = «H$$

$$B = \frac{«Ni}{l_c}$$



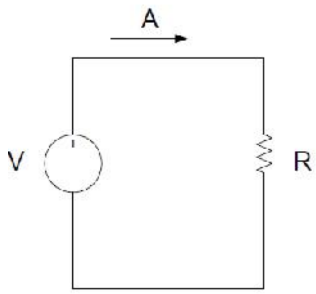
Remembering the definition of magnetic flux and using in this last eqn:

$$¤ = BA_c \rightarrow B = \frac{«Ni}{l_c}$$

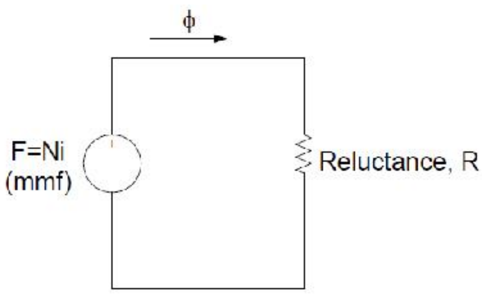
$$¤ = \frac{«NiA_c}{l_c}$$

Magnetic circuits- the analogy

The flow of magnetic flux induced in the ferromagnetic core can be made analogous to an electrical circuit hence the name magnetic circuit.



Electric Circuit Analogy



Magnetic Circuit Analogy

Magnetic circuits- magnetomotive force

Referring to the magnetic circuit analogy, F is denoted as magnetomotive force (mmf) which is similar to Electromotive force in an electrical circuit (emf).

Therefore, we can safely say that F is the prime mover or force which pushes magnetic flux around a ferromagnetic core. (refer to ampere's law).

$$F_{mmf} = Ni$$

Hence F is measured in ampere turns. Hence the magnetic circuit equivalent equation is as shown:

$$F_{mmf} = ¤R_{mag}$$

Magnetic circuits- the Reluctance

The element of R in the magnetic circuit analogy is similar in concept to the electrical resistance. Reluctance is measured in Ampere-turns per weber.

It is basically the measure of material resistance to the flow of magnetic flux.

$$R_{mag} = \frac{l_c}{«A_c}$$

Reluctance in this analogy obeys the rule of electrical resistance (Series and Parallel Rules).

$$R_{mag,eq} = \sum R_{mag,i} \qquad R_{mag,eq} = \sum \frac{1}{R_{mag,i}}$$

Magnetic circuits- the Inductance

The inductance is typified by the behavior of a coil of wire in resisting any change of electric current through the coil.

Arising from Faraday's law, the inductance L may be defined in terms of the emf generated to oppose a given change in current:

$$V = -L\frac{di}{dt}$$

The unit for inductance is Henry.

Magnetic circuits- the Inductance

The inductance is a parameter which is also related with the reluctance of the magnetic circuit.

$$V = -N\frac{d¤}{dt}$$

$$¤ = \frac{F_{mmf}}{R_{mag}} = \frac{ANi«}{l}$$

$$V_{emf} = -N\frac{d}{dt}\left(\frac{ANi«}{l}\right)$$

$$V_{emf} = -\left(N^2\frac{A«}{l}\right)\frac{di}{dt} \Rightarrow L = N^2\frac{A«}{l}\ [H]$$

$$L = N^2\frac{A«}{l} = \frac{N^2}{R_{mag}}$$

Magnetic circuits- the assumptions

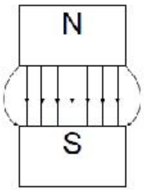
The magnetic circuit approach simplifies calculations related to the magnetic field in a ferromagnetic material, however, this approach has inaccuracy due to assumptions made in.

- The magnetic circuit assumes that all flux are confined within the core, but in reality a small fraction of the flux escapes from the core into the surrounding low-permeability air, and this flux is called **leakage flux.**
- The reluctance calculation assumes a certain mean path length and cross sectional area (csa) of the core. This is alright if the core is just one block of ferromagnetic material with no corners, for practical ferromagnetic cores which have **corners due to its design, this assumption is not** accurate.

Magnetic circuits- the assumptions

The magnetic circuit approach simplifies calculations related to the magnetic field in a ferromagnetic material, however, this approach has inaccuracy due to assumptions made in.

- In ferromagnetic materials, the permeability varies with the amount of flux already in the material. The material permeability is not constant hence there is an existence of **non-linearity of permeability.**
- For ferromagnetic core which has air gaps, there are **fringing effects that should be taken into** account as shown:



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