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Electrical Engineering Materials

Pedagogical Handout

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Chapter 4 : Magnetic Materials

2nd Year Engineering students

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4.1 Introduction

Magnetic materials play a fundamental role in electrical engineering, particularly in devices that generate, convert, or control electrical energy, such as transformers, motors, generators, and inductors [10]. Their ability to guide and concentrate magnetic flux makes them essential for efficient energy conversion and electromagnetic operation.

The magnetic behavior of materials originates from the motion and spin of electrons. In most materials, the magnetic moments associated with electrons cancel each other. However, in ferromagnetic materials, some magnetic moments remain aligned, producing a net magnetization under the influence of an external magnetic field [4], [12].

Magnetic materials are generally classified into two main categories:

- **soft magnetic materials**, which are easily magnetized and demagnetized,
- **hard magnetic materials**, which retain their magnetization and are used as permanent magnets.

Understanding their magnetic properties is essential for selecting appropriate materials in electrical and electronic applications.

4.2 Fundamentals of Magnetism

The magnetic properties of materials originate from the magnetic moments associated with the orbital motion and spin of electrons. In ferromagnetic materials, these magnetic moments interact and align within microscopic regions called magnetic domains (Weiss domains), giving rise to strong magnetic behavior [4], [12].

A. Magnetic Moments and Domains

In the absence of an external magnetic field, magnetic domains are randomly oriented, resulting in zero net magnetization. When a magnetic field is applied, the domains gradually align with the field, increasing the magnetization of the material [2].

B. Magnetization and Hysteresis

The relationship between the magnetic flux density (B) and the magnetic field intensity (H) is expressed by:

$$B = \mu H$$

where (μ) is the magnetic permeability of the material.

For ferromagnetic materials, the magnetization process is not completely reversible. When the magnetic field is cycled, the material exhibits a hysteresis loop characterized by:

- **Remanence (B_r)**: the residual magnetic flux density remaining after the external field is removed.

- **Coercivity (H_c)**: the reverse magnetic field required to cancel the residual magnetization [2], [16].

C. Magnetic Losses

Under alternating magnetic fields, part of the energy is dissipated as heat within the magnetic material. The main sources of magnetic losses are:

- **Hysteresis losses**, caused by repeated magnetization and demagnetization cycles.
- **Eddy current losses**, generated by currents induced inside conductive magnetic materials [16].

Reducing these losses is essential for improving the efficiency of transformers, motors, and other electromagnetic devices.

4.3 Soft Magnetic Materials

Soft magnetic materials are materials that are easily magnetized and demagnetized. They are characterized by high magnetic permeability, low coercivity, and a narrow hysteresis loop, which makes them ideal for applications where magnetic fields vary with time, such as transformers and electrical machines [4], [16].

A. Fe–Si Electrical Steels

Iron-silicon (Fe–Si) alloys are the most widely used soft magnetic materials in power engineering applications operating at industrial frequencies (50/60 Hz).

The addition of silicon (typically 2–4%) increases the electrical resistivity of iron, which significantly reduces eddy current losses. In practical applications, Fe–Si cores

are manufactured in the form of thin laminated sheets separated by an insulating layer to further minimize induced currents [2], [16].

These materials are mainly used in transformer cores, electric motors, and generators due to their good magnetic performance and relatively low cost.

B. Soft Ferrites

Soft ferrites are ceramic magnetic materials composed of iron oxides combined with elements such as manganese, zinc, or nickel.

Unlike metallic materials, ferrites have very high electrical resistivity, which almost eliminates eddy current losses, especially at high frequencies. However, they exhibit lower magnetic saturation compared to Fe–Si steels [4].

Because of these properties, soft ferrites are mainly used in high-frequency applications such as switching power supplies, inductors, and electromagnetic interference (EMI) filters.

4.4 Hard Magnetic Materials

Hard magnetic materials are characterized by a wide hysteresis loop, high coercivity, and high remanent magnetization. Once magnetized, they retain their magnetic state for a long time, which makes them suitable for permanent magnet applications [4], [16].

A. Hard Ferrites

Hard ferrites are ceramic-based permanent magnets composed mainly of iron oxides combined with barium or strontium. They are relatively inexpensive, chemically stable, and resistant to corrosion. However, their magnetic energy density is moderate compared to advanced alloys [2].

B. Rare-Earth Magnets

Rare-earth magnets represent the most powerful class of permanent magnets currently available.

- **Neodymium–Iron–Boron (NdFeB):**

These magnets exhibit very high energy density, allowing the design of compact and efficient electrical machines. However, they are sensitive to temperature and corrosion [12].

- **Samarium–Cobalt (SmCo):**

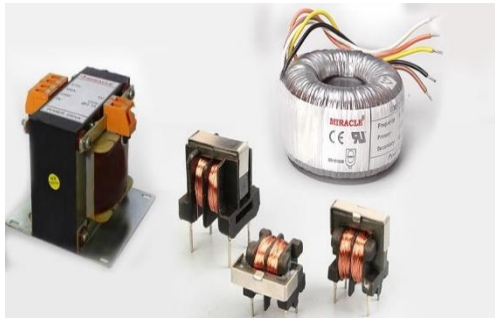
These magnets offer slightly lower magnetic strength than NdFeB but provide excellent thermal stability and can operate at high temperatures without significant performance loss [12].

4.5 Applications of Magnetic Materials

Magnetic materials are widely used in electrical and electronic systems where energy conversion and electromagnetic control are required.

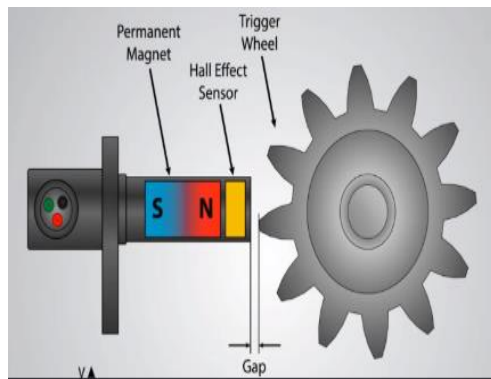
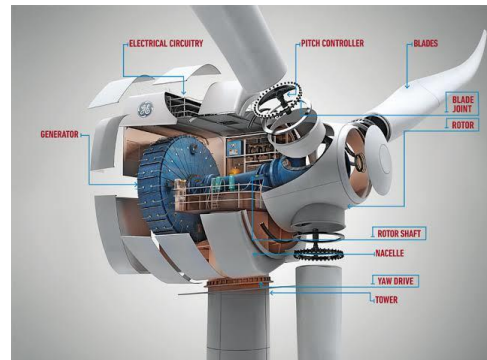
Electrical Machines: Permanent magnet synchronous motors (PMSM) and brushless DC motors use NdFeB or SmCo magnets to achieve high efficiency and power density





Transformers and Inductors: Soft magnetic materials such as Fe–Si steels and ferrites are used to guide magnetic flux and minimize losses.

Energy Generation: Wind turbines and generators use magnetic materials to convert mechanical energy into electrical energy efficiently



Sensors: Magnetic sensors (e.g., Hall effect sensors) are used in position detection, speed measurement, and automotive systems [10], [12].

The performance and efficiency of these systems strongly depend on the appropriate selection of magnetic materials based on their magnetic properties and operating conditions.

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