ELECTROMAGNETIC DEVICES AND MAGNETIC CIRCUITS

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Contents

Summary

This chapter introduces magnetic circuit concepts to relatively simple magnetic structures. The objective is to introduce the fundamental notions of electromechanical energy conversion, leading to an understanding of the operation of various electromagnetic devices. The basic principles of energy conversion in electro-magneto-mechanical systems are described, and its usefulness and potential for application is illustrated by presenting several examples of energy transducers.

1. Introduction

Electric systems that generate, convert, or control huge amounts of energy almost always involve devices whose operation depends on magnetic phenomena. In this chapter we shall proceed from introductory magnetic circuit concepts to relatively simple magnetic structures and then to a consideration of transformers. The objective is to introduce the fundamental notions of electromechanical energy conversion, leading to an understanding of the operation of various electromagnetic devices. The magnetic material determines the size of the equipment, its capabilities, and the limitations on its performance. Practically all transformers and electrical machinery utilize magnetic material for shaping the magnetic fields that act as the medium for transferring and converting energy. Transformers are found in various applications such as radio, television, and electric power transmission and distribution circuits. Other devices, such as circuit breakers, automatic switches, and relays, also require the presence of a confined magnetic field for their proper operation.

Electrical energy can be transmitted and controlled simply, reliably, and efficiently. Among the energy conversion devices, electromechanical energy converters are the most important. Electromechanical energy conversion involves the interchange of energy between an electric system and a mechanical system, while using magnetic field as a means of conversion.

2. Magnetic Materials

For magnetic material media, the magnetic flux density B (Wb/m^2 or tesla) and the magnetic field intensity H (A/m) are related through the relationship

$$B = \mu H \ , \tag{1}$$

where μ stands for the permeability of the material expressed in henrys per meter (H/m). The free space permeability μ_0 is a constant given by $4\pi \times 10^{-7}$ H/m. The same value holds good for air and any nonmagnetic materials. For a linear magnetic material which exhibits a straight-line relationship between B and H and the permeability is a constant given by the slope of the *B-H* curve. However, the *B-H* curve is non-linear in general and the variation of B with H is depicted by the saturation curve of Fig. 1. The slope of the curve clearly depends on the operating flux density.

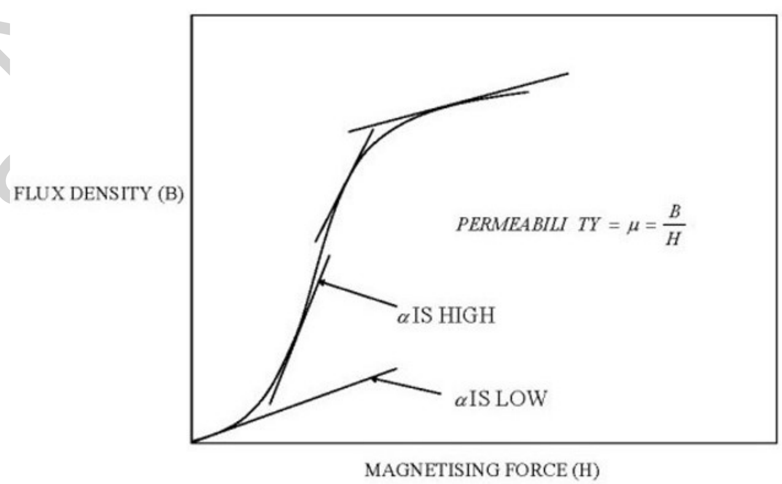

Figure 1: A typical B-H curve

The factor B/H is not constant and it is different at various points on the slope because the slope varies. Therefore the permeability can be defined only at given points on the curve. The different slopes are indicated by tangents drawn on the curve shown in Fig. 1. Two examples of slope measurement are shown by the small triangles that are drawn at two points on the slope given in Fig. 2.

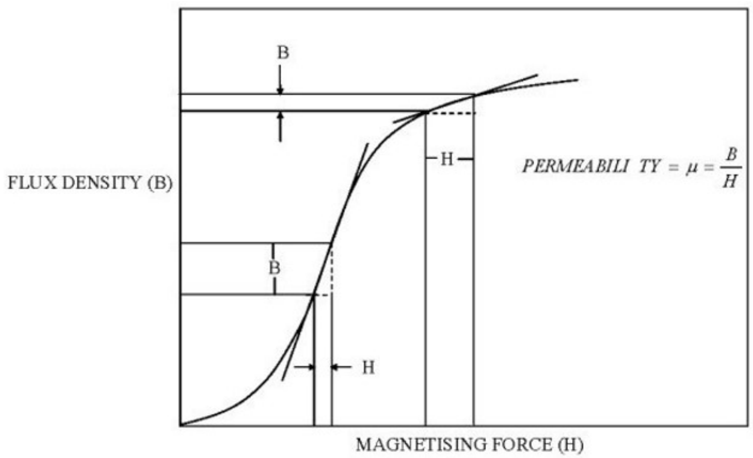

Figure 2: Permeability Estimation

Here, a small change in *B* for a small change in *H* is being measure; that is to say, the length of the vertical line of the triangle is plotted against the length of its base. The smaller the triangle, the more accurate is the measurement. This can be done by using calculus, which deals in infinitely small changes, but we are more concerned at this point with the principle rather than with the mathematics. In the case of the *B-H* curve the permeability is highest where the curve is steepest and it falls to near zero where the curve levels out at the top and bottom.

2.1. Ferromagnetic Materials

All ferromagnetic materials exhibit a phenomenon called saturation in which the flux density increases in proportion to the field intensity until it cannot do so any longer. Some actual B-H curves for common ferromagnetic materials are shown in Fig. 3.

The basic idea behind magnetic materials is that the spin of electrons constitutes motion charge, and therefore leads to magnetic effects. In most materials, the electron spins cancel out on the whole and no net effect remains. In ferromagnetic materials, however, atoms can align so that the electron spins cause a net magnetic effect. All ferromagnetic materials have atomic magnetic moments that are aligned parallel to each other within small regions called domains. Within these domains, the spontaneous magnetization present is equal to the saturation magnetization of the material, and so the individual domains are fully magnetized at all times. In the absence of an applied field, there is no net magnetic moment or field generated by the material because the magnetization direction of each domain is randomly oriented. During magnetization of the material, domains whose magnetization directions have a component in the direction of the applied field will grow at the expense of those that do not. As the field increases, more and more domains become aligned. When all of the domains have become aligned, any further increase in magnetic field intensity does not yield an increase in flux density beyond the increase that would be caused in a nonmagnetic material. Fig. 4 indicates the process of magnetization.

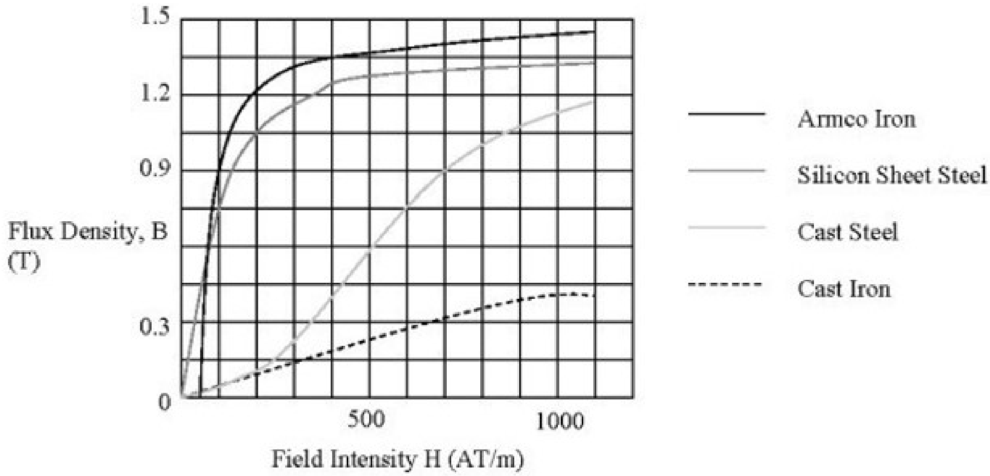

Figure 3: B-H curves for common ferromagnetic materials

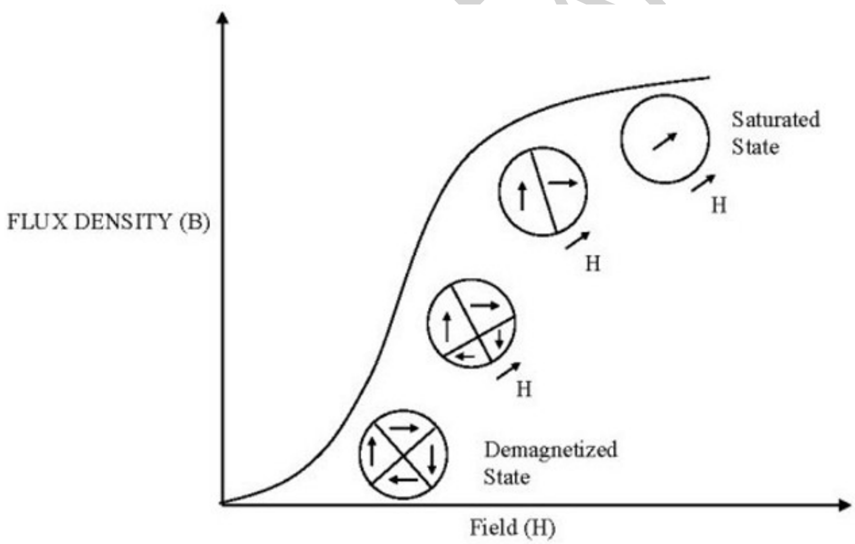

Figure 4: Process of magnetization

2.2. Iron-core Losses

Iron-core losses are usually divided into two components: hysteresis loss and eddy current loss. Hysteresis is loss mechanism in magnetic materials. It is a complex behavior and related to the magnetization properties of a material. The curve of Fig. 5 reveals that the *B-H* curve for a magnetic material during magnetization is displayed with respect to the curve that is measured when the material is demagnetized.

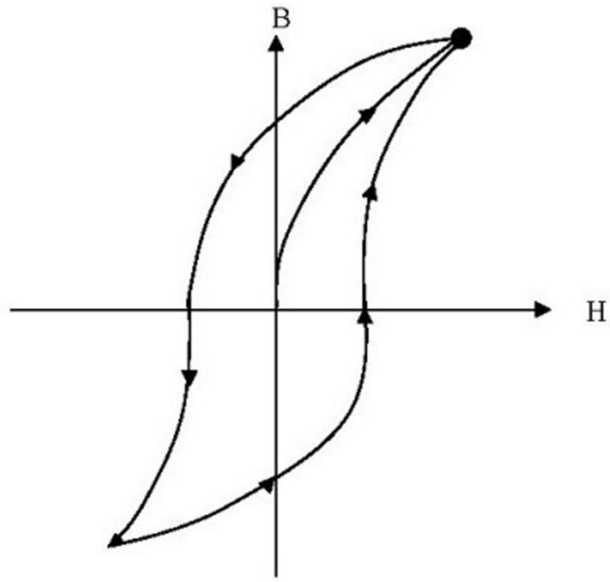

Figure 5: Typical hysteresis loop of a magnetic material

The area of the loop represents the heat energy loss during one cycle in the core material. The hysteresis loss per second is approximated empirically by the Steinmetz formula:

$$P_{\mathrm{h}} = hVfB_{\mathrm{m}}^{1.5 \text{ to } 2.5}, \tag{2}$$

where h is a constant depends on the characteristics of the material, V is the volume of the core, f is the frequency of excitation and B_{m} is the maximum magnetic flux density of the core. Choosing a material that has a narrow hysteresis loop can reduce the core loss.

The eddy currents are caused by any time-varying flux in the core material due to the electromagnetic induction. The induced voltage inside the magnetic core will cause eddy currents in the core which depend on the resistivity of the core. The effect of these currents is to dissipate energy in the form of heat. Eddy currents are reduced by selecting high resistivity core materials or by laminating the core, i.e. introducing tiny and discontinuous air gaps between core layers. Lamination of core reduces eddy current greatly without much affecting the magnetic properties of the core. The eddy current loss is

$$P_{\mathrm{e}} = lVf^{2}t^{2}B_{\mathrm{m}}^{2}, \tag{3}$$

where l is a constant depends on the characteristics of the core , V is the volume of the core, f is the frequency, t is the lamination thickness and B_{m} is the maximum core flux density.

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Biographical Sketches

K.K. Li received the MSc degree from University of Manchester Institute of Science and Technology, U.K., and PhD degree from City University, London, U.K.
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