

Magnetic Circuits

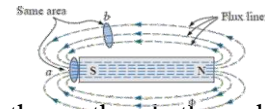
INTRODUCTION

Magnetism plays an integral part in almost every electrical device used today in industry, research, or the home. Generators, motors, transformers, circuit breakers, televisions, computers, tape recorders, and telephones all employ magnetic effects to perform a variety of important tasks.

MAGNETIC FIELDS

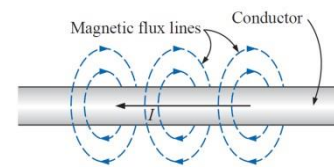
In the region surrounding a permanent magnet there exists a magnetic field, which can be represented by **magnetic flux lines** similar to electric flux lines. Magnetic flux lines, however, do not have origins or terminating points as do electric flux lines but exist in continuous loops, as shown in Figure below.

The symbol for magnetic flux is the Greek letter (ϕ).

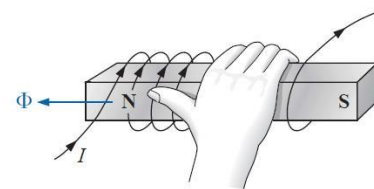


The magnetic flux lines radiate from the north pole to the south pole, returning to the north pole through the metallic bar.

A magnetic field is present around every wire that carries an electric current. The direction of the magnetic flux lines can be found simply by placing the thumb of the right hand in the direction of conventional current flow and noting the direction of the fingers. (This method is commonly called the right-hand rule.)



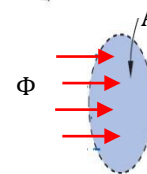
In the SI system of units, magnetic flux is measured in *webers*. The number of flux lines per unit area is called the **flux density**, is denoted by the capital letter B , and is measured in *teslas*. Its magnitude is determined by the following equation:



$$B = \frac{\Phi}{A}$$

$B = \text{teslas (T)}$
 $\Phi = \text{webers (Wb)}$
 $A = \text{square meters (m}^2\text{)}$

where Φ is the number of flux lines passing through the area A .



Example

Determine the flux density



$$\Phi = 6 \times 10^{-5} \text{ Wb}$$

$$A = 1.2 \times 10^{-3} \text{ m}^2$$

PERMEABILITY

If cores of different materials with the same physical dimensions are used in the electromagnet described in Section 11.2, the strength of the magnet will vary in accordance with the core used. This variation in strength is due to the greater or lesser number of flux lines passing through the core. Materials in which flux lines can readily be set up are said to be *magnetic* and to have *high permeability*. The **permeability** of a material, therefore, is a measure of the ease with which magnetic flux lines can be established in the material. It is similar in many respects to conductivity in electric circuits. The permeability of free space (vacuum) is

The ratio of the permeability of a material to that of free space is called its **relative permeability**; that is,

RELUCTANCE

The resistance of a material to the flow of charge (current) is determined for electric circuits by the equation

The reluctance of a material to the setting up of magnetic flux lines in the material is determined by the following equation:

$$\mathcal{R} = \frac{l}{\mu A}$$

Where \mathcal{R} is the reluctance, l is the length of the magnetic path, and A is the cross-sectional area.

OHM'S LAW FOR MAGNETIC CIRCUITS

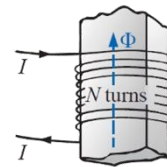
For magnetic circuits, the effect desired is the flux Φ . The cause is the **magnetomotive force (mmf)** \mathcal{F} which is the external force (or "pressure") required to set up the magnetic flux lines within the magnetic material. The opposition to the setting up of the flux Φ is the reluctance \mathcal{R} .

Substituting, we have

$$\Phi = \frac{\mathcal{F}}{\mathcal{R}}$$

The magnetomotive force \mathcal{F} is proportional to the product of the number of turns around the core (in which the flux is to be established) and the current through the turns of wire.

$$\mathcal{F} = NI \text{ (ampere-turns, At)}$$



MAGNETIZING FORCE

The magnetomotive force per unit length is called the **magnetizing force (H)**.

$$H = \frac{\mathcal{F}}{l} \text{ (At/m)}$$

Substituting for the magnetomotive force will result in

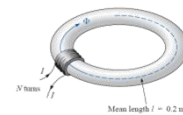
$$H = \frac{NI}{l} \text{ (At/m)}$$

Example:

Determine the magnetizing force for the following figure if $N=20$ and $I=2A$.

Sol

$$H = \frac{NI}{l} = \frac{20 \times 2}{1} = 40 \text{ (At/m)}$$



The flux density and the magnetizing force are related by the following equation:

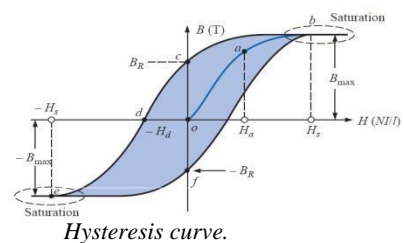
HYSTERESIS

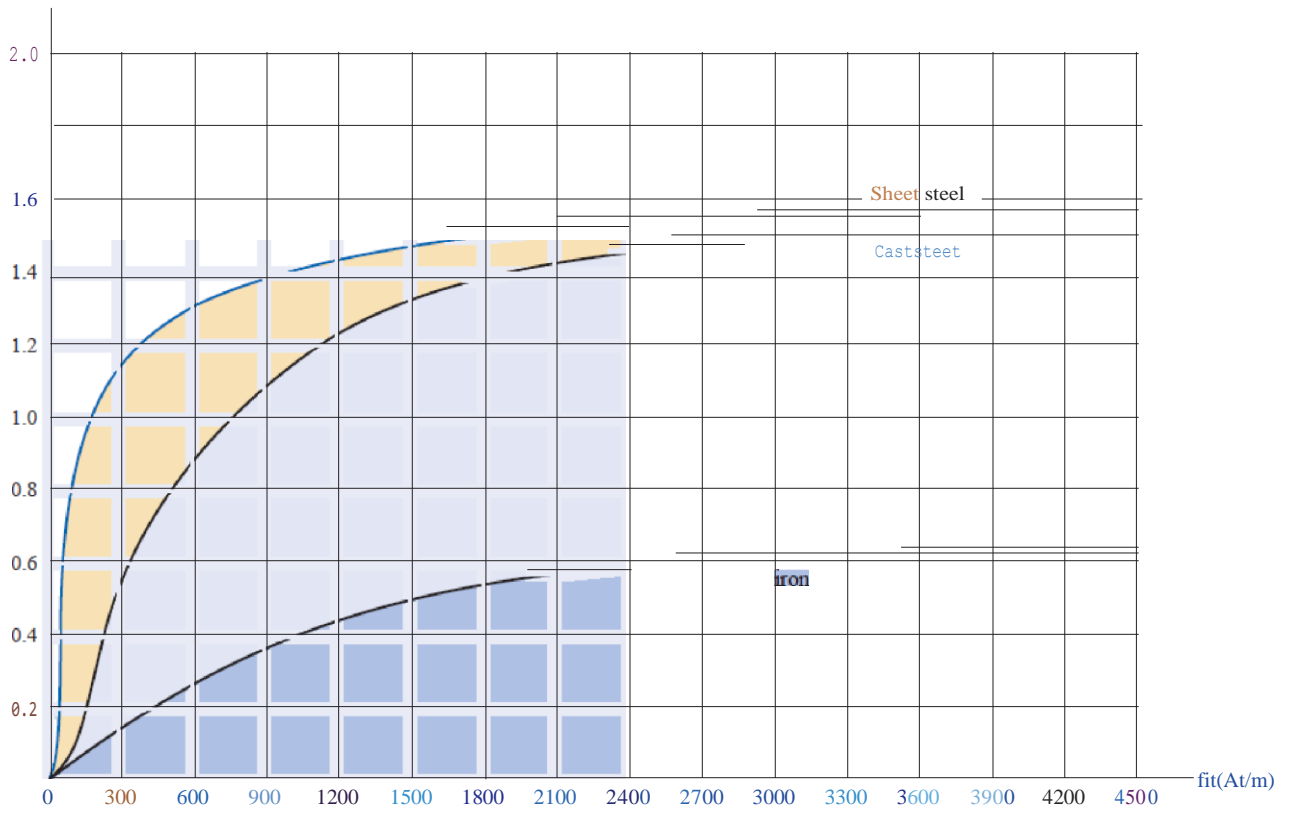
A curve of the flux density B versus the magnetizing force H of a material is of particular importance to the engineer. Curves of this type can usually be found in manuals, descriptive pamphlets, and brochures published by manufacturers of magnetic materials. A typical $B-H$ curve for a ferromagnetic material such as steel can be derived using the following setups.

The core is initially unmagnetized and the current $I = 0$. If the current I is increased to some value above zero, the magnetizing force H will increase to a value determined by

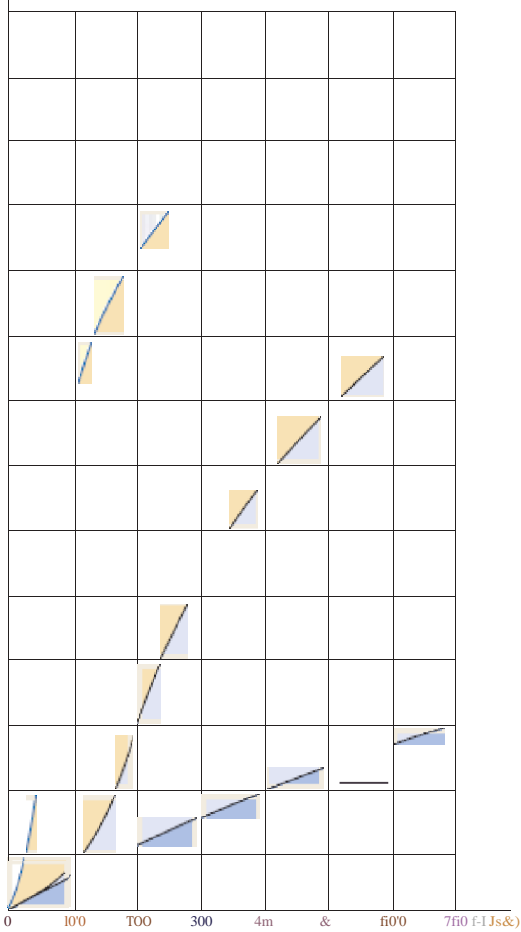
$$H \uparrow \frac{NI}{l} \uparrow$$

The flux and the flux density B will also increase with the current I (or H).





Normal magnetization curve for three ferromagnetic materials



low magnetizing force region for three ferromagnetic materials

AMPÈRE'S CIRCUITAL LAW

Electric Circuits

Magnetic Circuits

Cause	E	\mathcal{F}
Effect	I	Φ
Opposition	R	\mathcal{R}

If we apply the “cause” analogy to Kirchhoff’s voltage law $\sum_{\mathcal{C}} V = 0$, we obtain the following:

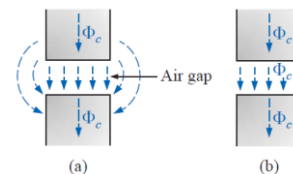
$$\sum_{\mathcal{C}} \mathcal{F} = 0$$

which, in words, states that the algebraic sum of the rises and drops of the mmf around a closed loop of a magnetic circuit is equal to zero; that is, the sum of the rises in mmf equals the sum of the drops in mmf around a closed loop.

This equation referred to as **Ampère’s circuital law**. When it is applied to magnetic circuits, sources of mmf are expressed as And

AIR GAPS

The spreading of the flux lines outside the common area of the core for the air gap in Fig. a is known as *fringing*. For our purposes, we shall neglect this effect and assume the flux distribution to be as in Fig. b.



The flux density of the air gap in is given by

—

where, for our purposes,

And

For most practical applications, the permeability of air is taken to be equal to that of free space. The magnetizing force of the air gap is then determined by

—

- and the mmf drop across the air gap is equal to Hgl . An equation for Hg is as follow