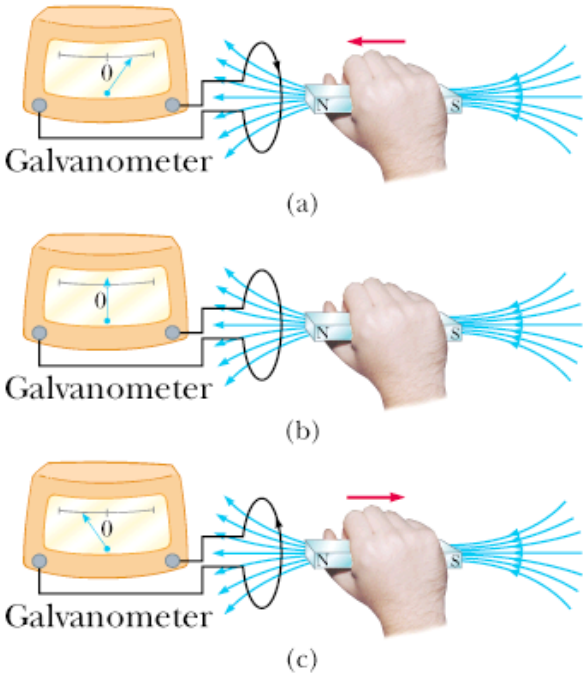
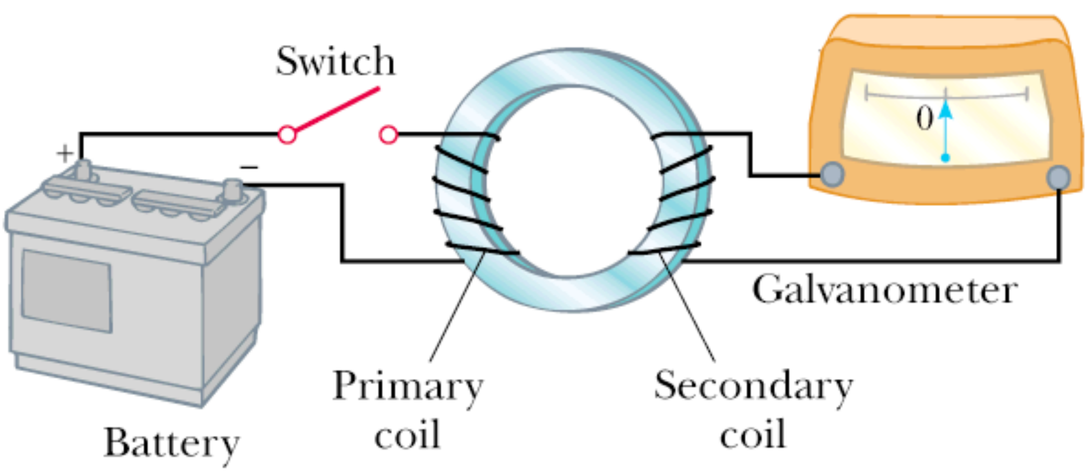
Induced EMF



A current flows through the loop when a magnet is moved near it, without any batteries!



The needle deflects momentarily when the switch is closed

Faraday's Law of Induction

The emf induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit.

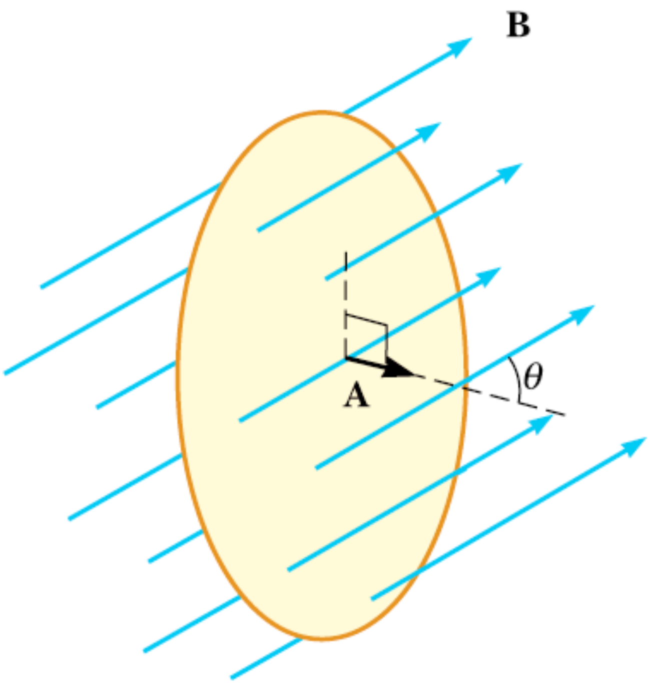
$$\boxed{\mathcal{E} = -\frac{d\Phi_B}{dt}}$$

where, $$\boxed{\Phi_B = \int \mathbf{B}.d\mathbf{A}}$$

For N loops, $$\boxed{\mathcal{E} = -N\frac{d\Phi_B}{dt}}$$

Faraday's Law of Induction

$$\boldsymbol{E} = -\frac{d\Phi_B}{dt} \qquad \boldsymbol{E} = -\frac{d}{dt}\left(BA\cos\theta\right)$$



To induce an emf we can change,

- the magnitude of B
- the area enclosed by the loop
- the angle between B and the normal to the area
- any combination of the above

over time.

Magnetic Circuits

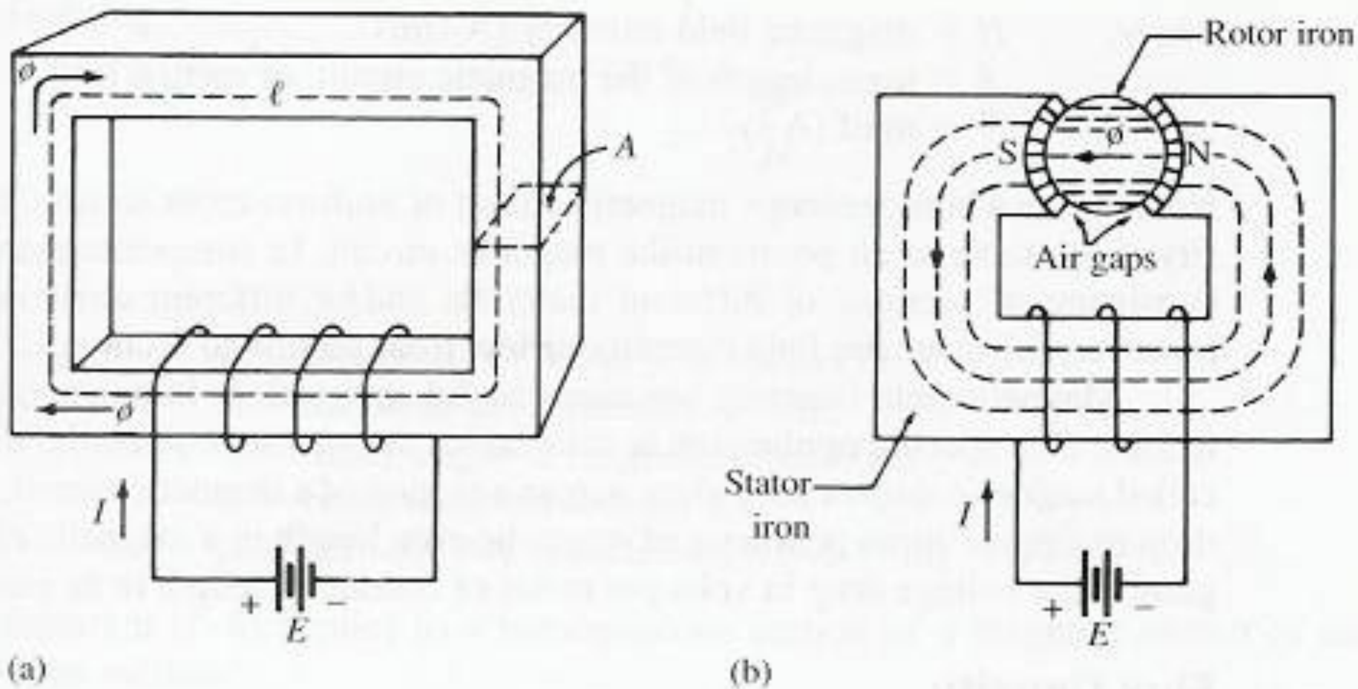


FIGURE 1.2
Magnetic circuit: (a) for a transformer; (b) for a simple two-pole motor.

Magnetic Circuit Definitions

- Magnetomotive Force
  - The "driving force" that causes a magnetic field
  - Symbol, $\mathcal{F}$
  - Definition, $\mathcal{F} = \mathcal{N}I$
  - Units, Ampere-turns, (A-t)

Magnetic Circuit Definitions

- Magnetic Field Intensity
  - mmf gradient, or mmf per unit length
  - Symbol, H
  - Definition, $\mathcal{H} = \mathcal{F}/\ell = \mathcal{N}I/\ell$
  - Units, (A-t/m)

Magnetic Circuit Definitions

- Flux Density
  - The concentration of the lines of force in a magnetic circuit
  - Symbol, B
  - Definition, $B = \Phi / A$
  - Units, (Wb/m^2), or T (Tesla)

Magnetic Circuit Definitions

- Reluctance
  - The measure of "opposition" the magnetic circuit offers to the flux
  - The analog of Resistance in an electrical circuit

  - Symbol, $\mathcal{R}$
  - Definition, $\mathcal{R} = \mathcal{F}/\Phi$
  - Units, (A-t/Wb)

Magnetic Circuit Definitions

- Permeability
  - Relates flux density and field intensity
  - Symbol, μ
  - Definition, $\mu = B/H$
  - Units, (Wb/A-t-m)

Magnetic Circuit Definitions

- Permeability of free space (air)
  - Symbol, μ_0
  - $\mu_0 = 4\pi x 10^{-7}$ Wb/A-t-m

Magnetic Circuit Definitions

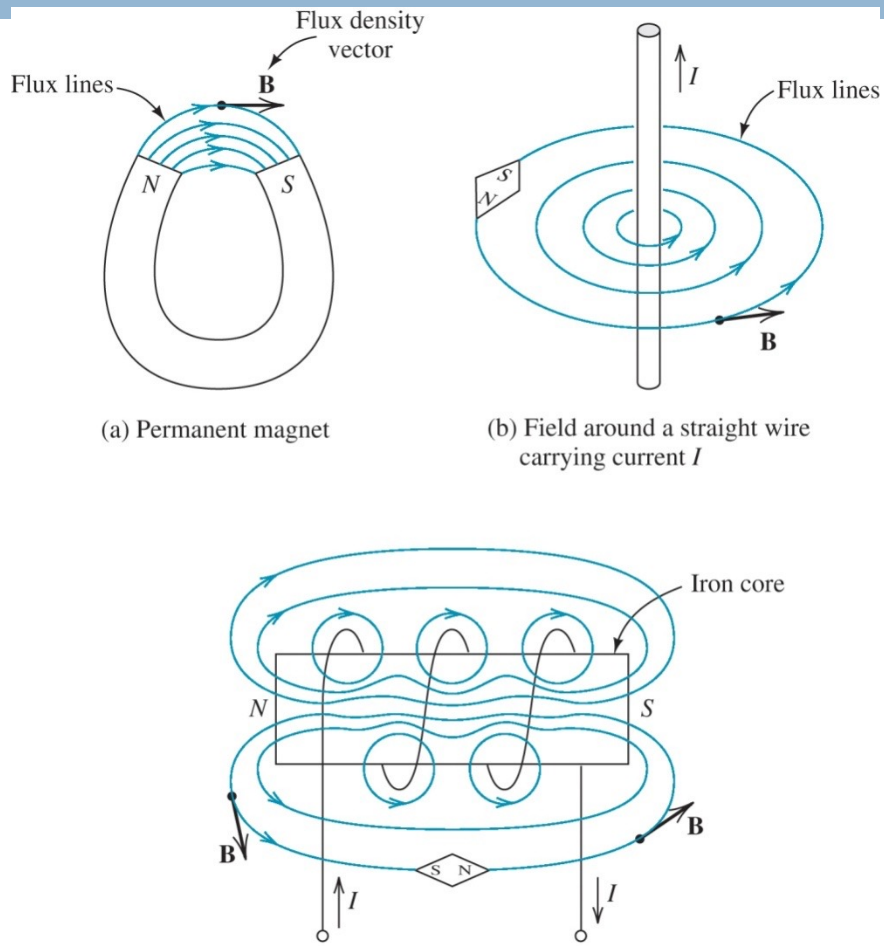
- Relative Permeability
  - Compares permeability of material with the permeability of free space (air)
  - Symbol, μ_r
  - $\mu_r = \mu/\mu_0$ Dimensionless

Magnetic Fields

Magnetic fields can be visualized as lines of flux that form closed paths.

Using a compass, we can determine the direction of the flux lines at any point.

Note that the **flux density vector B** is tangent to the lines of flux.



(a) Permanent magnet

(b) Field around a straight wire carrying current I

(c) Field for a coil of wire

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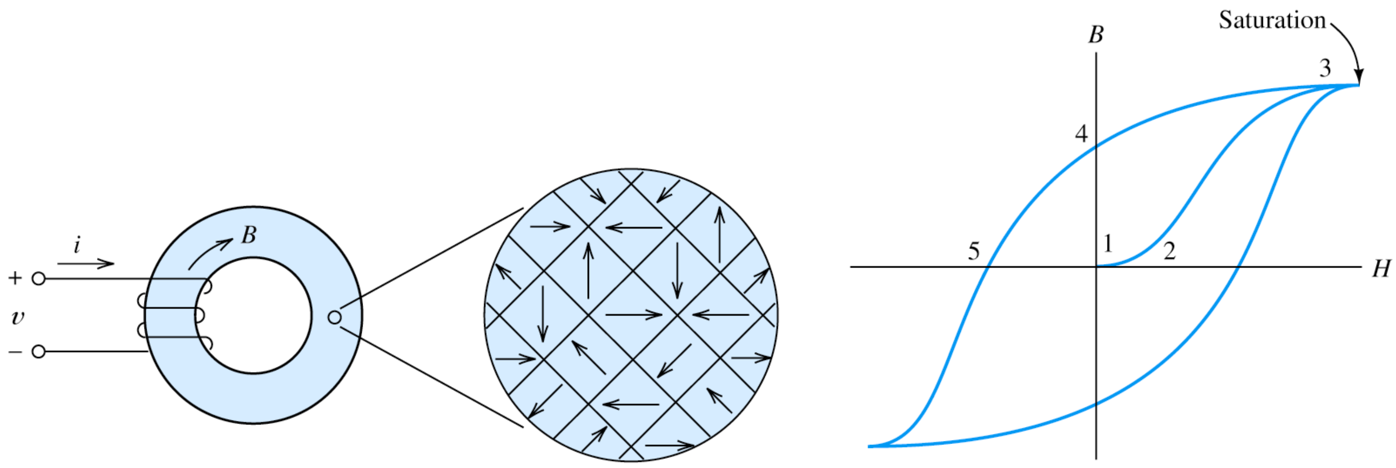
Magnetic Materials

- In general, relationship between B and H in magnetic materials is nonlinear.
- Magnetic fields of atoms in small domains are aligned (Fig. 15.18 b).
- Field directions are random for various domains, so the external magnetic field is zero.
- When H is increased the magnetic fields tend to align with the applied field.

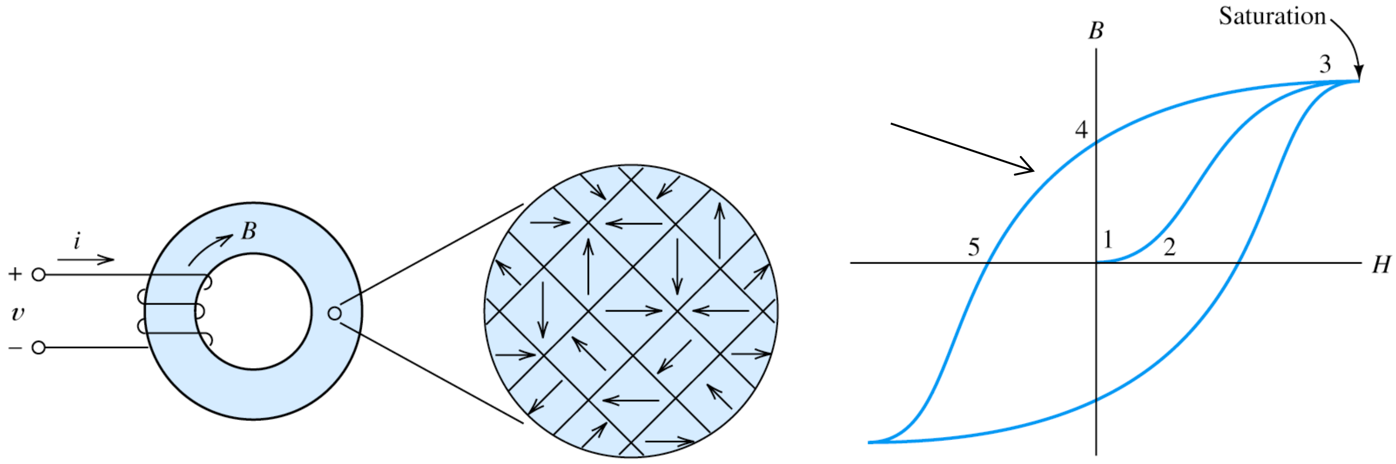


(a) Sample and coil for applying H (b) Magnetic domains (c) Hysteresis loop in the $B - H$ plane

Figure 15.18 Materials such as iron display a $B-H$ relationship with hysteresis and saturation.

Magnetic Materials

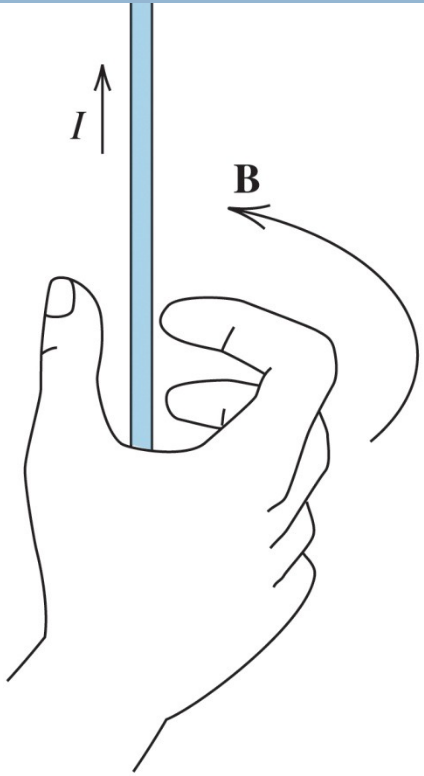
- Domains tend to maintain their alignment even if the applied field is reduced to zero.
- For very large applied field all the domains are aligned with the field and the slope of B-H curve approaches μ_0.
- When H is reduced to 0 from point 3 on the curve, a residual flux density B remains in the core.
- When H is increased in the reverse direction B is reduced to 0.
- Hysteresis result from ac current



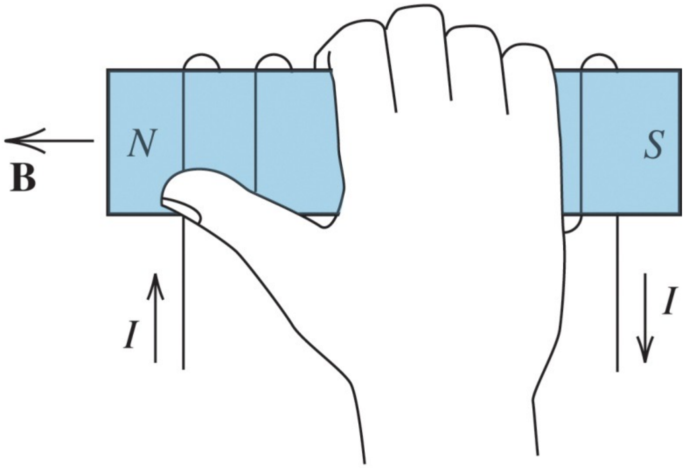
(a) Sample and coil for applying H (b) Magnetic domains (c) Hysteresis loop in the $B-H$ plane

Figure 15.18 Materials such as iron display a $B-H$ relationship with hysteresis and saturation.

Illustrations of the right-hand rule



(a) If a wire is grasped with the thumb pointing in the current direction, the fingers encircle the wire in the direction of the magnetic field



(b) If a coil is grasped with the fingers pointing in the current direction, the thumb points in the direction of the magnetic field inside the coil

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Flux Linkage and Induced Voltage

When the flux linking a coil changes, a voltage is induced in the coil.

The polarity of the voltage is such that if a circuit is formed by placing a resistance across the coil terminals, the resulting current produces a field that tends to oppose the original change in the field.

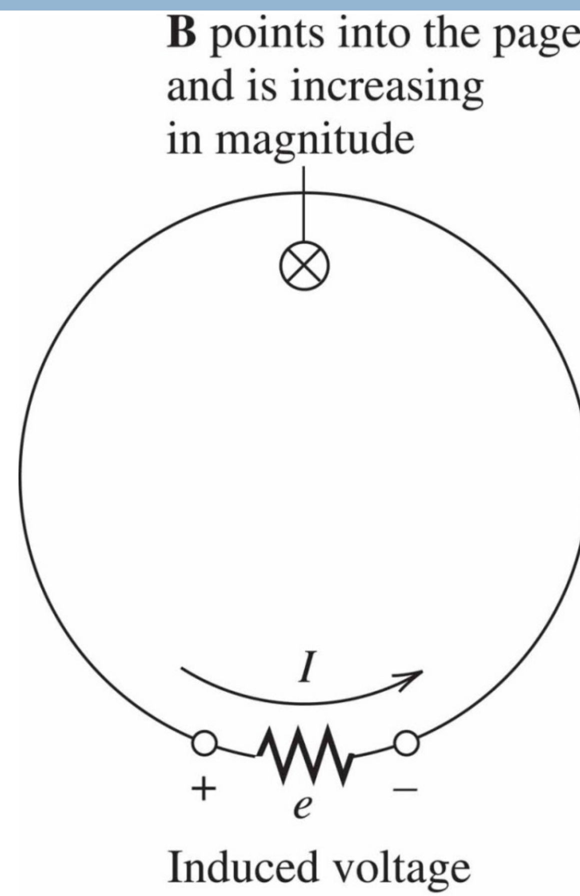
Faraday Law of magnetic induction: voltage **e** induced by the flux changes is

$$e = \frac{d\lambda}{dt}$$

where **total flux linkage** λ is

$$\lambda = N\phi = N\int_A BdA$$

N-number of turns, ϕ magnetic flux passing through the surface area **A**, and **B** is the magnetic field



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Magnetic Hysteresis and Hysteresis Loss

- Magnetic circuit with alternating mmf

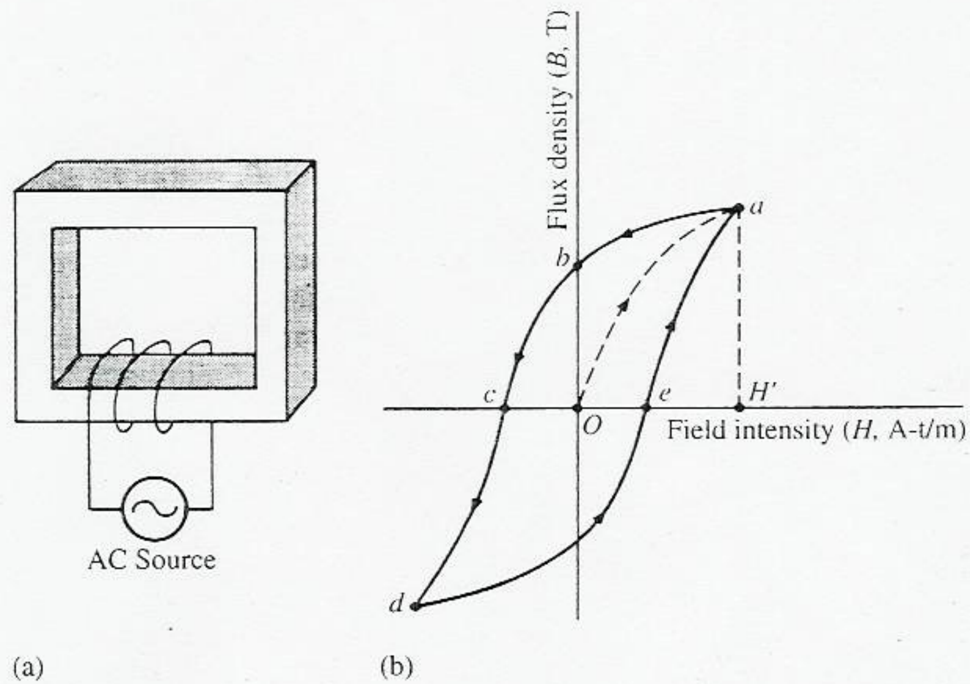


FIGURE 1.8
(a) Magnetic circuit with an alternating mmf; (b) representative hysteresis loop.

Magnetic Hysteresis Loss

- Power loss due to hysteresis
  - Produces heat due to re-alignment of magnetic domains
  - Varies directly with the frequency of the flux density
  - Varies directly as the nth power of the flux density

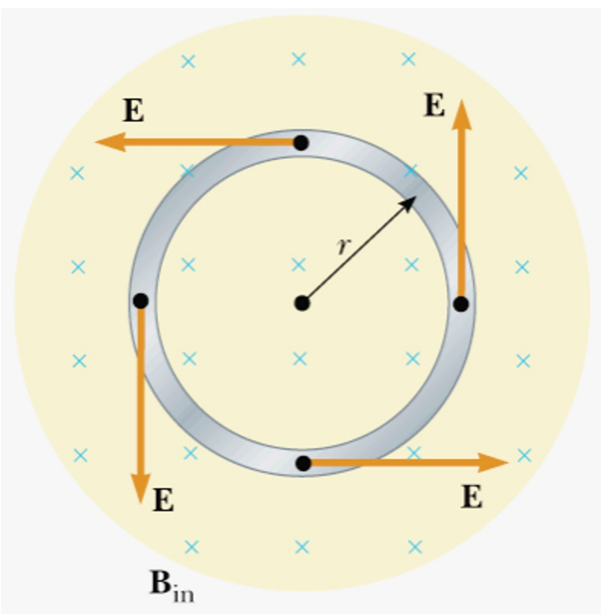
Magnetic Hysteresis Loss

- $P_h = (k_h)(f)(B_{max})^n$ where
  - P_h = hysteresis loss (W/unit mass)
  - f = frequency of the flux (Hz)
  - B_{max} = maximum value of the flux
  - k_h = constant
  - n = Steinmetz exponent
    - Value of 1.6 for silicon steel sheets

Induced EMF and Electric Fields

Changing Magnetic Flux → EMF → **Electric Field Inside a Conductor**

This induced electric field is non-conservative and time-varying



$$\mathcal{E} = -\frac{d\Phi_B}{dt} \longrightarrow \oint \mathbf{E}.d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

General Form of Faraday's Law

$$W = q\mathcal{E} = F_E(2\pi r)$$

$$q\mathcal{E} = qE(2\pi r)$$

$$E = \frac{\mathcal{E}}{2\pi r}$$

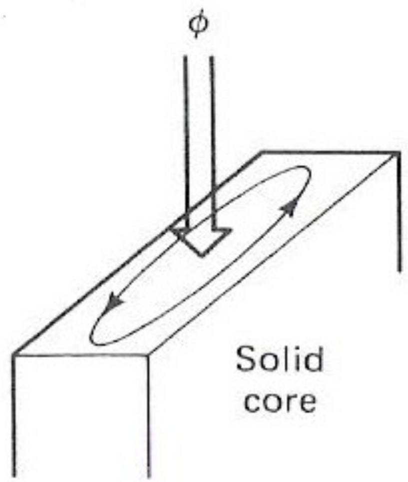
$$E = -\frac{1}{2\pi r}\frac{d\Phi_B}{dt} = -\frac{1}{2\pi r}\frac{d}{dt}\left(\pi r^2 B\right)$$

$$E = -\frac{r}{2}\frac{dB}{dt}$$

EDDY CURRENT LOSS

- Another power loss of mag. Core is due to rapid variation of B (using ac source)
- In core cross section, voltage induced

  and i_e passes, resistance of core cause:



$$P_e = i_e{}^\wedge 2\ R \quad \textbf{(Eddy Current loss)}$$

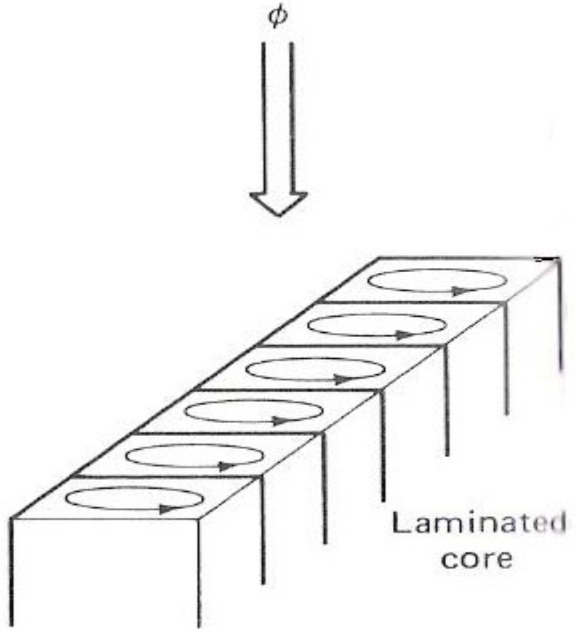
- this loss can be reduced as follows when:

  a- using high resistive core material, few % Si

  b- using a laminated core

EDDY CURRENT LOSS

- Application of Laminated Core



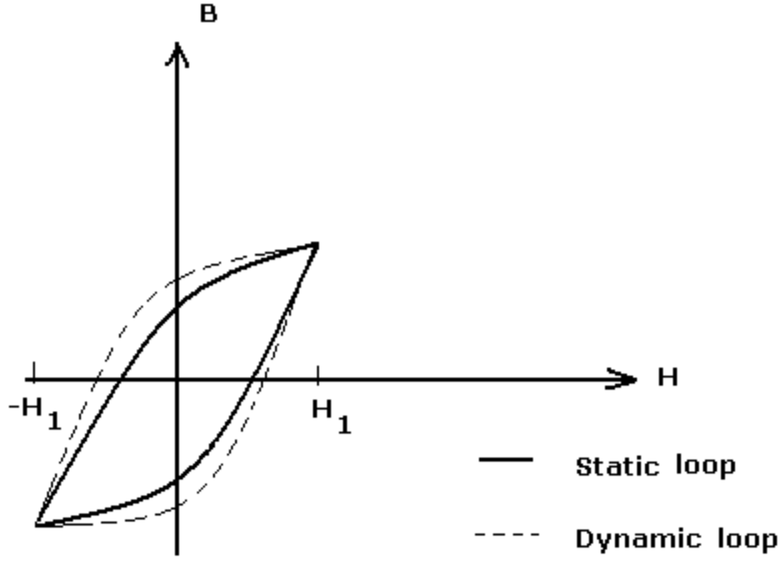
Eddy current loss: Pe=KeBmax^2 f^2

Ke: constant depends on material & lamination thickness which varies from 0.01 to 0.5 mm

CORE LOSS

- $P_c = P_h + P_e$
- If current I varies slowly eddy loss negligible
- Total core loss determined from dynamic B-H loop:

$$P_c = V_{core} f \oint_{dynamic\,loop} H\,dB$$



- Using a wattmeter core loss can be measured
- However It is not easy to know what portion is eddy & hysteresis

Residential Circuits

- Residential loads are connected in parallel, since the voltage remains the same through the loads and if a circuit fails it does not affect the others
- Purelly resistor load (e.g. lights, toaster)
  - Demand $P = VI\cos(a_v - a_i)$
  - $\cos(a_v - a_i)$ is the power factor
- If a motor is added (e.g. celing fan, refrigerator)
  - Demand $Q = VI\sin(a_v - a_i)$, as well as P
  - $\sin(a_v - a_i)$ is the reactive factor

Improving Power Consumption

- Add a capacitor/capacitor block in parallel to the load
- Make sure is the right one
- Don’t add it to purely resistor circuits