EE 6503
Modern Electrical Drives (Week 1 to 6)

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Chapters

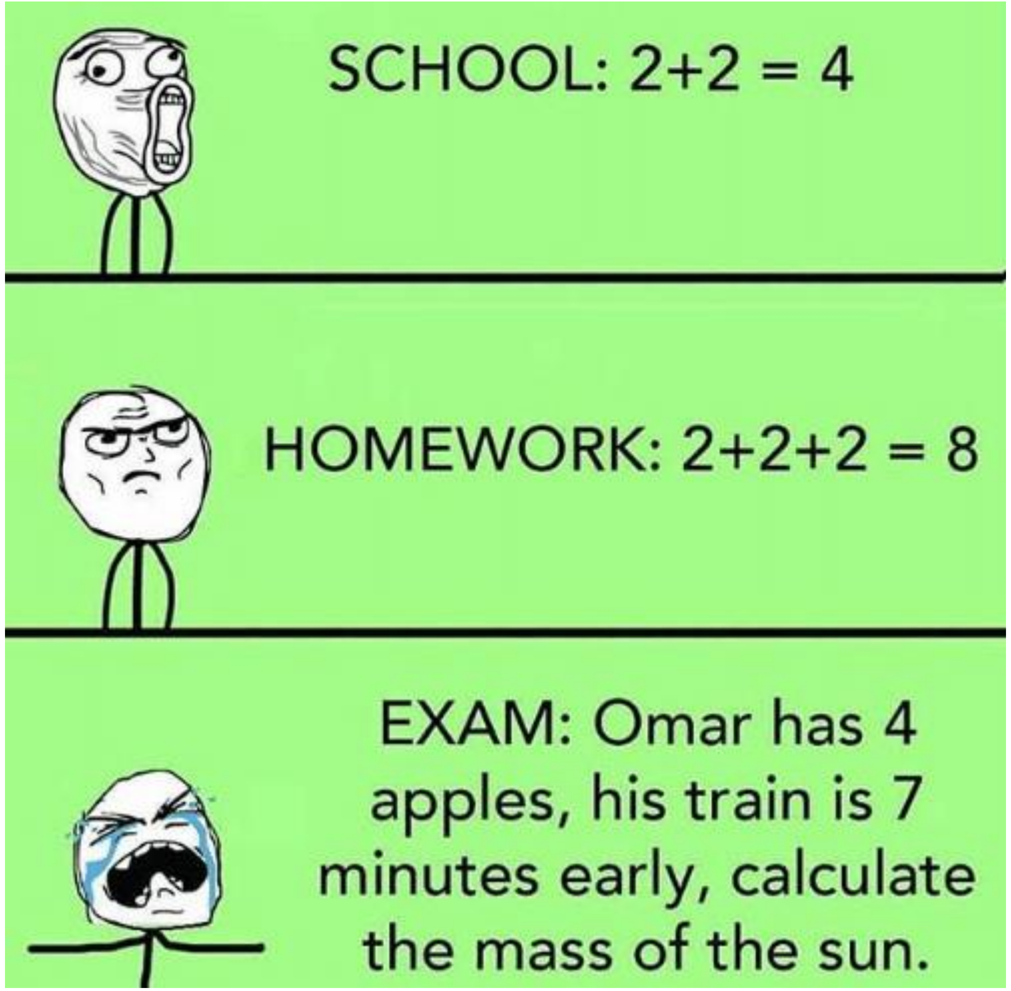
1. Magnetic circuits
2. Electromechanical energy conversions
3. DC machines
4. Power converters
5. Transients and dynamics

Reference Books

- A. E. Fitzgerald, Charles Kingsley, Stephen D. Umans, Electric Machinery, 6th Edition, McGraw-Hill Higher Education, 2003.
- Paresh C. Sen, Principles of Electric Machines and Power Electronics, 3rd Edition, John Wiley and Sons, 2014.
- N. Mohan, Tore M. Undeland, William P. Robbins, Power Electronics – Converters, Applications and Design, 3rd Edition, John Wiley & Sons, 2002.

Suggested Learning "Rules"

- Read reference book / lecture notes
- Attend lectures / tutorials
- Be proactive and interactive
- Understand before you memorize
- Work on exercises
- Enjoy learning !!!



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Grading

Type	Description	Date
CA – Quiz #1 **(10%)**	Prof Lee’s Practice Question from Weeks 1 to 4 – questions which requires understanding of concepts, analytical thinking and numerical calculations. Closed book in lecture theatre.	11 Feb 2020 (Tue)
CA – Quiz #1 **(10%)**	Prof Zhang’s Practice Question from Weeks 7 to 11 (tentative). Covered contents subjected to be changed.	TBC
Final Exam **(80%)**	All lecture and tutorial materials covered in the class from Weeks 1 to 13. Closed book in exam hall.	TBC

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Consultation

- No regular consultation hour
- Feel free to make appointment by emails
- Ask questions during breaks and after lectures

A.O.B.

- Be punctual (a few minutes buffer may be addressed)
- Break between every 50 minutes
- Dismiss 5 minutes earlier than designated time

Why I Started my Career as Academia?

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My Research

TESLA

Goal

Market Leader

ROLLS ROYCE

EEE

Chris
Motor Lab

Boston Dynamics

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SIA ENGINEERING COMPANY

Chapter 1 Magnetic Circuits

Learning Objectives

- Learn fundamentals of magnetic circuits
- Classify compositions of core losses
- Understand basics of permanent-magnet materials

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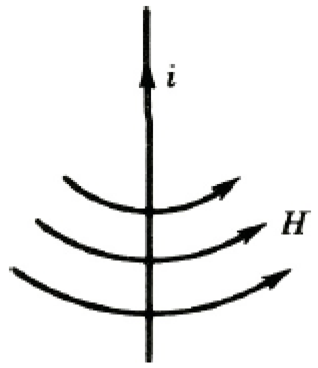
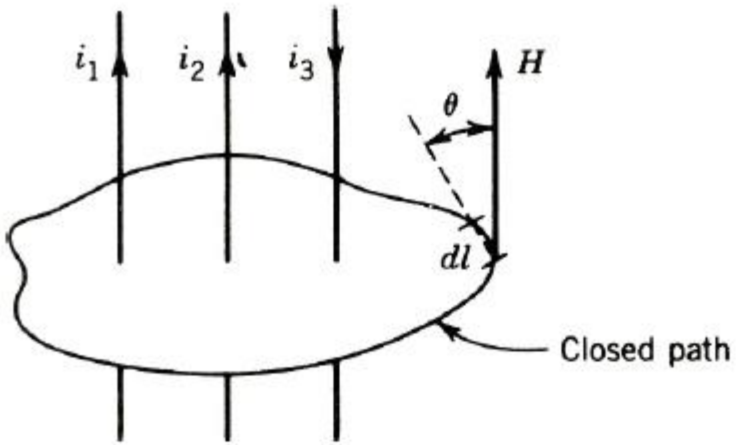
1.1 Fundamentals



- In electrical machines, magnetic circuits can be formed by ferromagnetic materials in conjunction with an air medium
- In most electrical machines, except permanent magnet machines, magnetic field or magnetic flux is produced by passing electric current through ferromagnetic materials

1.1 Fundamentals



- By Ampere's circuit law

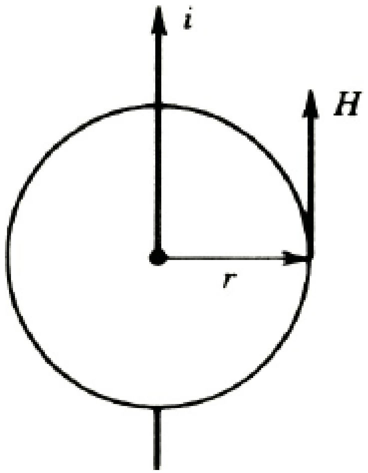
$$\oint H \cdot dl = \sum i$$

where *H* is magnetic field intensity

- and

$$\oint H \cdot dl\, cos\theta = \sum i$$

1.1 Fundamentals



- Consider a conductor with current *i*

$$\oint H \cdot dl = \sum i$$

$$H = \frac{i}{2\pi r}$$

1.1 Fundamentals

- Magnetic flux density *B* can be produced with existence of magnetic field intensity *H*

$$B = \mu H$$

$$B = \mu_r \mu_0 H$$

where μ is permeability of the medium

μ_0 is permeability of free space of $4\pi \times 10^{-7}$

μ_r is relative permeability of the medium

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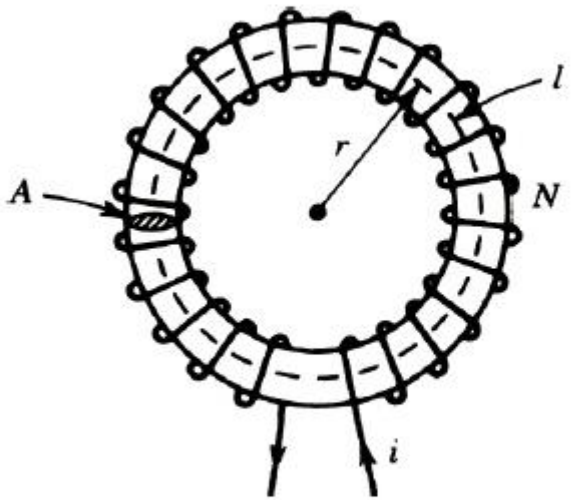
1.2 Magnetic Equivalent Circuit



- Consider a ring-shaped magnetic core, or known as toroid

$$\oint H \cdot dl = Ni$$

$$Hl = Ni$$

$$H2\pi r = Ni$$

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1.2 Magnetic Equivalent Circuit

- Quantity of *Ni* is known as magnetomotive force (mmf)

$$Hl = Ni = F$$

$$B = \frac{\mu Ni}{l}$$

- Assume no flux leakage

$$\Phi = \int B\, dA = BA$$

$$= \frac{\mu Ni}{l} A$$

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

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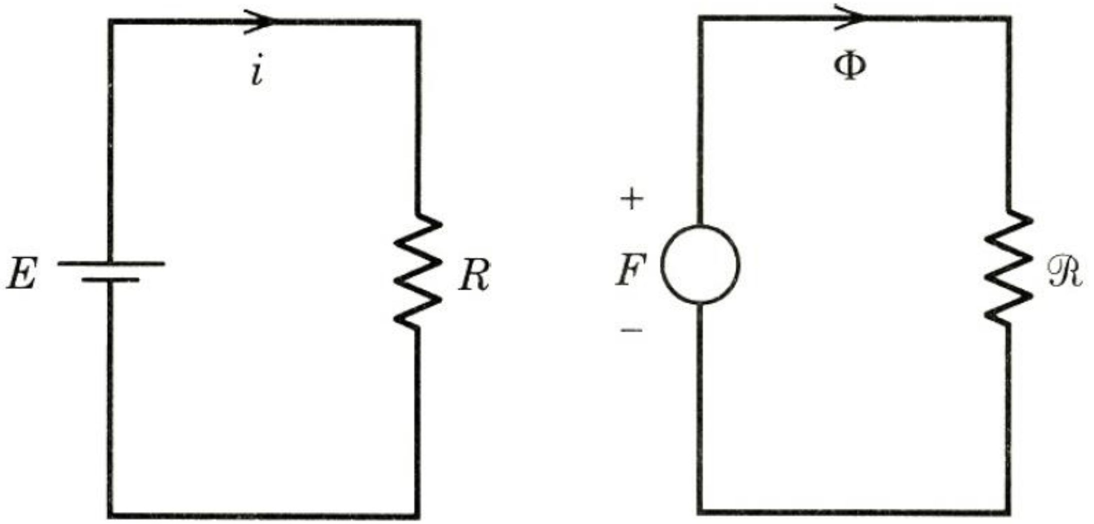
1.2 Magnetic Equivalent Circuit



	Electric circuit	Magnetic circuit
Driving force	EMF (E)	MMF (F)
Product	Current ($I = E/R$)	Flux ($\Phi = F/\mathbb{R}$)
Limiting factor	Resistance ($R = l/\sigma A$)	Reluctance ($\mathbb{R} = l/\mu A$)

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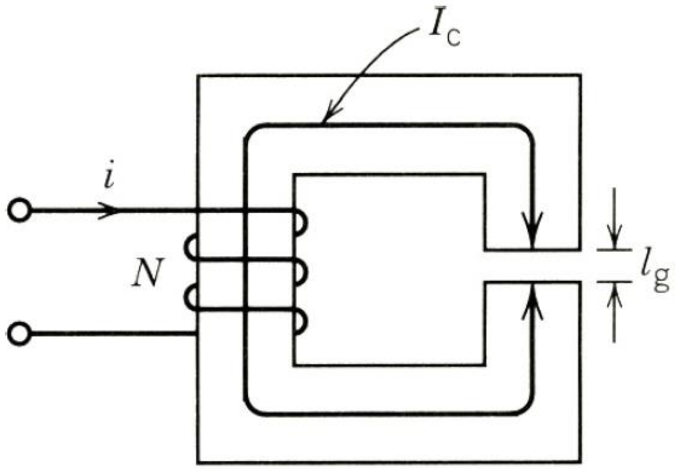
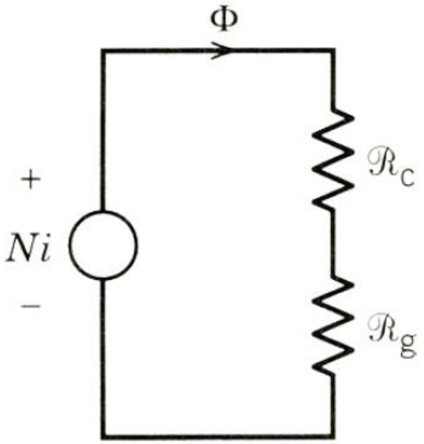
1.2 Magnetic Equivalent Circuit





- Equivalent magnetic circuit

$$\mathcal{R}_c = \frac{l_c}{\mu_c A_c} \qquad \mathcal{R}_g = \frac{l_g}{\mu_0 A_g} \qquad \Phi = \frac{Ni}{\mathcal{R}_c + \mathcal{R}_g} \qquad Ni = H_c l_c + H_g l_g$$

where l_c is the mean length of the core

l_g is the length of the air gap

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1.2 Magnetic Equivalent Circuit

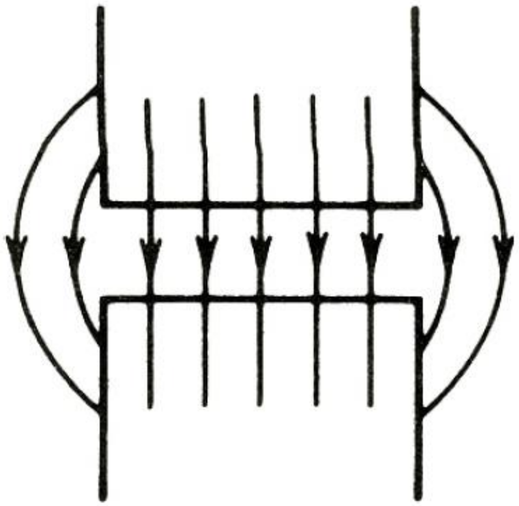
- Flux densities are

$$B_c = \frac{\Phi_c}{A_c} \qquad B_g = \frac{\Phi_g}{A_g}$$

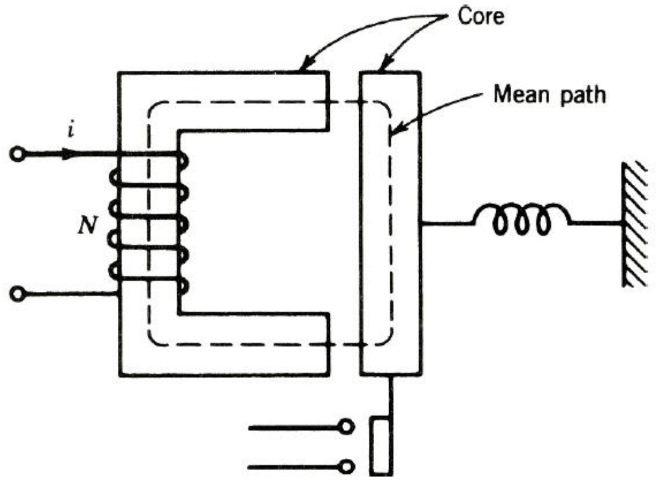
- Magnetic fluxes bulge outward as known as fringing effect
- Fringing effect can be neglected for small air gap as

$$A_g = A_c$$

$$B_g = B_c = \frac{\Phi}{A_c}$$



Concept Check 1.1



Consider a magnetic circuit of a primitive relay as shown above. It consists of coils of 500 turns and its mean core path is 360 mm. The air gap lengths are 1.5 mm each with a flux density of 0.8 T for relay activation. Assume the core is a cast steel with flux density of 0.8 T and field intensity of 510 At/m.

(a) Find the current in the coil (Ans: 4.19 A)

(b) Calculate the permeability and relative permeability of the core (Ans: 1.57 x 10^{-3}; 1250)

(c) If the air gap is zero, find the current in the coil in the core (Ans: 0.368 A)

Concept Check 1.1

Concept Check 1.1

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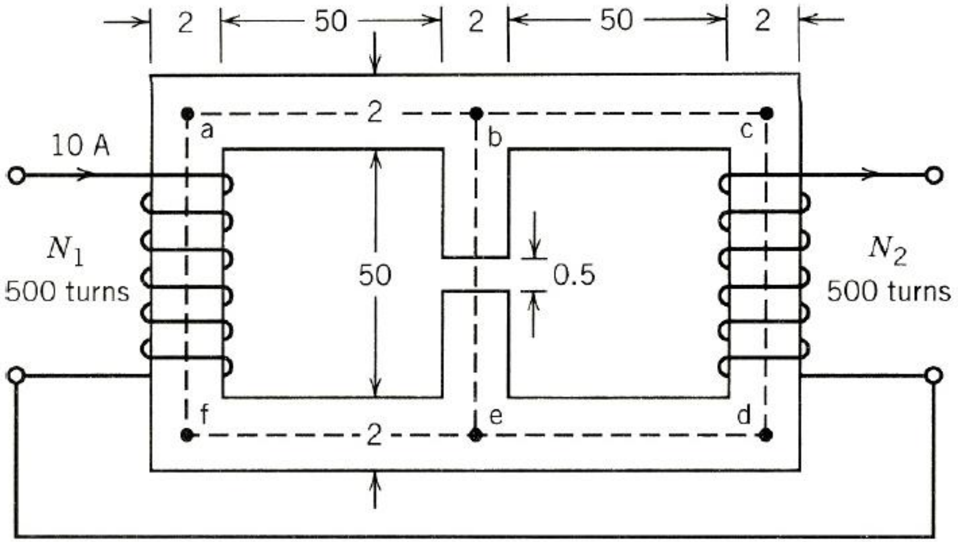
Concept Check 1.2



Consider a magnetic circuit as shown above. The relative permeability of its ferromagnetic materials is 1200. Assume magnetic leakage and fringing effect are negligible. All dimensions are in centimeters with square cross-sectional area. Calculate the air gap flux, air gap flux density, and magnetic field intensity in the air gap (Ans: 4.134×10^{-4} Wb; 1.034 T; 0.822×10^{6} At/m)

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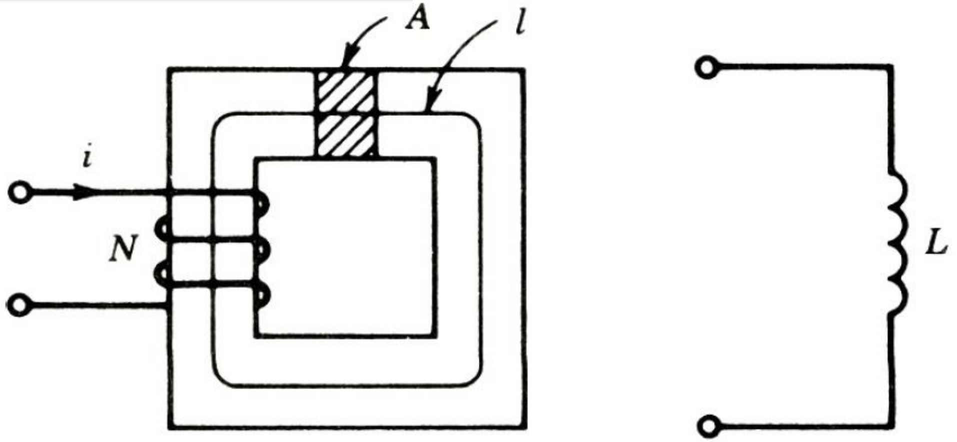
Concept Check 1.2

Concept Check 1.2

1.2 Magnetic Equivalent Circuit



- Consider a coil wound on a magnetic core

$$\lambda = N\,\Phi \qquad\qquad L = \frac{\lambda}{i}$$

$$= \frac{N^2}{\mathcal{R}}$$

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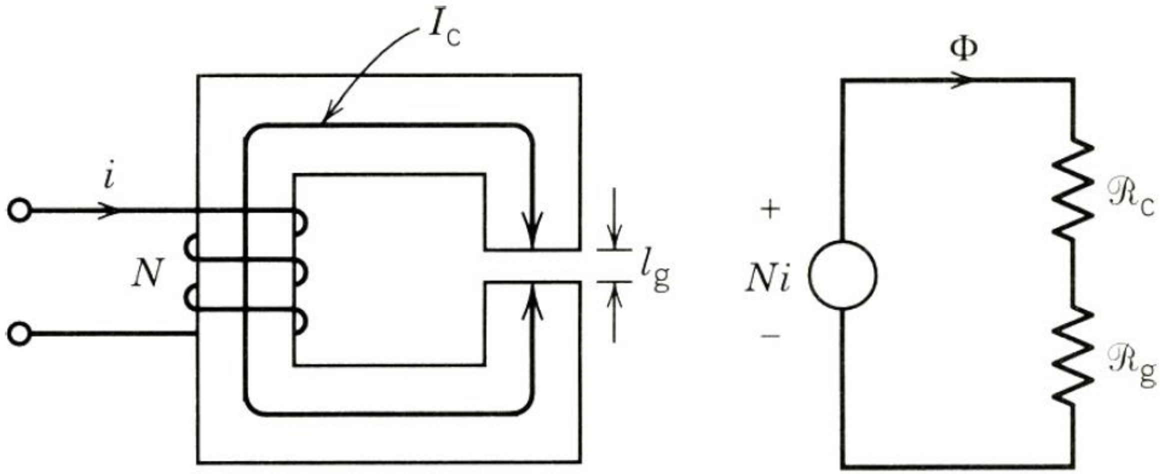
Concept Check 1.3



Consider a magnetic circuit as shown above. It consists of coil turns of 400, mean core length of 50 cm, air gap length of 1.0 mm, cross-sectional area of 15 cm^2, relative permeability of core as 3000, and current as 1.0 A. Find

(a) Flux and flux density in the air gap (Ans: 0.646 x 10^{-4} Wb; 0.431 T)

(b) Inductance of the coil (Ans: 258.5 x 10^{-3} H)

Concept Check 1.3

Concept Check 1.3

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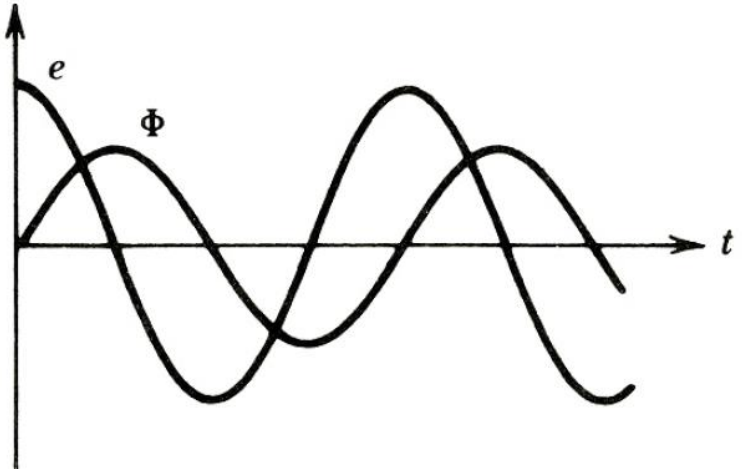
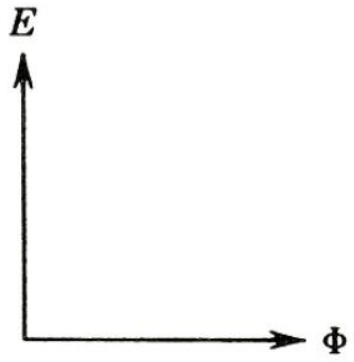
1.2 Magnetic Equivalent Circuit





- Assume the core flux varies sinusoidally with time

$$e(t) = N\frac{d\Phi}{dt}$$

$$= E_{max}\cos\omega t$$

- Induced voltage in rms form

$$E_{rms} = \frac{E_{max}}{\sqrt{2}}$$

$$= 4.44Nf\Phi_{\max}$$

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Concept Check 1.4

Consider a square-wave voltage source with amplitude of 100 V and frequency of 60 Hz is applied on a coil wound on a closed iron core. This coil consists of 500 turns and cross-sectional area of 0.001 m^2. Assume coil resistance to be zero.

(a) Find the maximum value of the flux (Ans: 0.833×10^{-3} Wb)

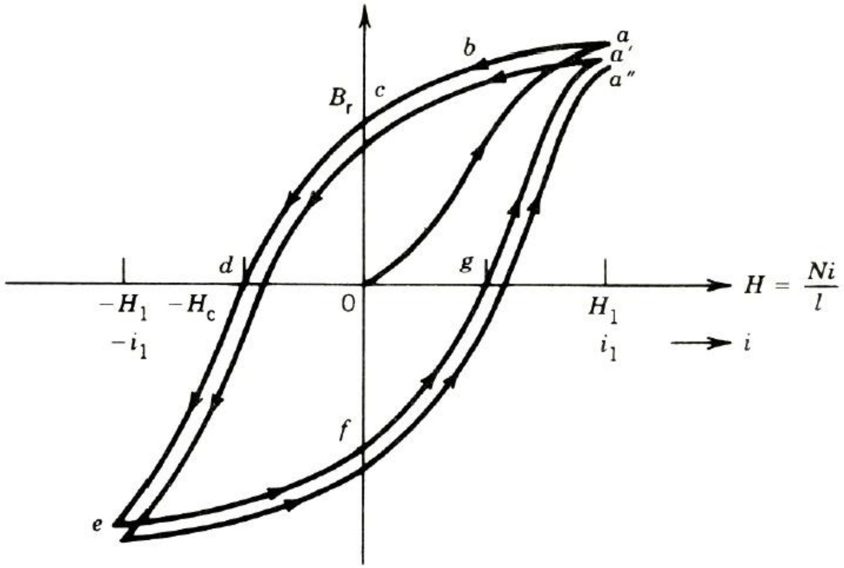
(b) Sketch the waveforms of voltage and flux against time

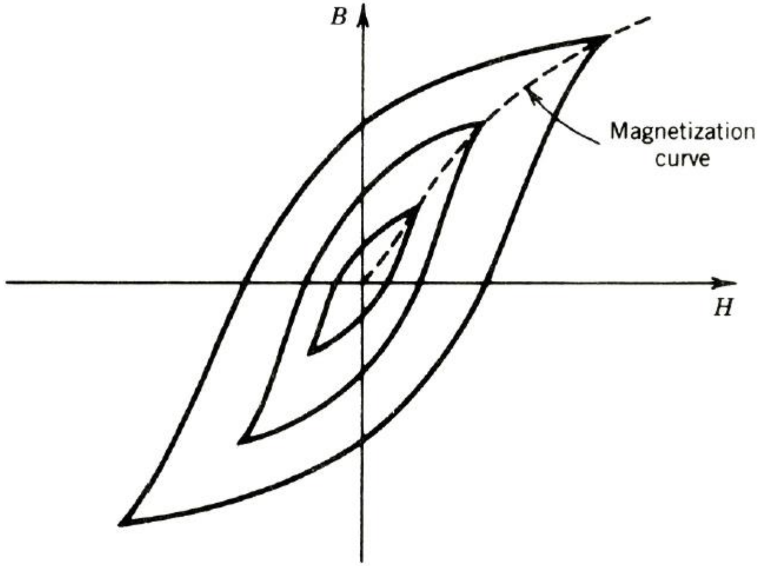
(c) If maximum flux density is not allowed to exceed 1.2 T, find the maximum value of voltage (Ans: 144 V)

Concept Check 1.4

Concept Check 1.4

1.3 Core Losses





- Consider a coil-core is excited by a sinusoidal current
- After a few cycles, the loop becomes almost close and it is known as hysteresis loop
- Upon a whole cycle of magnetization, the flux density lags behind magnetic intensity
- This lagging phenomenon is known as hysteresis

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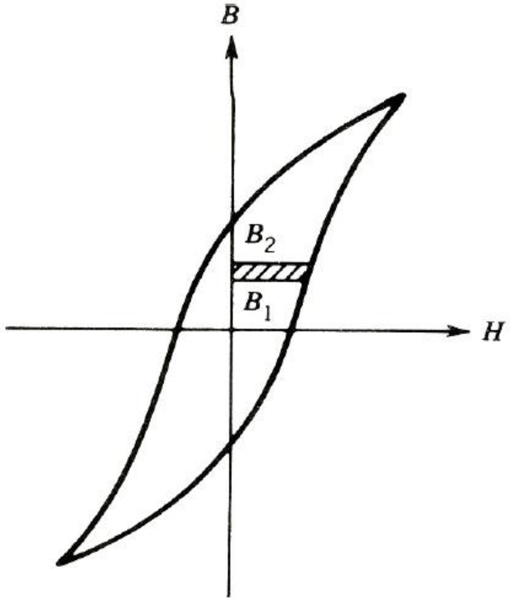
1.3 Core Losses



- Loss of power because of hysteresis effect is known as hysteresis loss
- Hysteresis loss is proportional to the size of the hysteresis loop
- Consider a coil with no resistance

$$e = N\frac{d\Phi}{dt}$$

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1.3 Core Losses

- Energy transfer during an interval

$$W = \int_{t_1}^{t_2} p\,dt$$

$$= \int_{\Phi_1}^{\Phi_2} Ni\,d\Phi$$

$$= \int_{\mathrm{B}_1}^{\mathrm{B}_2} N \frac{Hl}{N} A\,d$$

$$= V_{core} \int_{\mathrm{B}_1}^{\mathrm{B}_2} H\,d\mathrm{B} = V_{core} \oint H\,d\mathrm{B}$$

$$= V_{core}\ x\ W_h$$

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1.3 Core Losses

- Power loss due to hysteresis effect

$$P_h = V_{core} W_h f$$

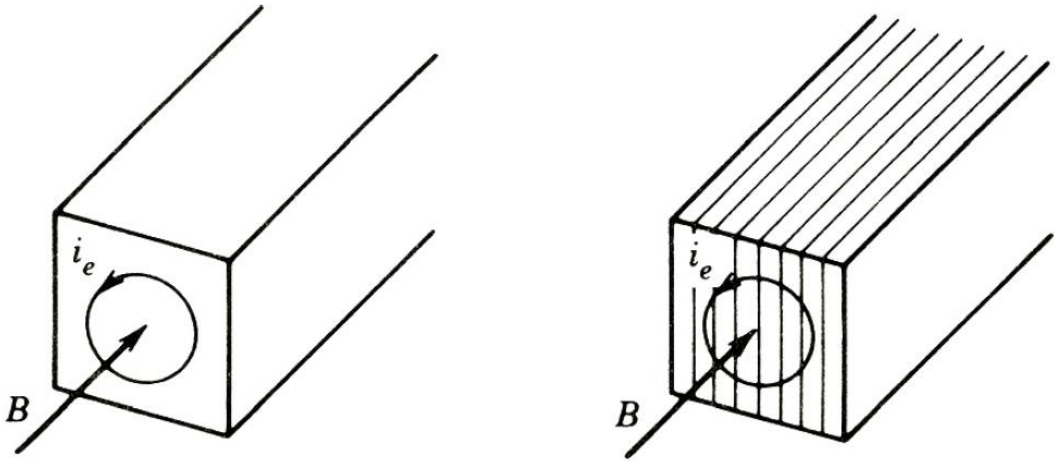
- Since B-H characteristics is nonlinear and multivalued, it can only be described based on large number of experimental results

$$Area\ of\ B - H\ loop = K B_{max}^n$$

- Hysteresis loss becomes

$$P_h = K_h B_{max}^n f$$

1.3 Core Losses



- Eddy current loss occurs when the flux density changes rapidly

$$P_e = K_e B_{max}^n f^2$$

- It can be reduced by (i) A high-resistivity core material and (ii) Laminated core
- Total core loss

$$P_c = P_h + P_e$$

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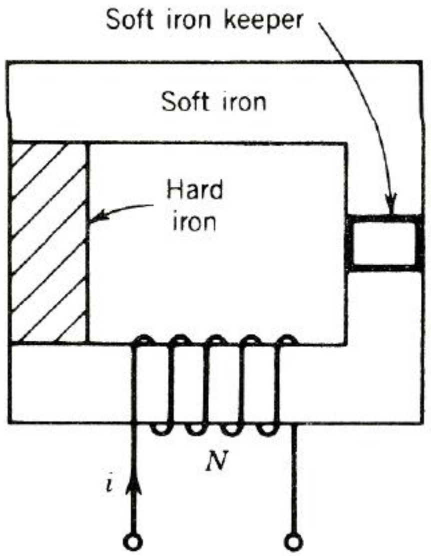
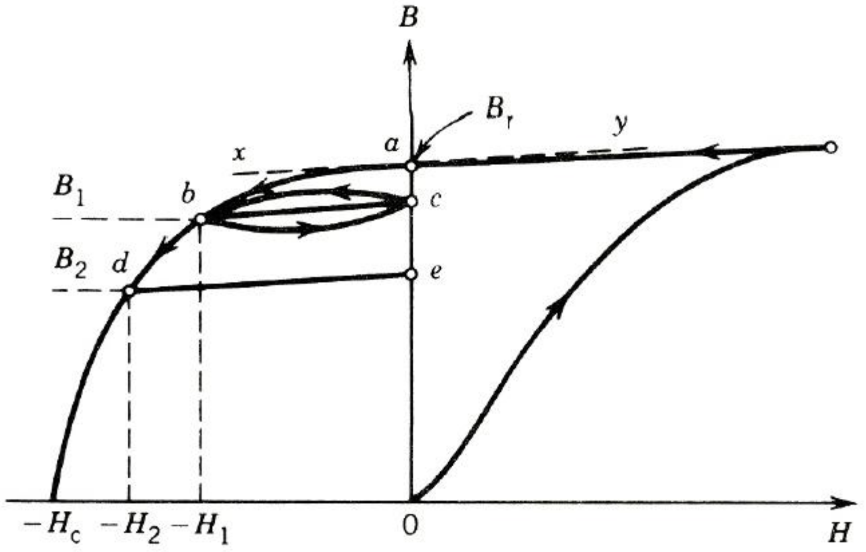
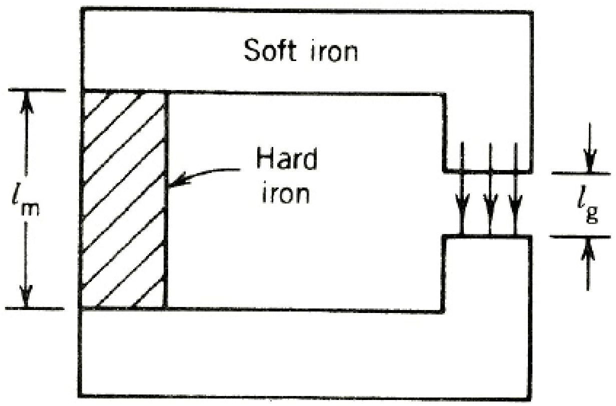
1.4 Permanent-Magnet

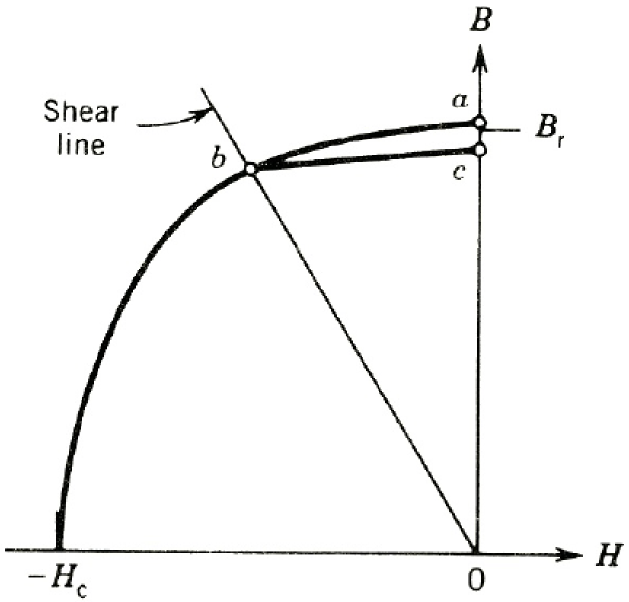




- Upon a reversed magnetic field intensity is applied and removed, a minor loop is generated with a B-H locus
- As long as the reversed magnetic field intensity does not exceed certain value, the magnet can be considered as reasonably permanent
- If the reversed magnetic field intensity exceeds certain value, the flux density will decrease to a new value and move along a new recoil line

1.4 Permanent-Magnet





- According to Ampere's circuit law

$$H_m l_m + H_g l_g = 0$$

$$H_m = -\frac{l_g}{l_m} H_g$$

1.4 Permanent-Magnet

- For continuity of flux

$$\Phi = B_m A_m = B_g A_g$$

- Therefore

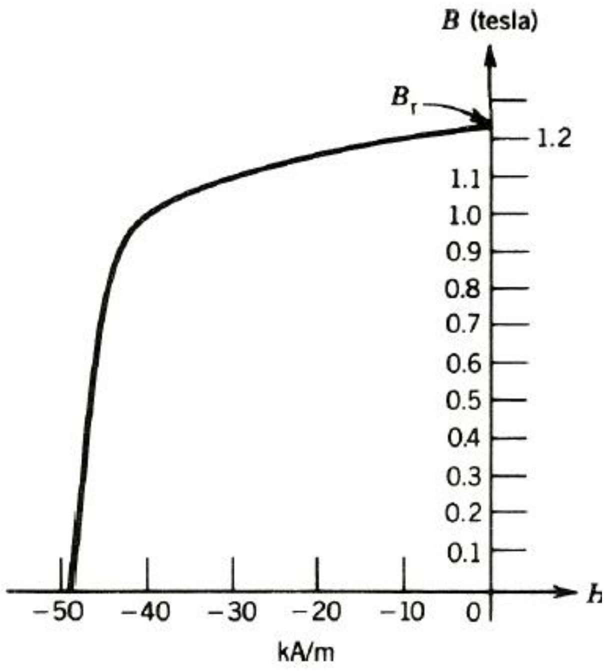
$$B_m = \mu_0 \frac{A_g}{A_m} \frac{l_m}{l_g} H_m$$

- It represents a straight line through the origin as known as shear line
- The volume of the permanent-magnet material can be

$$V_m = A_m l_m$$

$$= \frac{B_g^2 V_g}{\mu_0 B_m H_m}$$

Concept Check 1.5



Consider a permanent-magnet material with demagnetization as shown above. Flux density of 0.8 T is to be established in the air gap when the keeper is removed. The air gap consists of dimension as A_g = 2.5 cm^2 and l_g = 0.4 cm. Find the dimension (l_m and A_m)of the permanent magnet (Ans: 6.06 cm; 2.105 cm^2)

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Concept Check 1.5

Concept Check 1.5