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Lecture 1: Electromagnetic Principles and Actuators

EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

Lecture Schedule

Topic	Week	Course Instructor
Electromagnetic Principles and Actuators	1 – 3	A/P So Ping Lam
Transformers	4 – 7	A/P So Ping Lam
AC Machines	7 – 9	A/P Lee Peng Hin
DC Machines	10 – 12	A/P Lee Peng Hin

Books

- Main textbook:
  - Bhag S. Guru and Huseyin R. Hiziroglu, **Electric Machinery and Transformers**, 3rd Edition, Oxford University Press, 2001.
    (The lecture notes will follow the textbook very closely. Students are encouraged to read the book.)

- Reference textbooks:
  - P. C. Sen, **Principles of Electric Machines and Power Electronics**, 2nd Edition, John Wiley, 1997.
  - Stephen J. Chapman, **Electric Machinery and Power System Fundamentals**, 1st Edition, McGraw-Hill, 2002.
  - G. B. Shrestha and M. H. Haque, **AC Circuits and Machines**, Singapore: Pearson Education South Asia, 2006.

Topics

(**Chapters 2 and 3 – Bhag S. Guru, Electric Machinery and Transformers**)

1. Electromagnetism
   i. Magnetic Materials, Magnetic Circuits
   ii. Flux Linkage, Laws of Induction, Inductance
   iii. Magnetic Field/ Stored Energy
   iv. AC Operation, Core Losses

2. Electromechanical Energy Conversion
   i. Energy Conversion Process: Energy Balance
   ii. Stored Energy
   iii. Production of Mechanical Force

Learning Objectives

By the end of this lecture, you should be able to:

- Apply the basic electromagnetic principles in subject, including the Right Hand Rule and Ampere's Law.
- Describe how a magnetic field is created around a conductor when an electric current is flowing in a conductor.
- Examine the relationship between the flux density and field intensity in a medium of air and in a medium of magnetic material.
- Explain how the magnetic flux and flux density can be enhanced in a magnetic field by using magnetic core materials and large number of turns.

Introduction

- The operations of different electric machines are based on different aspects of the principles of electromagnetism.

- Basic understanding of electromagnetic fields is important to clearly understand the behaviour of electric machines.

- Electric machines can be classified as:
  - **Static machines** involving no motion, such as transformers and inductors.
  - **Linear motion and rotating machines** involving mechanical movement, such as solenoids, relays and motors, generators, etc.

Introduction

- The fundamental theory of electromagnetic fields is based on the Maxwell's Equations (see Appendix I).

- General concepts in electromagnetism, without going into such complex equations, will be discussed in this chapter.

- Our discussions will be from the viewpoint of practical application.

Notations

- B, H: Normal letters indicate vectors.
- B, H: Italic letters indicate the magnitudes of the corresponding vectors.
- i, v: Lower case letters indicate **dc** quantities, or the instantaneous values of **ac** quantities.

Table 1. Important terms, symbols and units in electromagnetism.

Quantity	Symbol(s)	Unit(s)	
Magnetomotive Force (mmf)	F, (NI)	A	At
Magnetic Field Strength	H	A/m	At/m
Magnetic Flux	φ	Wb	-
Magnetic Flux Density	B	T	Wb/m^2
Flux Linkage	λ	Wb	Wb t
Inductance	L	H	-
Permeability	μ, μ_0	H/m	-
Relative Permeability	μ_r	-	-
Reluctance	$\Re$	H^{-1}	At/Wb
Key: A: Ampere, Wb: Weber	t: turns, T: Tesla	m: metre, H: Henry	

Magnetic Field Intensity (H)

❖ A flow of electric current in a conductor creates a magnetic field around the conductor as shown in Fig. 1.

- The direction of the magnetic field is defined by the Right Hand Rule.

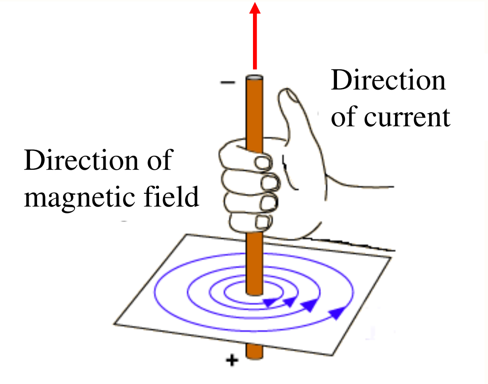

Fig. 1. Right Hand Rule.

Magnetic Field Intensity (H)

- The relationship between the magnetic field intensity (H) along a closed path established by a current I (see Fig. 2) is specified by **Ampere's Law**, which states

$$\oint_c \vec{H}\,\overrightarrow{d\ell} = I_{enc \leftarrow \text{enclosed}}$$

- In general, the evaluation of this integral around any closed loop may not be easy.

- However, the application of this principle can be easily adopted in many practical situations. For example, when H is constant,

$$\oint_c \vec{H}\,\overrightarrow{d\ell} = H\oint_c d\ell = H\ell$$

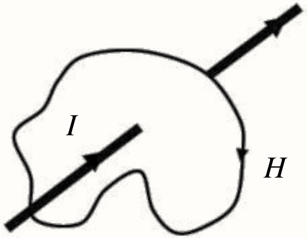

Fig. 2. Magnetic field intensity along a closed path.

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Magnetic Field Produced by a Conductor

❖ Consider a long straight conductor carrying a current I as shown in Fig. 3. To find the magnetic field at a distance r from the conductor, imagine a circular path of radius r around the conductor. Because of symmetry, it is clear that the field intensity H will be the same throughout the circular path.

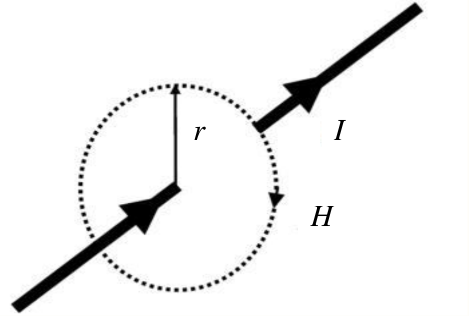

Fig. 3. Single conductor.

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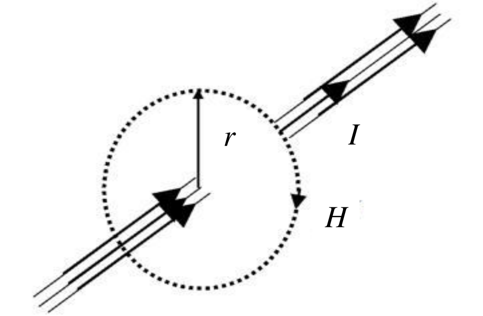

Fig. 4. Multiple conductors.

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Magnetic Field Produced by a Conductor

- Therefore,

$$\oint_c \vec{H}\,\overrightarrow{d\ell} = I_{enc} \Rightarrow H\oint_c \overrightarrow{d\ell} = H\ell = H\,2\pi r = I_{enc} = I$$

$$\Rightarrow H = I/(2\pi r)\ \text{A/m or At/m}$$

- When there are N conductors as shown in Fig. 4, each carrying a current I, then

$$I_{enc} = NI \Rightarrow H = NI/(2\pi r)\ \text{A/m or At/m}$$

$$\Rightarrow H\ell = NI$$

Magnetic Flux (φ) and Flux Density (B)

- The magnetic field intensity H produces a magnetic flux (φ) and the flux per unit area is the flux density (B) as shown in Fig. 5.

- In a medium of free space (or air) the flux density is related to the field intensity as

$$B = \mu_0 H \;\; [\mathrm{Wb/m^2} \text{ or } \mathrm{T}\ (\mathrm{Tesla})]$$

where μ_0 $(=4\pi \times 10^{-7}\ \mathrm{H/m})$ is the permeability of free space.

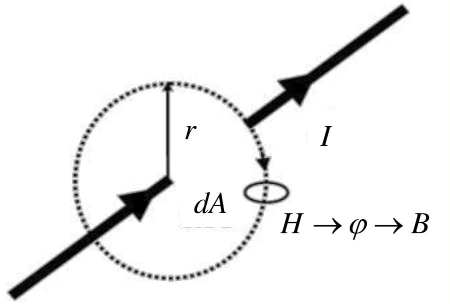

Fig. 5. Magnetic field strength, flux, and flux density.

Magnetic Flux (φ) and Flux Density (B)

- The flux can then be calculated as

$\varphi = \int_A BdA = B\int_A dA = BA$, when B is constant.

- It should be noted that both B and φ remain very small in the medium of air because of the very small value of μ_0.

Magnetic Materials

- The magnetic flux or the flux density may be enhanced in a magnetic field by the use of magnetic materials. Consider a toroid of steel (see Fig. 6) of radius r around the current carrying conductor. Then,

$H = \dfrac{I}{2\pi r}$ as before.

But $B = \mu_0 \mu_r H = \mu H$ [Wb/m^2 or T(Tesla)]

where

μ_0 is the permeability of free space,

μ_r is the relative permeability of steel, and

$\mu = \mu_0 \mu_r$ is the permeability of steel.

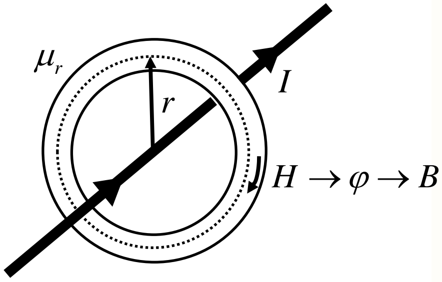

Fig. 6. Toroid of steel.

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Magnetic Materials

- μ_r is near unity (1) for non-magnetic materials, but it can be very high (2000 – 6000) for ferro-magnetic materials.

- Thus, the use of magnetic materials can enhance the flux density B and therefore the flux φ by several orders of magnitude for the same field intensity H.

Example 1

Consider a single conductor transmission line carrying 200 A of current as shown in Fig. 7. Find the magnetic field strength in a house located 20 m from the conductor. If the floor area of the house is 80 m^2, estimate the total flux passing through the house.

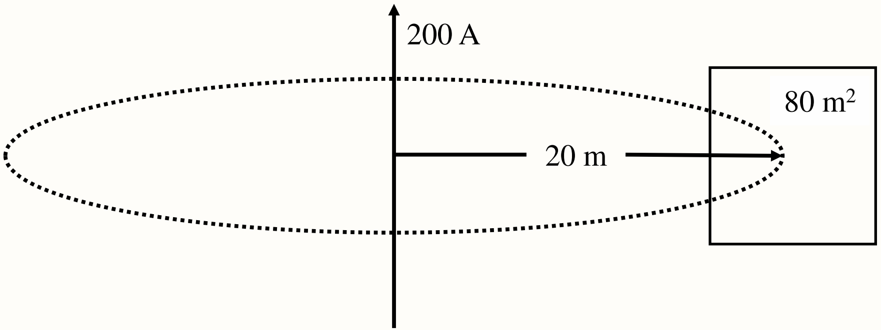

Fig. 7. Magnetic field produced by a current carrying conductor.

(Solutions →)

Example 1 – Solutions

Using the earlier results,

$$H = \frac{I}{2\pi r} = \frac{200}{2\pi \times 20} = 1.59 \text{ A/m}$$

Therefore,

$$B = \mu_0 H = 4\pi \times 10^{-7} \frac{I}{2\pi r} = 2\times 10^{-7} \frac{I}{r} = 2\times 10^{-7} \frac{200}{20} = 2\times 10^{-6} \text{ T}$$

and,

$$\varphi = BA = 2\times 10^{-6} \times 80 = 1.6\times 10^{-4} \text{ Wb}$$

Magnetic Circuits in Electric Machines

In order to obtain reasonably high values of flux density and flux, most electromagnetic machines (see Figs. 8 and 9) commonly use:

- A structure of magnetic materials to utilise the benefit of high permeability.
- Coils of a large number of turns to increase the total enclosed current.

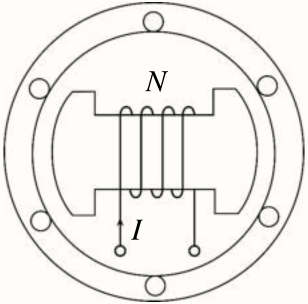

Fig. 8. Rotating machine.

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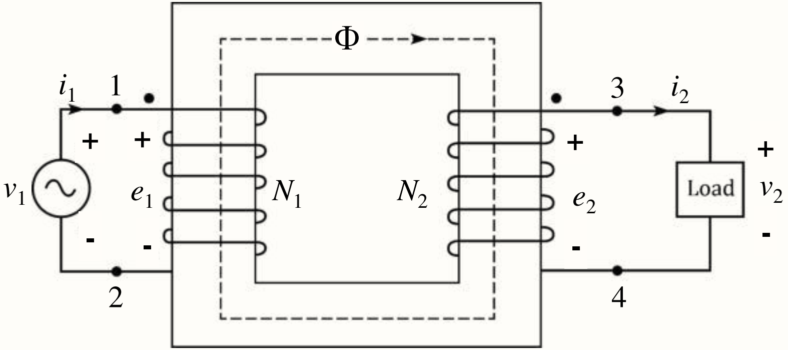

Fig. 9. Transformer.

Magnetic Circuits in Electric Machines

- In such structures, the flux density inside the core structure will be several orders of magnitude higher than in the surrounding space.
- Therefore, the flux outside the magnetic core can be conveniently ignored when analysing electromagnetic machines and magnetic structures.

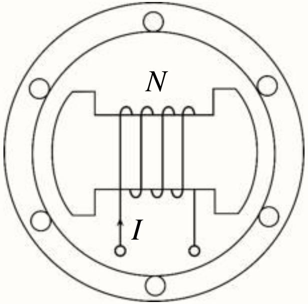

Fig. 8. Rotating machine.

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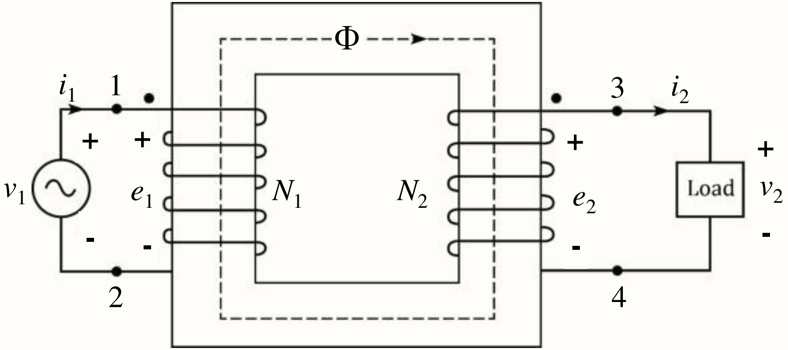


Fig. 9. Transformer.

Magnetic Materials – Non-magnetic Materials

- Non-magnetic materials are classified into two groups:
  - **Diamagnetic materials** have relative permeability slightly less than unity as shown in Table 2, and these materials experience a very feeble repulsive force in magnetic fields.

Table 2. Relative permeabilities of some diamagnetic materials.

Material	**Relative Permeability**
Bismuth	0.999 981
Beryllium	0.999 987
Copper	0.999 991
Methane	0.999 969
Silver	0.999 980
Water	0.999 991

Magnetic Materials – Non-magnetic Materials

- **Paramagnetic materials** have relative permeability slightly more than unity as shown in Table 3, and these materials experience a very feeble attractive force in magnetic fields.

Table 3. Relative permeabilities of some paramagnetic materials.

Material	Relative Permeability
Air	1.000 304
Aluminium	1.000 023
Oxygen	1.001 330
Manganese	1.000 124
Palladium	1.000 800
Platinum	1.000 014

❖ Ferro-magnetic materials have very high relative permeability and experience very strong attractive force in magnetic fields.

Ferro-magnetism

❖ Consider the magnetic circuit as shown in Fig. 10.

- The current I in the coil produces field strength H, which in turn produces flux φ and flux density B.

- The relationship between B and H can be explained using the notions of magnetic dipoles and magnetic domains.

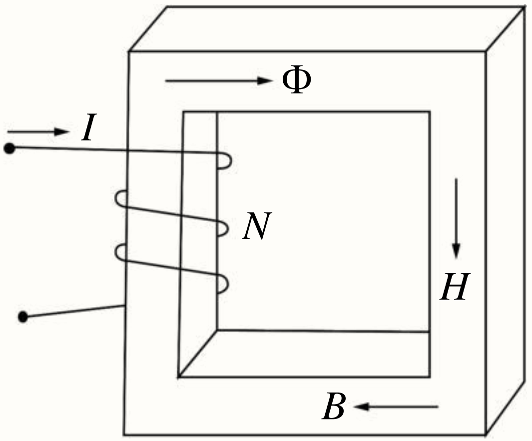


Fig. 10. Magnetic core.

Ferro-magnetism

- In the absence of any current in the coil (i.e., with no H applied), the dipoles are all randomly oriented and the magnetic domains cancel out each other, resulting in no net flux and flux density as shown in Figs. 11 and 12.
- With the injection of current (i.e., with H applied), the magnetic domains become aligned, resulting in higher flux and flux density. Once all the domains are aligned, increase in I (i.e., H) cannot produce further increase in B.

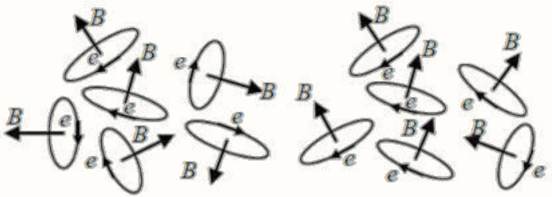


Fig. 11. Magnetic dipoles.

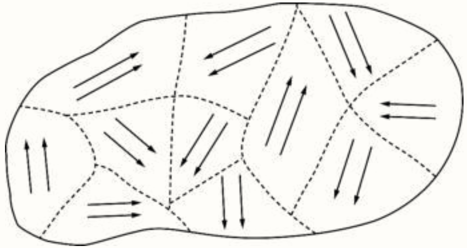


Fig. 12. Magnetic domains.

Summary

In this lecture, you have learnt:

- A magnetic field produced in a conductor when an electric current is flowing in a conductor.
- The flux density B related to the field intensity H in a medium of air and in a medium of magnetic material.
- The magnetic flux and flux density enhanced in a magnetic field by using structure of magnetic materials and coils of a large number of turns.

Appendix 1: Maxwell's Equations

- The four Maxwell's equations are

a) $\nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t}$ or $\oint_c \vec{E} \bullet \vec{d\ell} = -\int_s \dfrac{\partial \vec{B}}{\partial t} \bullet \vec{ds}$

b) $\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}$ or $\oint_c \vec{H} \bullet \vec{d\ell} = \oint_s \vec{J} \bullet \vec{ds} + \int_s \dfrac{\partial \vec{D}}{\partial t} \bullet \vec{ds}$

c) $\nabla \bullet \vec{B} = 0$ or $\oint_s \vec{B} \bullet \vec{ds} = 0$

d) $\nabla \bullet \vec{D} = \rho$ or $\oint_s \vec{D} \bullet \vec{ds} = \int_\upsilon \rho \, d\upsilon$

Appendix 1: Maxwell's Equations

- The four Maxwell's equations are used along with the following additional equations:

a) $\nabla \bullet \vec{J} = -\dfrac{\partial \rho}{\partial t}$

b) $\vec{F} = q\left[\vec{E} + \vec{\upsilon} \times \vec{B}\right]$

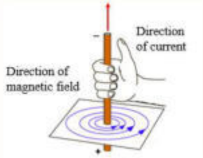
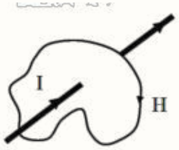
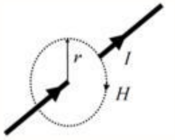
c) $\vec{D} = \in \vec{E} = \in_r \in_0 \vec{E}$

$\vec{B} = \mu \vec{H} = \mu_r \mu_0 \vec{H}$

d) $\in_0 = 8.854 \times 10^{-12} \approx \dfrac{10^{-9}}{36\pi}$ farad/meter (F/m)

$\mu_0 = 4\pi \times 10^{-7}$ henry/meter (H/m)

References

No.	Slide No.	Image	Reference
1	11		From *Moving Electrical Charges Create Magnetic Field*, by R. Kurtus, 2012 (http://www.school-for-champions.com/science/magnetic_field_moving_charges.htm#.WVEU8lR97IW). Copyright 2016 by Ron Kurtus and School for Champions LLC. Retrieved on 26 June 2017.
2	12		Reprinted from *AC Circuits and Machines*, (p. 85), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
3	13		Reprinted from *AC Circuits and Machines*, (p. 86), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.

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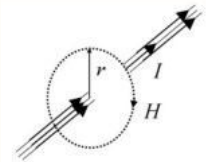
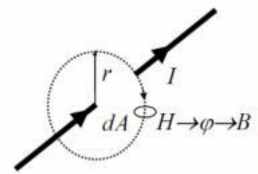
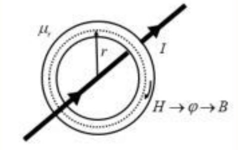
4	13		Reprinted from *AC Circuits and Machines*, (p. 86), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
5	15		Reprinted from *AC Circuits and Machines*, (p. 87), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
6	17		Reprinted from *AC Circuits and Machines*, (p. 88), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.

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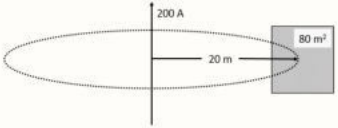
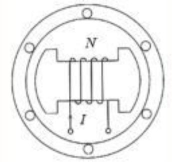
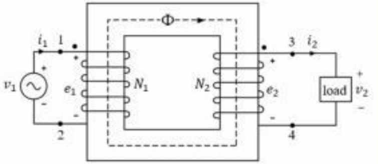
7	19		Reprinted from *AC Circuits and Machines*, (p. 89), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
8	21 and 22		Reprinted from *AC Circuits and Machines*, (p.90), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
9	21 and 22		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 207), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.

References

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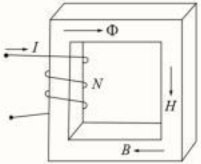
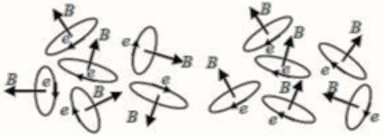
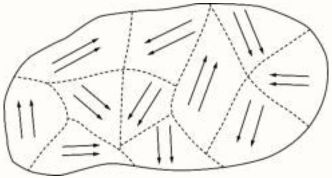
10	25		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 79), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
11	26		Reprinted from *AC Circuits and Machines*, (p. 91), by G. B. Shrestha, & M. H. Haque, 2006, Singapore: Pearson Education South Asia Pte. Ltd. Copyright 2006 by Pearson Education South Asia Pte. Ltd. Reprinted with permission.
12	26		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 79), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.

References

<table>
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Beryllium / 0.999 987
Copper / 0.999 991
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Water / 0.999 991</td><td>Reprinted from Electric Machinery and Transformers, 3rd ed., (p. 77), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.</td></tr>
<tr><td>2</td><td>24</td><td>Material / Relative Permeability
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Oxygen / 1.001 330
Manganese / 1.000 124
Palladium / 1.000 800
Platinum / 1.000 014</td><td>Reprinted from Electric Machinery and Transformers, 3rd ed., (p. 77), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.</td></tr>
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