Lecture 5: Electromagnetic Principles and Actuators

EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

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Learning Objectives

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

- Employ the concepts learnt in hysteresis loop to explain the basics of core losses which consist of hysteresis loss and eddy current loss.
- Describe the principles of using laminations of high resistivity core material to reduce eddy current loss.
- Apply voltage equations to solve simple hysteresis loss and eddy current loss problems.

Magnetisation Curve (Revisit)

- When the field strength H in a magnetic circuit shown in Fig. 43 is increased by increasing the current through the coil, the flux density increases as shown in Fig. 44.

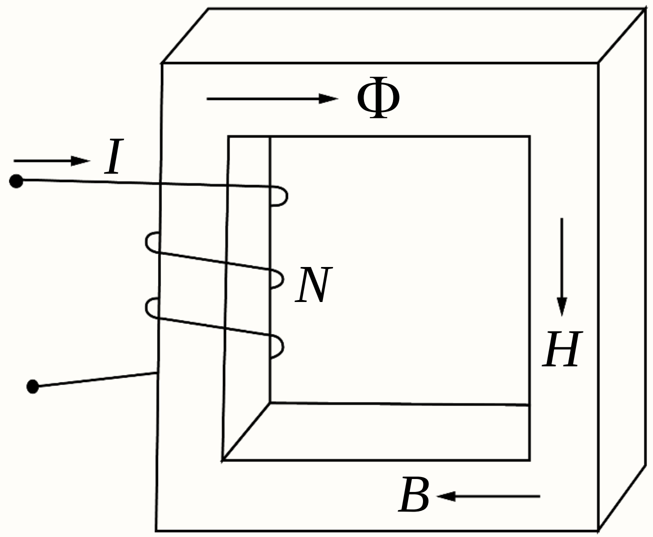

Fig. 43. Magnetic circuit.

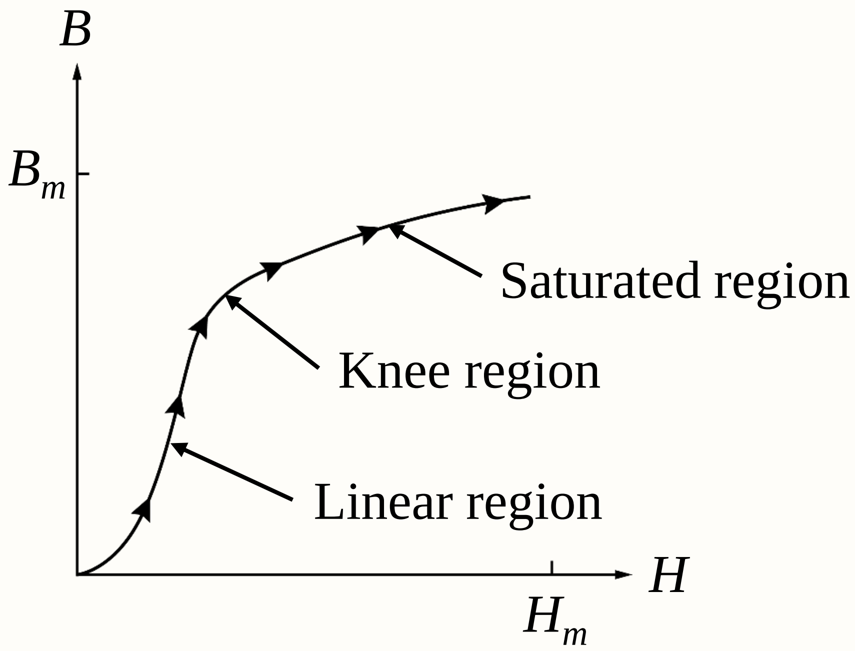

Fig. 44. Magnetisation curve.

Magnetisation Curve (Revisit)

- If the field strength H is now reduced by decreasing the current through the coil, the decrease in flux density does not follow the path as shown in Fig. 45. In fact, the core has retained some flux density when the current and therefore the field strength H is reduced to zero. This is called the remanence or the residual flux density B_r.

- A current flow in the opposite direction, i.e., a negative field strength H is required to reduce the flux density to zero, known as coercive force H_c.

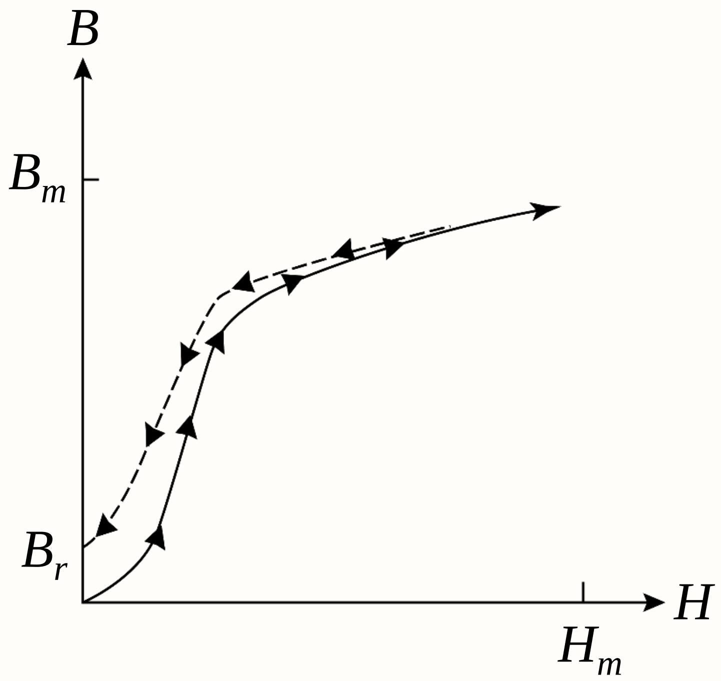

Fig. 45. Magnetisation curve.

Hysteresis Loop

❖ If a magnetic circuit is excited by ac source as shown in Fig. 46, the input current and therefore the field strength follows a cycle:

- Increasing slowly to a maximum value (H_m)
- Decreasing slowly to zero
- Reversing the direction and increasing to a maximum value in the reverse direction (-H_m)
- Finally, reversing the direction to track back to a maximum positive value (H_m)

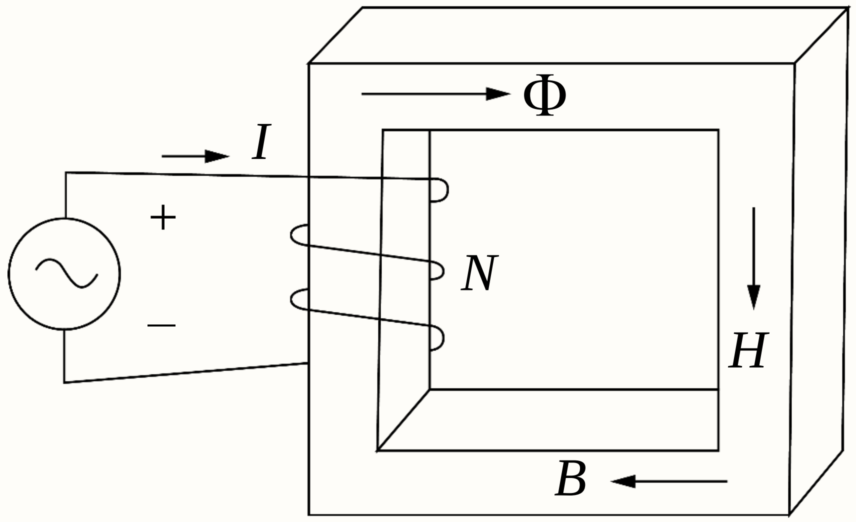

Fig. 46. Magnetic circuit.

Hysteresis Loop

- The path traced by the B-H curve for such a cycle shown Fig. 47 is called **Hysteresis Loop**.
- The actual shape of the hysteresis loop depends on the magnetic material.

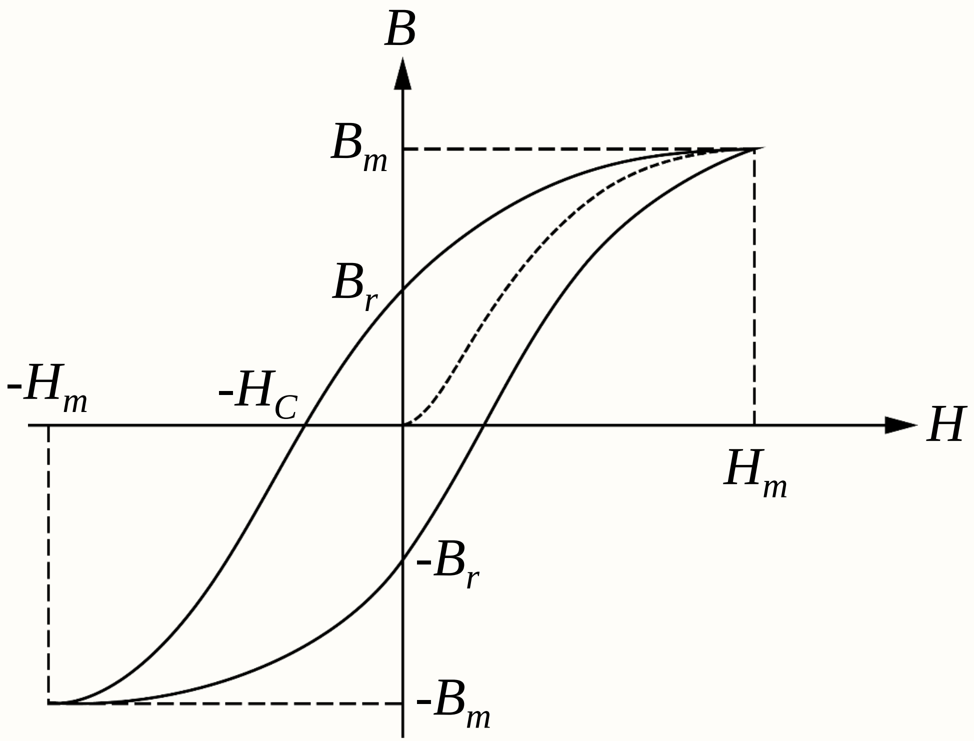

Fig. 47. Hysteresis loop.

Magnetic Losses

- **Magnetic losses**, also called **'core losses'** or '**iron losses'**, consist of **Hysteresis Loss** and **Eddy Current Loss**.
- **Hysteresis Loss** For magnetic circuits excited by ac sources, the flux density in the core traverses a complete hysteresis loop for each cycle of the input current. This process incurs a power loss in the core known as **'Hysteresis Loss'**. Hysteresis loss $\boldsymbol{P_h}$ is commonly estimated using empirical formula proposed by Steinmetz.

$$P_h = K_h B_m{}^n f \ \text{W}$$

where
B_m is the maximum flux density in the magnetic core,
f is the frequency of the source,
K_h is a constant, and
n is the Steinmetz index (1.5 ~ 2.5 for common core materials).

Eddy Current Loss

❖ **Eddy Current Loss**: When a time varying flux is created in a solid magnetic core as shown in Fig. 48, it will produce induced voltage in any perceivable closed path. The direction of these “Eddy” currents will be such that they tend to oppose the original flux.

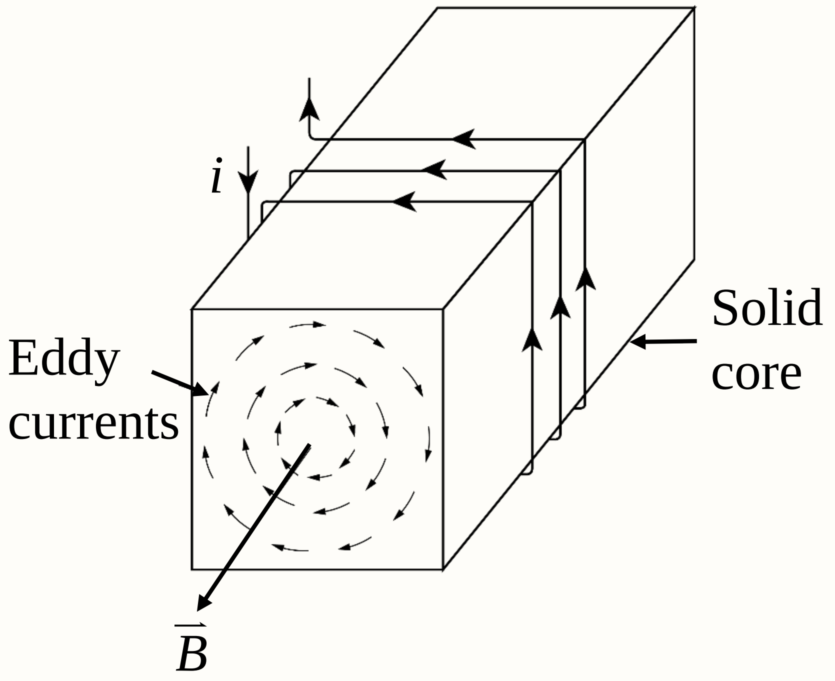

Fig. 48. Solid magnetic core.

Eddy Current Loss

❖ The eddy currents flowing in these closed paths incur power losses, which are called **'Eddy Current Losses'**. The magnitude of the 'Eddy Current' and therefore the 'Eddy Current Loss' will depend on:

- The magnitude of the induced voltage in each closed path
- The resistance of such closed paths

Therefore, it is very difficult to quantify eddy current losses.

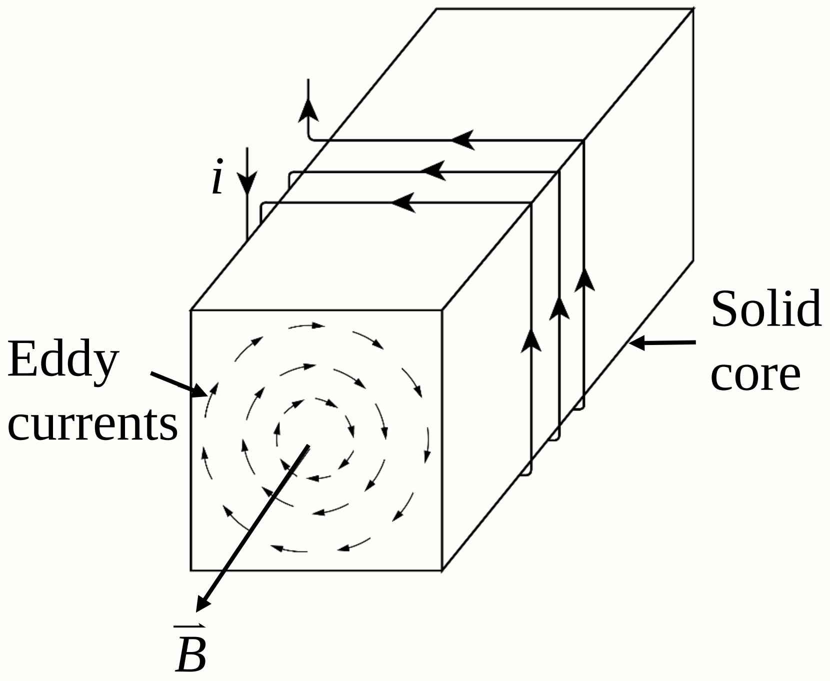

Fig. 48. Solid magnetic core.

Eddy Current Loss

- Eddy current loss $\boldsymbol{P_e}$ in a magnetic circuit excited by a sinusoidal source is commonly estimated using the empirical formula:

$$P_e = K_e B_m{}^2 f^2 \text{ W}$$

where
B_m is the maximum flux density in the magnetic core,
f is the frequency of the source, and
K_e is a constant.

Eddy Current Loss

- ❖ Eddy currents and therefore eddy current losses are reduced by using laminations of high resistivity core material as shown in Fig. 49, instead of solid core material. This increases
  - The effective length of eddy current paths
  - The resistance of these eddy current paths
- ❖ Reduced ‘Eddy Currents’ lead to reduced ‘Eddy Current Losses’.

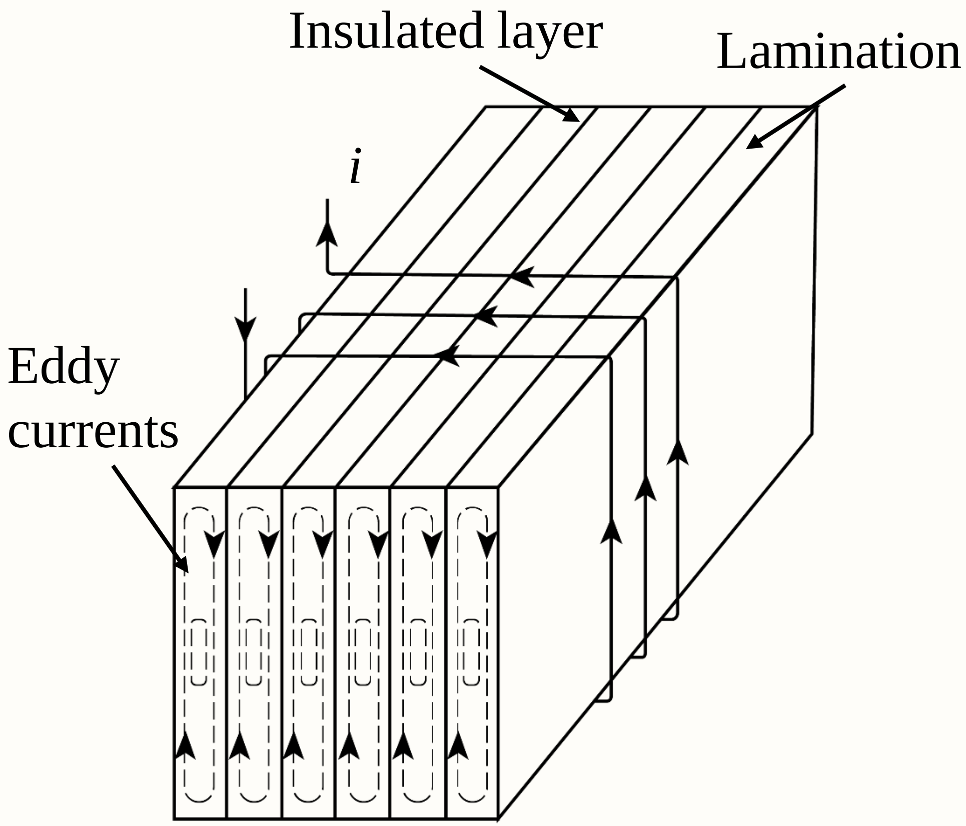

Fig. 49. Laminated magnetic core.

Sinusoidal Excitation of Magnetic Circuits (Revisit)

- Both **Hysteresis Loss** as well as **Eddy Current Loss** depend on f and B_m. It should be noted that these two variables are not fully independent.
- For a magnetic circuit excited by a sinusoidal input as shown in Fig. 50, it was shown earlier that

$$V = V_m / \sqrt{2} = 2\pi NA(B_m f) / \sqrt{2} = 4.44NA(B_m f)$$

is called **Voltage Equation**.

- Thus, it is seen that the product $B_m f$ is jointly related to the input voltage, and these two variables cannot vary independently for a given input voltage.

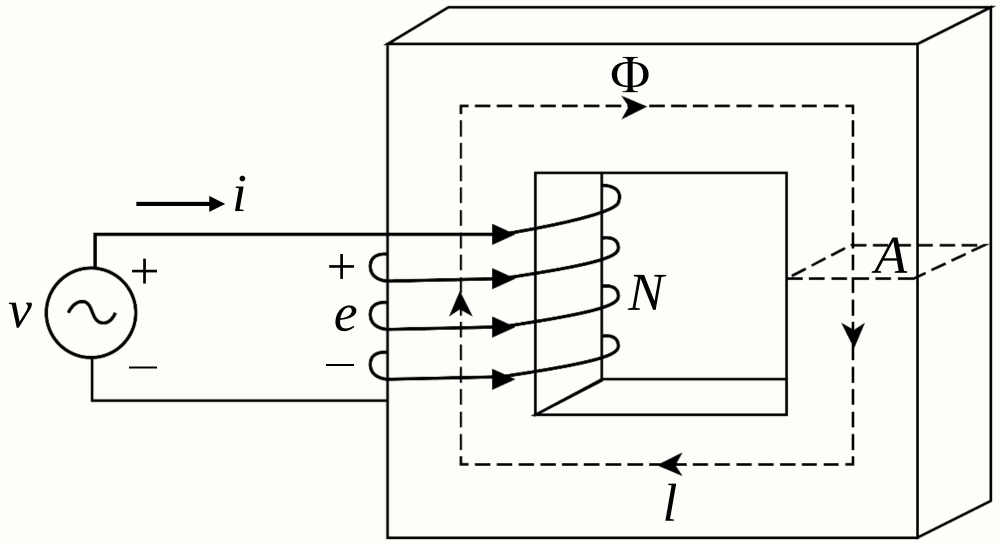

Fig. 50. Magnetic circuit.

Example 8

An electromagnet is known to have hysteresis loss of 80 W when excited by a 120 V, 60 Hz source. If the Steinmetz index of the core material is 1.6, estimate the hysteresis loss when the electromagnet is connected to a 120 V, 50 Hz source.

(Solutions →)

Example 8 – Solutions

Let B_{m1} and B_{m2} be the maximum flux densities under the two conditions.

Then, $P_{h1} = K_h B_{m1}^{1.6} f_1$, and $P_{h2} = K_h B_{m2}^{1.6} f_2 = ?$

Therefore, $\dfrac{P_{h2}}{P_{h1}} = \dfrac{B_{m2}^{1.6}}{B_{m1}^{1.6}} \dfrac{f_2}{f_1}$, and $P_{h1} = 80\ \mathrm{W}$, $f_1 = 60\ \mathrm{Hz}$ and $f_2 = 50\ \mathrm{Hz}$

The voltage equations under the two conditions yield,

$V_1 = 120\ \mathrm{V} = K B_{m1} f_1$, and $V_2 = 120\ \mathrm{V} = K B_{m2} f_2$

$$\Rightarrow B_{m1} f_1 = B_{m2} f_2 \Rightarrow B_{m2} / B_{m1} = f_1 / f_2 = 60/50 = 1.2$$

Therefore, $P_{h2} = \dfrac{B_{m2}^{1.6}}{B_{m1}^{1.6}} \dfrac{f_2}{f_1} P_{h1} = 1.2^{1.6} \times \dfrac{50}{60} \times 80 = 89.25\ \mathrm{W}$

Summary

In this lecture, you have learnt:

- ❖ Concepts of hysteresis loop to explain the basics of core losses which consist of hysteresis loss and eddy current loss.
- ❖ Principles of using laminations of high resistivity core material to reduce eddy current loss.
- ❖ Application of voltage equations to solve simple hysteresis loss and eddy current loss problems.

References

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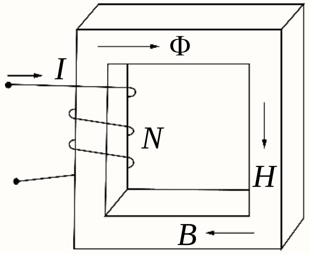
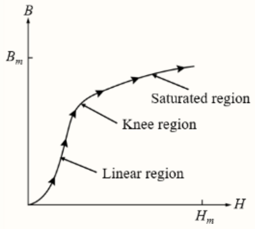
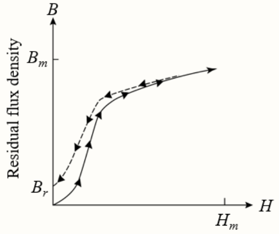
1	4		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 79), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission.
2	4		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 80), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission.
3	5		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 80), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press. Reprinted with permission.

References

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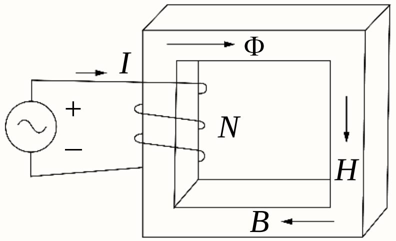
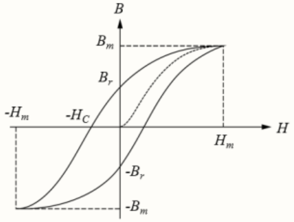
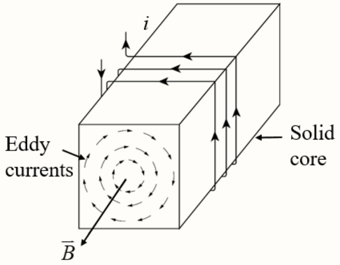
4	6		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 79), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
5	7		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 8), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
6	9 and 10		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 110), 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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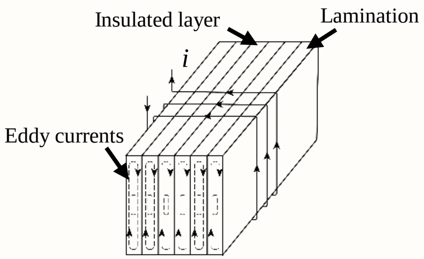
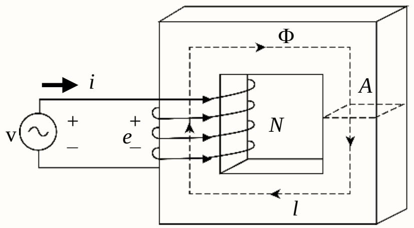
7	12		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 110), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.
8	13		Reprinted from *Electric Machinery and Transformers, 3rd ed.*, (p. 147), by B. S. Guru, & H. R. Hiziroglu, 2001, New York, NY: Oxford University Press. Copyright 2001 by Oxford University Press.