Lecture -24
Magnetic Materials

Lecture Delivered by

Session Topics

- Inductance in Series
- Inductance in Parallel
- Magnetic Materials

Topics

- Inductance in Parallel
- Magnetic Materials
- B-H Curve

Objectives

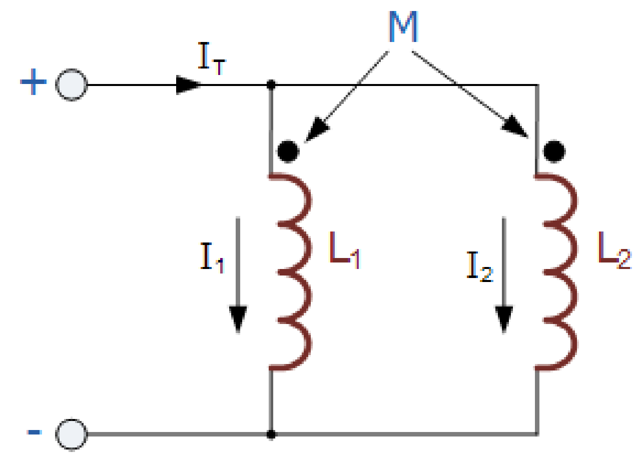
At the end of this lecture, student will be able to:

- Describe the coupling effect for magnetic circuits
- Solve circuits involving coupled coils using Dot Rule
- Classify and explain properties of Magnetic Materials
- Analyze loss mechanism in the Magnetic Materials

Coupled Inductors in Parallel (Case-1)

$$V = j\omega L_1 I_1 + j\omega M I_2$$

$$V = j\omega M I_1 + j\omega L_2 I_2$$



Solving above equations we get,

$$I_1 = \frac{V(L_2 - M)}{j\omega(L_1 L_2 - M^2)} \qquad I_2 = \frac{V(L_1 - M)}{j\omega(L_1 L_2 - M^2)}$$

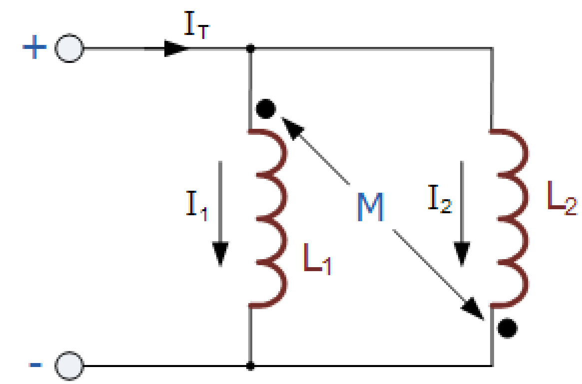
Coupled Inductors in Parallel (Case-1)

$$I = I_1 + I_2 \Rightarrow I = \frac{V(L_1 + L_2 - 2M)}{j\omega(L_1 L_2 - M^2)}$$

$$= \frac{V}{j\omega L_{eq}}$$

$$\therefore L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}$$

Coupled Inductors in Parallel (Case-2)



$$V = j\omega L_1 I_1 - j\omega M I_2$$

$$V = -j\omega M I_1 + j\omega L_2 I_2$$

Solving above equations we get,

$$I_1 = \frac{V(L_2 + M)}{j\omega(L_1 L_2 - M^2)}$$

$$I_2 = \frac{V(L_1 + M)}{j\omega(L_1 L_2 - M^2)}$$

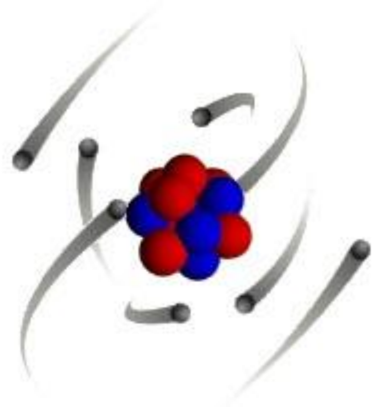
Coupled Inductors in Parallel (Case-2)

$$I = I_1 + I_2 \Rightarrow I = \frac{V(L_1 + \ L_2 + 2M)}{j\omega(L_1 L_2 - M^2)}$$

$$= \frac{V}{j\omega L_{eq}}$$

$$\therefore L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + \ L_2 + 2M}$$

Magnetic Materials and Magnetism

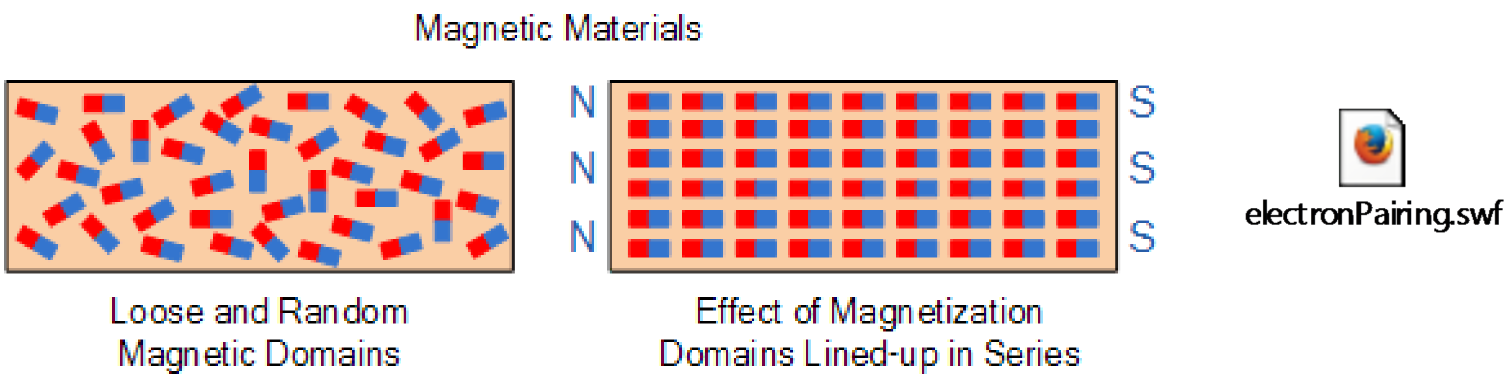


- All matter is composed of atoms, and atoms are composed of protons, neutrons and electrons
- The electrons are in constant motion around the nucleus
- A magnetic field is produced whenever an electrical charge (electron) is in motion

Magnetic Materials and Magnetism

- Materials can react quite differently to the presence of an external magnetic field
- This reaction is dependent on a number of factors, such as the atomic and molecular structure of the material, and the net magnetic field associated with the atoms

Magnetic Materials and Magnetism



- In most atoms, electrons occur in pairs
- When electrons are paired together, their opposite spins cause their magnetic fields to cancel each other
- Materials with some unpaired electrons will have a net magnetic field and will react more to an external field

Magnetic Materials and Magnetism

- **Diamagnetic** materials have a weak, negative susceptibility to magnetic fields (μ_r<1)
- They are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed
- In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom

Example: copper, silver, and gold

Magnetic Materials and Magnetism

- **Paramagnetic** materials have a small, positive susceptibility to magnetic fields (μ_r>1)
- They are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed
- Paramagnetic properties are due to the presence of some unpaired electrons, and from the realignment of the electron paths caused by the external magnetic field.

Example: magnesium, molybdenum, lithium, and tantalum

Magnetic Materials and Magnetism

- **Ferromagnetic** materials have a large, positive susceptibility to an external magnetic field (μ_r>>1)
- They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties even after the removal of field
- When a magnetizing force is applied, the magnetic domains become aligned to produce a strong magnetic field.

Example: Iron, nickel, and cobalt

Magnetic Saturation

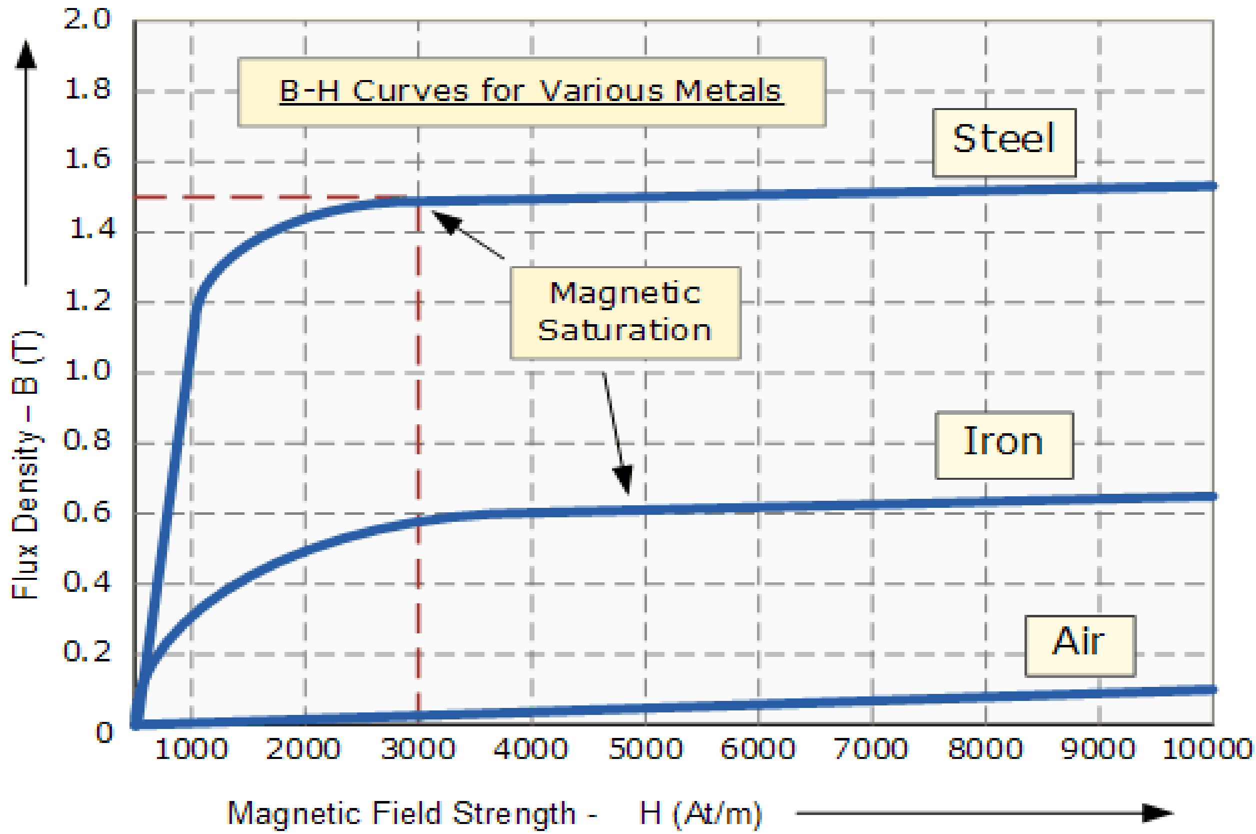
$$B = \mu_0 \mu_r H$$

B- Magnetic flux density, T

H-Magnetic field or M.M.F per unit mean length, AT/m

- Ferromagnetic materials have large μ_r (1,000 to 10,000) but it is not constant
- Saturation is the state reached when an increase in applied external magnetic field (H) cannot increase the magnetization (B) of the material further

Magnetic Saturation

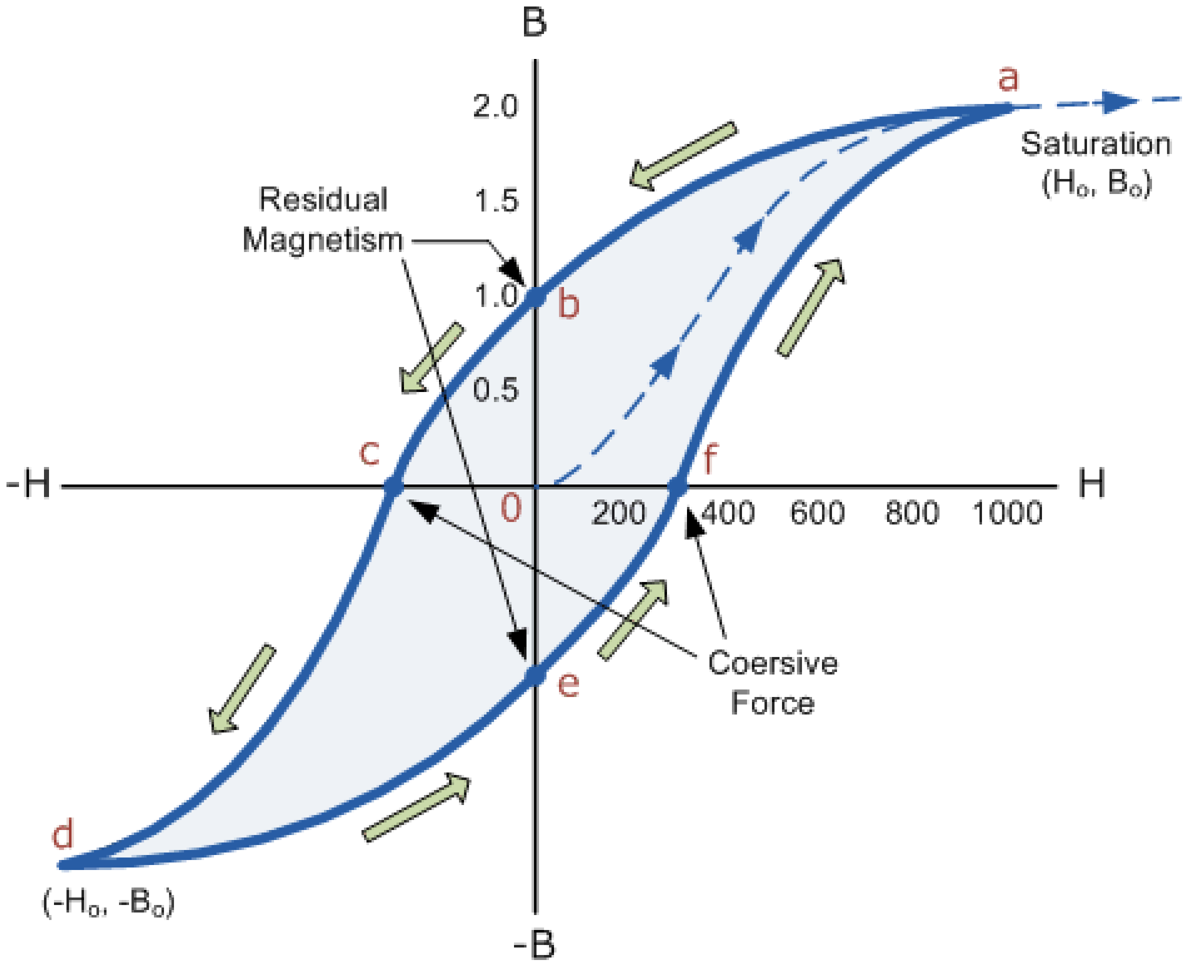


- When all the magnetic domains are perfectly aligned there is no enhancement of magnetic flux even if the field strength is increased

Hysteresis

- When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed
- The lack of retraceability of the magnetization curve is the property called hysteresis
- A hysteresis loop shows the relationship between the induced magnetic flux density **(B)** and the magnetizing force **(H)** in both increasing and decreasing fashion

B-H Curve



Hysteresis Loop

B-H Curve

- **Retentivity** it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation
- **Residual Residual Flux** is the magnetic flux density that remains in a material when the magnetizing force is zero
- **Coercive Force** is the amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero

Hysteresis Loss

- When a ferromagnetic material is excited by an ac current, it undergoes a series of magnetization and demagnetization cycles
- During each cycle certain amount of energy is lost as heat, which is proportional to the area under B-H curve
- This loss is known as hysteresis loss

$$E_h \propto \int H dB$$

Steinmetz's empirical formula for Hysteresis loss

- Charles Steinmetz proposed the empirical formula for calculating hysteresis loss analytically,

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

P_h - Hysteresis loss per unit volume

B_{max} - Peak value of flux density

f - frequency of ac current

k_h - coefficient depends on the material

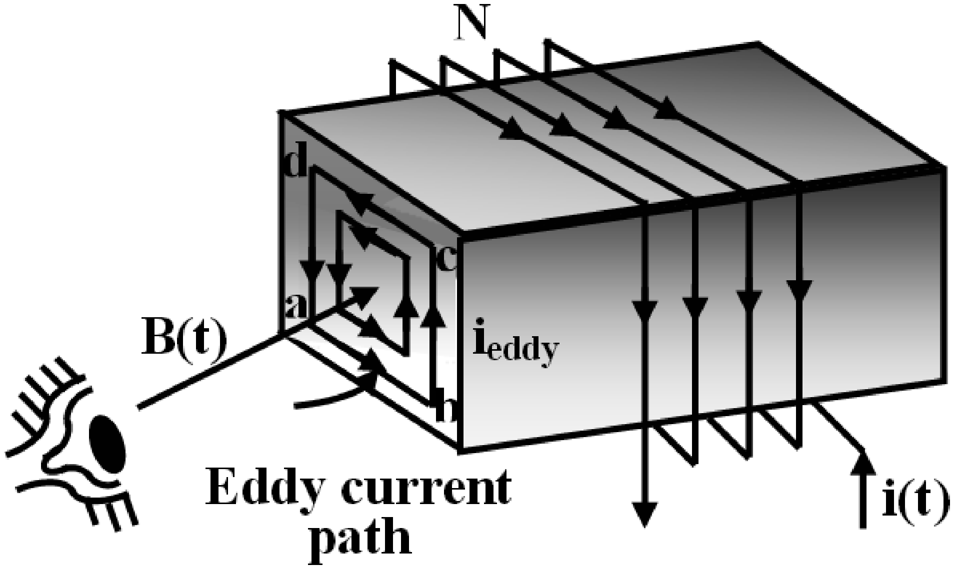
n - Steinmetz exponent may vary from 1.5 to 2.5 (1.6 for iron)

Eddy Current Loss

- When a magnetic material contains alternating flux, there will be an induced e.m.f within the material as given by Faraday's law
- As the material is conductive, the free electrons will experience a force and will move in circular fashion (swirling) in a direction given by Lenz's law
- These induced currents are called as Eddy Currents and power loss associated with them is called as Eddy Current Loss

Eddy Current Loss

Motion of free electrons is similar to swirling of water



Direction of eddy currents

- To reduce eddy current loss several laminations (which are insulated from each other by paint or varnish) are used instead of a single solid material

Eddy Loss Formula

$$P_{eddy} = k_e f^2 B_{max}^2 \tau^2$$

P_{eddy} - Eddy Loss per unit volume

K_e - Coefficient depends on the material

f - Frequency of AC

B_{max} - Peak value of flux density

τ - Thickness of each lamination

Summary

$$\therefore L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \qquad \therefore L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M}$$

- Most materials can be classified as diamagnetic, paramagnetic or ferromagnetic
- The lack of retrace ability of the magnetization curve is the property called hysteresis
- During each cycle certain amount of energy is lost as heat, which is proportional to the area under B-H curve