Electromagnetism

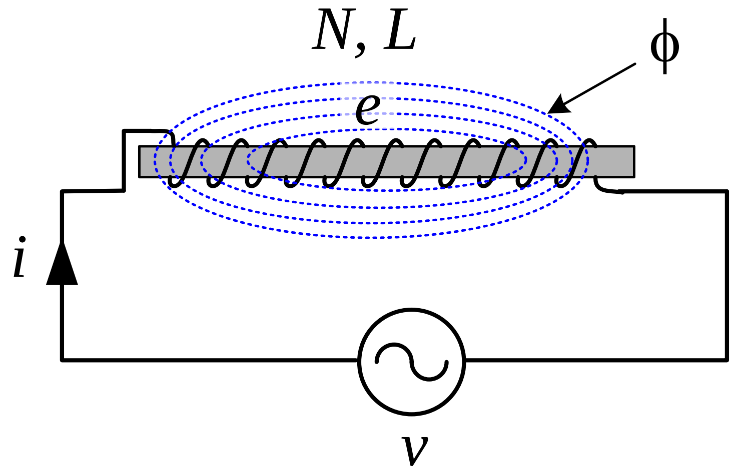
Day 22

ILOs – Day 22

- Derive expression for energy stored in an electromagnet
- Derive expression for lifting force (pulling force) of a magnet
- Describe magnetization characteristics of a magnetic material with AC supply
- Explain energy losses during magnetization:
  - Hystereis loss
  - Eddy current loss

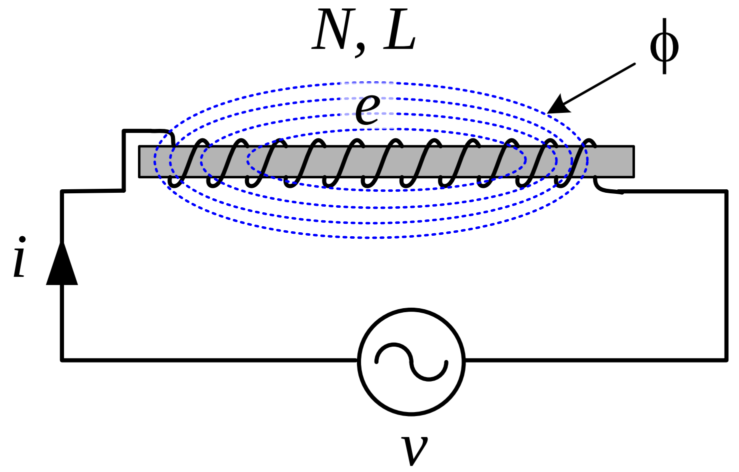
Energy stored in an electromagnet

Energy stored in an electromagnet



- An electromagnet is produced by passing current through a solenoid
- The electrical energy supplied from the voltage source is partly stored in the electromagnet as magnetic energy
- The remaining part of the input energy is wasted as power loss (heat) during the magnetization process

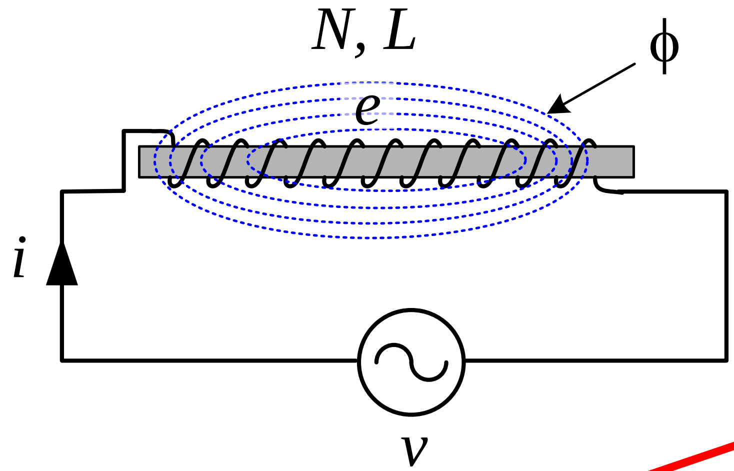
Energy stored in an electromagnet



- Let the electromagnet is produced by passing current i through a coil of N number of turns
- Let, self-inductance of the coil is L
- The flux ϕ linking with the coil itself produces a self-induced EMF of e in it

$$\boxed{e = L\frac{di}{dt} = N\frac{d\phi}{dt}}$$

Energy stored in an electromagnet



$$e = L\frac{di}{dt} = N\frac{d\phi}{dt}$$

- Electric energy supplied from the source in small time *dt* is:

$$dE = P \times dt = (e \times i) \times dt$$

- If the losses are neglected, then this amount of electrical energy supplied will entirely be stored as magnetic energy
- Thus, during that small time interval *dt*, energy consumed by the electromagnet coil can hence be given as:

$$dE = N\frac{d\phi}{dt} \times i \times dt = Nid\phi$$

Energy stored in an electromagnet

$$\boxed{dE = Nid\phi}$$

- Total energy stored in the magnetic field can be found out by integration:

$$\boxed{E = \int dE = Ni\int_0^{\phi} d\phi}$$

- Alternate expression:

$$dE = e \times i \times dt$$

$$dE = L\frac{di}{dt} \times i \times dt$$

$$dE = Lidi$$

$$E = \int dE = L\int_0^{I} idi = \frac{1}{2}Li^2\Big|_0^{I} \boxed{= \frac{1}{2}LI^2} \quad \text{Joules}$$

Energy stored in an electromagnet

$$\boxed{E = \frac{1}{2} L I^2}$$

- Expression for self-inductance of a coil : $L = \dfrac{N^2 \mu_0 \mu_r a}{l}$

$$E = \frac{1}{2} L I^2 = \frac{1}{2} \frac{N^2 \mu_0 \mu_r a}{l} I^2 = \frac{1}{2} \mu_0 \mu_r (al) \boxed{\frac{N^2 I^2}{l^2}} = \frac{1}{2} \mu_0 \mu_r (al) H^2$$

$$\boxed{E = \frac{1}{2} \mu_0 \mu_r (V) H^2}$$ where $V = al$ = Volume of the core material

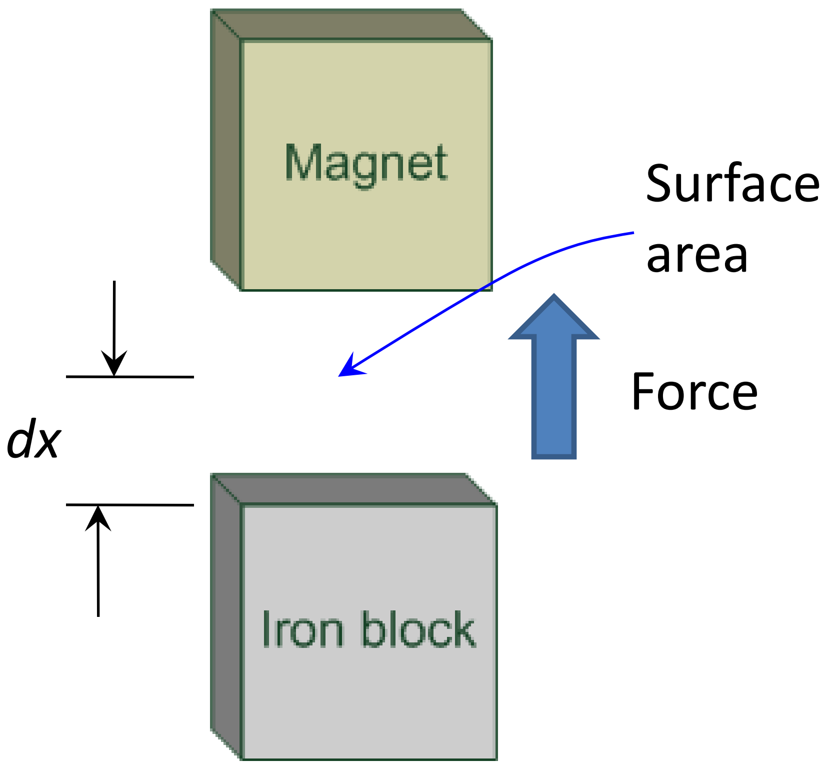
- Energy density:

$$E_V = \frac{E}{V} \boxed{= \frac{1}{2} \mu_0 \mu_r H^2} = \frac{1}{2} \boxed{(\mu_0 \mu_r H)} H \boxed{= \frac{1}{2} BH} \text{ Joules/m}^3$$

Lifting force or pulling force of a magnet

Lifting force or pulling force of a magnet

- It is a common experience that when we put a piece of iron close to a magnet, the iron piece is pulled in towards the magnet
- Here, we will try to find out an expression for that force exerted by the magnet on a piece of iron



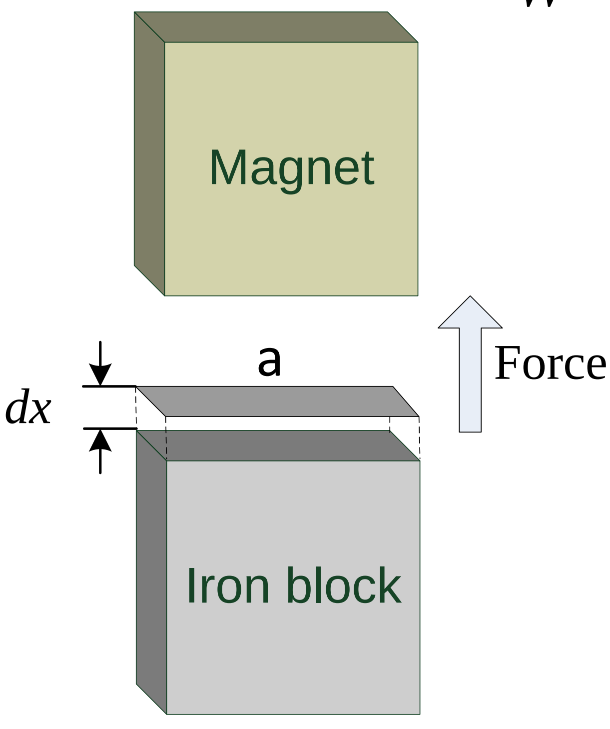
- Due to pull of the magnet, let the iron piece moves up by a small distance *dx* through air
- The work done in moving up the iron is equal to the change in stored energy

Lifting force or pulling force of a magnet

- Work done in moving up the iron is equal to the change in stored energy

$$\boxed{E = \frac{1}{2}\mu_0\mu_r(V)H^2}$$

$$W = dE = \frac{1}{2}\mu_0\mu_r(dV)H^2 = \frac{1}{2}\mu_0\mu_r(adx)H^2$$



- Since the iron piece moves through air, $\mu_r = 1$
- If the lifting force is *F*, then we have:

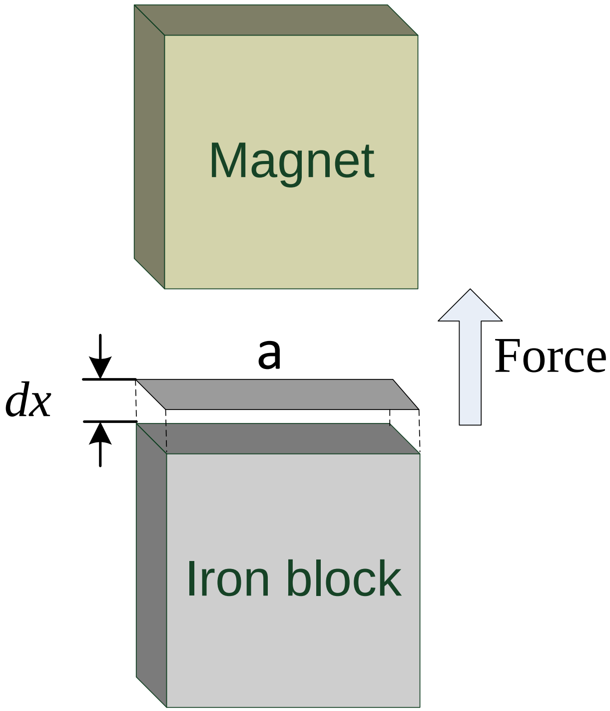
$$W = F.dx$$

$$F.dx = \frac{1}{2}\mu_0(adx)H^2$$

Lifting force or pulling force of a magnet

$$\boxed{F.dx = \frac{1}{2}\mu_0 (adx) H^2}$$

- Thus, lifting force: $\boxed{F = \frac{1}{2}\mu_0 (a) H^2}$ $\boxed{= \frac{B^2 a}{2\mu_0}}$



- Lifting force per unit area, i.e. lifting pressure:

$$P = \frac{F}{a} = \frac{1}{2}\mu_0 H^2$$

$$= \frac{1}{2}(\mu_0 H) H$$

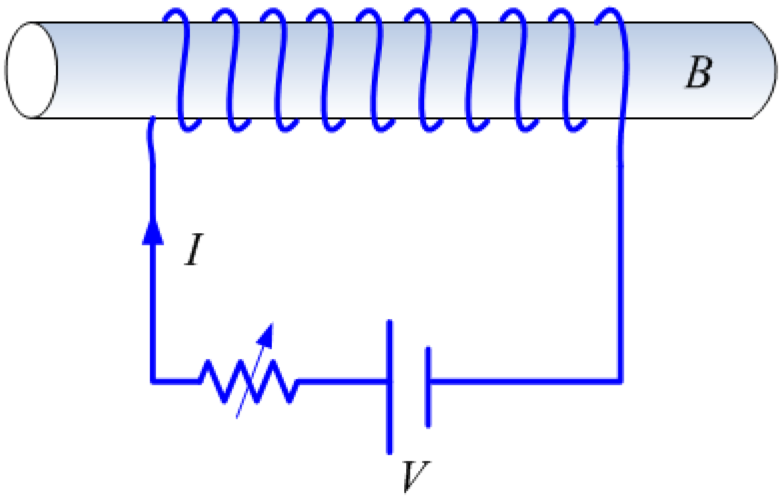
$$\boxed{= \frac{1}{2} BH}$$

Magnetization characteristics of a magnetic material

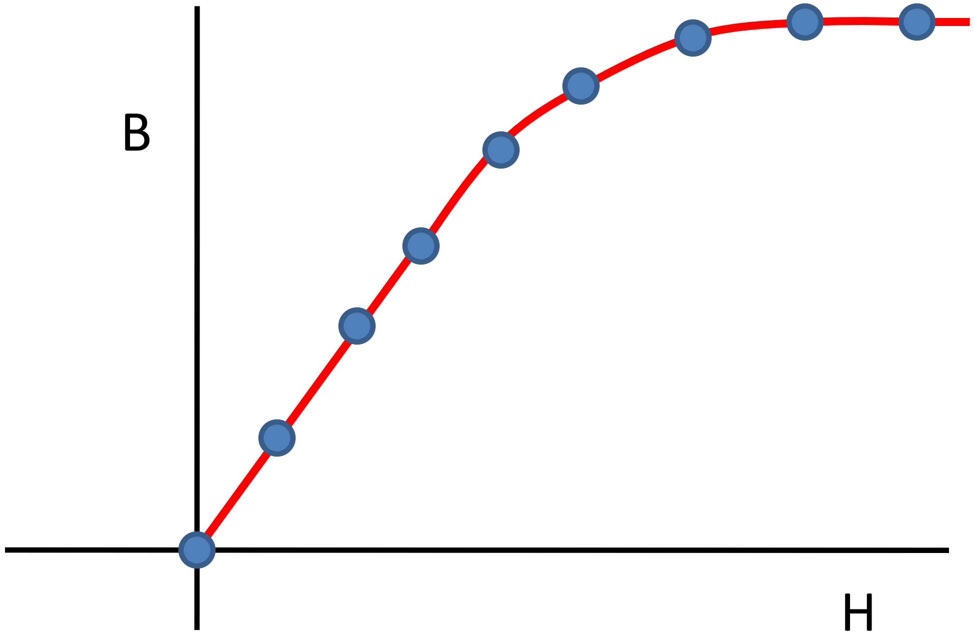
Magnetization characteristics of a magnetic material

- Relation between the magnetizing force (H) and the magnetic property developed [flux density (B)]

$$B = \mu H = \mu_0 \mu_r H$$



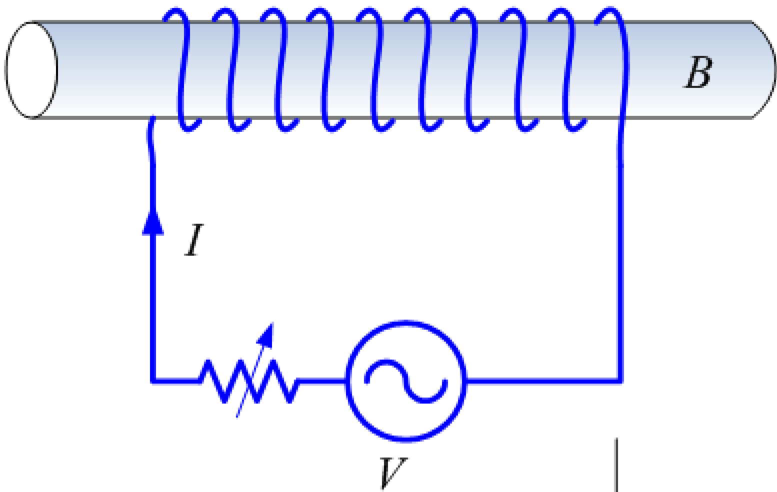
$$H = \frac{NI}{l}$$



- Initially linear increase in B, but **saturated** afterwards
- When all the magnetic **domains** get fully oriented then saturated
- B-H characteristics is thus **non-linear**

Magnetization with AC supply

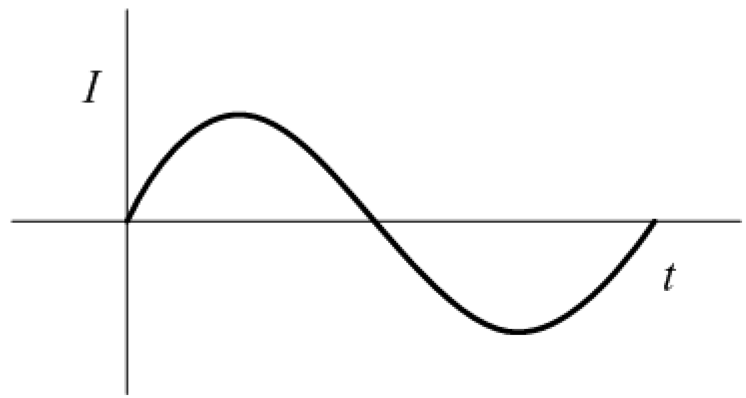
- Input voltage is AC, *i.e.* varies sinusoidally from + to -



- Thus, input current I is also AC, *i.e.* varies sinusoidally from + to -

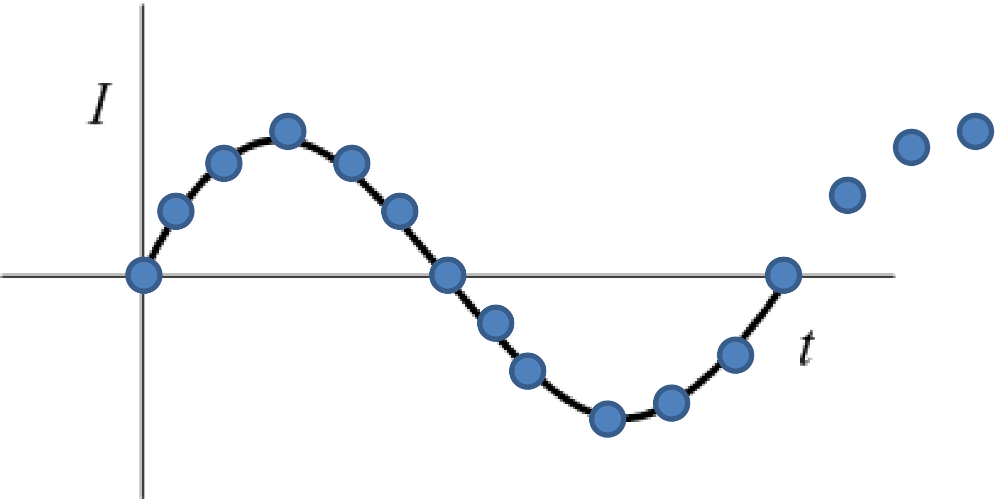
$$H = \frac{NI}{l}$$

- Thus, magnetizing force H is also AC, *i.e.* varies sinusoidally from + to -

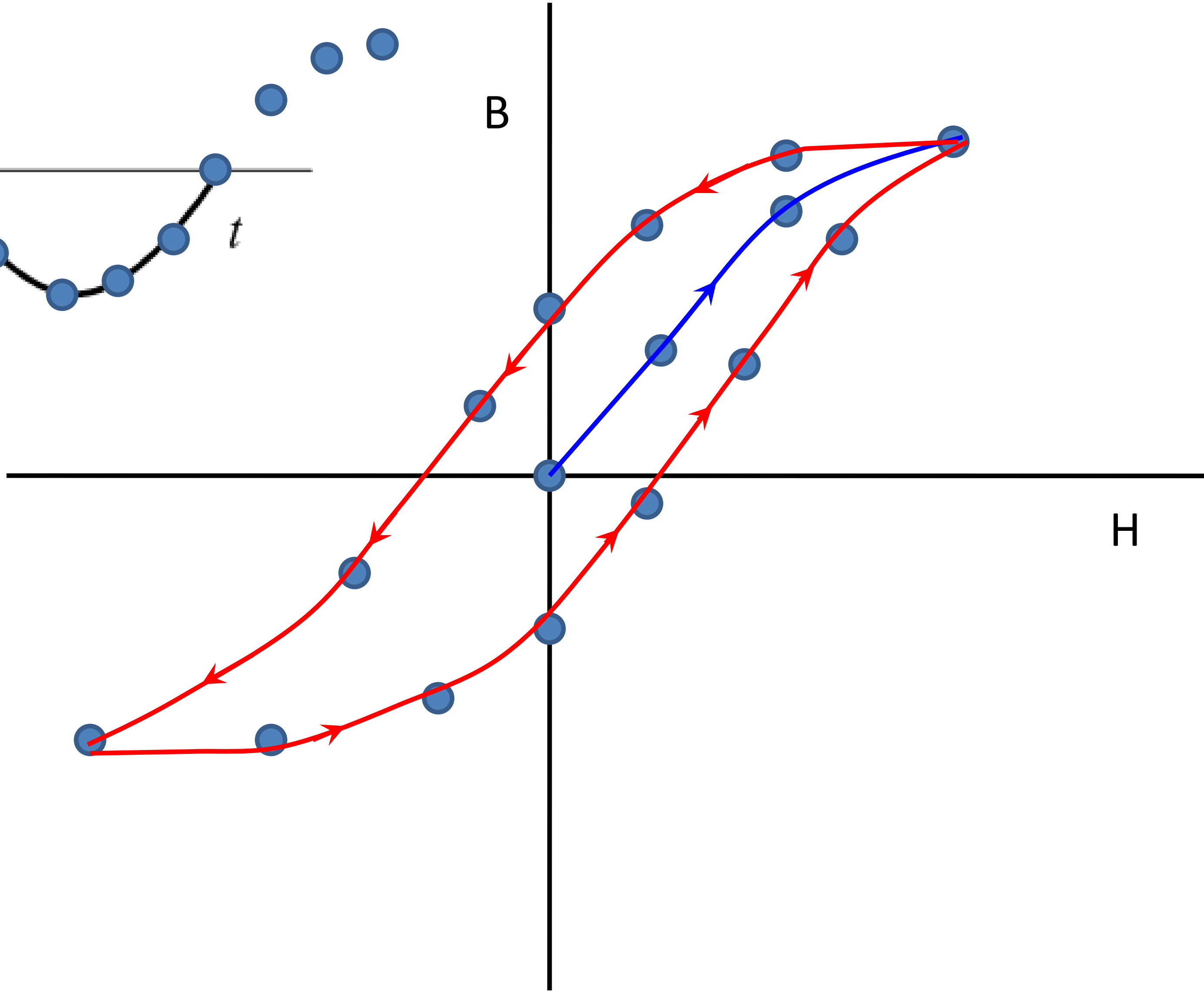


- Thus, the magnetizing force starts from zero, rises up to a positive maximum value, then comes down back to zero, drops down to a negative minimum value and goes back again to zero. This cycle continues

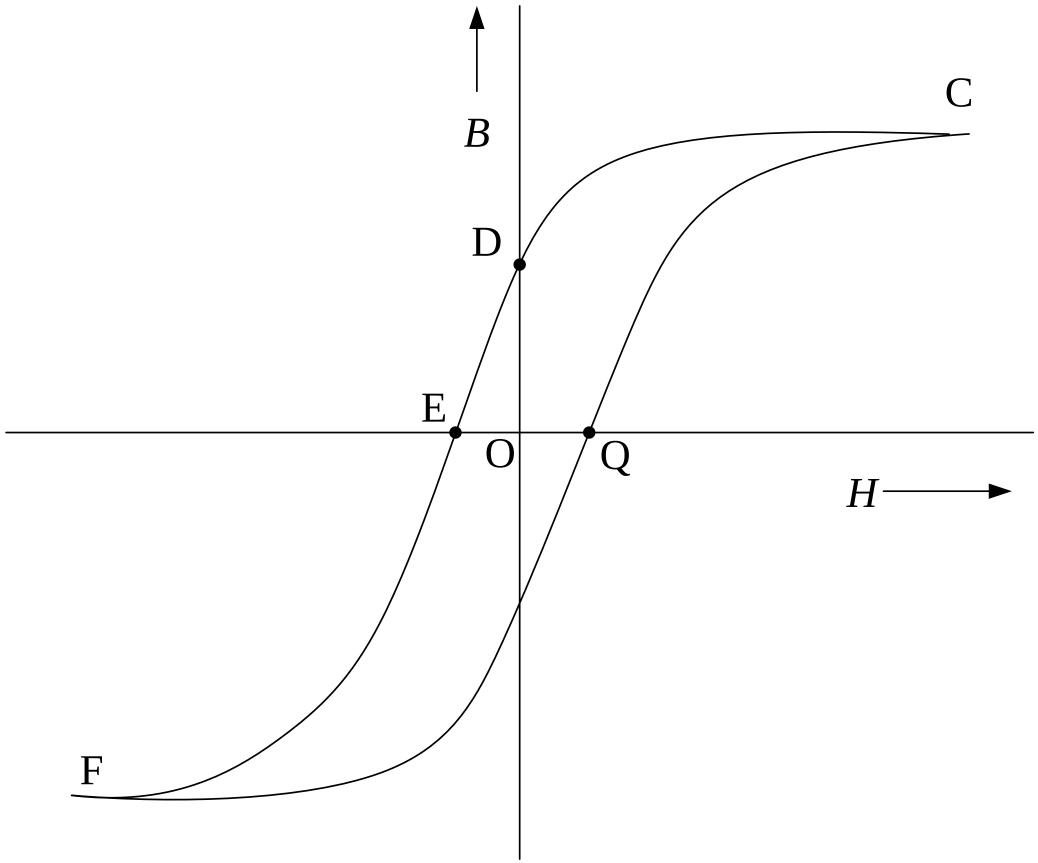
Magnetization with AC supply



$$H = \frac{NI}{l}$$



Magnetization with AC supply



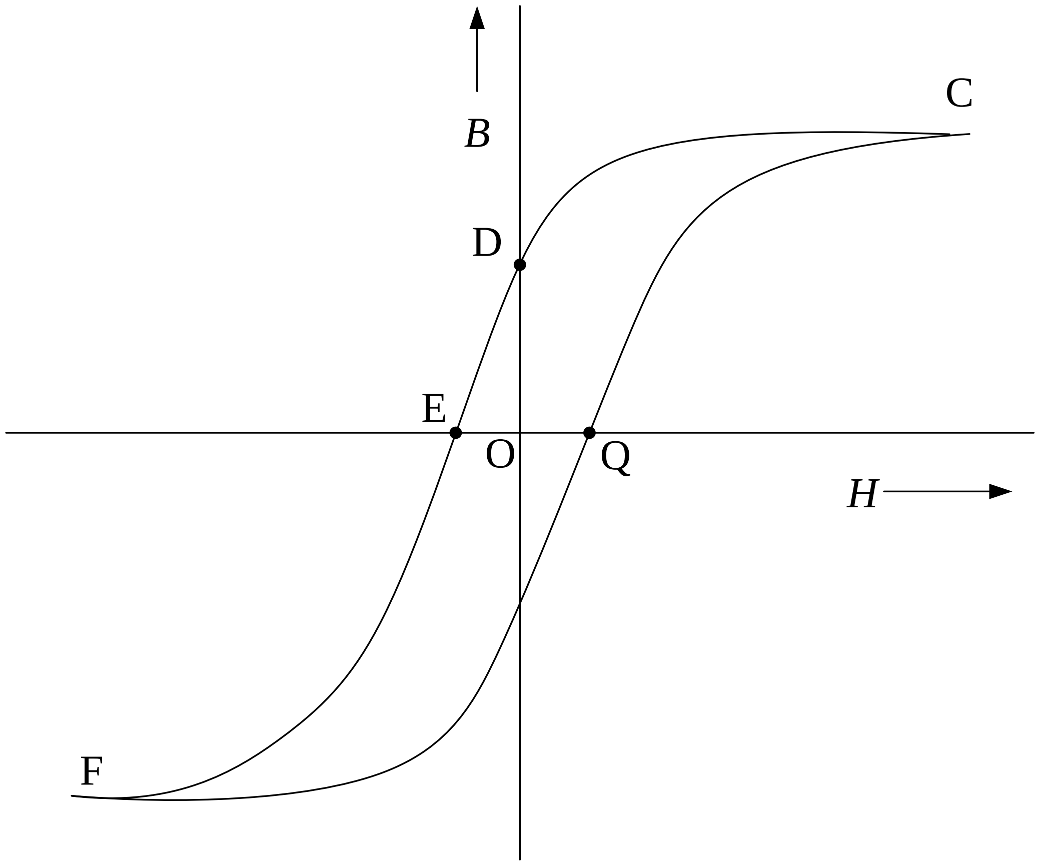
- The loop CDEFQC is called **hysteresis loop**

- C = Positive saturation
- OD = Retentivity (residual flux density) or remanence
- OE = Coercivity
- F = Negative saturation

Loss of energy during magnetization with AC supply

- Hysteresis loss
- Eddy current loss

Loss of energy during magnetization with AC supply

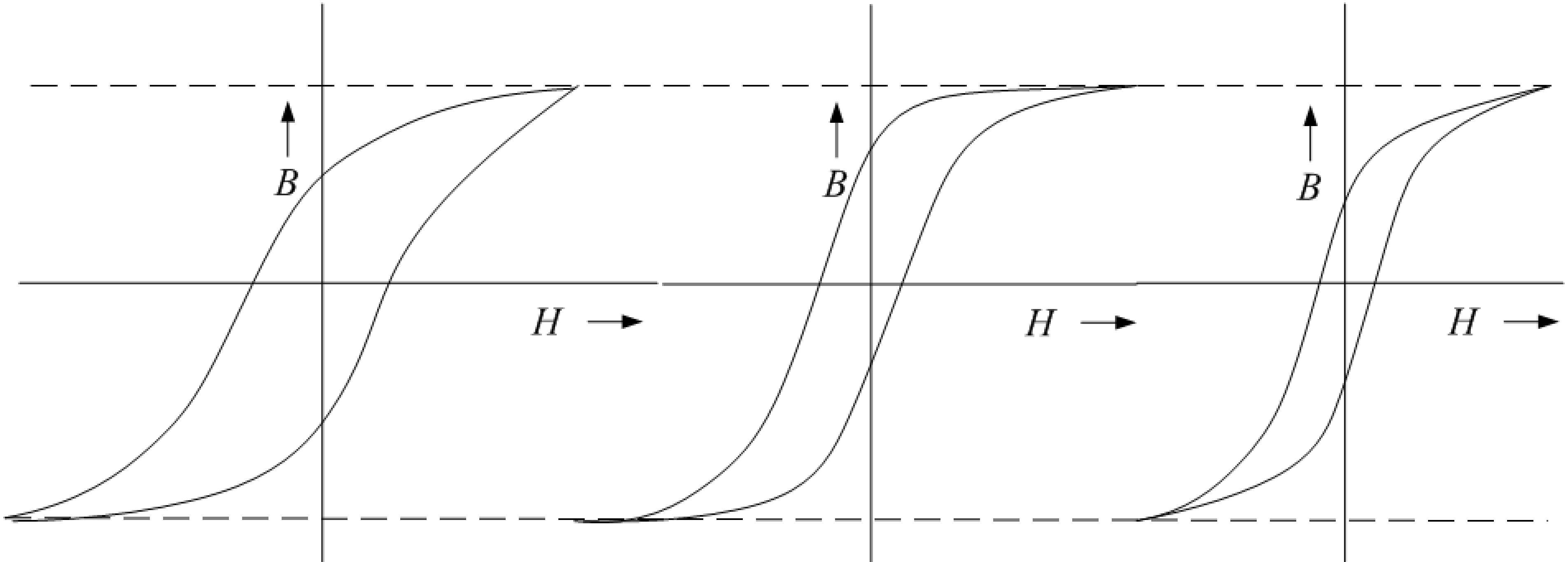


- Energy spent during magnetization is more than the energy released during de-magnetization
- This is evident from the residual magnetism
- The amount of energy thus lost during each cycle of magnetization is called **Hysteresis Loss**
- This heats up the material during magnetization

Total hysteresis loss in a magnetic material is proportional to the area of its hysteresis loop. **The loop area is equal to hysteresis loss (in W) per cycle of the input AC signal.**

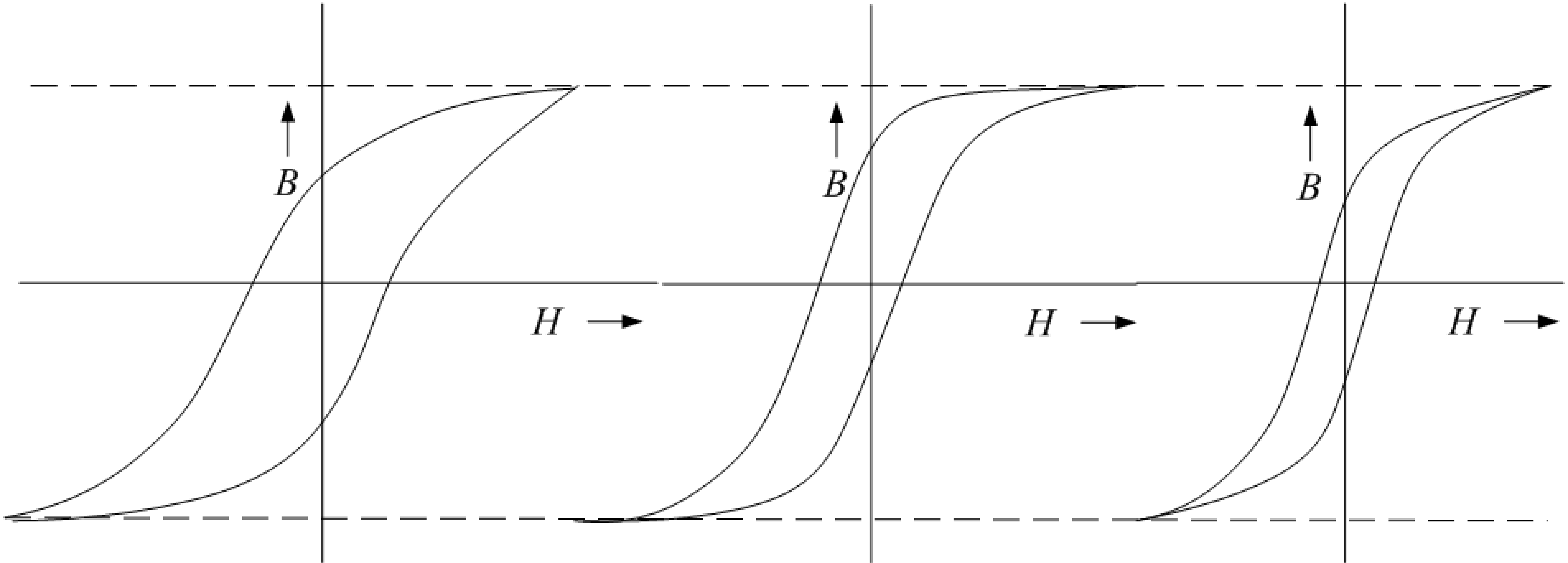
Loss of energy during magnetization with AC supply

- Hysteresis loop thus measures the energy dissipated due to hysteresis loss
- This loss appears in the form of heat and so raises the temperature of that portion of the magnetic circuit which is subjected to magnetic reversal
- The shape of the hysteresis loop depends on the nature of the magnetic material



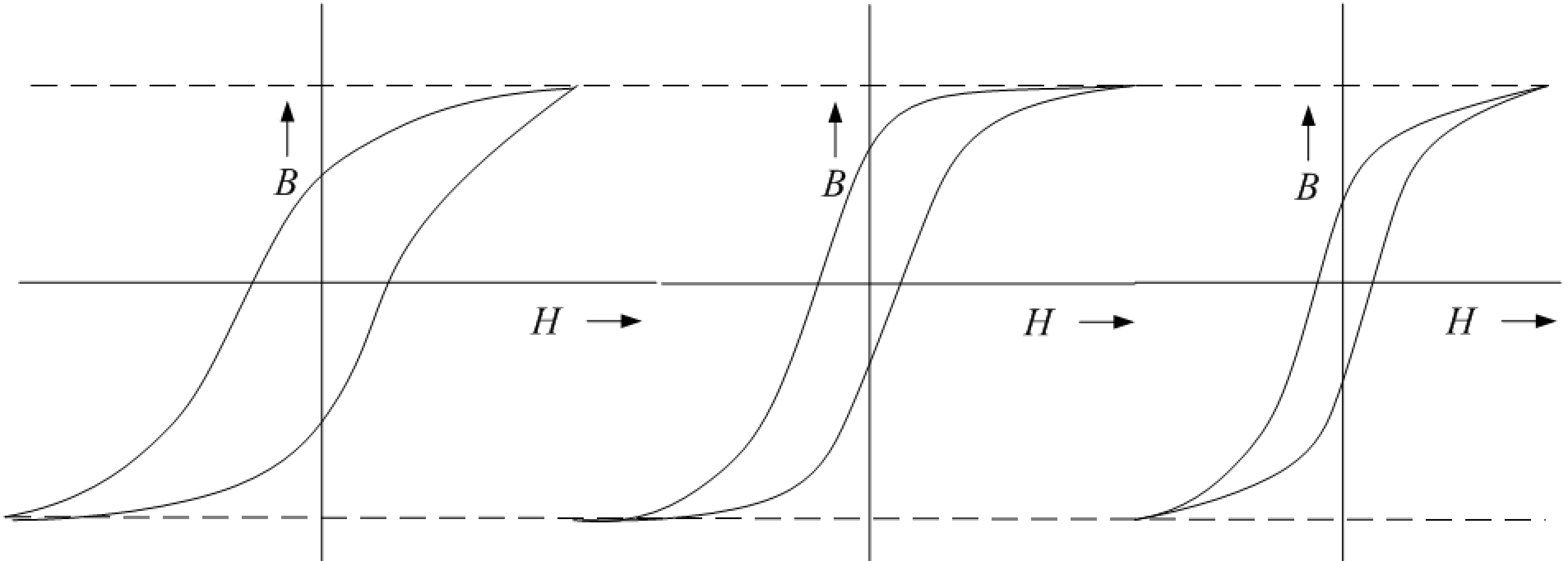
Loss of energy during magnetization with AC supply

- Loop 1 (left) is for hard magnetic materials
- Due to its high retentivity and coercivity, it is well suited for making permanent magnets
- But due to large hysteresis loss (as shown by large loop area) it is not suitable for rapid reversals of magnetization as in AC machines
- Certain alloys of aluminum, nickel and steel called Alnico alloys are suitable for making permanent magnets



Loss of energy during magnetization with AC supply

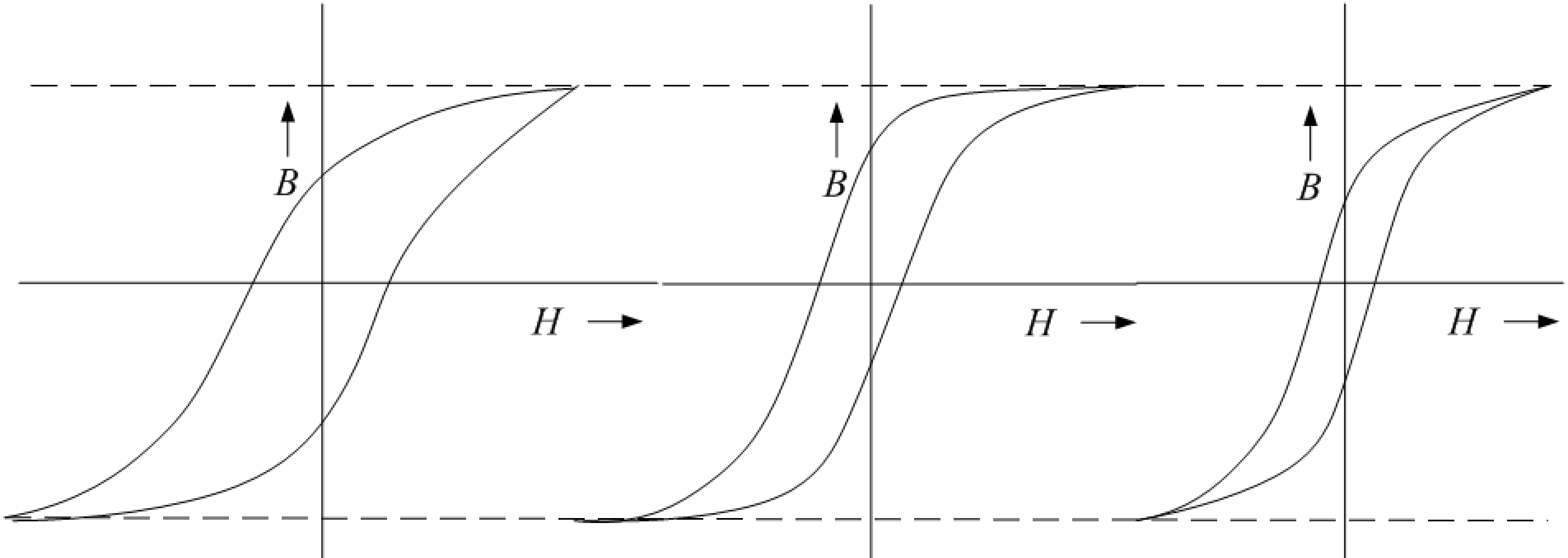
- Loop 2 (middle) is for wrought iron and cast steel
- It shows that these materials have high permeability and fairly good coercivity, hence making them suitable for cores of electromagnets
- The loop area and hence the hysteresis losses are moderate



Loss of energy during magnetization with AC supply

- Loop 3 is for alloyed sheet steel and it shows high permeability and low hysteresis loss

- Hence, such materials are most suited for making armature and transformer cores in AC machines which are subjected to rapid reversals of magnetization



Loss of energy during magnetization with AC supply

- An analytical expression for hysteresis loss can be written following the equation established by *Charles Steinmetz* as:

- Hysteresis loss $P_h = K_h f B_m{}^x$ W/m^3

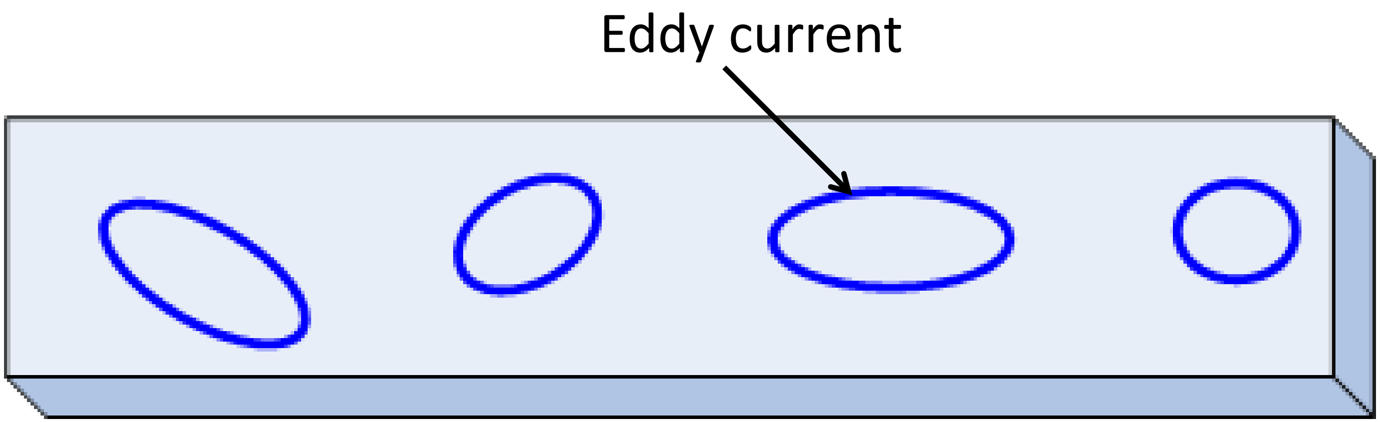
- Where,
  B_m = Maximum value of flux density in the material
  f = frequency of flux reversal, i.e. frequency of the input AC source
  K_h = Steinmetz coefficient, its value depends on property of the material
  x = A coefficient in the range $1 < x < 2$ depending on value of B_m; commonly used value is $x = 1.6$

Loss of energy during magnetization with AC supply

- The second type of loss that takes place in a magnetic material during magnetization by an alternating field is called **Eddy current loss**
- Most magnetic materials are either metallic or are alloys of metallic base
- This makes them conducting to some extent in addition to being magnetic
- The flux that passes through the material is time varying

Loss of energy during magnetization with AC supply

- The flux that passes through the material is time varying
- This will induce voltage inside the body of the material
- This causes flow of currents in small loops within body of the material



- This causes I^2R power loss in the material
- This loss is called eddy current loss

Loss of energy during magnetization with AC supply

- An analytical expression for Eddy current loss is available:

$$P_e = K_e f^2 t^2 B_m^2 \quad \text{W/m}^3$$

- Where,
  K_e is constant depending on the material properties including its resistivity
  f is the supply frequency
  t is the thickness of the material body
  B_m is maximum value of flux density in the material

Hysteresis loss and eddy current loss are collectively called *iron loss* or *core loss* because they take place invariably in the core material of all electrical machines including transformers, motors, and generators.