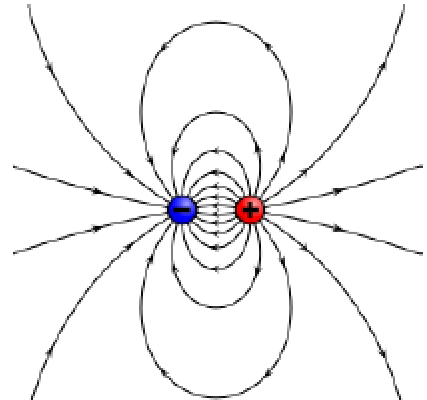
CHAPTER FOUR

Iron Core Inductor

Learning Outcomes:

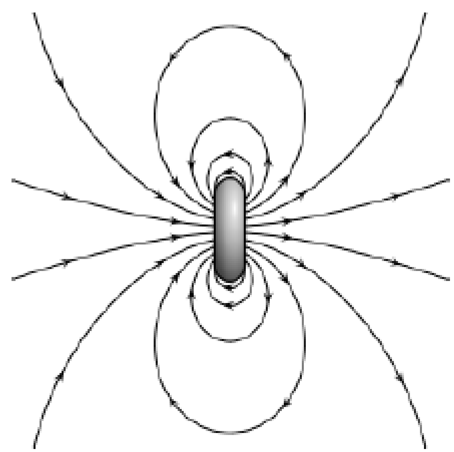
- How magnetic field lines are different from electric field lines.
- What Ampere's law is, and what it tells us about magnetic fields.
- How to analyze magnetic forces on current-carrying conductors.
- How to use Ampere's law to calculate the magnetic field of symmetric current distributions
- Some practical applications of magnetic fields in physics.

An electric field occurs wherever a voltage is present.



Electric dipole field lines

Magnetic fields are created whenever there is a flow of electric current



Magnetic dipole field lines

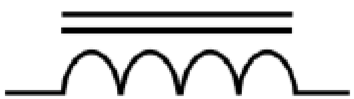
Comparison chart

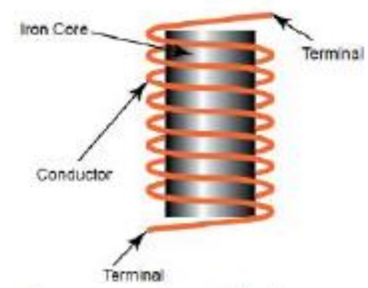
	Electric Field	Magnetic Field
Nature	Created around electric charge	Created around moving electric charge and magnets
Units	volts per meter	Ampere/meter
Force	Proportional to the electric charge	Proportional to charge and speed of electric charge
Movement In Electromagnetic field	Perpendicular to the magnetic field	Perpendicular to the electric field
Electromagnetic Field	Generates VARS (Capacitive)	Absorbs VARS (Inductive)
Pole	Monopole or Dipole	Dipole
Nature	Created around electric charge	Created around moving electric charge and magnets

The symbols for different inductors

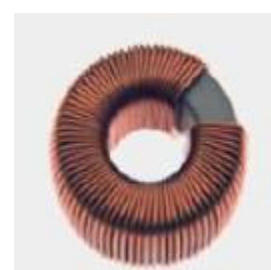
Air core inductor

Iron core inductor

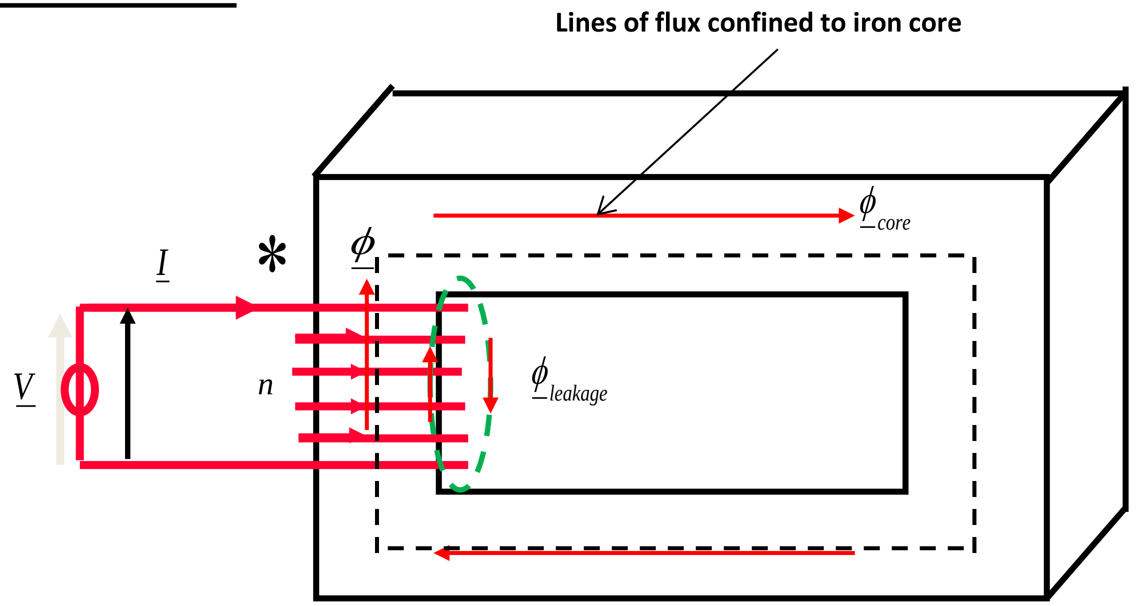




Ferrite core inductor



Iron core inductor



$$\Phi = \phi_{core} + \phi_{leakage}$$

$$\Phi = n \times \phi$$

$$\Phi = B \times S$$

Φ is the total flux in weber

ϕ_{core} is the flux in the core in weber

$\phi_{leakage}$ is the leakage flux in weber

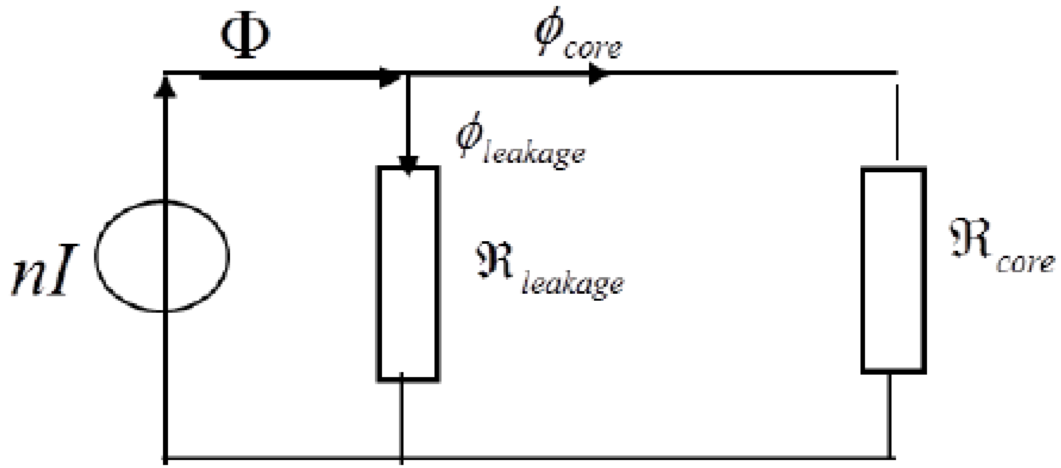
l_{core}: Mean magnetic path length in meters

Where n is the number of turns

B is the maximum flux density in tesla

S **is the cross-sectional area of the core in square meters**

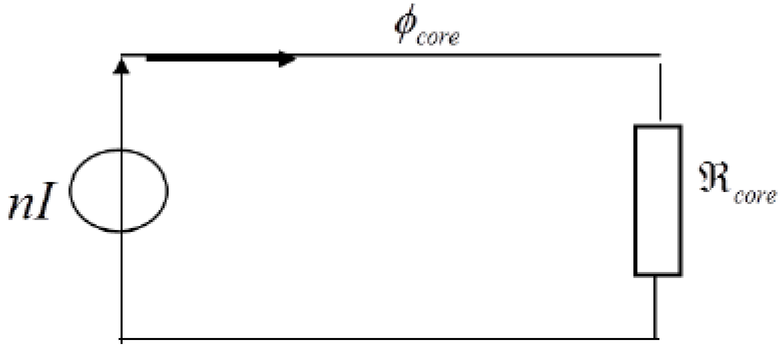
The Magnetic equivalent circuit



For simplicity, the effect of leakage flux is **negligible**

$$\Phi = \phi_{core}$$

The Magnetic equivalent circuit becomes:



the following relation can be obtained:

$$n \times I = \Re \times \phi_{core}$$

We can describe **units** for reluctance $\Re$ as amp-turns per weber (At / Wb)

From Ampere's law, we have: $n \times I = H \times l_{core}$

H is the magnetizing force that generated the flux.

$B = \mu H$ H is measured in (At/m)

Permeability

$$\mu_r = \frac{\mu}{\mu_0}$$

μ_r: Relative permeability.

μ_0: The permeability of free space

Where $\mu_0 = 4\pi \times 10^{-7}$

μ : permeability of a specific medium

SELF-INDUCTANCE

$$n \times I = \Re \times \phi$$

$$n \times \phi = L \times I \rightarrow \phi = \frac{L \times I}{n}$$

$$n \times I = \Re \times \frac{L \times I}{n}$$

$$L = \frac{n^2}{\Re}$$

Inductance is measured in henry (H)

Inductive reactance

$$X_L = L\omega = 2\pi f L$$

X_L is measured in (Ohm)

Reluctance

$$\Re = \frac{l_{core}}{\mu \times S}$$

Reluctance is measured in (At/Wb)

Reluctance depends on the dimensions of the core as well as its materials:

Analogy between magnetic circuit and electric circuit

Electric quantities	Magnetic quantities
Current I	Magnetic flux Φ
Current density J	Magnetic flux density B
Conductivity σ	Permeability μ
Electromotive force = resistance ×I	Magnetomotive force = reluctance ×Φ
Electric field intensity E	Magnetic field intensity H
Conductance = 1/resistance	Permeance = 1/reluctance
Resistance = l/σ×S	Reluctance = l/μS

Magnetic Circuits

- Use Ohm's law analogy to model magnetic circuits

$$V \Leftrightarrow NI$$

$$I \Leftrightarrow \Phi$$

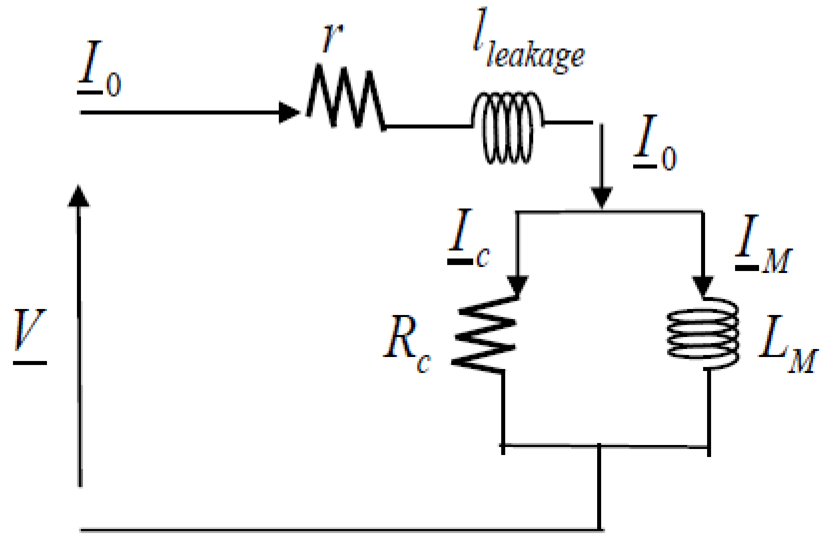
$$R \Leftrightarrow \Re$$

- Use magnetic "reluctance" instead of resistance

$$R = \frac{l}{\sigma A} \Leftrightarrow \Re = \frac{l}{\mu A}$$

- This is a very powerful method to get approximate answers in magnetic circuits

Electrical Equivalent circuit for the practical iron-core



$$\underline{I}_0 = \underline{I}_c + \underline{I}_M$$

r is the dc resistance of the winding
R_c represents the hysteresis and eddy current losses
L_m (magnetizing inductance) is the inductance associated with the magnetization of the core
$l_{leakage}$ is the inductance associated with the leakage flux
I_0 excitation current
I_M is magnetizing current
I_c is core loss current

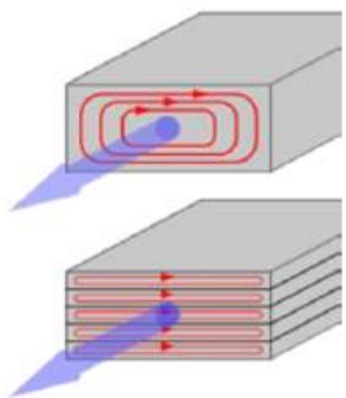
Core Losses

1. **Copper losses**: The power lost by current flowing through the winding. The power loss is equal to the square of the current multiplied by the resistance of the wire ($I^2 R$). This power loss is transferred into heat.

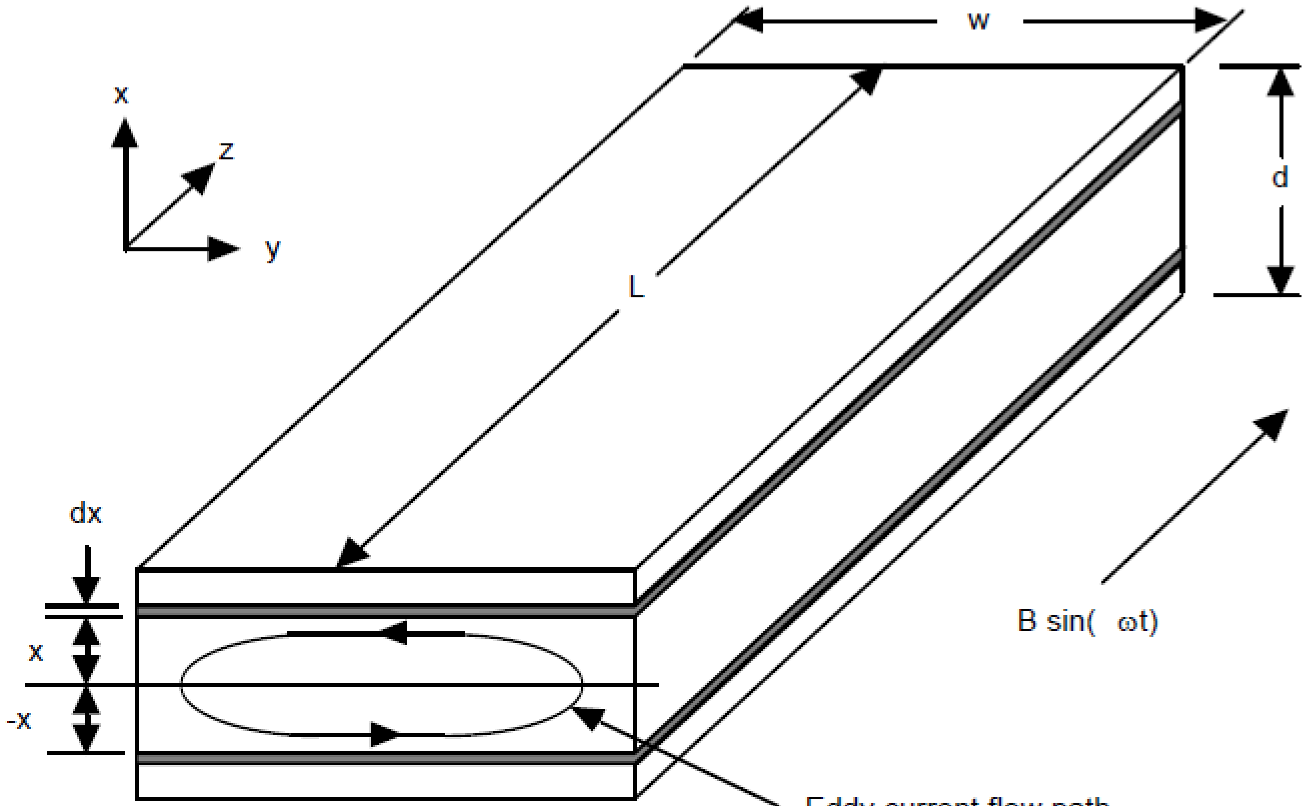
$$R = \rho \frac{l}{S}$$

2. **Eddy current losses**: Eddy current losses are present in the magnetic core:

Laminated cores:

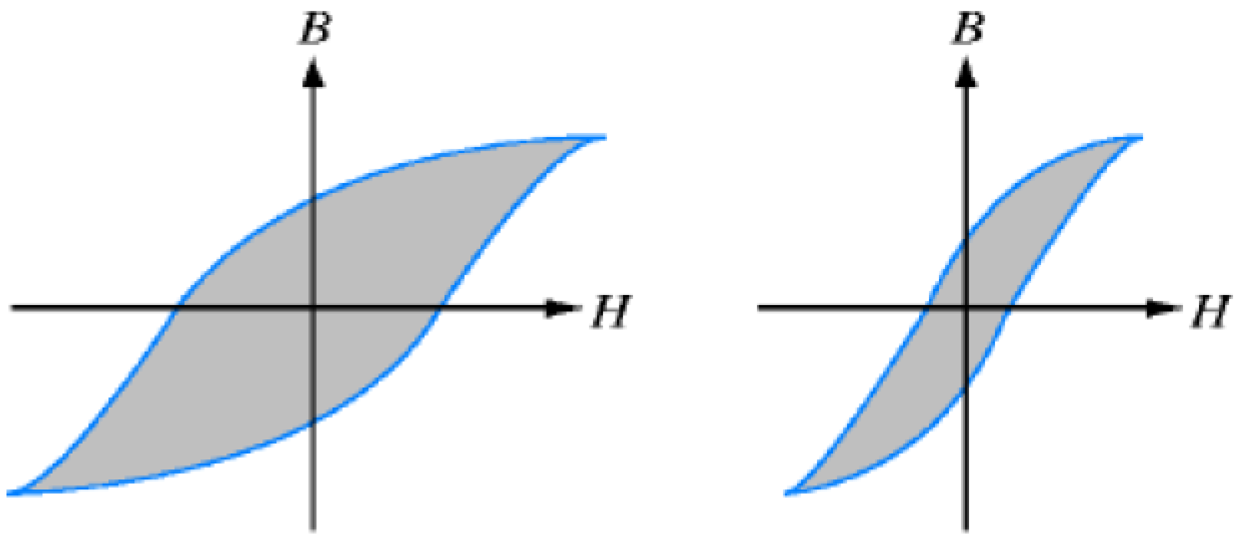


Eddy Current Loss in Lamination



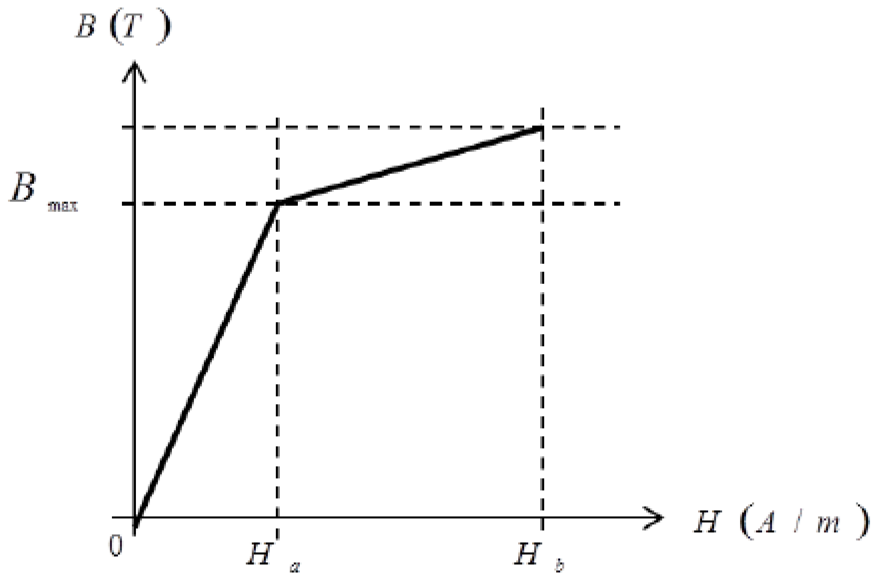
3. Hysteresis losses

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core



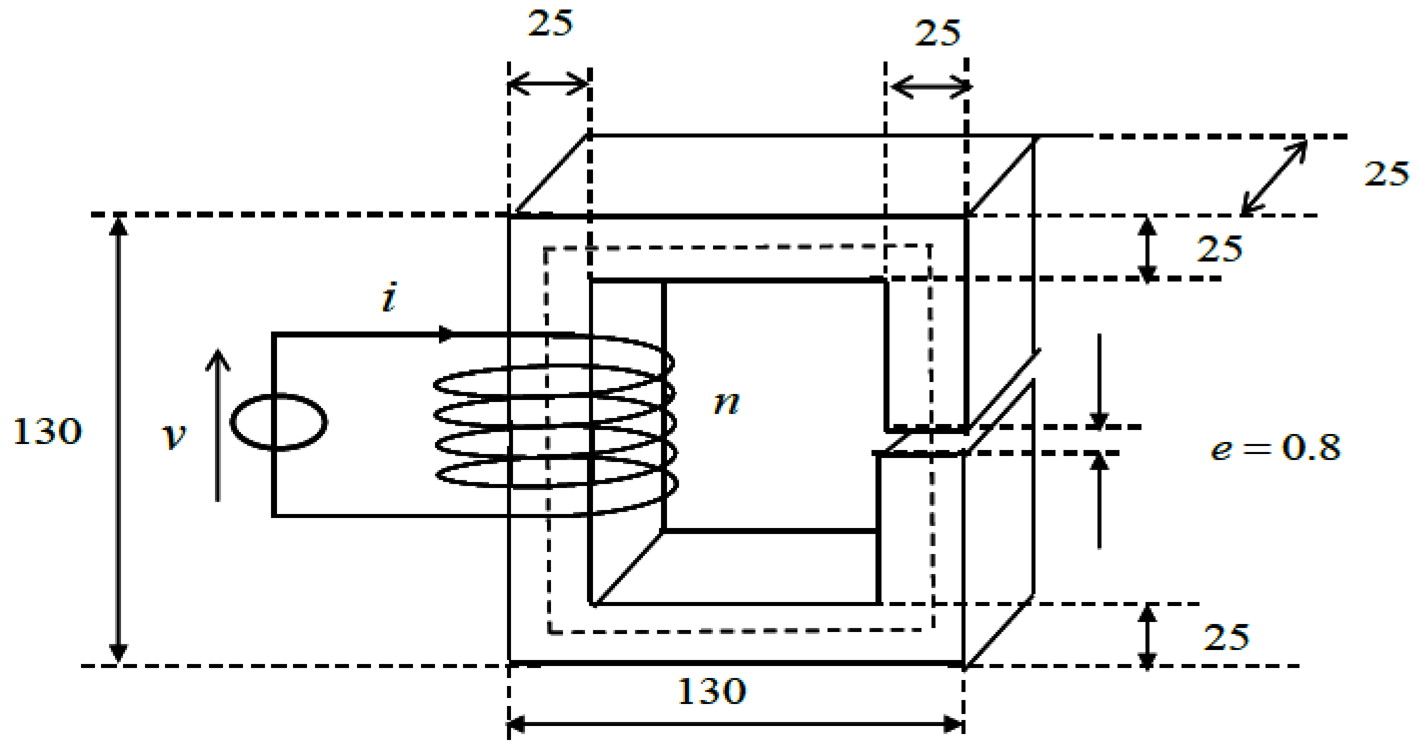
(a) Hard material (b) Soft material

nonlinear magnetic system.



$$H_c = \frac{1}{\mu_0 \times \mu_r} \int_a^b dB$$

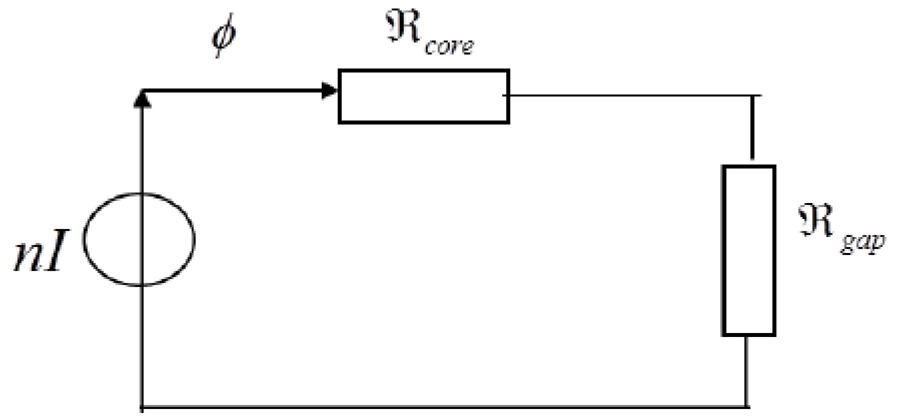
Magnetic system with and Air Gap



$$\Re_{core} = \frac{l_{core}}{\mu_r \times \mu_0 \times S}$$

$$\Re_{gap} = \frac{l_{gap}}{\mu_0 \times S}$$

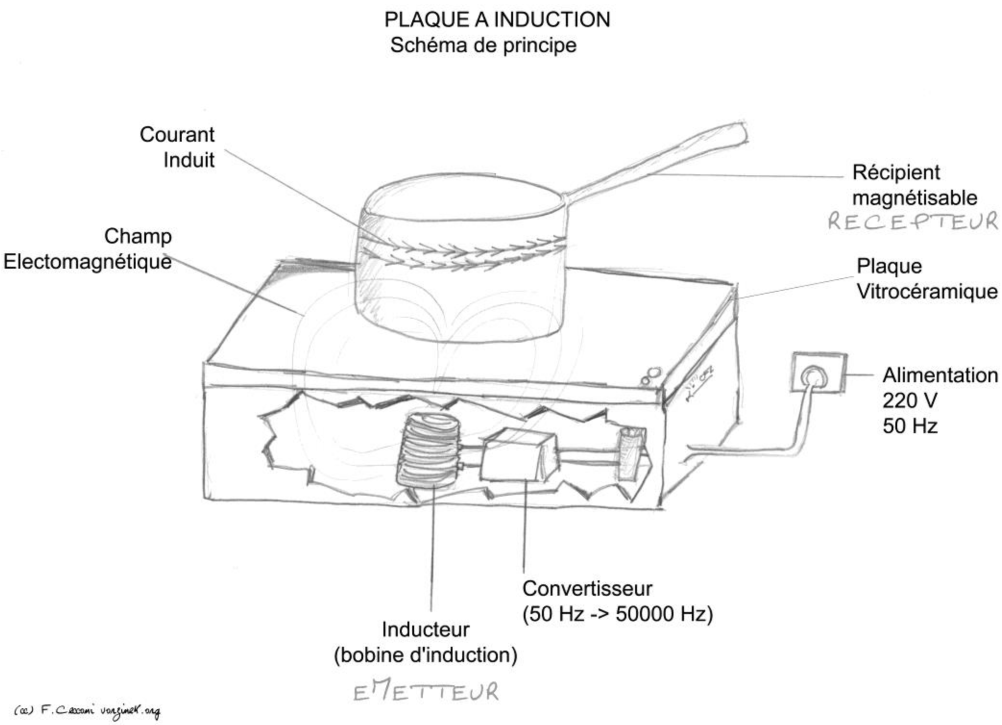
The Magnetic equivalent circuit is:



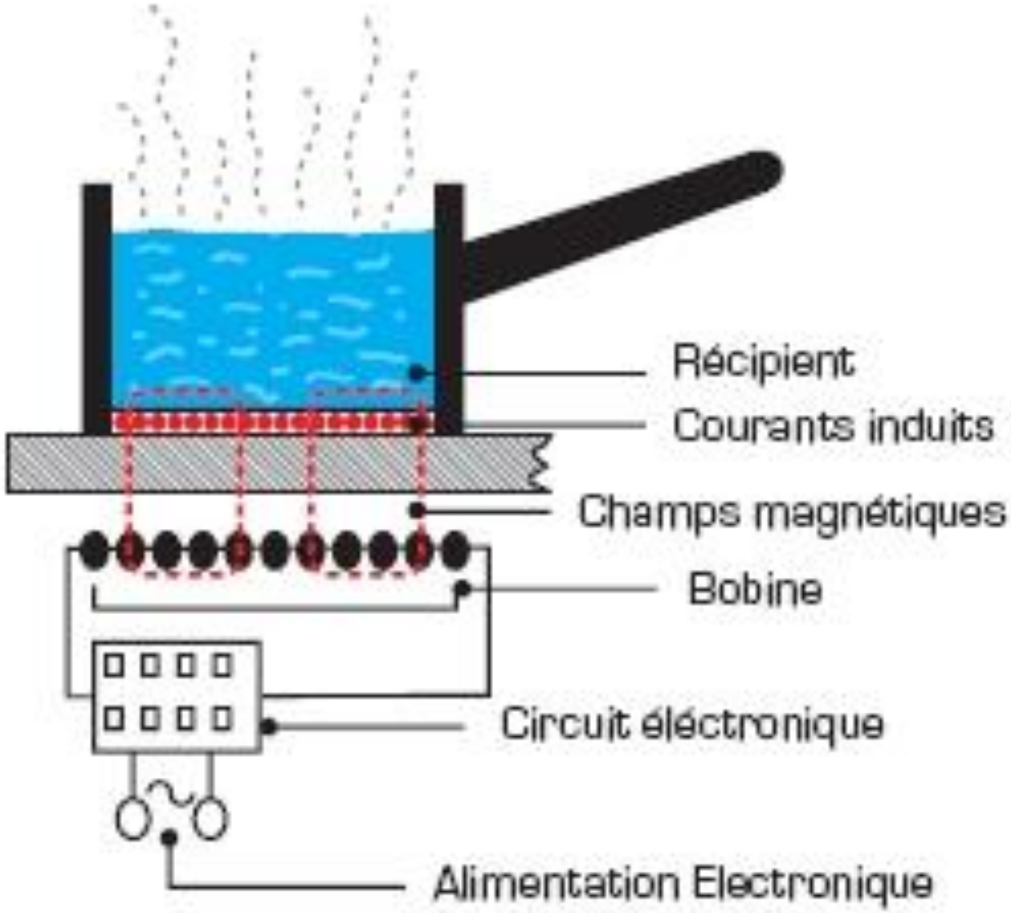
$$nI = \phi\left(\Re_{core} + \Re_{gap}\right)$$

Applications

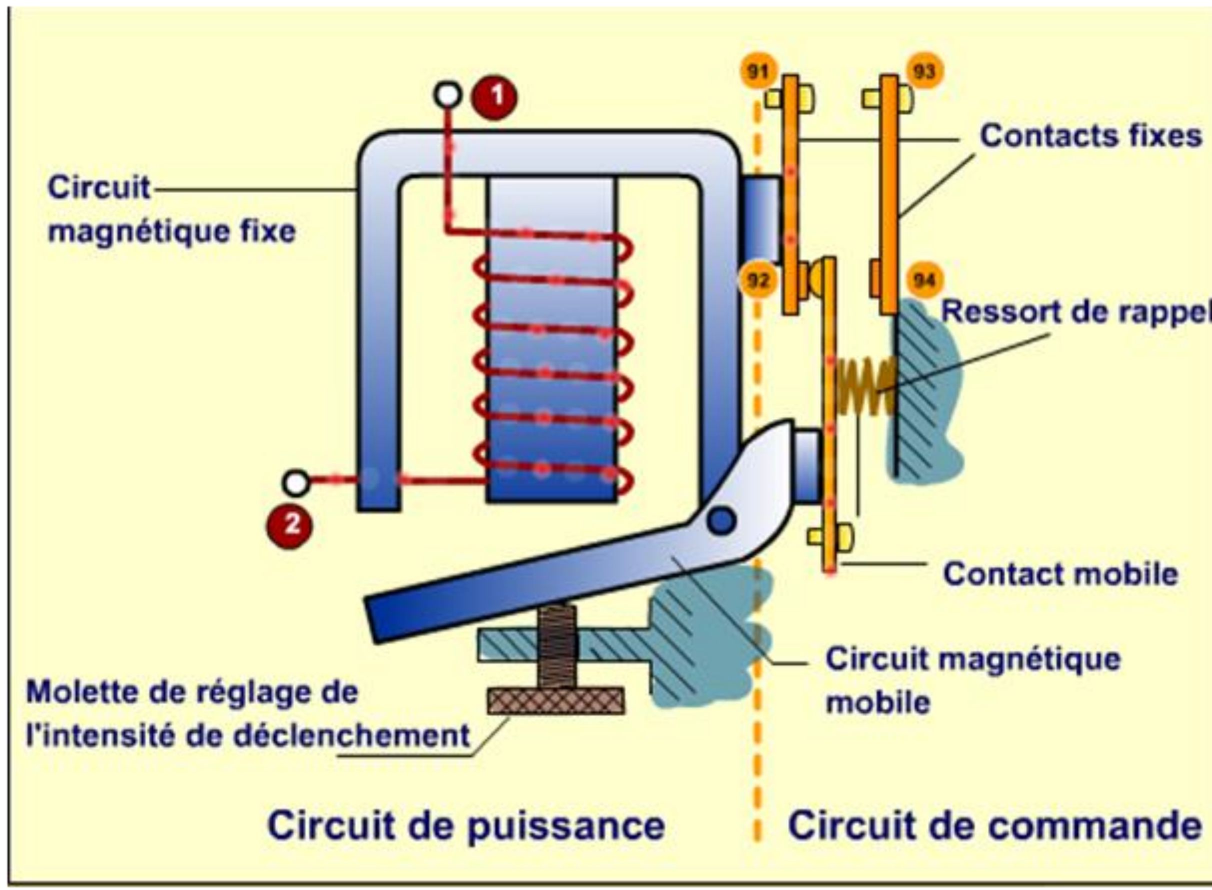
Plaque à induction ouverte, on voit bien la bobine inductrice.



Plaque à induction ouverte, on voit bien la bobine inductrice.

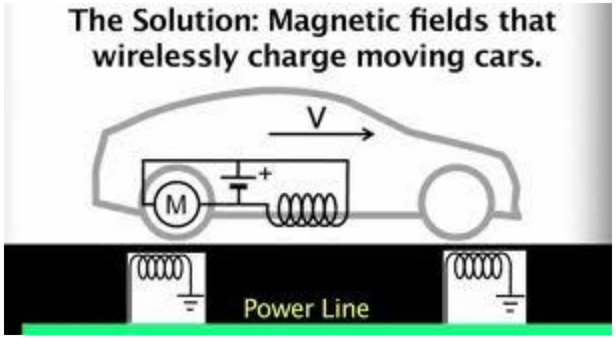


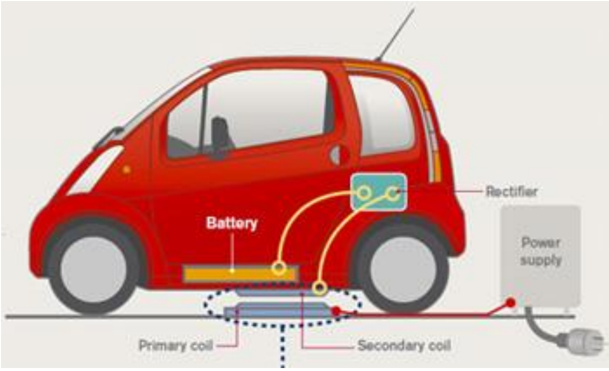
Relais magnétique



Levage de boîtes de conserves

Train à ***sustentation*** magnétique

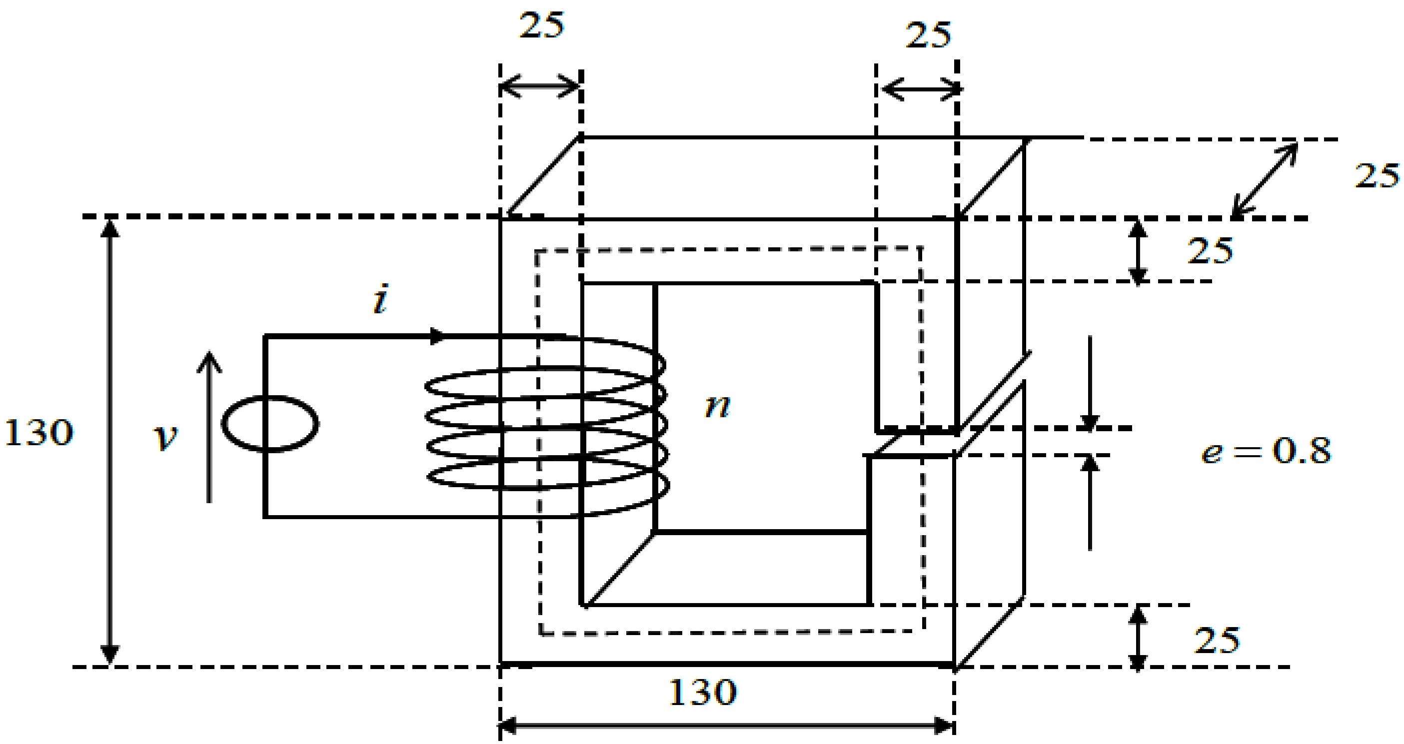

The Solution: Magnetic fields that wirelessly charge moving cars.
V
M
Power Line


Battery
Rectifier
Power supply
Primary coil
Secondary coil

Exercise 1

Give the Magnetic equivalent circuit and find the value of the current I required to establishing a flux density of 1.4 T in the magnetic system as shown in figure 1. Leakage flux is ignored.

Given $n = 1200 turns; \mu_0 = 4\pi \times 10^{-7}\ S.I.$

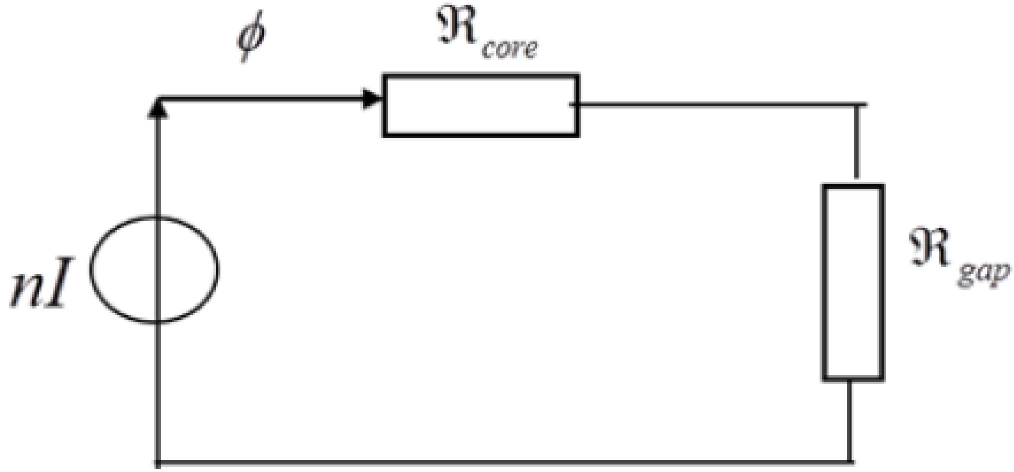


The magnetization date for the material is as follows:

B (T)	0	0,5	0,8	1	1,2	1,4	1,6	1,8
H (A/m)	0	220	490	760	1300	2450	4700	11500

Solution:

The above device can be analysed by its magnetic equivalent circuit as shown in figure



The flux for each section is:

$$\phi = B \times S$$
$$\phi_{core} = 1.4 \times 25 \times 25 \times 10^{-6} = 0.875 \times 10^{-3} Wb$$

The flux density of steel is:

$B = 1.4(Tesla) \rightarrow H = 2450(At/m)$ Table1.

The Magnetomotive force of steel is:

$$\varepsilon_{core} = H_{core} \times l = 2450 \times (80 + 25) \times 4 \times 10^{-3} = 1029\,At$$

The flux for air gap section is:

$$\phi_g = \phi_{core} = 1.4 \times 25 \times 25 \times 10^{-6} = O.875 \times 10^{-3}\,Wb$$

The magnetic field intensity of air gap is

$$H_g = \frac{B}{\mu_0}$$

$$H_g = \frac{1.4}{4\pi \times 10^{-7}} = 1.11 \times 10^{6}\,At/m$$

The Magnetomotive force of air gap is:

$$\varepsilon_g = H_g \times e = 1{,}11 \times 10^{6} \times 0{,}8 \times 10^{-3} = 888\,At$$

Applying Ampère circuital law:

$$\varepsilon = \varepsilon_{core} + \varepsilon_g = 888 + 1029 = 1917\,At$$

$$\varepsilon = n \times I = 1200 \times I = 1917\,At$$

$$I = \frac{1917}{1200} \cong 1.6\,A$$


The End