UNIT-4

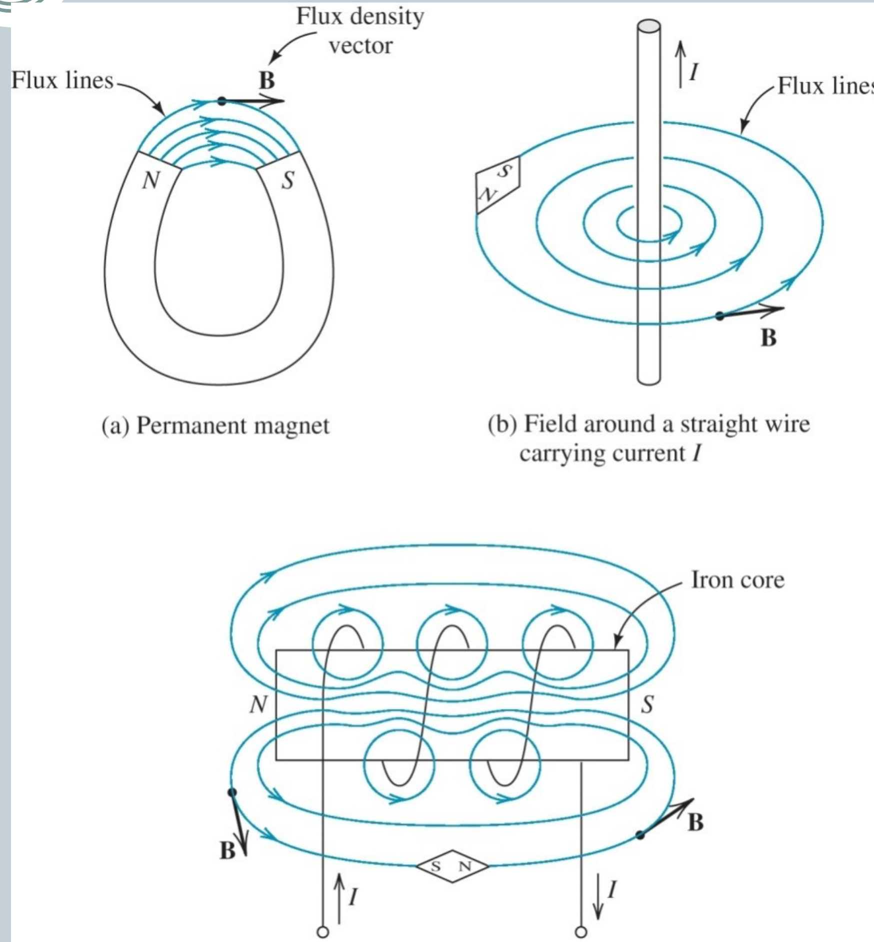
- **5. Magnetic Circuit:**
- Magnetic circuit concepts, analogy between electric & magnetic circuits with DC excitations,
- magnetic circuit calculations.
- **6. Introduction to Earthing and Electrical Safety:**
- Need of Earthing of equipment and devices, important electrical safety issues. transmission and distribution voltages, concept of grid (elementary treatment only).
- **7. Single Phase Transformer:**
- Principle of operation, construction, e.m.f. equation, equivalent circuit, power losses,
- efficiency (simple numerical problems), introduction to auto transformer.

Magnetic Fields

Magnetic fields can be visualized as lines of flux that form closed paths.

Using a compass, we can determine the direction of the flux lines at any point.

Note that the **flux density vector B** is tangent to the lines of flux.

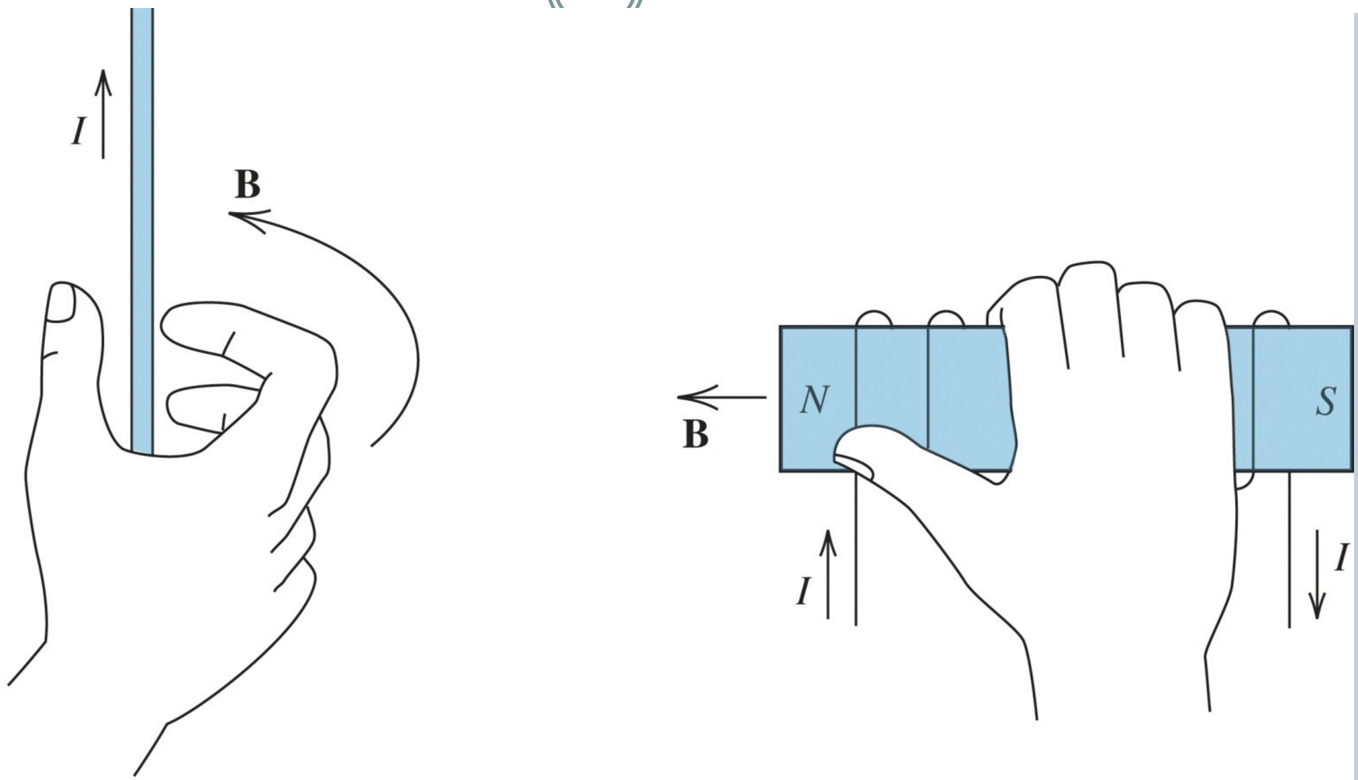


(a) Permanent magnet

(b) Field around a straight wire carrying current I

(c) Field for a coil of wire

Illustrations of the right-hand rule

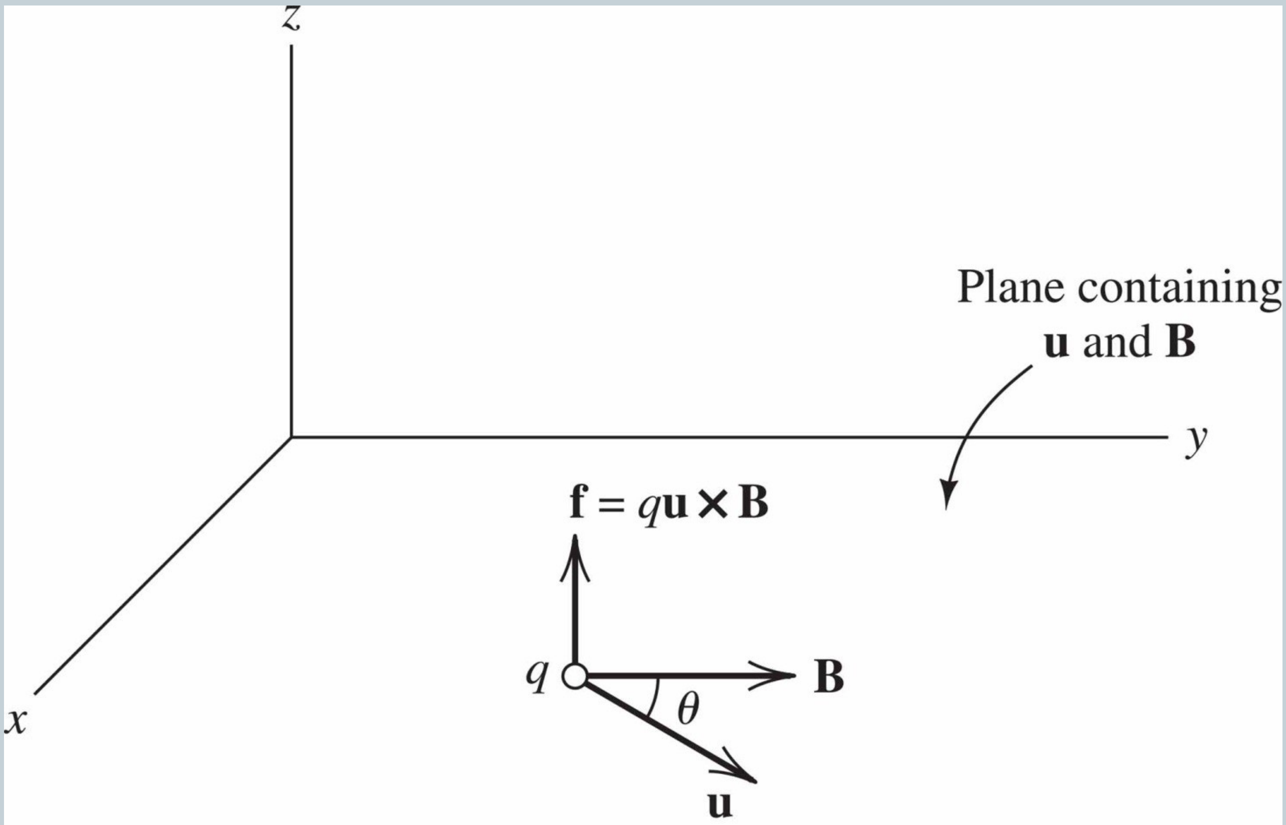


(a) If a wire is grasped with the thumb pointing in the current direction, the fingers encircle the wire in the direction of the magnetic field

(b) If a coil is grasped with the fingers pointing in the current direction, the thumb points in the direction of the magnetic field inside the coil

Force on Moving Electric Charge

A charge moving through a magnetic field experiences a force **f** perpendicular to both the velocity **u** and flux density **B**.



Force on Moving Electric Charge

A charge q moving through a magnetic field experiences a force **f** perpendicular to both the velocity **u** and flux density **B**.

$$f = qu \times B$$

where u is the velocity vect

The magnitude of this force

$$|f| = quB\sin(\theta)$$

Current that flows through a … s in motion so the force acting on the wire with current in the magneti

$$df = i\ dl \times B$$

and in the straight wire of th … er angle

$$f = i\ l\ B\sin(\theta)$$

Flux Linkage and Induced Voltage

When the flux linking a coil changes, a voltage is induced in the coil.

The polarity of the voltage is such that if a circuit is formed by placing a resistance across the coil terminals, the resulting current produces a field that tends to oppose the original change in the field.

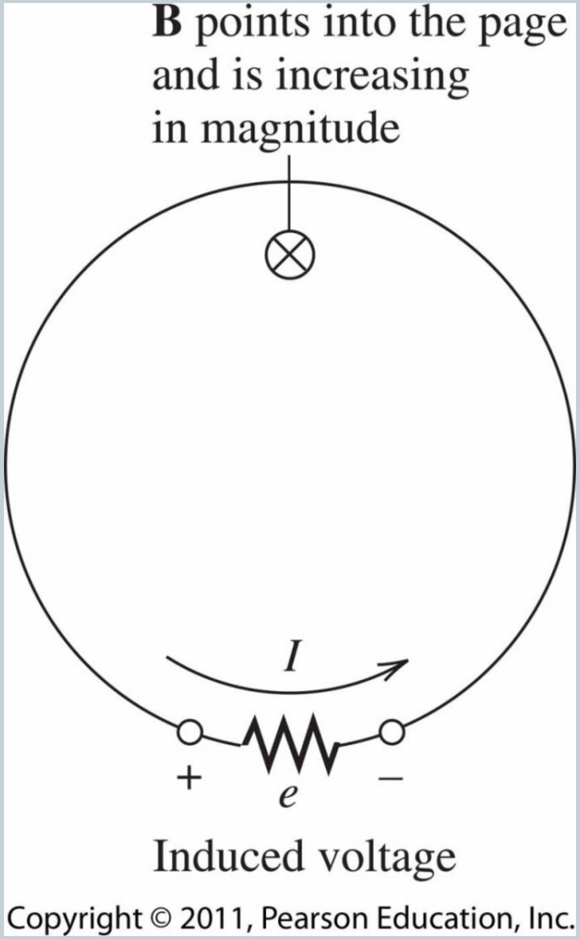
Faraday Law of magnetic induction: voltage **e** induced by the flux changes is

$$e = \frac{d\lambda}{dt}$$

where **total flux linkage** λ is

$$\lambda = N\phi = N\int_A B\,dA$$

N-number of turns, ϕ magnetic flux passing through the surface area **A**, and **B** is the magnetic field



Induced Voltage in a Moving Conductor

A voltage is also induced in a conductor moving through a magnetic field in the direction such that the conductor cuts through magnetic flux lines.
The flux linkage of the coil is (with uniform magnetic field B)

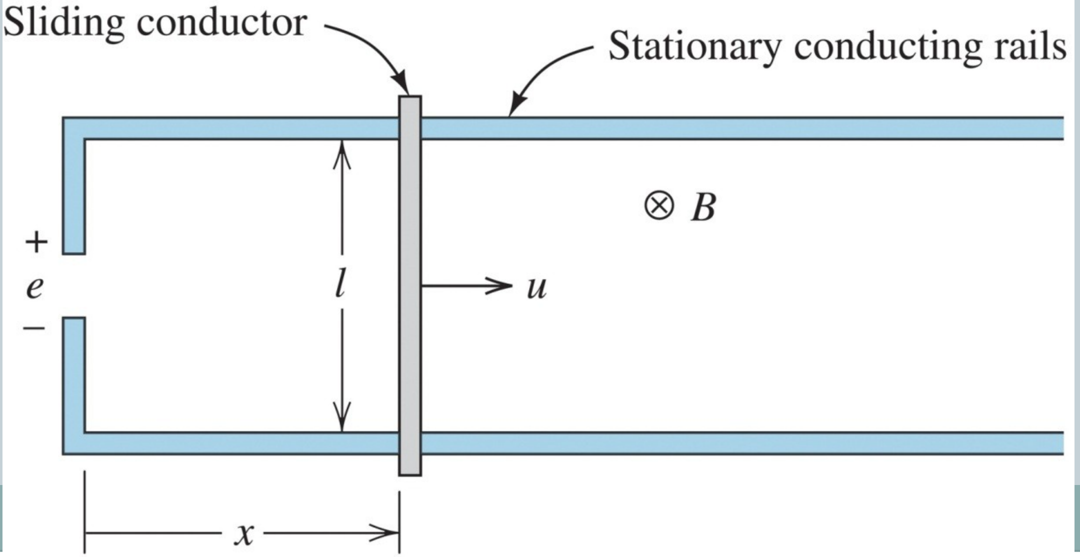
$$\lambda = \phi = BA$$

so according to Faraday's law the voltage induced in the coil is

$$e = \frac{d\lambda}{dt} = Bl\frac{dx}{dt} = Blu$$

where

$$u = \frac{dx}{dt}$$



Ampère's Law

Ampère's law (generalization of Kirchhoff's law) states that the line integral of **magnetic field intensity H** around a closed path is equal to the sum of the currents flowing through the surface bounded by the path.

$$\oint H \cdot dl = \sum i$$

where magnetic field intensity H is related to flux density B and **magnetic permeability**

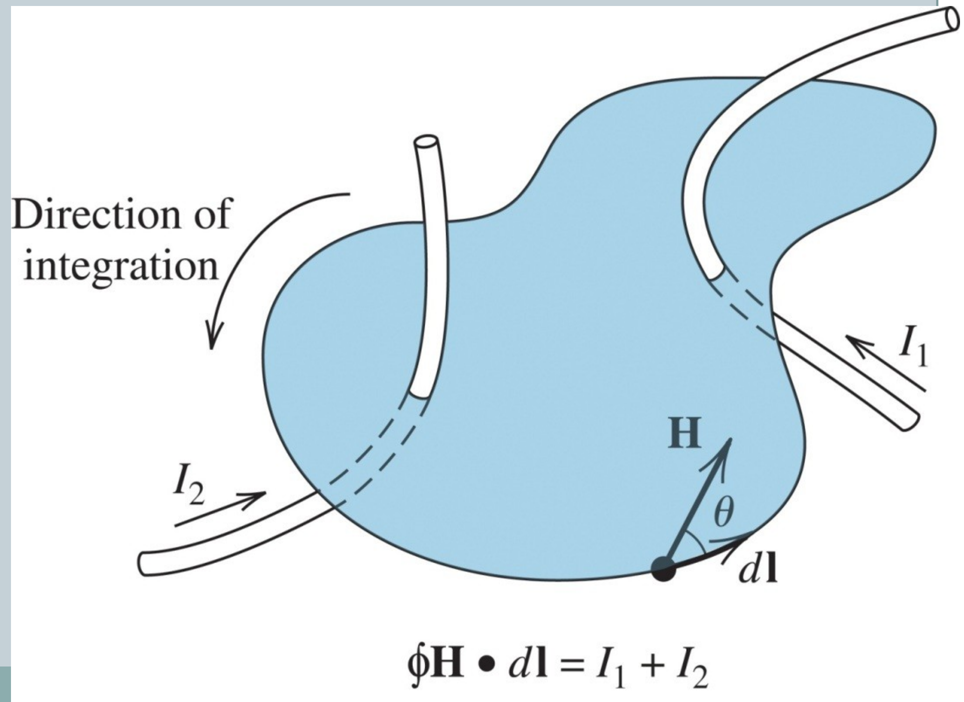
$$\mu$$

since $$H = \frac{B}{\mu}\left[\frac{A}{m}\right]$$

so if H and dl point in the same direction

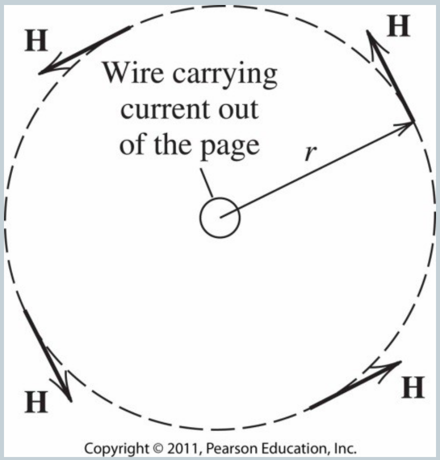
$$H \cdot dl = H\, dl \cos(\theta)$$

$$H\, l = \sum i$$



Ampère's Law

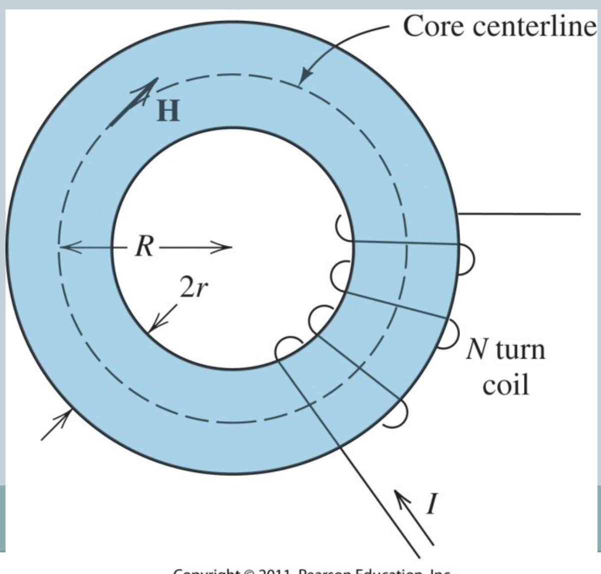
The magnetic field around a long straight wire carrying a current can be determined with Ampère's law aided by considerations of symmetry.



$$H\,l = H2\pi r = I$$

So the magnetic flux density

$$B = \mu H = \frac{\mu I}{2\pi r} \qquad (*)$$



Using Ampère's law in the toroidal coil, filed intensity is

$$H\,l = H2\pi R = NI$$

Using (*) we get inside the toroidal coil:

$$B = \frac{\mu NI}{2\pi R}$$

Reluctance of a Magnetic Path

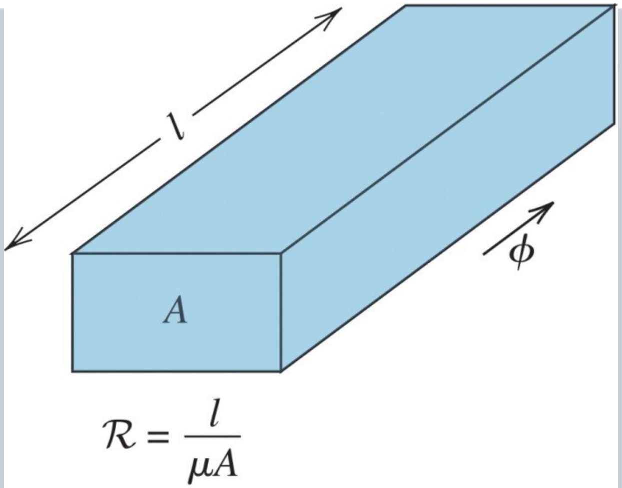
Magnetic circuits are analogue of electrical circuits.

The **magnetomotive force** of N-turn current carrying coil is

$$F = Ni$$

The **reluctance R** of a magnetic path depends on the mean length *l*, the area *A*, and the **permeability** *μ* of the material.

$$\mathrm{R} = \frac{l}{\mu A}$$



Magnetic flux is analogous to current in electrical circuit and is related to F and R in a similar way as Ohm's law

$$F = \mathrm{R}\,\phi$$

Magnetic Circuits

The magnetic circuit for the toroidal coil can be analyzed to obtain an expression for flux.

Magnetomotive force is

$$F = NI = \mathcal{R}\phi$$

Where the reluctance is

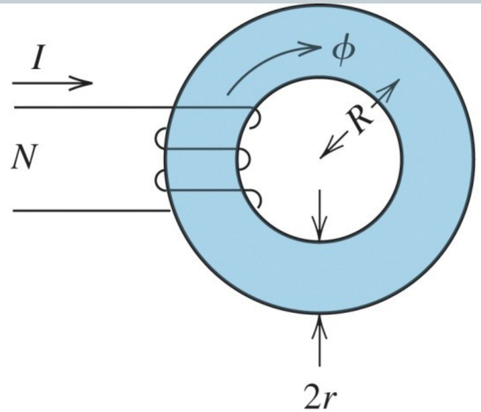
$$\mathcal{R} = \frac{l}{\mu A} = \frac{2\pi R}{\mu \pi r^2} = \frac{2R}{\mu r^2}$$

so

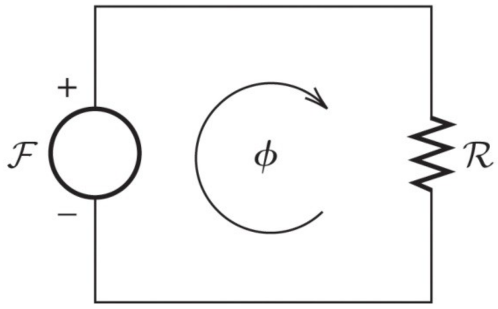
$$NI = \frac{2R}{\mu r^2}\phi$$

and the magnetic flux is

$$NI = \frac{2R}{\mu r^2}\phi \quad so \quad \phi = \frac{NI\mu r^2}{2R}$$



(a) Coil on a toroidal iron core

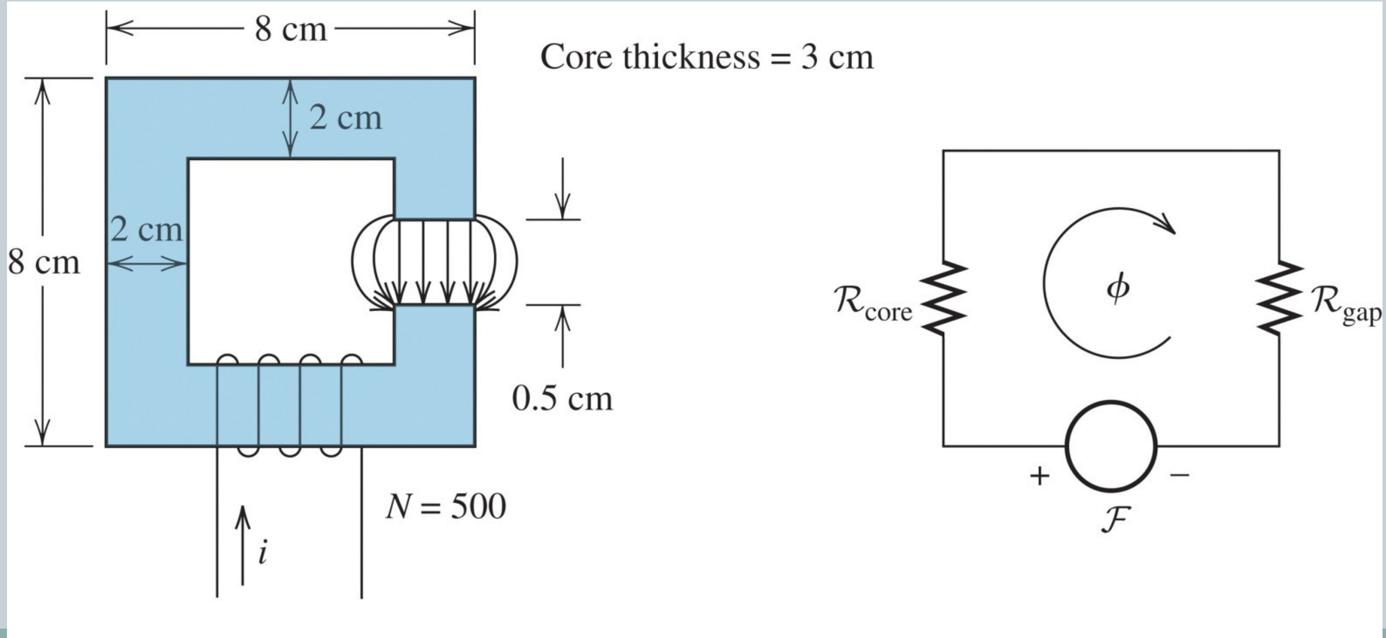


(b) Magnetic circuit

Magnetic Circuits

Example 15.5.

Magnetic circuit below relative permeability of the core material is 6000 its rectangular cross section is 2 cm by 3 cm. The coil has 500 turns. Find the current needed to establish a flux density in the gap of B_{gap}=0.25 T.



(a) Iron core with an air gap (b) Magnetic circuit

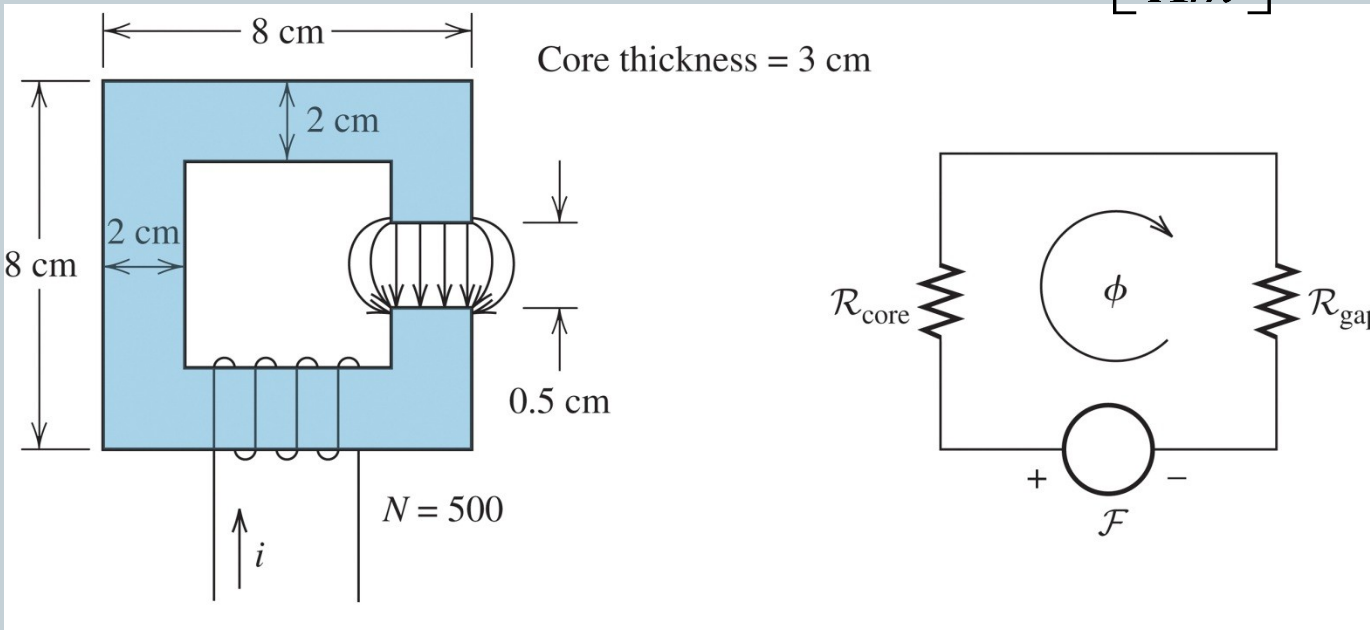
Magnetic Circuits

Example 15.5.

Magnetic circuit below relative permeability of the core material is 6000 its rectangular cross section is 2 cm by 3 cm. The coil has 500 turns. Find the current needed to establish a flux density in the gap of B_{gap}=0.25 T.

Medium length of the magnetic path in the core is l_{core}=4*6-0.5=23.5cm, and the cross section area is A_{core}= 2cm*3cm = $6*10^{-4}$ m^2
the core permeability is

$$\mu_{core} = \mu_r \mu_0 = 6000 \times 4\pi \times 10^{-7} = 7.54 \times 10^{-3} \left[\frac{Wb}{Am} \right]$$



(a) Iron core with an air gap (b) Magnetic circuit

Magnetic Circuits

Example 15.5.

The core reluctance is

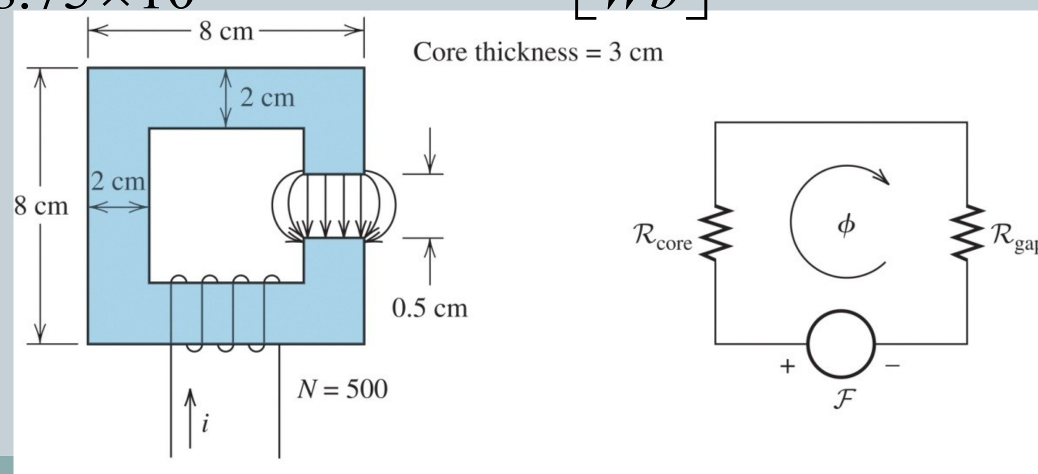
$$\mathrm{R}_{core} = \frac{l_{core}}{\mu_{core} A_{core}} = \frac{23.5 \times 10^{-2}}{7.54 \times 10^{-3} \times 6 \times 10^{-4}} = 5.195 \times 10^{4} \left[\frac{A}{Wb} \right]$$

the gap area is computed by adding the gap length to each dimension of cross-section:

$$A_{gap} = (2cm + 0.5cm) \times (3cm + 0.5cm) = 8.75 \times 10^{4} \left[m^{2} \right]$$

thus the gap reluctance is:

$$\mathrm{R}_{gap} = \frac{l_{gap}}{\mu_0 A_{gap}} = \frac{0.5 \times 10^{-2}}{4\pi \times 10^{-7} \times 8.75 \times 10^{-4}} = 4.547 \times 10^{6} \left[\frac{A}{Wb} \right]$$



(a) Iron core with an air gap (b) Magnetic circuit

Magnetic Circuits

Example 15.5.
Total reluctance is

$$R = R_{gap} + R_{core} = 4.6\times 10^{6}\left[\frac{A}{Wb}\right]$$

based on the given flux density B in the gap, the flux is

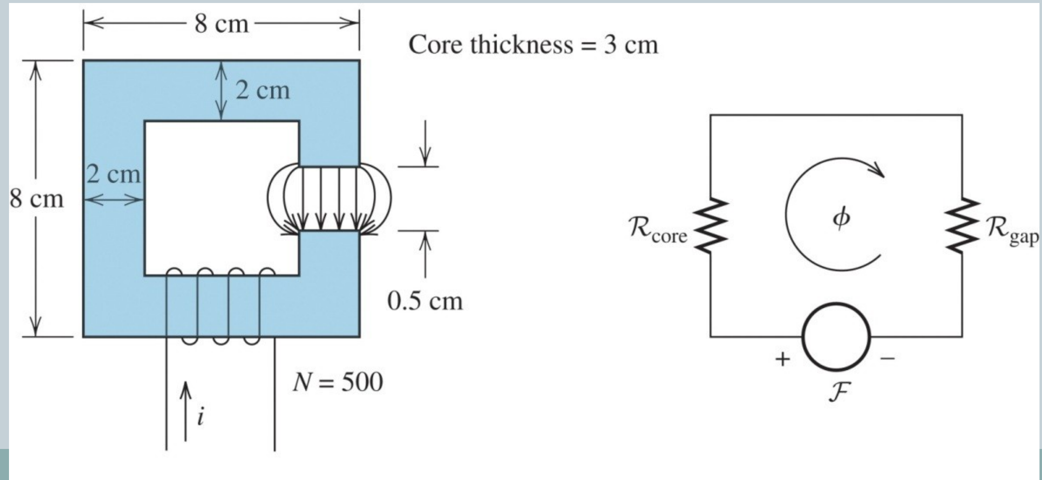
$$\phi = B_{gap}A_{gap} = 0.25\times 8.75\times 10^{-4} = 2.188\times 10^{-4}[Wb]$$

thus magnetomotive force is

$$F = \phi R = 4.6\times 10^{6}\times 2.188\times 10^{-4} = 1006[A]$$

thus the coil current must be

$$i = \frac{F}{N} = \frac{1006}{500} = 2.012[A]$$



(a) Iron core with an air gap (b) Magnetic circuit

Coil Inductance and Mutual Inductance

Coil inductance is defined as flux linkage divided by the current:

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} = \frac{N^2}{\mathrm{R}}$$

since

$$\mathrm{R} = \frac{Ni}{\phi}$$

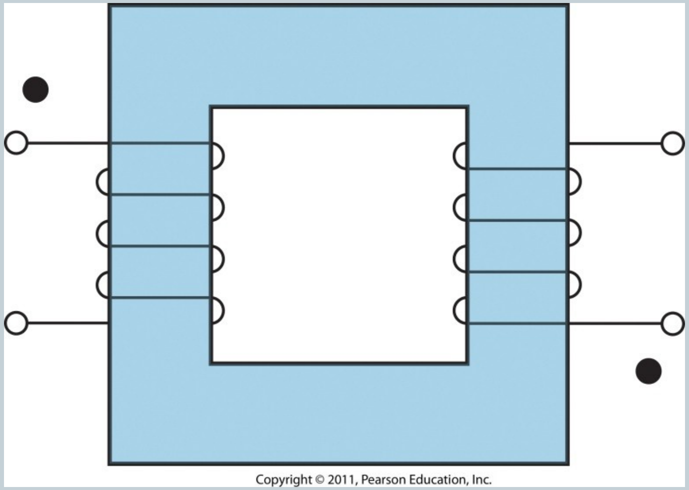
from the Faraday law

$$e = \frac{d\lambda}{dt} = \frac{d(Li)}{dt} = L\frac{di}{dt}$$

When two coils are wound on the same core we get from the Faraday law:

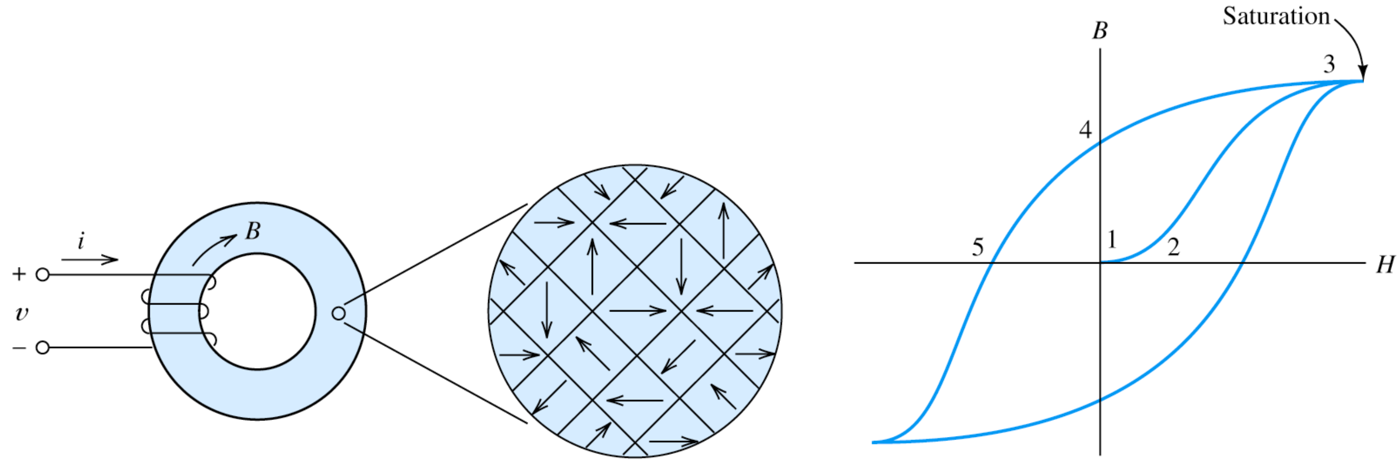
$$e_1 = \frac{d\lambda_1}{dt} = L_1\frac{di_1}{dt} \pm M\frac{di_2}{dt}$$

$$e_2 = \frac{d\lambda_2}{dt} = \pm M\frac{di_1}{dt} + L_1\frac{di_2}{dt}$$



Magnetic Materials

- In general, relationship between B and H in magnetic materials is nonlinear.
- Magnetic fields of atoms in small domains are aligned (Fig. 15.18 b).
- Field directions are random for various domains, so the external magnetic field is zero.
- When H is increased the magnetic fields tend to align with the applied field.

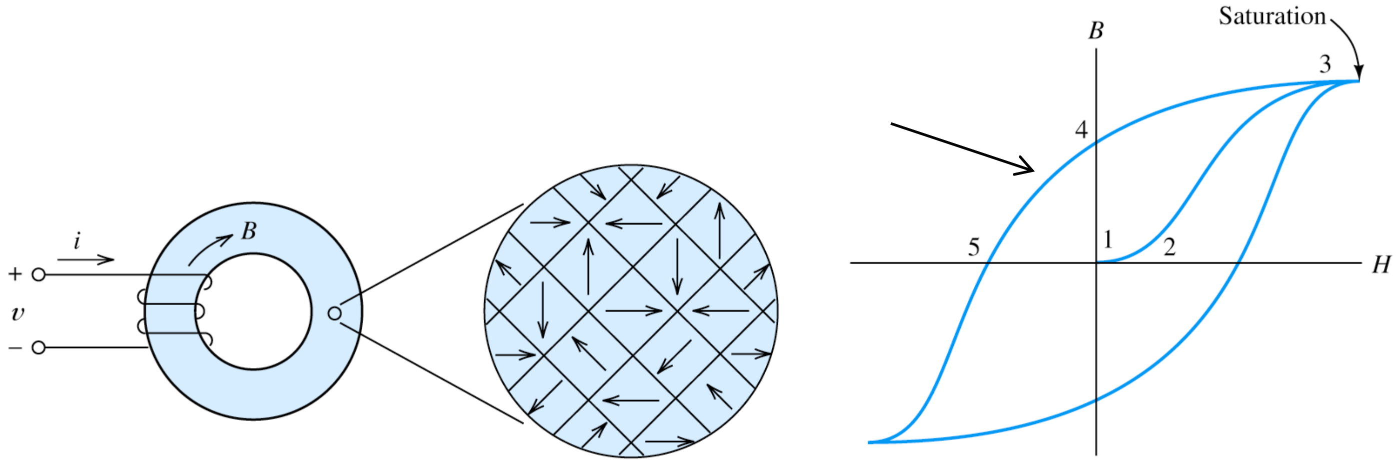


(a) Sample and coil for applying H (b) Magnetic domains (c) Hysteresis loop in the $B-H$ plane

Figure 15.18 Materials such as iron display a $B-H$ relationship with hysteresis and saturation.

Magnetic Materials

- Domains tend to maintain their alignment even if the applied field is reduced to zero.
- For very large applied field all the domains are aligned with the field and the slope of B-H curve approaches μ_0.
- When H is reduced to 0 from point 3 on the curve, a residual flux density B remains in the core.
- When H is increased in the reverse direction B is reduced to 0.
- Hysteresis result from ac current



(a) Sample and coil for applying *H* (b) Magnetic domains (c) Hysteresis loop in the *B* – *H* plane

Figure 15.18 Materials such as iron display a $B-H$ relationship with hysteresis and saturation.

Energy Consideration

- Energy delivered to the coil is the integral of the power:

$$W = \int_0^t vi\,dt = \int_0^t N\frac{d\phi}{dt}i\,dt = \int_0^\phi Ni\,d\phi$$

Since

$$Ni = Hl \quad and \quad d\phi = AdB$$

where l is the mean path length and A is the cross-section area, we get

$$W = \int_0^B AlH\,dB$$

And since Al is the volume of the core, the per unit volume energy delivered to the coil is

$$W_v = \frac{W}{Al} = \int_0^B H\,dB$$

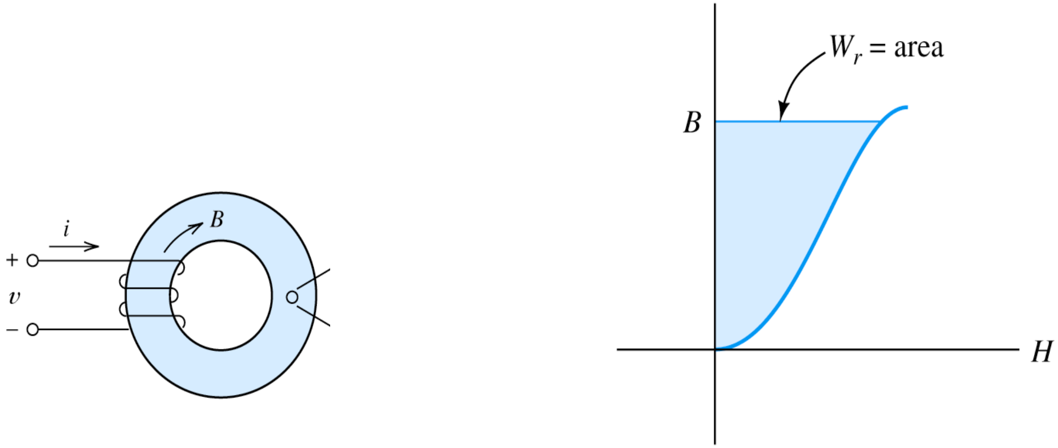


Figure 15.19 The area between the $B-H$ curve and the B axis represents the volumetric energy supplied to the core.

and saturation.

Energy Loss

- Energy lost in the core (converted to heat) during ac operation per cycle is proportional to the area of hysteresis loop.
    - To minimize this energy loss use materials with thin hysteresis

- But for permanent magnet we need to use materials with thicj hysteresis and large residual field.

- Energy is also lost due to eddy currents in the core material
    - This can be minimized with isolated sheets of metal or powdered iron cores with insulating binder to interrupt the current flow.

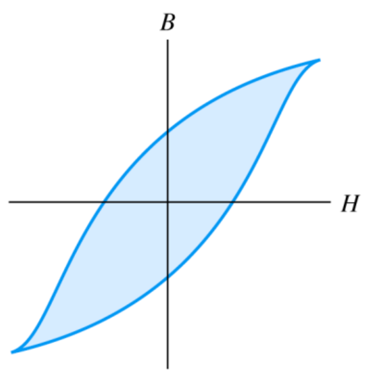


Figure 15.20 The area of the hysteresis loop is the volumetric energy converted to heat per cycle.

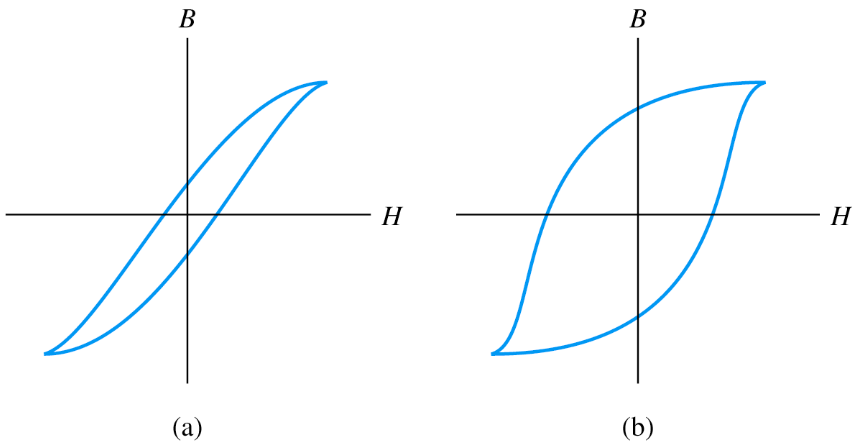
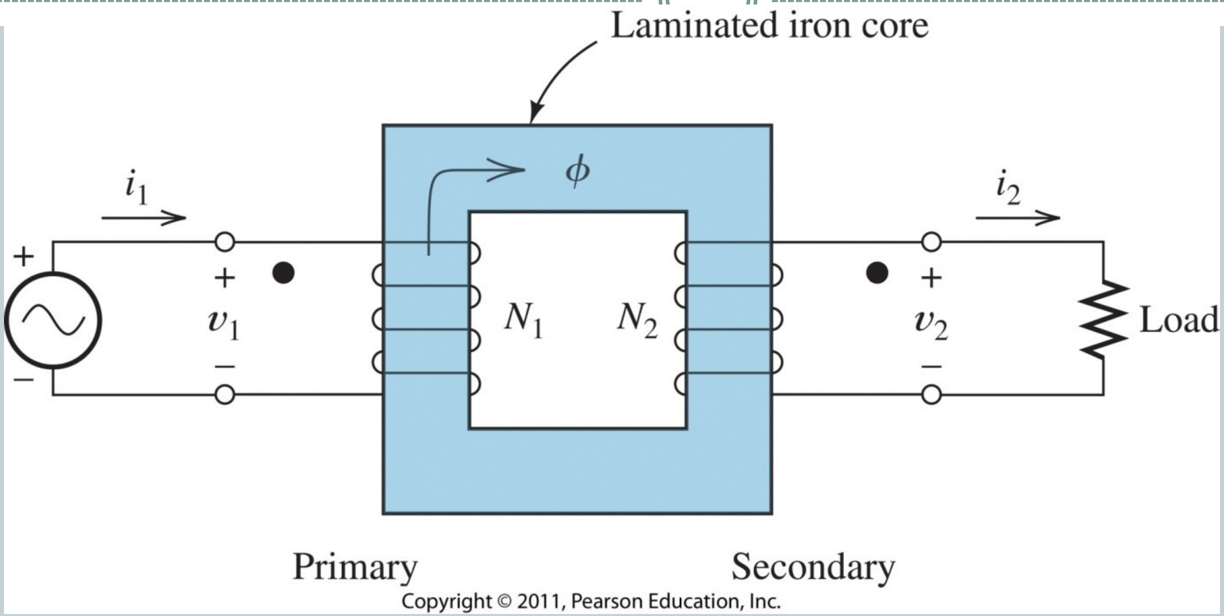


Figure 15.21 When we want to minimize core loss (as in a transformer or motor), we choose a material having a thin hysteresis loop. On the other hand, for a permanent magnet, we should choose a material with a wide loop.

Ideal Transformers

A transformer consists of several coils wound on a common core.



In ideal transformer we have:

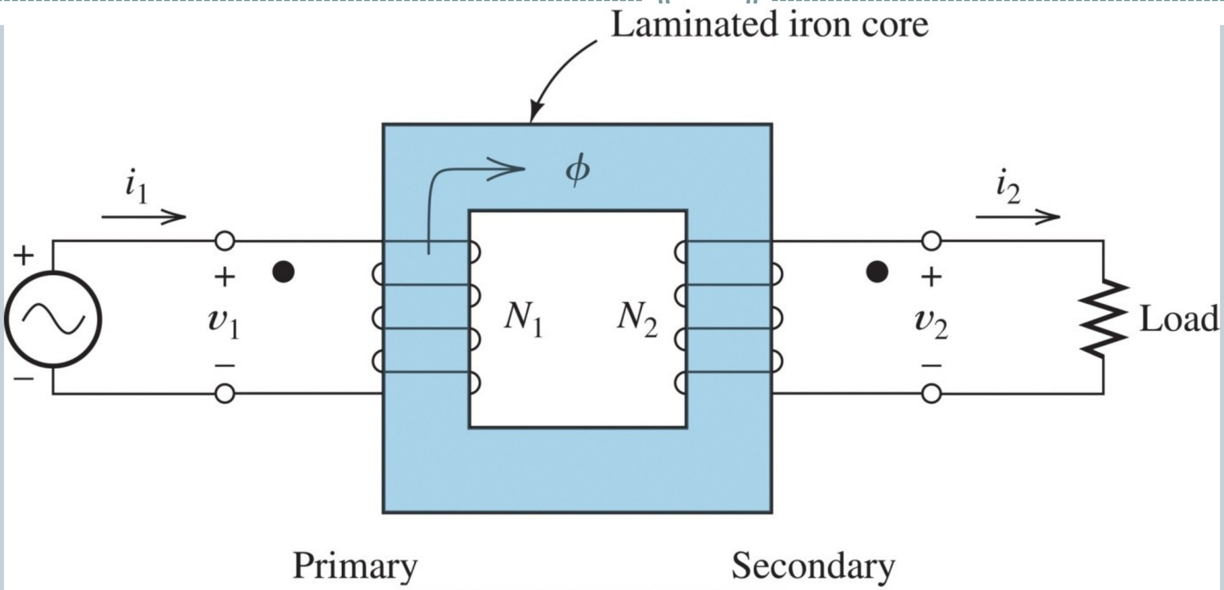
$$N_1 v_2(t) - N_2 v_1(t) = 0$$
$$N_1 i_1(t) - N_2 i_2(t) = 0$$

$$v_2(t) = \frac{N_2}{N_1} v_1(t)$$

$$i_2(t) = \frac{N_1}{N_2} i_1(t)$$

Ideal Transformers

A transformer consists of several coils wound on a common core.



Power in ideal transformer delivered to the load: $p_2(t) = v_2(t)i_2(t)$

$$v_2(t) = \frac{N_2}{N_1} v_1(t)$$

$$i_2(t) = \frac{N_1}{N_2} i_1(t)$$

$$p_2(t) = \frac{N_2}{N_1} v_1(t) \frac{N_1}{N_2} i_1(t) = v_1(t)i_1(t)$$

$$p_2(t) = p_1(t)$$

Ideal Transformers

Impedance transformation.

Using $$Z_L = \frac{V_2}{I_2}$$ and $$V_2 = \frac{N_2}{N_1} V_1$$ $$I_2 = \frac{N_1}{N_2} I_1$$

We get the input impedance of the ideal transformer equal to:

$$Z_L' = \frac{V_1}{I_1} = \left(\frac{N_1}{N_2}\right)^2 Z_L$$

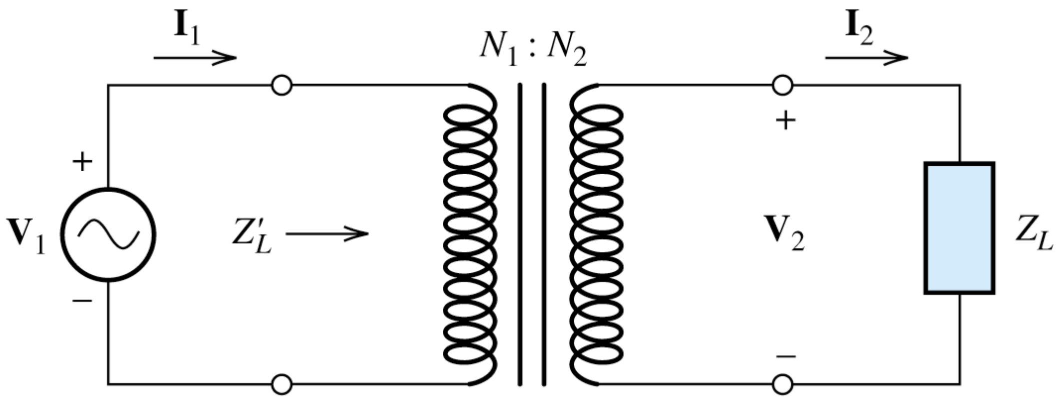


Figure 15.25 The impedance seen looking into the primary is $Z_L' = (N_1/N_2)^2 \times Z_L$.

Ideal Transformers

Consider the circuit with ideal transformer and find phasor currents and voltages, input impedance, as well as power delivered to the load.

The input impedance is

$$Z_L^{'} = \frac{V_1}{I_1} = \left(\frac{N_1}{N_2}\right)^2 Z_L = 100*(10+j20) = 1000+j2000$$

So the input current is

$$I_1 = \frac{V_s}{Z_s} = \frac{1000\angle 0^o}{2000+j2000} = 0.3536\angle -45^o$$

The input voltage is

$$V_1 = I_1 Z_L^{'} = 790.6\angle 18.43^o$$

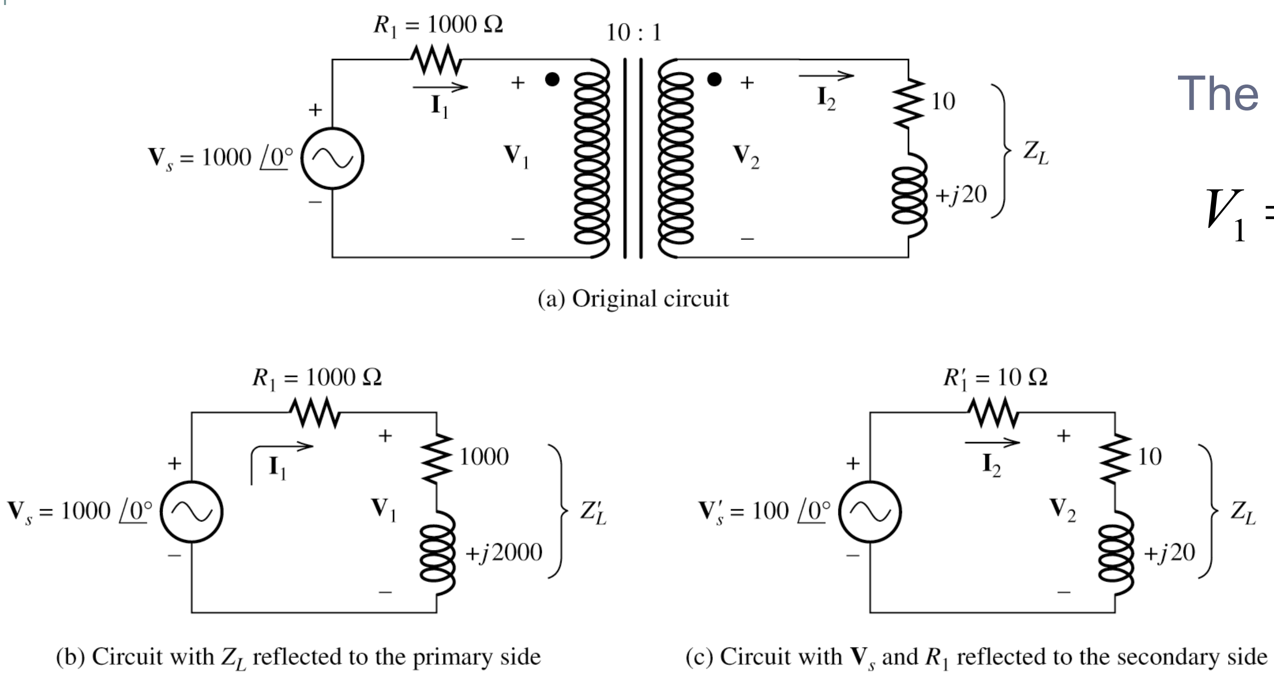


Figure 15.26 The circuit of Examples 15.11 and 15.12.

Ideal Transformers

Power delivered to the load is the same as the input power

$$P_2 = P_1 = \mathrm{Re}\left(\frac{V_1 I_1^*}{2}\right) = 0.5\,\mathrm{Re}\left(790.6\angle 18.43 * 0.3536\angle +45^o\right)$$

$$P_2 = 0.5\,\mathrm{Re}\left(279.5\angle +63.43^o\right) = 62.51\,W$$

Or directly

$$P_2 = \mathrm{Re}\left(\frac{V_1 I_1^*}{2}\right) =$$

$$= \mathrm{Re}\left(\frac{I_1 Z_L^{'} I_1^*}{2}\right) =$$

$$= \frac{\left|I_1\right|^2}{2}\mathrm{Re}\left(Z_L^{'}\right) =$$

$$= 0.06251 * 1000 =$$

$$= 62.51\,W.$$

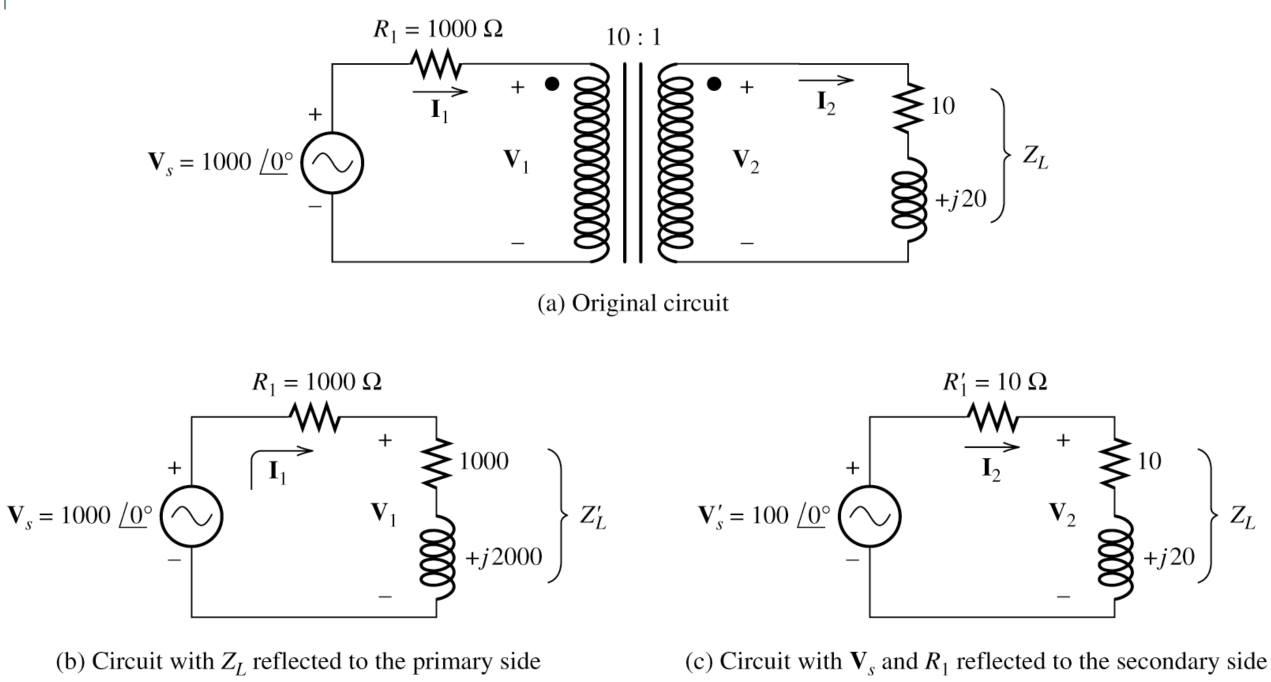


Figure 15.26 The circuit of Examples 15.11 and 15.12.

Real Transformers

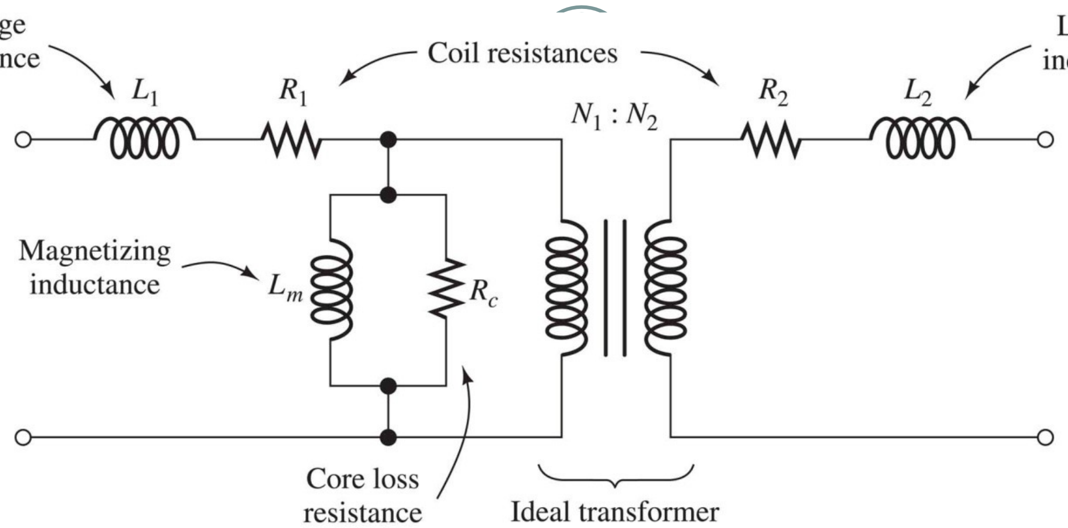


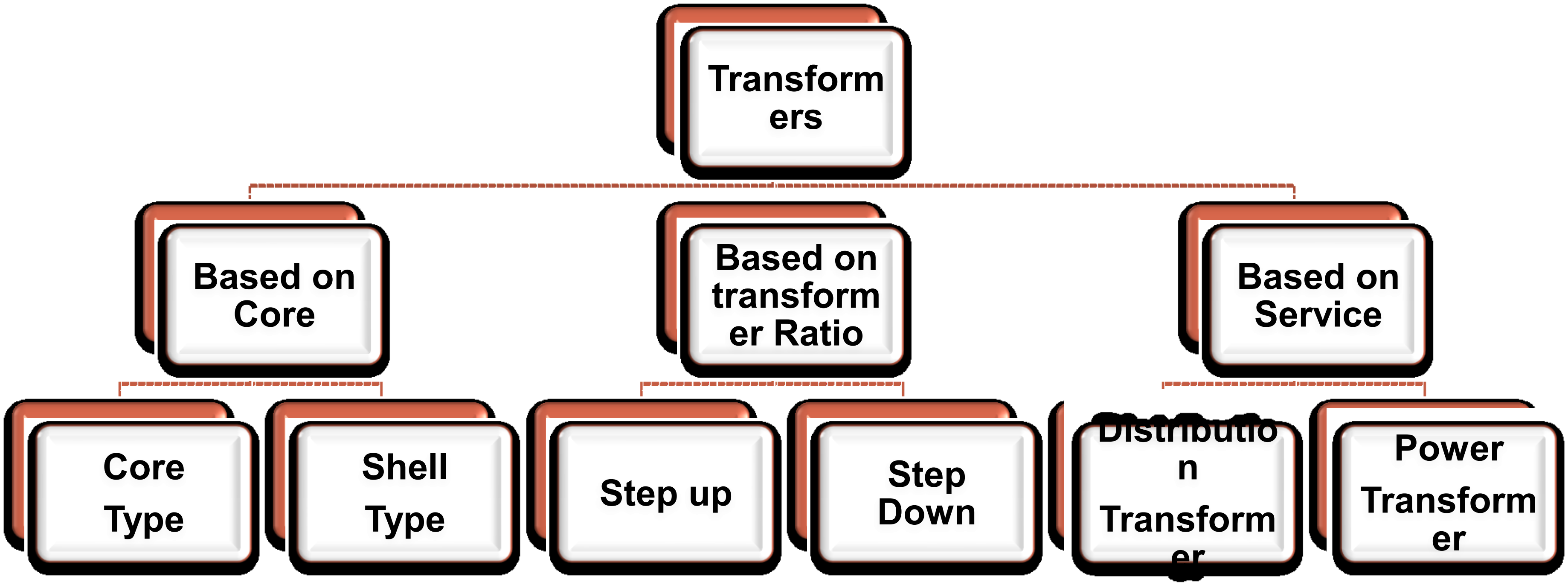
Figure 15.28 The equivalent circuit of a real transformer.

Table 15.1. Circuit Values of a 60-Hz 20-kVA 2400/240-V Transformer Compared with Those of an Ideal Transformer

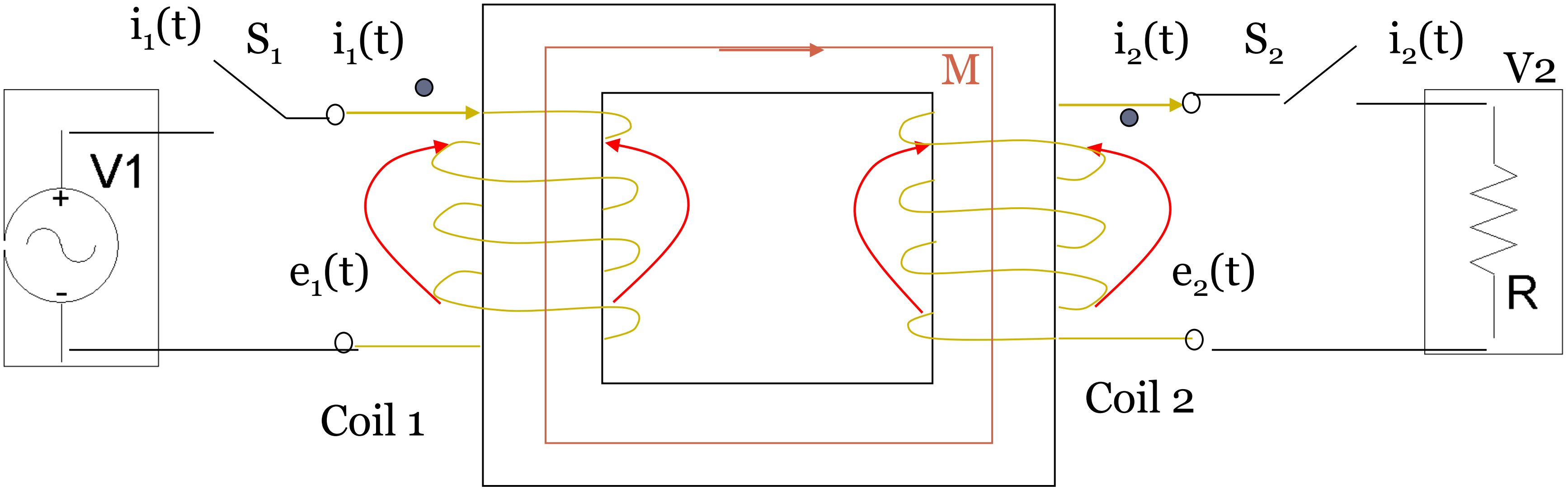
Element Name	*Symbol*	*Ideal*	*Real*
Primary resistance	R_1	0	3.0 Ω
Secondary resistance	R_2	0	0.03 Ω
Primary leakage reactance	$X_1 = \omega L_1$	0	6.5 Ω
Secondary leakage reactance	$X_2 = \omega L_2$	0	0.07 Ω
Magnetizing reactance	$X_m = \omega L_m$	∞	15 kΩ
Core-loss resistance	R_c	∞	100 kΩ

The Transformer

Transformer is static device that transformer electrical energy from one circuit to another circuit without change of frequency. It work on the principle of electromagnetic inductions.



The Transformer



(Primary has N_1 turns)

(Secondary has N_2 turns)

Transformer Losses and Efficiency

- Transformer Losses
  - Core/Iron Loss $= V_1^2 / R_{c1}$
  - Copper Loss $= I_1^2 R_1 + I_2^2 R_2$

Definition of % efficiency

$$= \frac{V_2 I_2 Cos\theta_2}{Losses + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_1^2 R_1 + I_2^2 R_2 + V_2 I_2 Cos\theta_2} * 100$$

$$= \frac{V_2 I_2 Cos\theta_2}{V_1^2 / R_{c1} + I_2^2 R_{eq2} + V_2 I_2 Cos\theta_2} * 100$$

$Cos\theta_2$ = load power factor

Maximum Transformer Efficiency

The efficiency varies as with respect to 2 independent quantities namely, current and power factor

- Thus at any particular power factor, the efficiency is maximum if core loss = copper loss .This can be obtained by differentiating the expression of efficiency with respect to I_2 assuming power factor, and all the voltages constant.

- At any particular I_2 maximum efficiency happens at unity power factor. This can be obtained by differentiating the expression of efficiency with respect to power factor, and assuming I_2 and all the voltages constant.

- Maximum efficiency happens when both these conditions are satisfied.

1. Electrical Faults

Overload

load applied greater than the design value of the circuit

Short Circuit

due to cable fault or external damage to the wiring system

1.3 Earth Faults

short circuit or low impedance between phase and the protective or earth system

2. Electricity Hazards

Electric Shock

- is the physical stimulation that occurs when electric current passes through the body
- the effect depends on:
  - a. the magnitude of the current
  - b. the body parts through which the current flows
  - c. duration
  - d. physical condition of the person being shocked

3.Nervous System of Human Body

- controls all movements, both conscious and unconscious

-the signals are electro-chemical in nature, with levels of a few millivolts

Electrical Impedance of Human Body

- human body is composed largely of water, and has very low resistance
- most of the resistance to the passage of current through the human body is at the points of entry and exit through the skin
- internal impedance - depends on:
  a. the length and cross sectional area of the path
  b. conductivity of the tissues in the path
- skin impedance - depends on:
  a. surface area of contact
  b. pressure of contact
  c. degree of moisture on the skin
  d. applied voltage (at high voltage, skin breaks down)
  e. duration of current flow (the flow of current cause the victim to sweat, reducing
  the resistance very quickly after the shock commences)