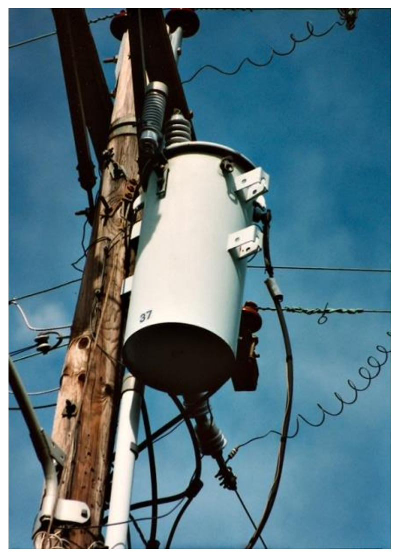
Introduction to Electric Machinery

Pinjia Zhang

Introduction to Electric Machinery

- Definition of electric machines
- Application of electric machines
- History of electric machines
- Classification of electric machines

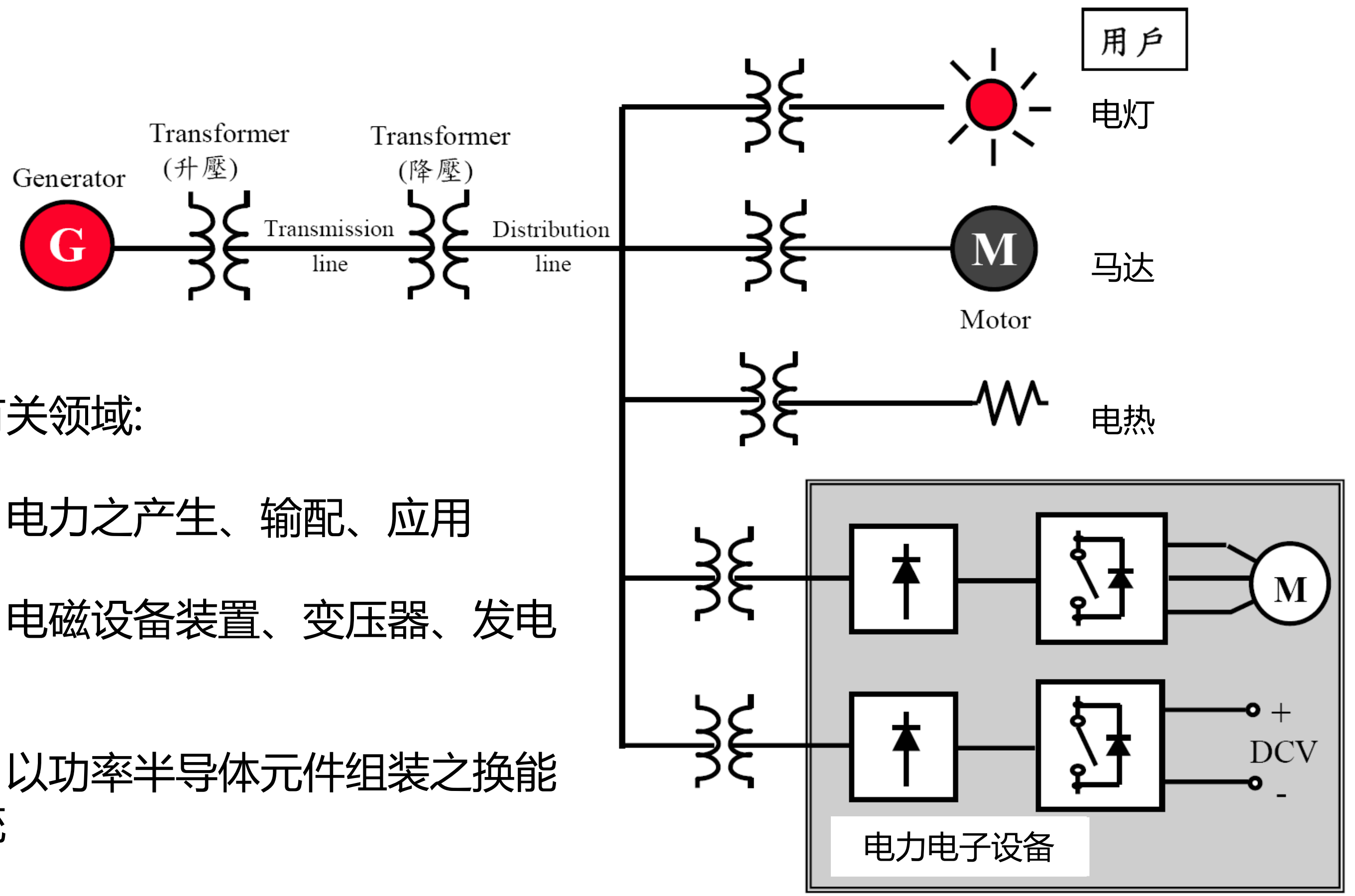
Electric Machinery



Electric Machines

- Generators
- Transformers
- Motors

Introduction to Electric machinery Fundamental



电力工程有关领域:

电力系统：电力之产生、输配、应用

电动机械：电磁设备装置、变压器、发电机、马达

电力电子：以功率半导体元件组装之换能装置及系统

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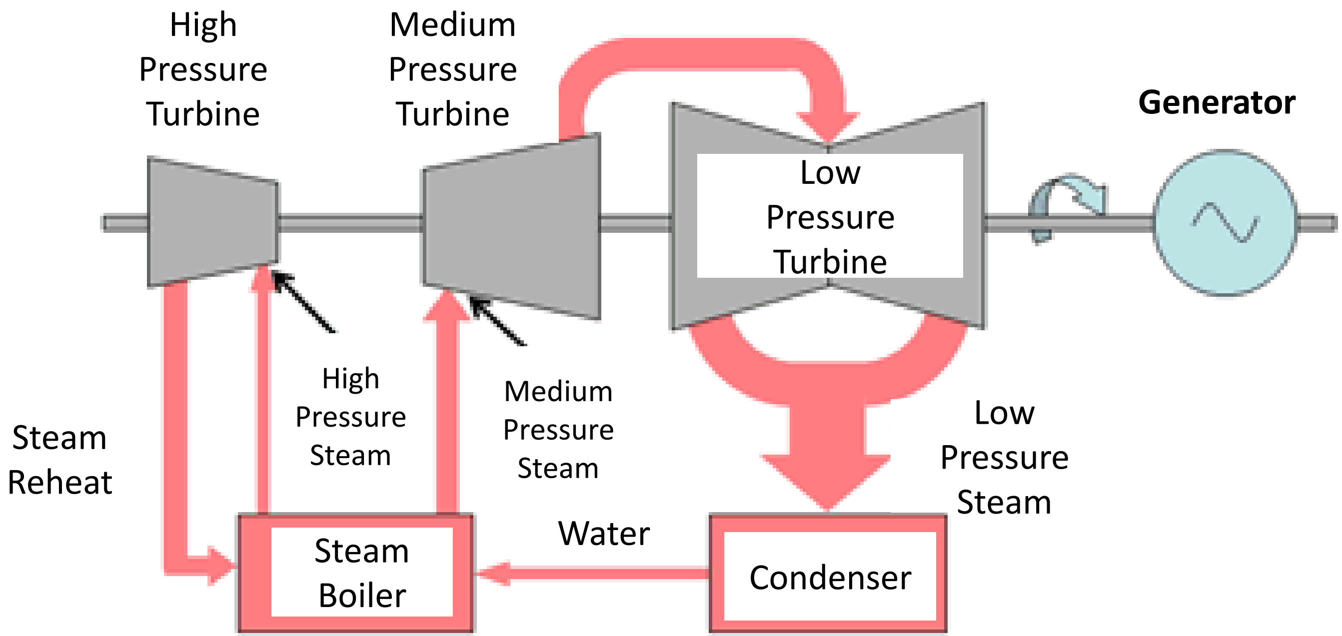
ELECTRIC MACHINES AND POWER SYSTEMS

- Generator converts mechanical energy to electrical energy
- Motor converts electrical energy to mechanical energy
- Power system is a network of components designed to transmit and distribute energy produced by generator to the locations where it is used

Generator

- Prime mover （原动机）spins the generator to produce electrical energy through magnetic field action
- Energy sources for prime mover: water, coal, nuclear, natural gas, renewable energy

Coal-based Power Generation



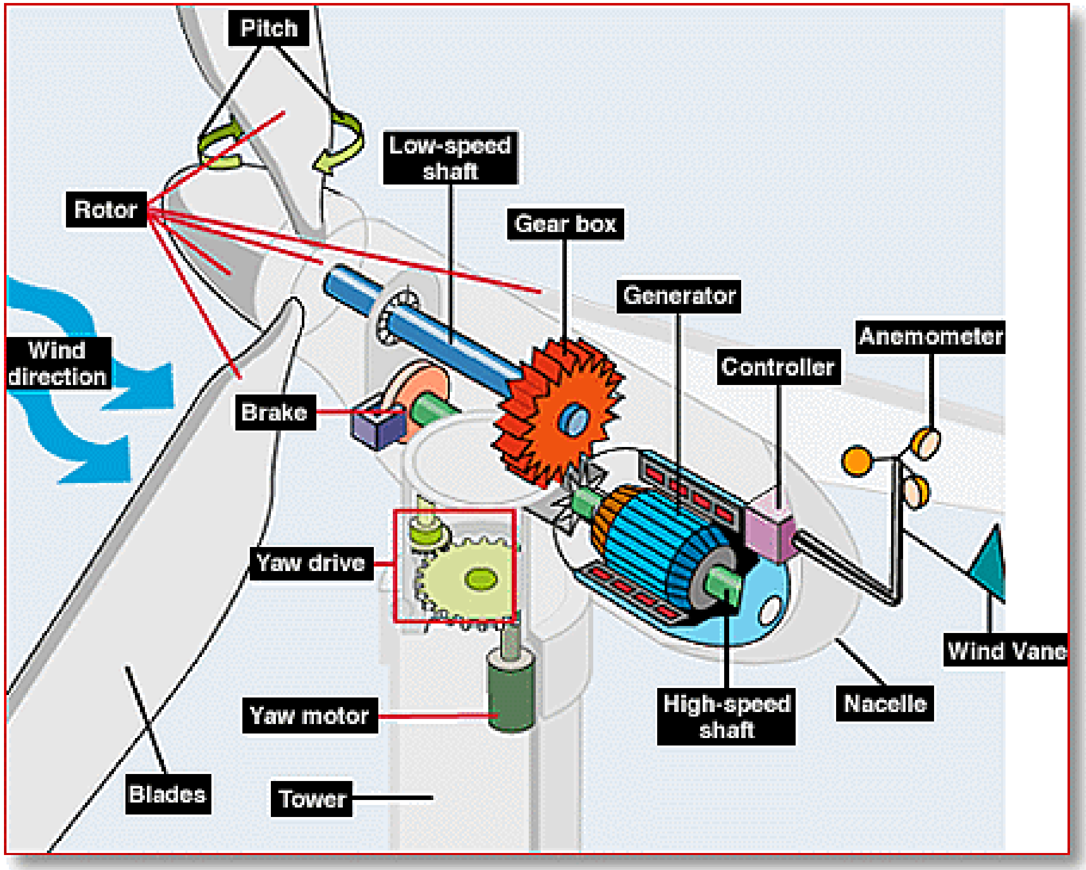
Multi Stage Steam Turbine Generator

- Steam turbine generator

Hydro Power Generation

- Hydro generator

Wind Turbine



Diesel Turbine

Transformer

Converts ac electrical energy at one voltage level to another voltage level

Sub station

Power Transformers

Loads

Motors, electric lighting and electronic products

Motors consume over 60% of electricity generated

Robotics

Power Train

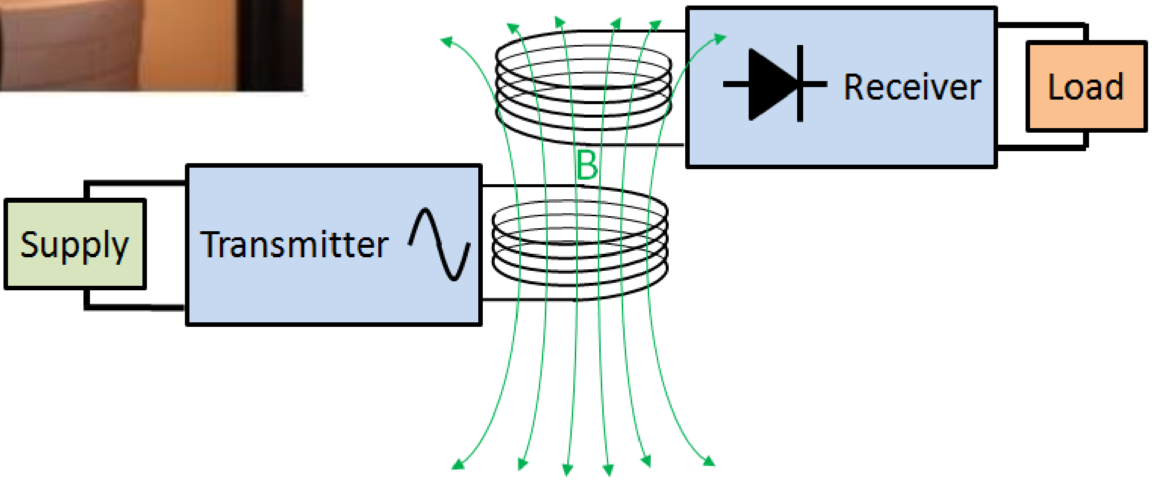
Hyperloop

Electrical Vehicle

Hybrid Bus

Electrical Plane

Wireless Charging



What to learn in this course ?

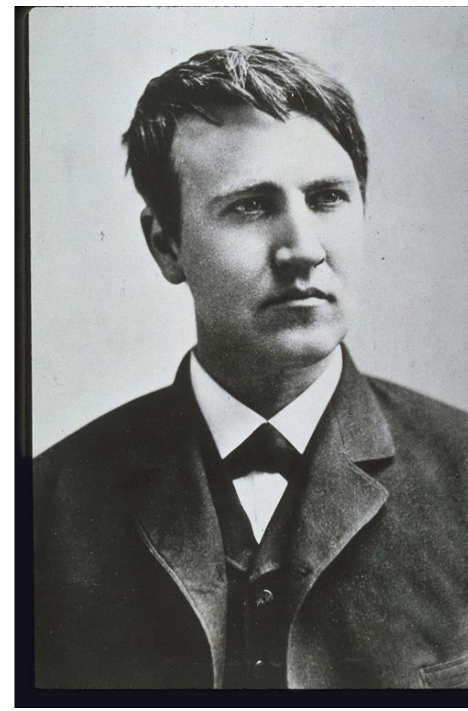
- ***Energy Conversion*** schemes are the key ideas introduced in this course
- Which types of energy conversion are concerned?
- Electric energy to electric energy
  - Transformer
- Electric energy to mechanical energy
  - Motor
- Mechanical energy to electric energy
  - Generator
- Magnetic energy is essential !

History of Electric Machinery

DC generator, driven by steam engines

1882

Thomas A. Edison opens Pearl St. Station, NYC



Waterwheel-driven DC generator installed in Appleton, Wisconsin

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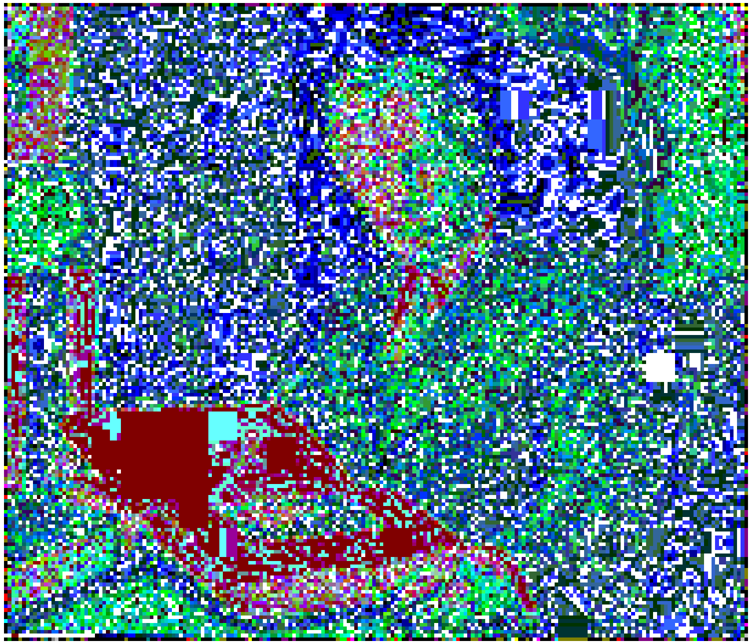
History of Electric Machinery

1884

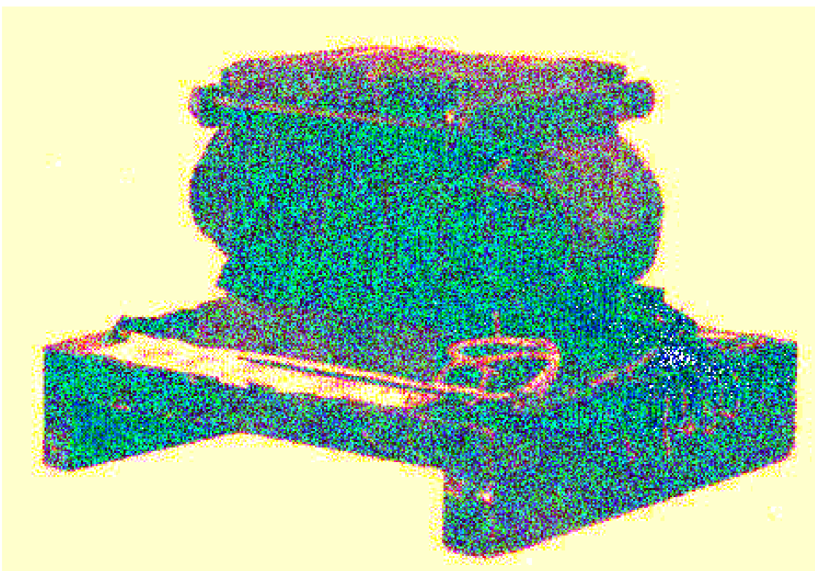
Frank J. Sprague produces DC motor for Edison systems



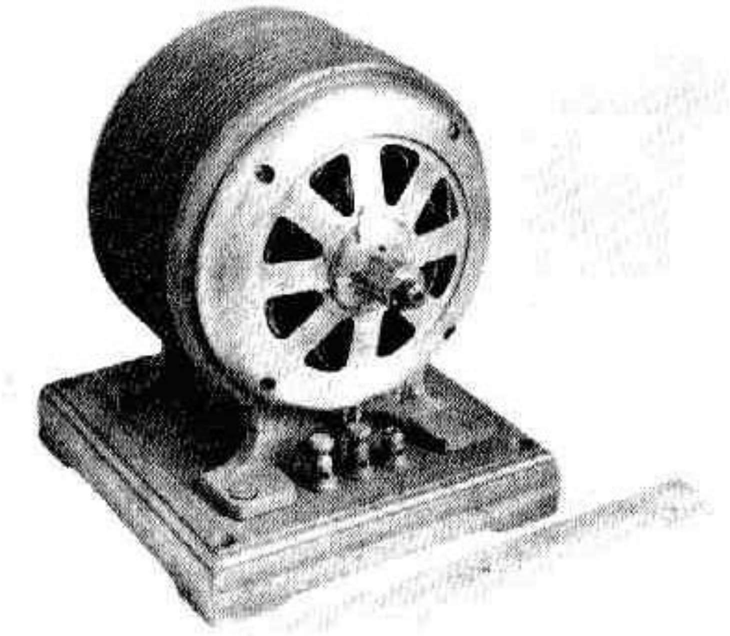
History of Electric Machinery

1885

William Stanley develops commercially practical transformer



History of Electric Machinery



The TESLA AC Motor-1888

1888

Nikola Tesla presents paper on two-phase ac induction and synchronous motors

DC vs AC video

Today’s development

- Transformer
  - Single phase
  - Three phases
- DC Machine
  - Motor
  - Generator
- AC Machine
  - Synchronous machine – motor, generator
  - Asynchronous machine (induction machine) – motor, generator

Today's development and future trends

- Micro-step stepping motor
- Permanent magnet synchronous motor (PMSM)
  - Brushless dc motor (BLDCM)
- Linear motor
- Reluctance motor
  - Synchronous reluctance
  - Switched reluctance
- Ultrasonic motor
- Bionic robotics
- MEMS motor

Course relation

- It is the fundamental course of the electrical engineering
- Future courses
  - Power electronics
  - Motor control
  - Electric motor drive
  - Power systems
  - Renewable energy
  - Electrical vehicle

Introduction to Electric Machinery Principles

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Introduction to machinery principles

1. Rotation motion, Newton’s law and power relationships
2. The magnetic field
3. Induced voltage - Faraday’s law
4. Produce an induced force on a wire
5. Produce an induced voltage on a conductor
6. Linear dc machine examples
7. Real, reactive and apparatus power in AC circuits

Rotation motion, Newton's law and power relationships

- Clockwise (CW) and Counterclockwise (CCW)
  - CCW is assumed as the positive direction, CW is assumed as the negative direction.
- Linear and rotation motion
  - Position and angular
  - (meter) (degree or radian)
  - Speed and angular speed $v = \frac{dr}{dt} \quad \omega = \frac{d\theta}{dt}$

ω_m angular velocity expressed in radians per second

f_m angular velocity expressed in revolutions per second

n_m angular velocity expressed in revolutions per minute

Rotation motion, Newton's law and power relationships

– relationships

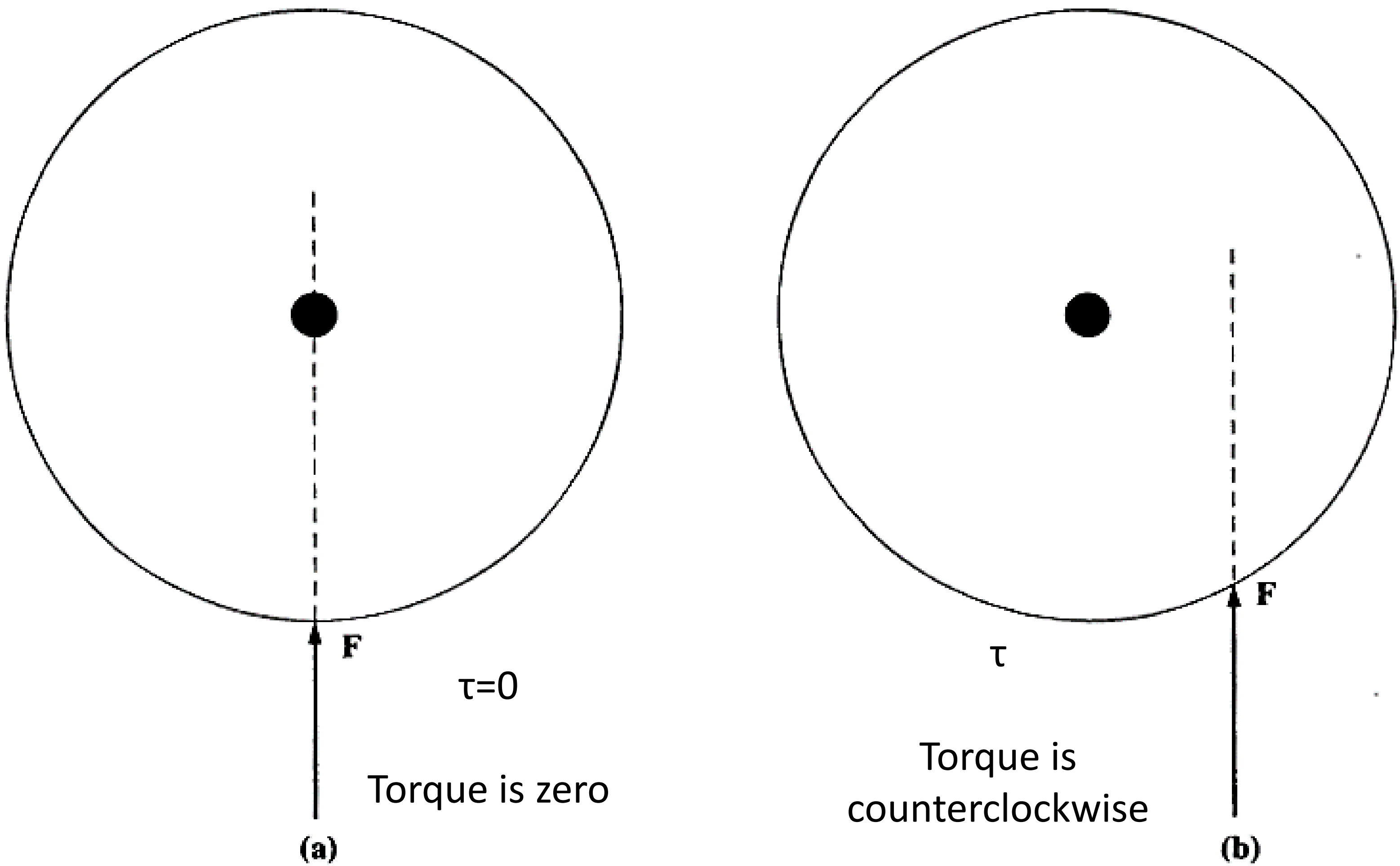
$$n_m = 60 f_m$$

$$f_m = \frac{\omega_m}{2\pi} n$$

– Acceleration and angular acceleration

$$a = \frac{dv}{dt} \quad \alpha = \frac{d\omega}{dt}$$

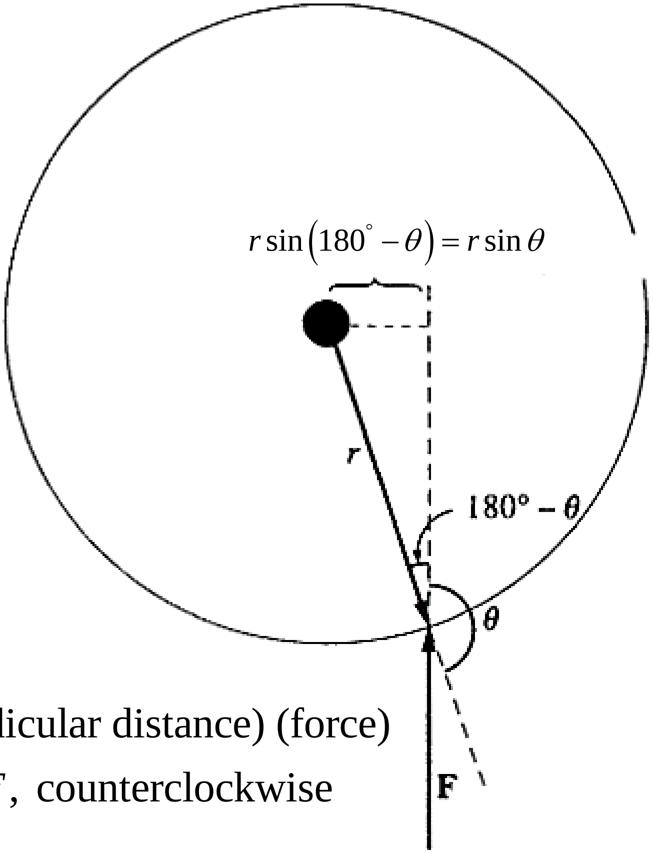
Torque



Torque

$$\begin{aligned}\tau &= (\text{ force applied })(\text{ perpendicular distance }) \\ &= (F)(r\sin\theta) \\ &= rF\sin\theta\end{aligned}$$

where θ is the angle between the vector $\mathbf{r}$ and the vector $\mathbf{F}$



$\tau =$ (perpendicular distance) (force)

$\tau = (r\sin\theta)F,$ counterclockwise

Newton's law of rotation

1. Force

$$F = ma \quad \begin{aligned} F &= \text{net force applied to an object} \\ m &= \text{mass of the object} \\ a &= \text{resulting acceleration} \end{aligned}$$

2. Torque

$$\tau = J\alpha$$

Torque and Work

For linear motion, work is defined as the application of a force through a distance. In equation form,

$$W = \int F dr$$

where it is assumed that the force is collinear with the direction of motion. For the special case of a constant force applied collinearly with the direction of motion, this equation becomes just

$$W = F\ r$$

The units of work are joules in SI and foot-pounds in the English system. For rotational motion, work is the application of a torque through an angle. Here the equation for work is

$$W = \int \tau d\theta$$

and if the torque is constant,

$$W = \tau\theta$$

Power (rate of doing work)

Power is the rate of doing work, or the increase in work per unit time. The equation for power is

$$P = \frac{dW}{dt}$$

It is usually measured in joules per second (watts), but also can be measured in foot-pounds per second or in horse power. By this definition, and assuming that force is constant and collinear with the direction of motion, power is given

$$P = \frac{dW}{dt} = \frac{d}{dt}(Fr) = F\left(\frac{dr}{dt}\right) = Fv$$

Similarly, assuming constant torque, power in rotational motion is given

$$P = \frac{dW}{dt} = \frac{d}{dt}(\tau\theta) = \tau\left(\frac{d\theta}{dt}\right) = \tau\omega$$

$$P = \tau\omega$$

The equation above is very important in the study of electric machinery, because it can describe the mechanical power on the shaft of a motor or generator.

Conversion between watts and horsepower

1. Watts and horsepower

$$P(\text{ watts }) = \frac{\tau(\text{lb}-\text{ft})n(\text{r}/\text{min})}{7.04}$$

$$P\ (\text{horsepower}) = \frac{\tau(\text{lb}-\text{ft})n(\text{r}/\text{min})}{5252}$$

2. Conversion between two units

- 5252 / 7.04 = 746.02
- 1hp = 746W = 0.746kW
-

The magnetic field

1. A current-carrying wire produces a magnetic field in the area around it.

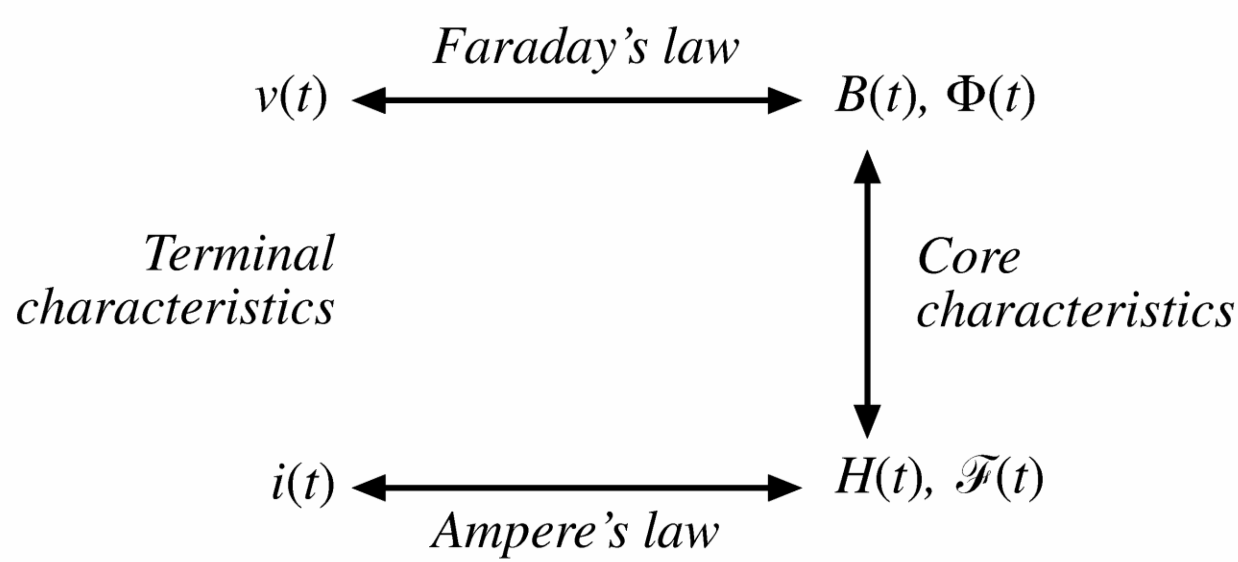
2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis of *transformer action*.)

3. A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of *motor action*.)

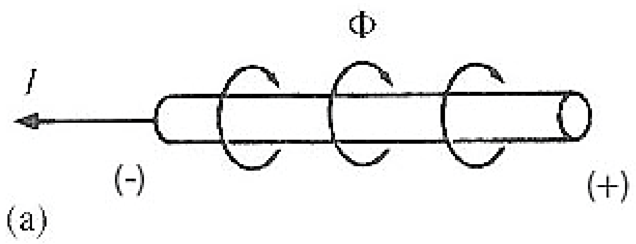
4. A moving wire in the presence of a magnetic field has a voltage induced in it. (This is the basis of *generator action*.)

Course Outlines - Overview of relative electromagnetic theories (1 wk)

- Magnetic field (磁场): Ampere’s law
- Magnetic flux (磁通): magnetic material, hysteresis characteristics
- Voltage: Faraday’s law

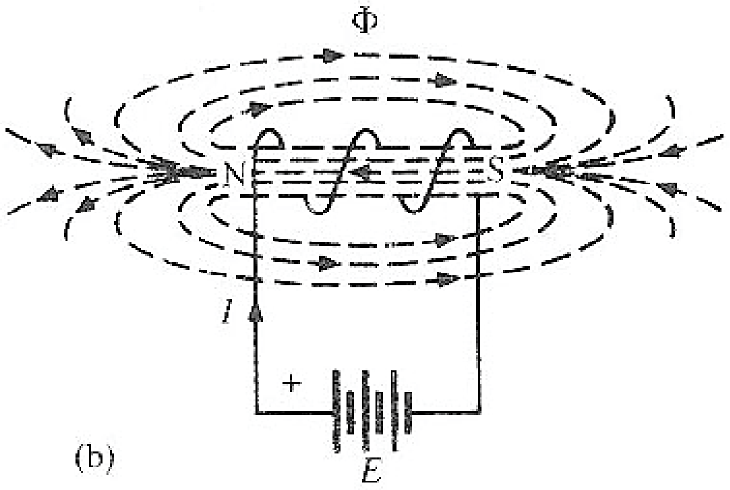


Magnetic Fields



Right hand rule:

current generated fields have the flux in the same direction as your fingers with the thumb of your right-hand pointed in the direction of current flow. Current flow is for conventions current flow with the positive source supplying the current.



Group fields are the combined effect of individual wires with the flux lines emanating from the north pole and entering the south pole.

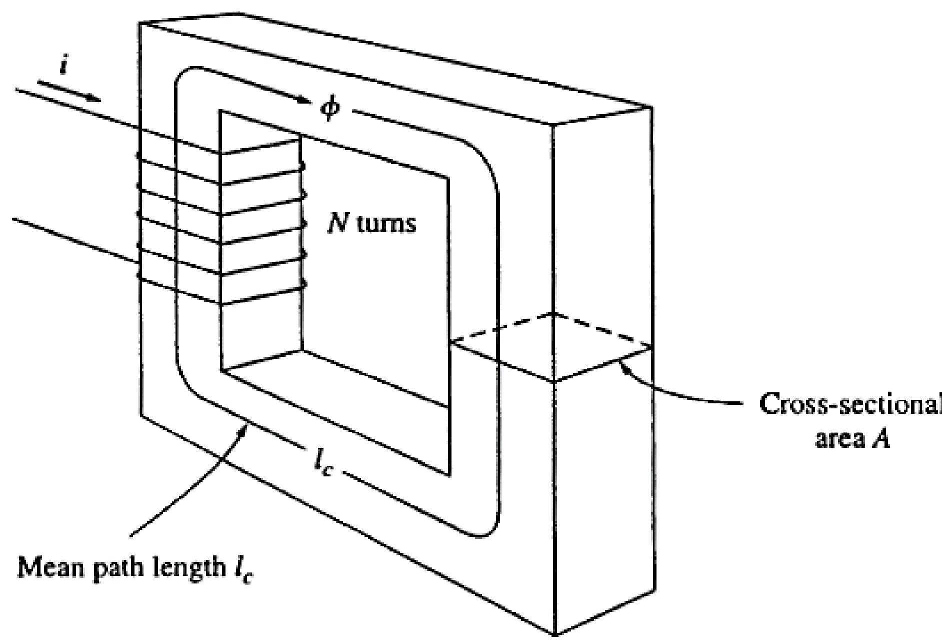
Produce a magnetic field – Ampere's law

1. The magnetic field is produced by ampere's law
2. The core is a ferromagnetic material

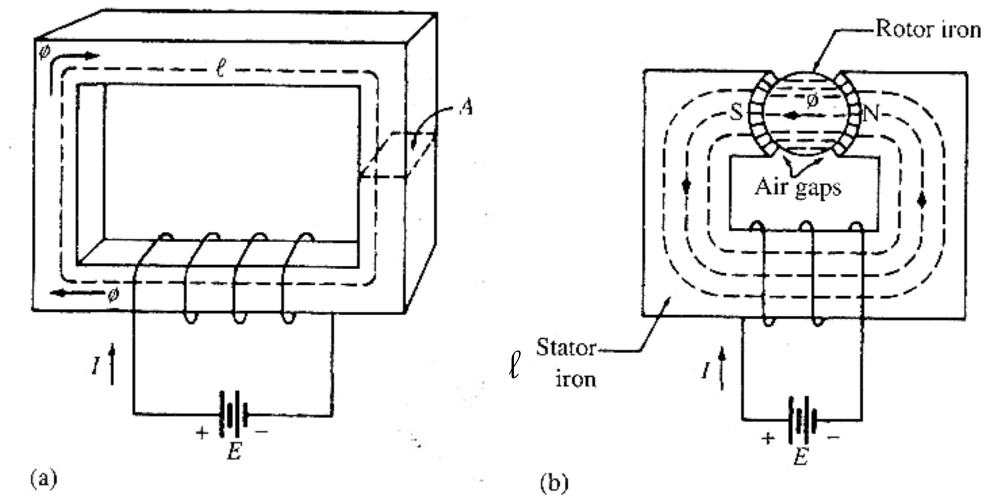
$$\oint \mathbf{H} \cdot d\mathbf{l} = I_{\text{net}}$$

$$Hl_c = Ni$$

$$H = \frac{Ni}{l_c}$$



Magnetic Circuits



Magnetic circuit: (a) for a transformer; (b) for a simple two-pole motor

(a) Transformer action captures magnetic flux within the circular path of the metallic core over length ℓ passing totally within the cross-sectional area A.

(b) Application of transformer application combined with motor action.

From the magnetic field to magnetic flux density

When the magnetic field is applied on a ferromagnetic material, the magnetic flux density **B** will be produced

$$\mathbf{B} = \mu \mathbf{H} \quad \begin{aligned} \mathbf{H} &= \text{ magnetic field intensity} \\ \mu &= \text{ magnetic permeability of material} \\ \mathbf{B} &= \text{ resulting magnetic flux density produced} \end{aligned}$$

The permeability of free space is called μ_0 and its value is

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H/m}$$

The permeability of any other material compared to the permeability of free space is called its relative permeability:

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

Magnetic flux density and magnetic flux

1. Magnetic flux density

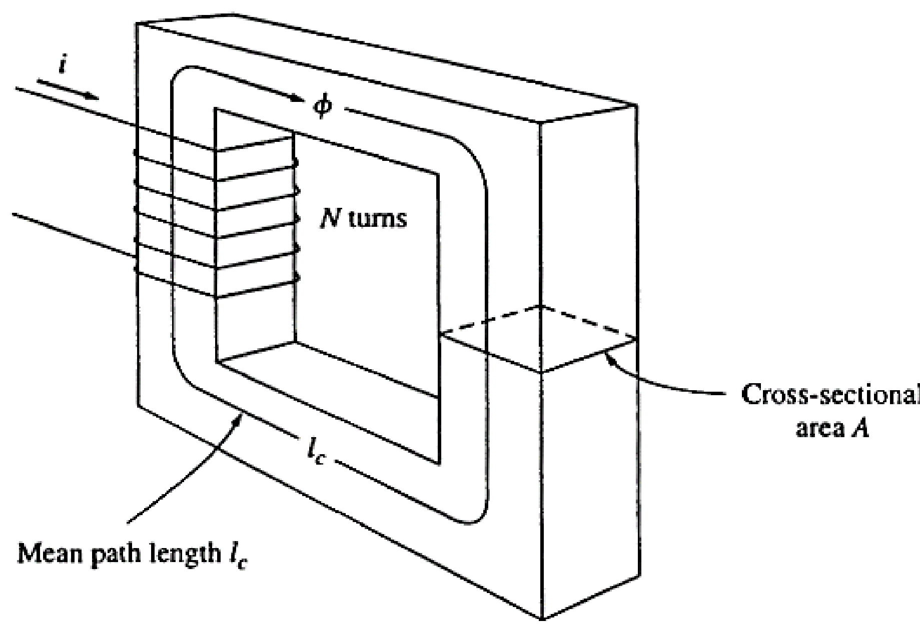
$$B = \mu H = \frac{\mu N i}{l_c}$$

2. Magnetic flux

$$\phi = \int_A \mathbf{B} \cdot d\mathbf{A}$$

$$\phi = BA$$

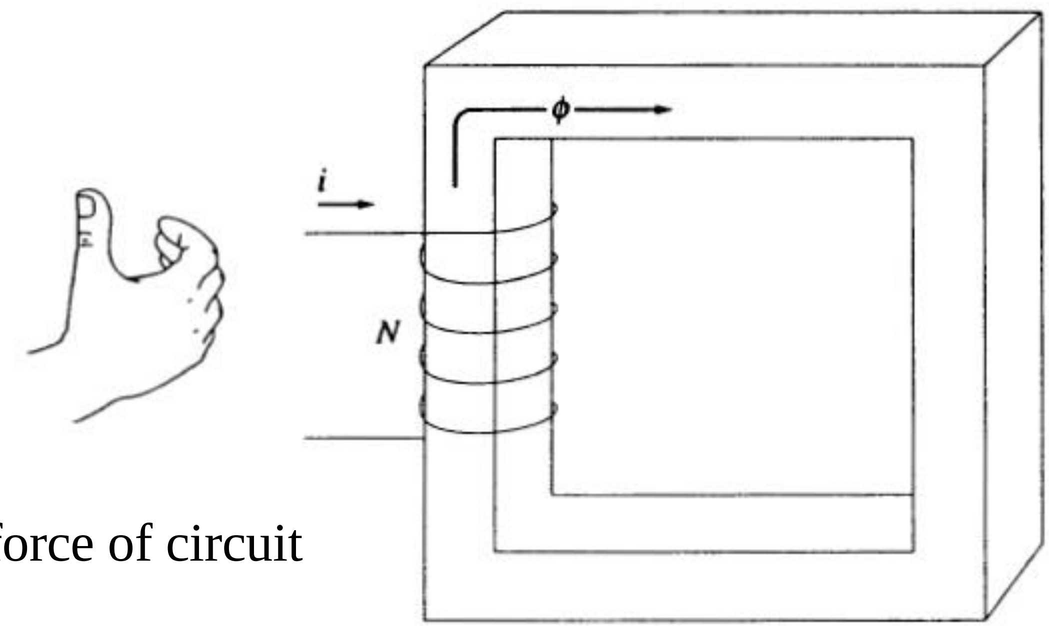
$$\phi = BA = \frac{\mu N i A}{l_c}$$



Magnetic Circuit – magnetomotive force

$\mathcal{F} = Ni$

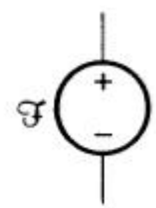
$\mathcal{F} = \phi\mathcal{R}$



$\mathcal{F}$ = magnetomotive force of circuit

ϕ = flux of circuit

$\mathcal{R}$ = reluctance o fcircuit

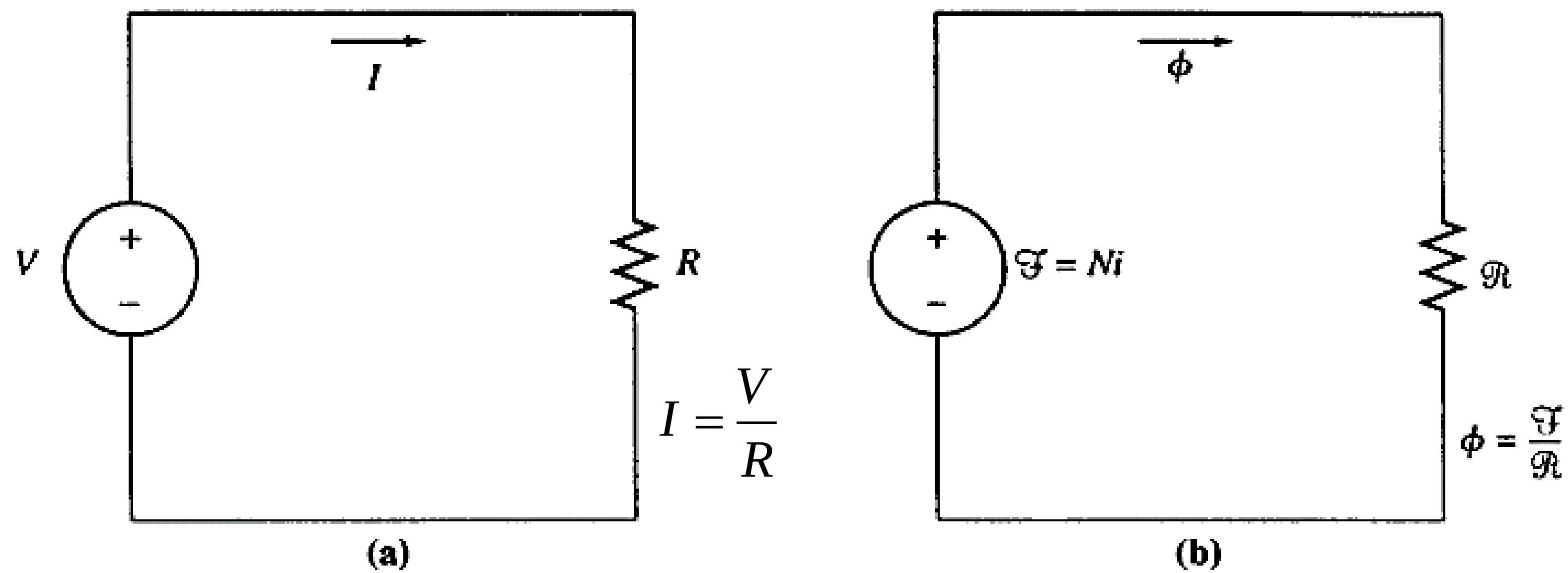


Magnetic circuit

1. Magnetic circuit

$$\begin{aligned}
\phi &= BA = \frac{\mu N i A}{l_c} \\
&= Ni\left(\frac{\mu A}{l_c}\right) \\
\phi &= \mathrm{F}\left(\frac{\mu A}{l_c}\right) \\
\mathrm{R} &= \frac{l_c}{\mu A} \\
\mathrm{F} &= \phi \mathrm{R}
\end{aligned}$$

Electric circuit and magnetic circuit



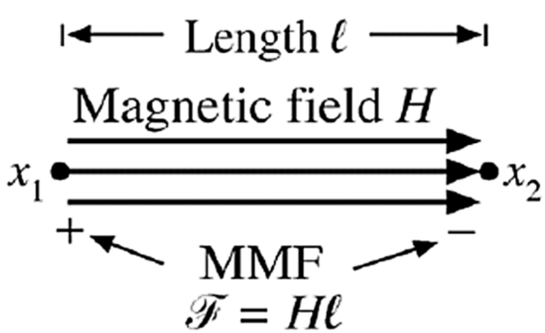
(a) A simple electric circuit. (b) The magnetic circuit analog to a transformer core.

Magnetic field **H** and magnetomotive force $\mathcal{F}$

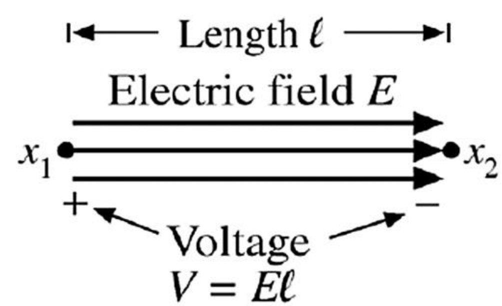
Magnetomotive force (MMF) $\mathcal{F}$ between points x_1, and x_2 is related to the magnetic field ***H*** according to

$$\mathrm{F} = \int_{x_1}^{x_2} \mathbf{H} \cdot d\mathbf{l}$$

Example: uniform magnetic field of magnitude H



Analogous to electric field of strength E, which induces voltage(EMF):



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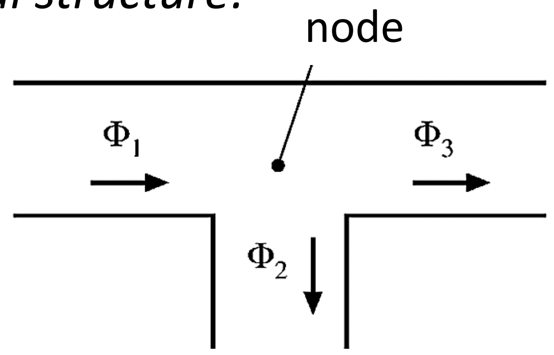
Magnetic analogue of Kirchhoff's current law

Divergence of ***B***= 0

Flux lines are continuous and cannot end

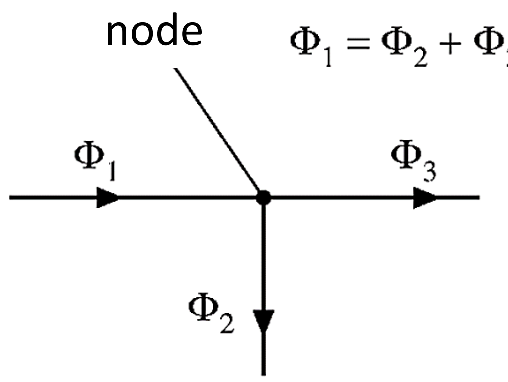
Total flux entering a node must be zero

Physical structure:



Magnetic circuit:

$$\Phi_1 = \Phi_2 + \Phi_3$$



Reluctance in magnetic circuit

1. Series connection

$$R_{eq} = R_1 + R_2 + R_3 + \cdots$$

2. Parallel connection

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

The errors in magnetic circuit computation

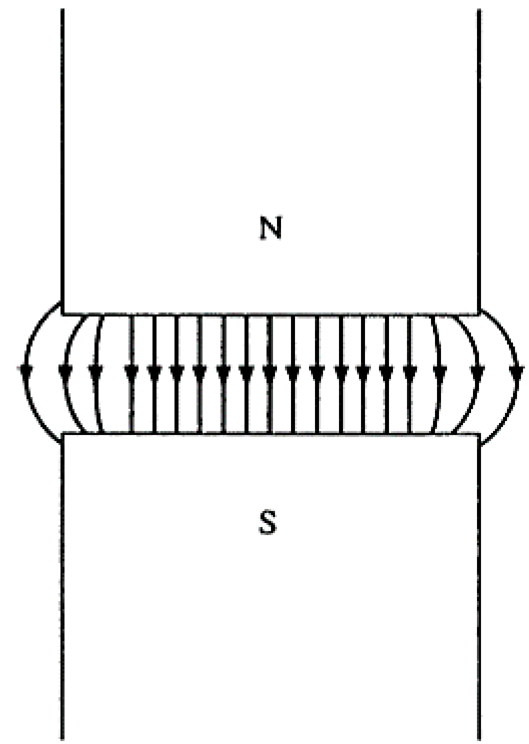
1. The magnetic circuit concept assumes that all flux is confined within a magnetic core. Unfortunately, this is not quite true. The permeability of a ferromagnetic core is 2000 to 6000 times that of air, but a small fraction of the flux escapes from the core into the surrounding low-permeability air, This flux outside the core is called *leakage flux*, and it plays a very important role in electric machine design.

2. The calculation of reluctance assumes a certain mean path length and cross-sectional area for the core. These assumptions are not really very good, especially at corners.

3. In ferromagnetic materials, the permeability varies with the amount of flux already in the material. This nonlinear effect is described in detail. It adds yet another source of error to magnetic circuit analysis, since the reluctances used in magnetic circuit calculations depend on the permeability of the material.

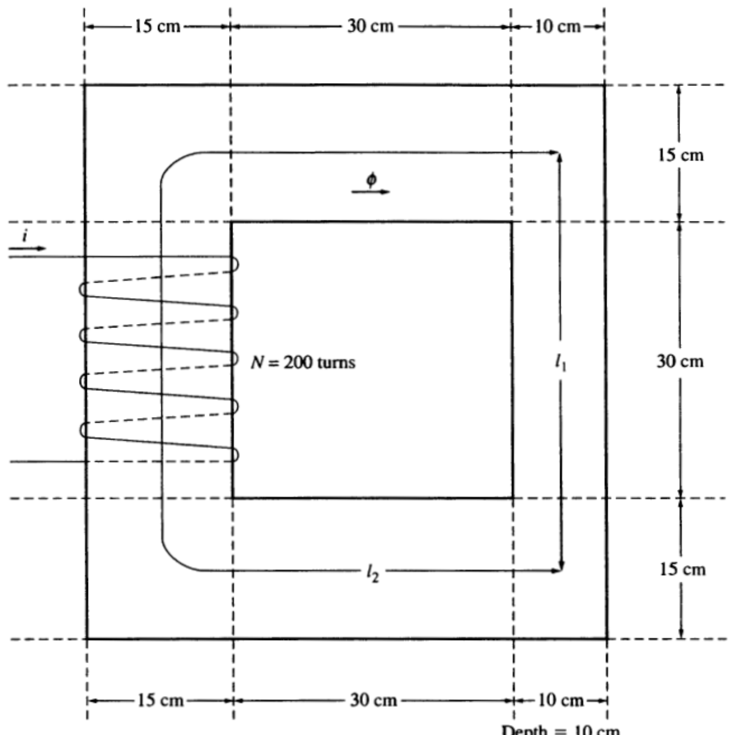
The errors in magnetic circuit computation

- 4. Air gap "fringing effect"



Example 1-1

A ferromagnetic core is shown in Figure below. Three sides of this core are of uniform width, while the fourth side is somewhat thinner. The depth of the core (into the page) is 10 cm, and the other dimensions are shown in the figure. There is a 200-turn coil wrapped around the left side of the core. Assuming relative permeability μ_r of 2500, how much flux will be produced by a 1-A input current?



(a)

The mean path length of region 1 is 45 cm, and the cross-sectional area is 10 X 10cm = 100 cm^2. Therefore, the reluctance in the first region is

$$\begin{aligned} \mathrm{R}_1 &= \frac{l_1}{\mu A_1} = \frac{l_1}{\mu_r \mu_0 A_1} \\ &= \frac{0.45\mathrm{m}}{(2500)\left(4\pi \times 10^{-7}\right)\left(0.01\mathrm{m}^2\right)} \\ &= 14,300 \mathrm{A} \cdot \mathrm{turns} / \mathrm{Wb} \end{aligned}$$

The mean path length of region 2 is 130 cm, and the cross-sectional area is 15 X 10cm = 150 cm^2. Therefore, the reluctance in the second region is

$$\begin{aligned} \mathrm{R}_2 &= \frac{l_2}{\mu A_2} = \frac{l_2}{\mu_r \mu_0 A_2} \\ &= \frac{1.3\mathrm{m}}{(2500)\left(4\pi \times 10^{-7}\right)\left(0.015\mathrm{m}^2\right)} \\ &= 27,600 \mathrm{A} \cdot \mathrm{turns} / \mathrm{Wb} \end{aligned}$$

Therefore, the total reluctance in the core is

$$\begin{aligned} \mathcal{R}_{eq} &= \mathcal{R}_1 + \mathcal{R}_2 \\ &= 14,300\,\mathrm{A\cdot turns/Wb} + 27,600\,\mathrm{A\cdot turns/Wb} \\ &= 41,900\,\mathrm{A\cdot turns/Wb} \end{aligned}$$

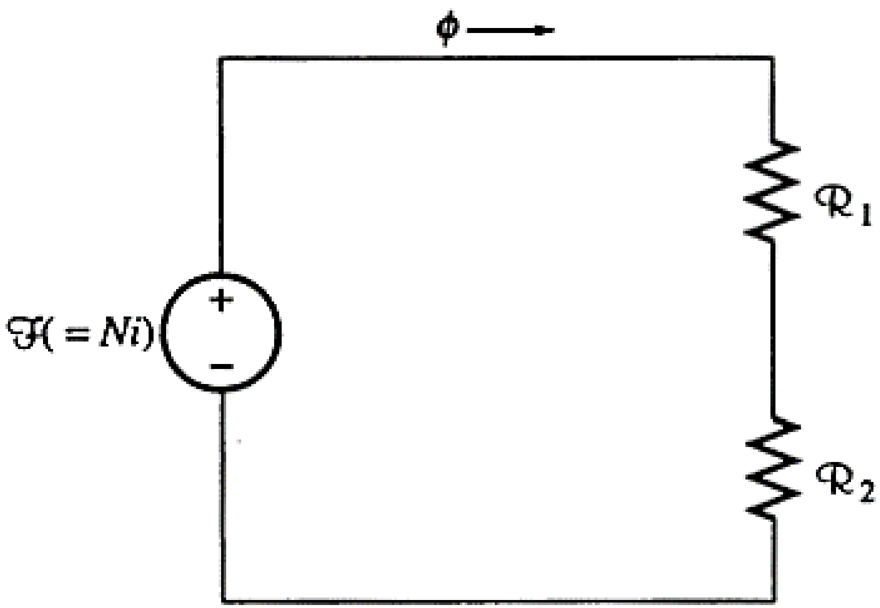
The total magnetomotive force is

$$\mathcal{F} = Ni = (200\ \mathrm{turns})(1.0\mathrm{A}) = 200\,\mathrm{A\cdot turns}$$

The total flux in the core is given by

$$\begin{aligned} \phi &= \frac{\mathcal{F}}{\mathcal{R}} = \frac{200\,\mathrm{A\cdot turns}}{41,900\,\mathrm{A\cdot turns/Wb}} \\ &= 0.0048\mathrm{Wb} \end{aligned}$$

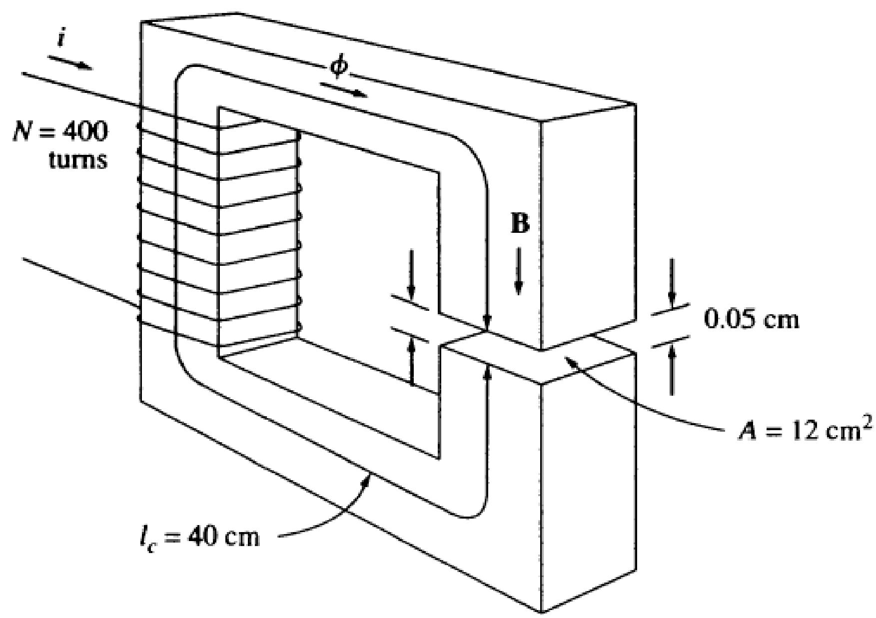
Magnetic circuit



(b)

Example 1-2

Figure below shows a ferromagnetic core whose mean path length is 40 cm. There is a small gap of 0.05 cm in the structure of the otherwise whole core. The cross-sectional area of the core is 12 cm, the relative permeability of the core is 4000, and the coil of wire on the core has 400 turns. Assume that fringing in the air gap increases the effective cross-sectional area of the air gap by 5 percent. Given this information, find **(a)** the total reluctance of the flux path (iron plus air gap) and **(b)** the current required to produce a flux density of 0.5 T in the air gap.



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The magnetic circuit corresponding to this core is shown previously.

(a) The reluctance of the core is

$$\mathcal{R}_c = \frac{l_c}{\mu A_c} = \frac{l_c}{\mu_r \mu_0 A_c}$$

$$= \frac{0.4\,\text{m}}{(4000)\left(4\pi\times10^{-7}\right)\left(0.002\,\text{m}^2\right)}$$

$$= 66,300\,\text{A}\cdot\text{ turns }/\text{Wb}$$

The effective area of the air gap is 1.05 X 12 cm^2 = 12.6 cm^2, so the reluctance of the airgap is

$$\mathcal{R}_a = \frac{l_a}{\mu_0 A_a}$$

$$= \frac{0.0005\,\text{m}}{\left(4\pi\times10^{-7}\right)\left(0.00126\,\text{m}^2\right)}$$

$$= 316,000\,\text{A}\cdot\text{ turns }/\text{Wb}$$

Therefore, the total reluctance of the flux path is

$$\begin{aligned} \mathcal{R}_{\text{eq}} &= \mathcal{R}_c + \mathcal{R}_a \\ &= 66{,}300\,\text{A}\cdot\text{turns}/\text{Wb} + 316{,}000\,\text{A}\cdot\text{turns}/\text{Wb} \\ &= 382{,}300\,\text{A}\cdot\text{turns}/\text{Wb} \end{aligned}$$

Note that the air gap contributes most of the reluctance even though it is 800 times shorter than the core.

(b) We have

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

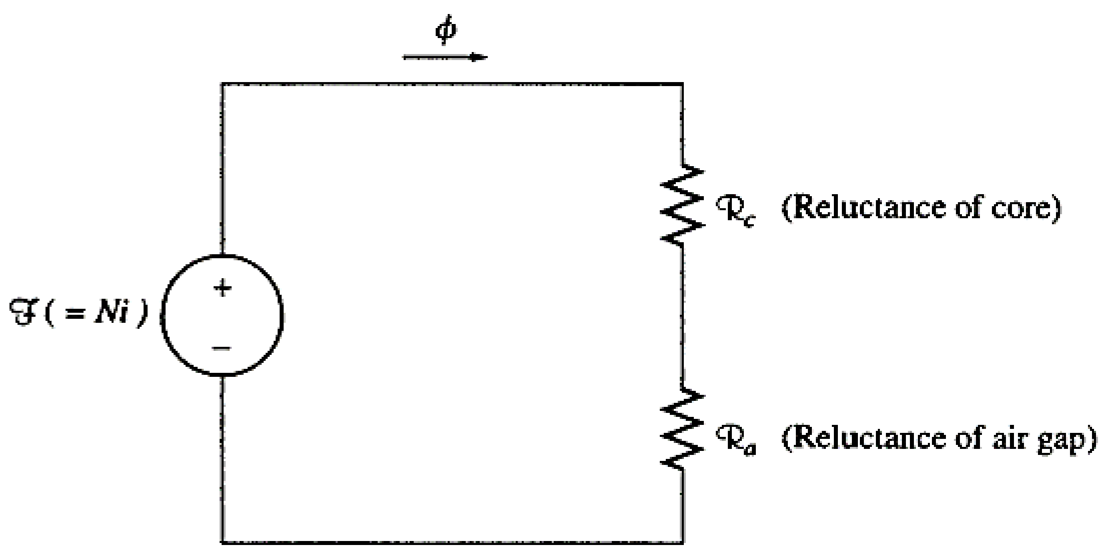
Since the flux *Φ = BA* and *F = Ni*, this equation becomes

$$Ni = BA\mathcal{R}$$

so

$$
\begin{aligned}
i &= \frac{BA\mathcal{R}}{N} \\
&= \frac{(0.5\text{T})\left(0.00126\text{m}^2\right)(383{,}200\text{A}\cdot\text{ turns }/\text{Wb})}{400\text{ turns}} \\
&= 0.602\text{A}
\end{aligned}
$$

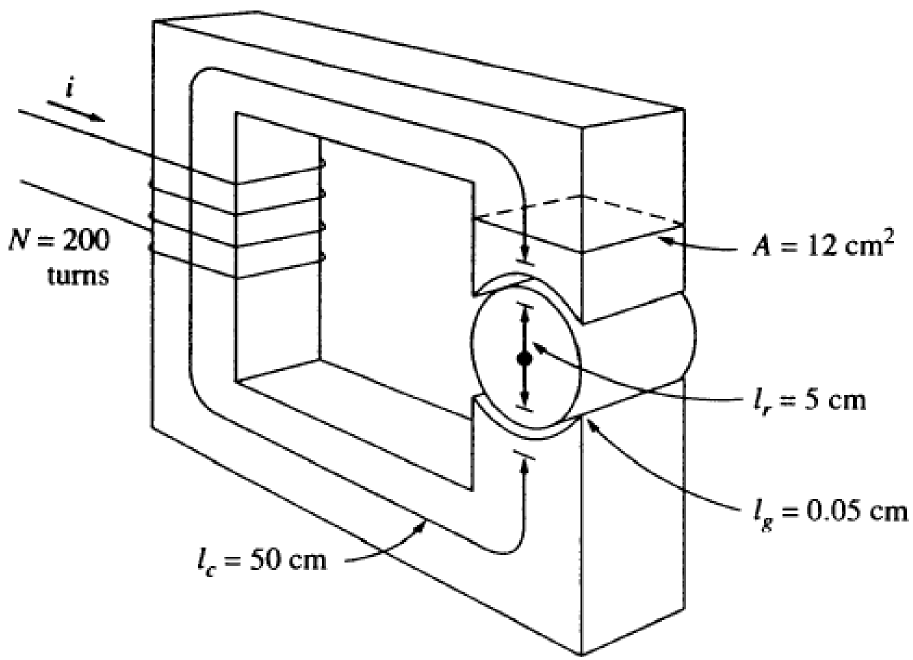
Notice that, since the *air-gap* flux was required, the effective air-gap area was used in the above equation.



(b)

Example 1-3

Figure below shows a simplified rotor and stator for a dc motor. The mean path length of the stator is 50 cm, and its cross-sectional area is 12 cm^2. The mean path length of the rotor is 5 cm, and its cross-sectional area also may be assumed to be 12 cm^2. Each air gap between the rotor and the stator is 0.05 cm wide, and the cross-sectional area of each air gap (including fringing) is 14 cm^2. The iron of the core has a relative permeability of 2000, and there are 200 turns of wire on the core. If the current in the wire is adjusted to be 1 A, what will the resulting flux density in the air gaps be?



To determine the flux density in the air gap, it is necessary to first calculate the magneto-motive force applied to the core and the total reluctance of the flux path. With this information, the total flux in the core can be found. Finally, knowing the cross-sectional area of the air gaps enables the flux density to be calculated.

The reluctance of the stator is

$$\begin{aligned} \mathrm{R}_s &= \frac{l_s}{\mu_r \mu_0 A_s} \\ &= \frac{0.5\mathrm{m}}{(2000)\left(4\pi \times 10^{-7}\right)\left(0.0012\mathrm{m}^2\right)} \\ &= 166,000\mathrm{A} \cdot \text{ turns } / \mathrm{Wb} \end{aligned}$$

The reluctance of the rotor is

$$\begin{aligned} \mathrm{R}_r &= \frac{l_r}{\mu_r \mu_0 A_r} \\ &= \frac{0.05\mathrm{m}}{(2000)\left(4\pi \times 10^{-7}\right)\left(0.0012\mathrm{m}^2\right)} \\ &= 16,600\mathrm{A} \cdot \text{ turns } / \mathrm{Wb} \end{aligned}$$

The reluctance of the air gaps is

$$\mathcal{R}_a = \frac{l_a}{\mu_r \mu_0 A_a}$$

$$= \frac{0.0005\text{m}}{(1)\left(4\pi \times 10^{-7}\right)\left(0.0014\text{m}^2\right)}$$

$$= 284,000\text{A} \cdot \text{turns} / \text{Wb}$$

The magnetic circuit corresponding to this machine is shown in the following figure. The total reluctance of the flux path is thus

$$\mathcal{R}_{eq} = \mathcal{R}_s + \mathcal{R}_{a1} + \mathcal{R}_r + \mathcal{R}_{a2}$$

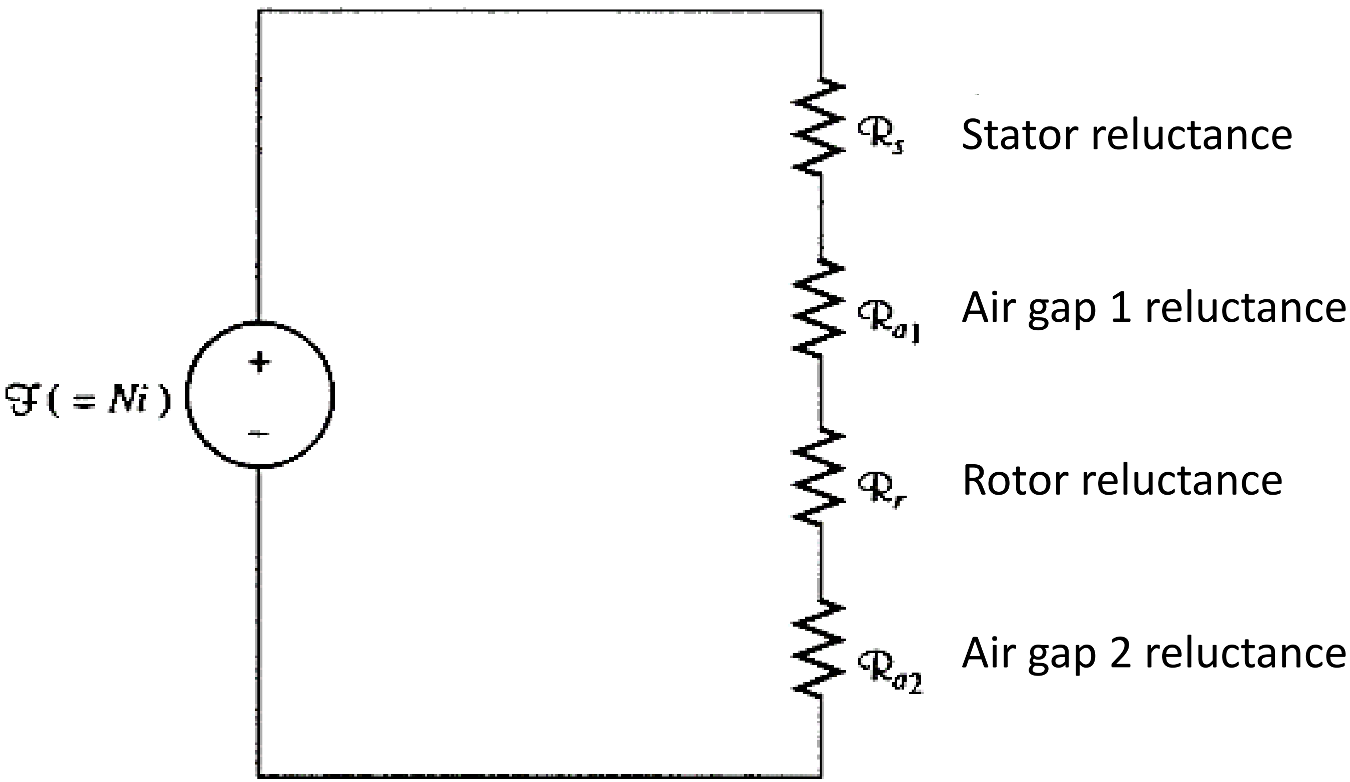
$$= 166,000 + 284,000 + 16,600 + 284,000\text{A} \cdot \text{turns} / \text{Wb}$$

$$= 751,000\text{A} \cdot \text{turns} / \text{Wb}$$

The net magnetomotive force applied to the core is

$$\mathcal{F} = Ni = (200 \text{ turns})(1.0\text{A}) = 200\text{A} \cdot \text{turns}$$

Therefore, the total flux in the core is



$\mathcal{F}(=Ni)$
+
−
$\mathcal{R}_s$
Stator reluctance
$\mathcal{R}_{a1}$
Air gap 1 reluctance
$\mathcal{R}_r$
Rotor reluctance
$\mathcal{R}_{a2}$
Air gap 2 reluctance

(b)

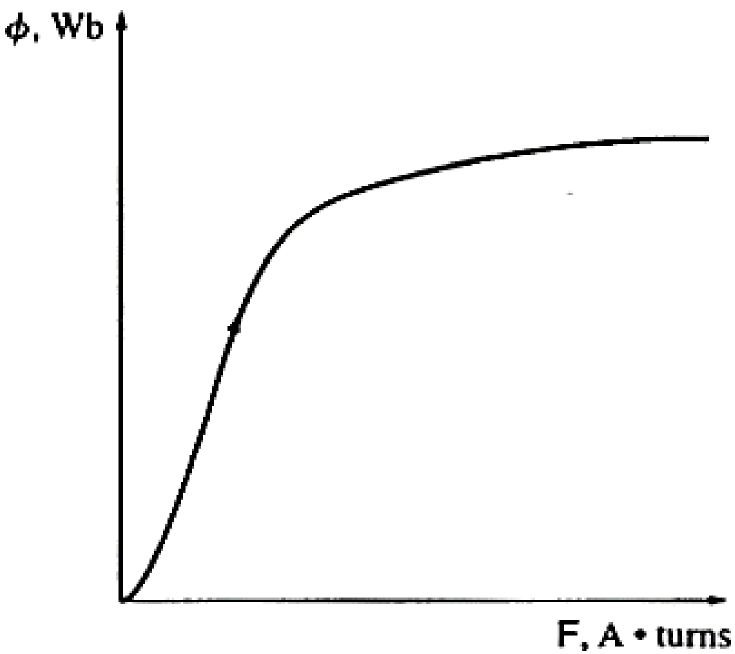
$$\phi = \frac{\mathrm{F}}{\mathrm{R}} = \frac{200\mathrm{A} \cdot \text{ turns}}{751{,}000\mathrm{A} \cdot \text{ turns } / \mathrm{Wb}}$$

$$= 0.00266\mathrm{Wb}$$

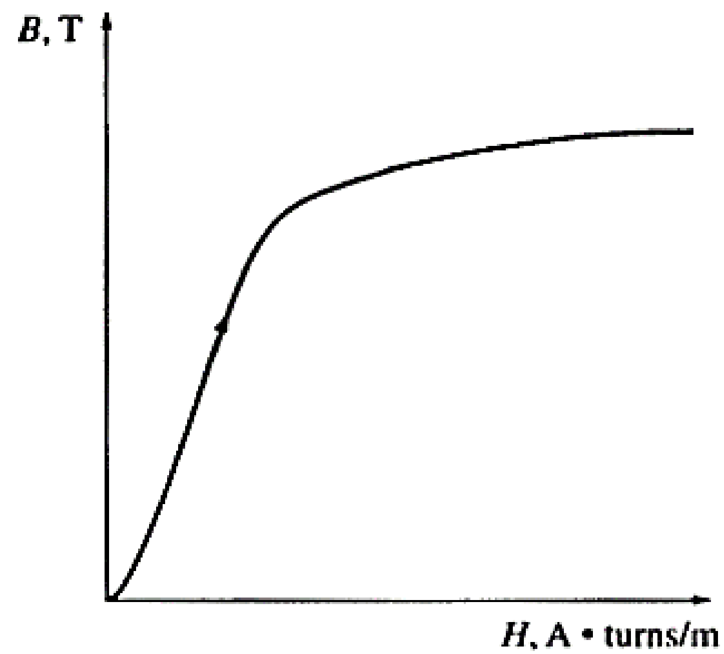
Finally, the magnetic flux density in the motor's air gap is

$$B = \frac{\phi}{A} = \frac{0.000266\mathrm{Wb}}{0.0014\mathrm{m}^2} = 0.19\mathrm{T}$$

Magnetic behavior of ferromagnetic material - Saturation

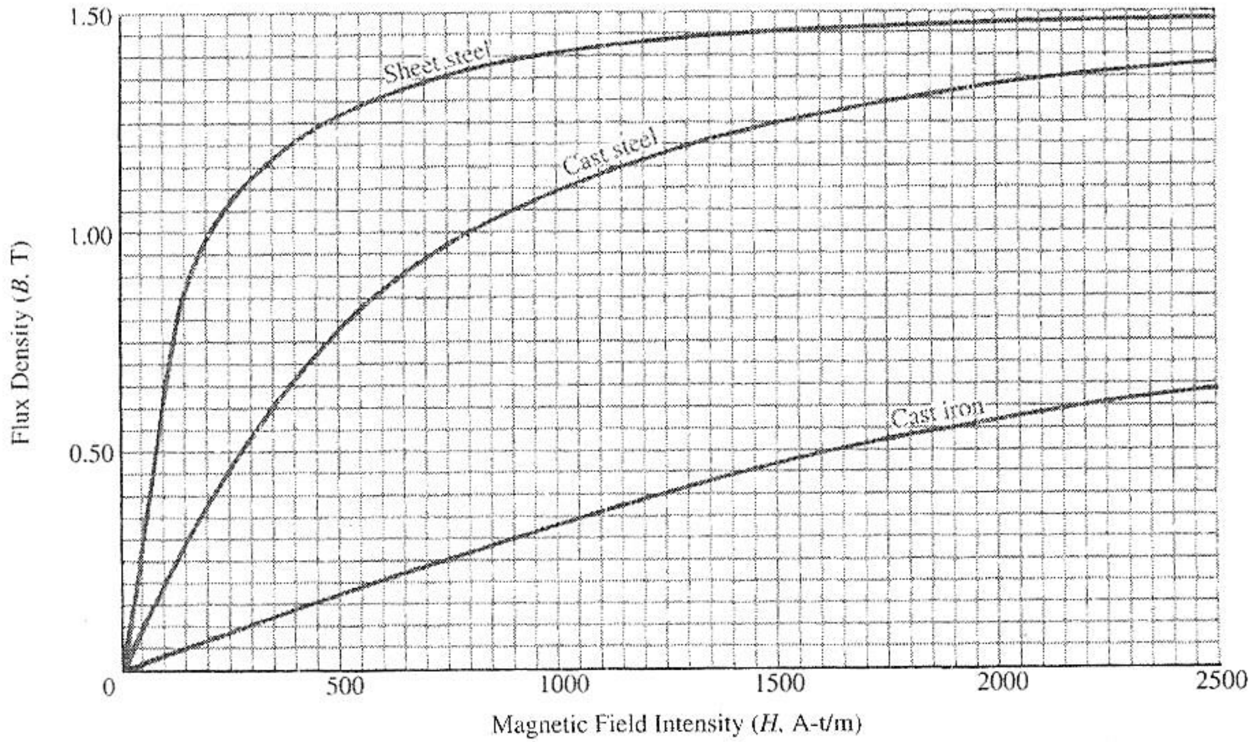


(a)



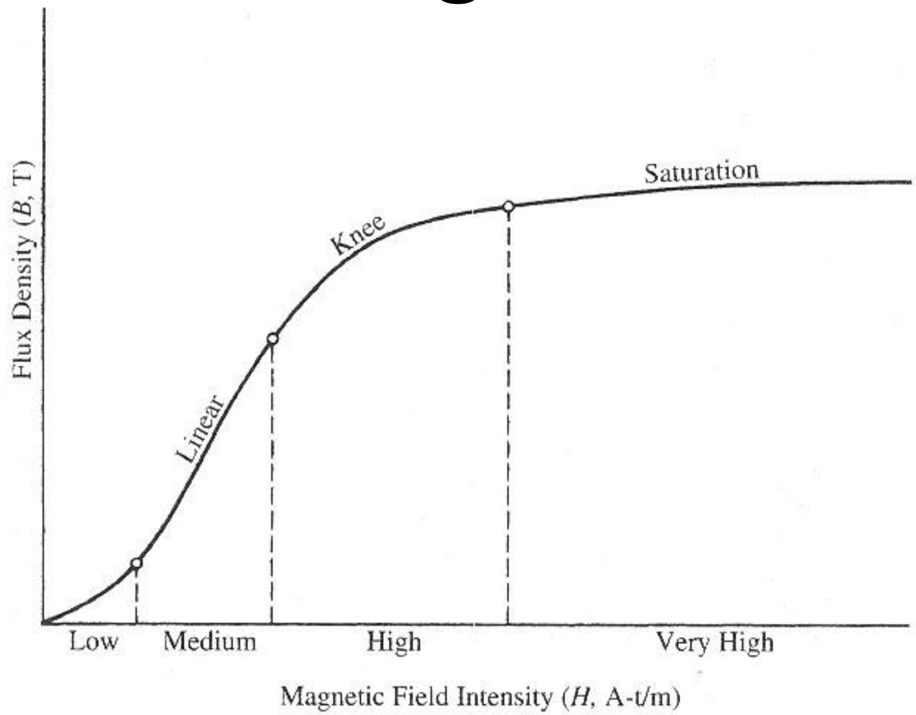
(b)

Magnetic Flux Density vs. Magnetic Field Intensity



Representative B-H curves for some commonly used ferromagnetic materials

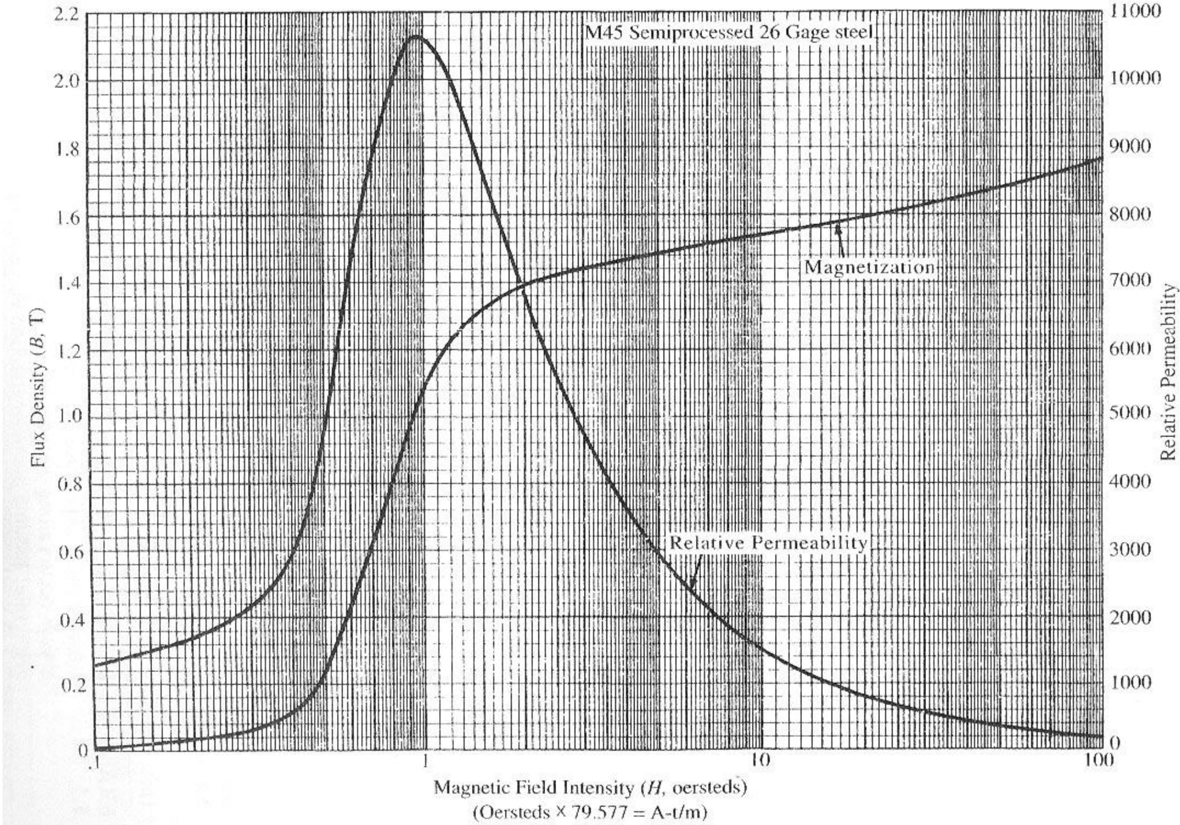
Labeling realms



Exaggerated magnetization curve illustrating the four principal sections.

Saturation occurs when all the magnetic domains in a material are aligned together. Since you are changing the material on the molecular level by reorienting the domains, this absorbs energy heating up the material.

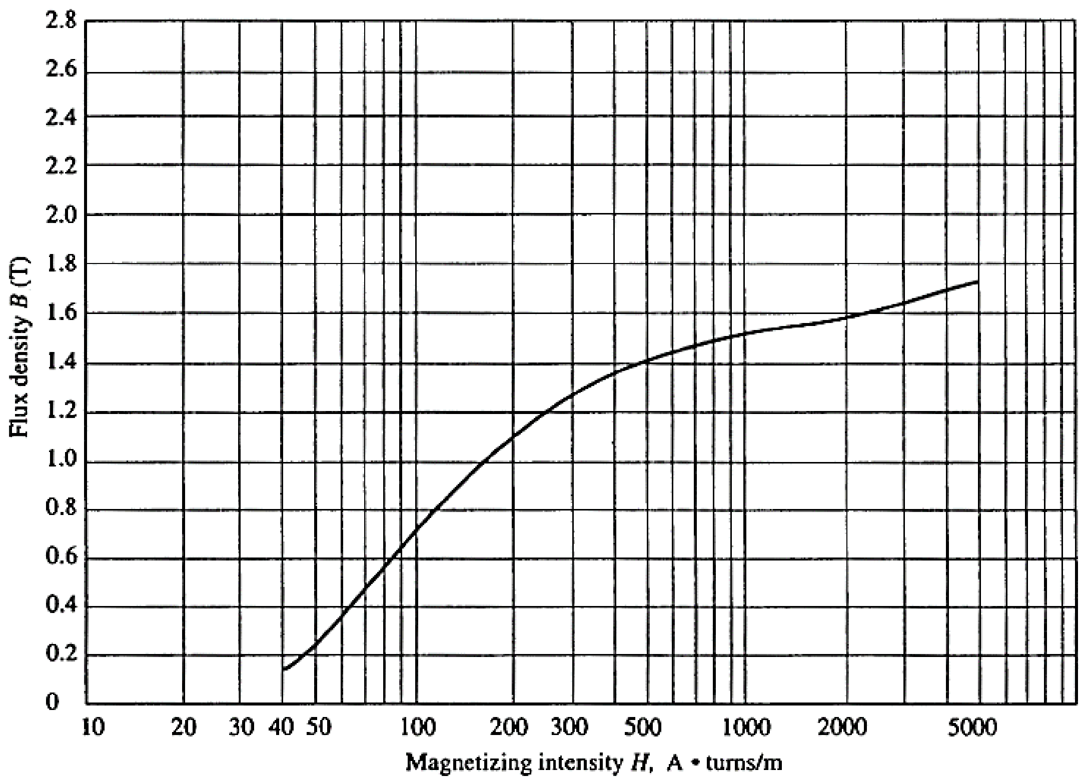
Magnetization & the relative permeability curves



The magnetization is H, the magnetic field intensity…given that N and l are constant for any one electromagnet, it's directly related to the current flow.

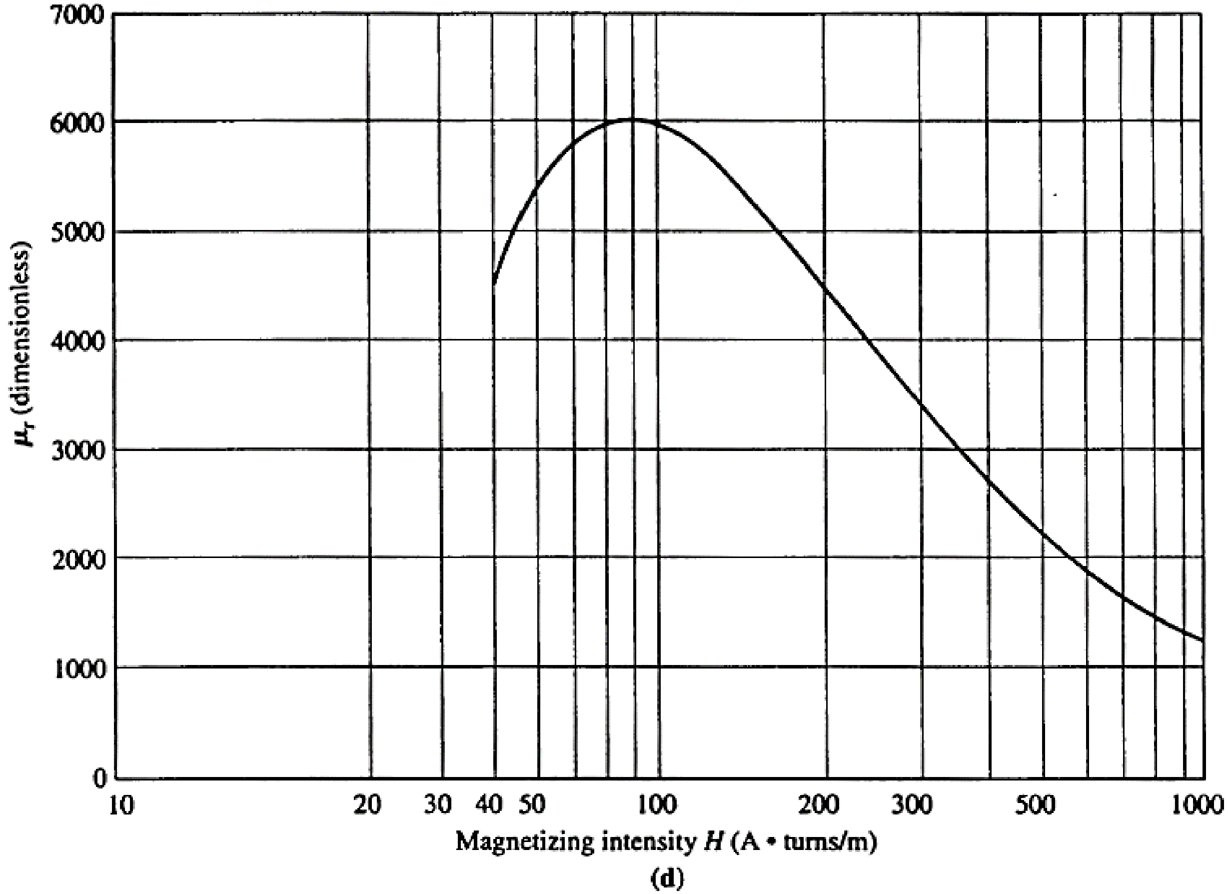
Example 1-4

Find the relative permeability of the typical ferromagnetic material whose magnetization curve is shown in the figure below at (a) H = 50,(b) H = 100,(C) H 500, and (d) H =1000 A·turns/m.



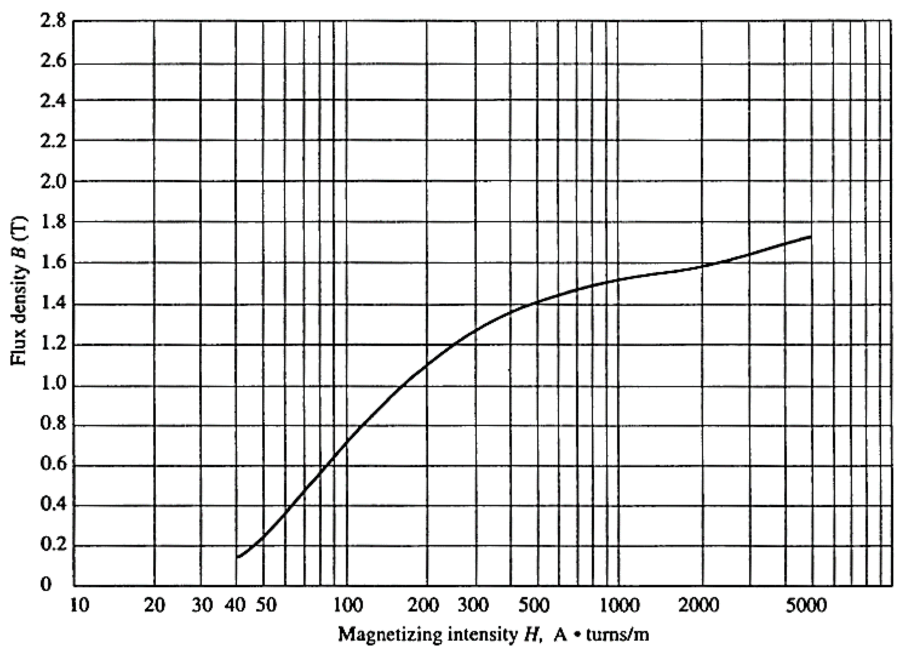
(c)

A plot of relative permeability μ_r



Example 1-5

A square magnetic core has a mean path length of 55 cm and a cross-sectional area of 150 cm^2. A 200-turn coil of wire is wrapped around one leg of the core. The core is made of a material having the magnetization curve shown in the figure below.
(a) How much current is required to produce 0.012 Wb of flux in the core? **(b)** What is the core's relative permeability at that current level? **(c)** What is its reluctance?



(c)

(a) The required flux density in the core is

$$B = \frac{\phi}{A} = \frac{1.012\text{Wb}}{0.015\text{m}^2} = 0.8\text{T}$$

From Figure 1-10c, the required magnetizing intensity is

$$H = 115\text{A} \cdot \text{ turns } / \text{m}$$

The magnetomotive force needed to produce this magnetizing intensity is

$$\begin{aligned} \mathcal{F} &= Ni = Hl_c \\ &= (115\text{A} \cdot \text{ turns } / \text{m})(0.55\text{m}) = 63.25\text{A} \cdot \text{ turns} \end{aligned}$$

so the required current is

$$i = \frac{\mathcal{F}}{N} = \frac{63.25\text{A} \cdot \text{turns}}{200\text{turns}} = 0.316\text{A}$$

(b) The core's permeability at this current is

$$\mu = \frac{B}{H} = \frac{0.8\mathrm{T}}{115\mathrm{A}\cdot\ \mathrm{turns}\ \ /\,\mathrm{m}} = 0.00696\mathrm{H}\,/\,\mathrm{m}$$

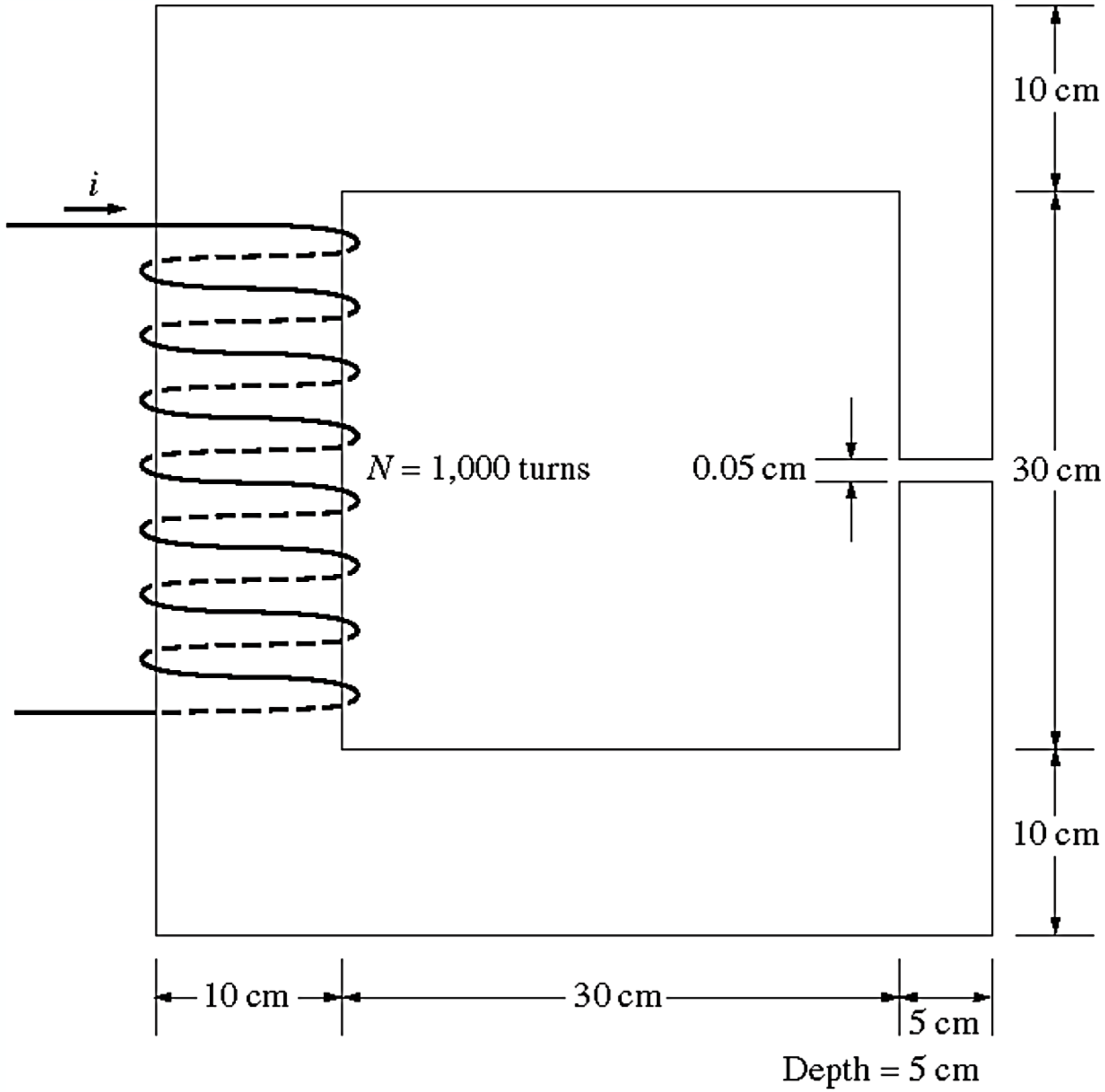
Therefore, the relative permeability is

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0.00696\mathrm{H}\,/\,\mathrm{m}}{4\pi\times 10^{-7}\,\mathrm{H}\,/\,\mathrm{m}} = 5540$$

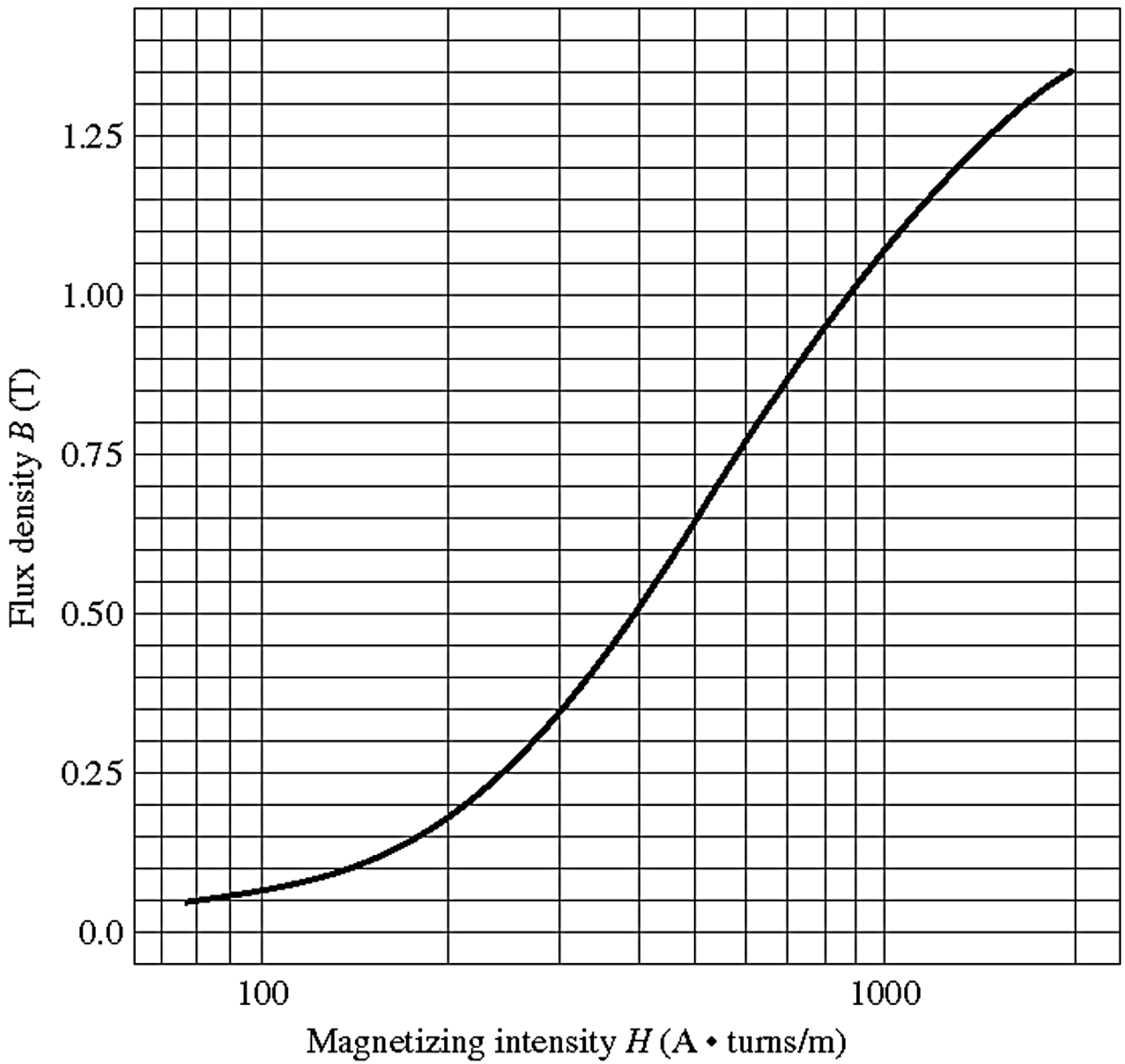
(c) The reluctance of the core is

$$R = \frac{\mathrm{F}}{\phi} = \frac{63.25\mathrm{A}\cdot\ \mathrm{turns}}{0.012\mathrm{Wb}} = 5270\mathrm{A}\cdot\ \mathrm{turns}\ \ /\,\mathrm{Wb}$$

Example 1-6



Assume the fringing effect increases the effective area of air gap cross-section by 5%. What is *i* if we need a flux density of 0.5T in the airgap?


1.25
1.00
0.75
0.50
0.25
0.0
Flux density B (T)
100
1000
Magnetizing intensity H (A • turns/m)

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An air-gap flux density of 0.5 T requires a total flux of

$$\phi = BA_{\text{eff}} = (0.5\text{T})(0.05\text{m})(0.05\text{m})(1.05) = 0.00131\text{Wb}$$

This flux requires a flux density in the right-hand leg of

$$B_{\text{right}} = \frac{\phi}{A} = \frac{0.00131\text{Wb}}{(0.05\text{m})(0.05\text{m})} = 0.524\text{T}$$

The flux density in the other three legs of the core is

$$B_{\text{top}} = B_{\text{left}} = B_{\text{bottom}} = \frac{\phi}{A} = \frac{0.00131\text{Wb}}{(0.10\text{m})(0.05\text{m})} = 0.262\text{T}$$

The magnetizing intensity required to produce a flux density of 0.5 T in the air gap can be found from the equation $B_{ag} = \mu_0 H_{ag}$

$$H_{\text{ag}} = \frac{B_{\text{ag}}}{\mu_0} = \frac{0.5\text{T}}{4\pi \times 10^{-7}\,\text{H/m}} = 398\text{kA}\cdot\text{t/m}$$

The magnetizing intensity required to produce a flux density of 0.524 T in the right-hand leg of the core can be found to be

$$H_{\text{right}} = 410\text{A}\cdot\text{t/m}$$

The magnetizing intensity required to produce a flux density of 0.262 T in the top, left, and bottom legs of the core can be found to be

$$H_{\text{top}} = H_{\text{left}} = H_{\text{bottom}} = 240\,\text{A} \cdot \text{t} / \text{m}$$

The total MMF required to produce the flux is

$$\mathcal{F}_{\text{TOT}} = H_{\text{ag}} l_{\text{ag}} + H_{\text{right}} l_{\text{right}} + H_{\text{top}} l_{\text{top}} + H_{\text{left}} l_{\text{left}} + H_{\text{bottom}} l_{\text{bottom}}$$

$$\mathcal{F}_{\text{TOT}} = (398\text{kA} \cdot \text{t} / \text{m})(0.0005\text{m}) + (410\text{A} \cdot \text{t} / \text{m})(0.40\text{m}) + 3(240\text{A} \cdot \text{t} / \text{m})(0.40\text{m})$$

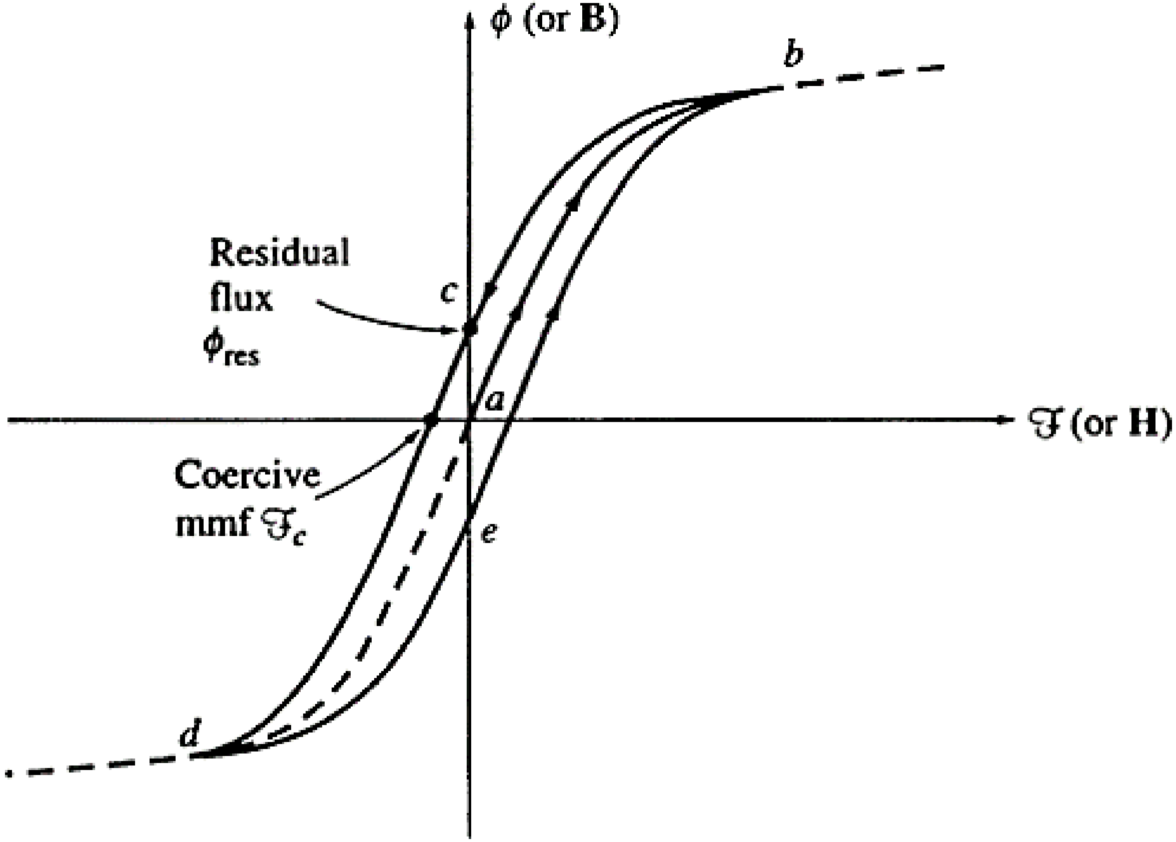
$$\mathcal{F}_{\text{TOT}} = 278.6 + 164 + 288 = 651\text{A} \cdot \text{t}$$

and the required current is

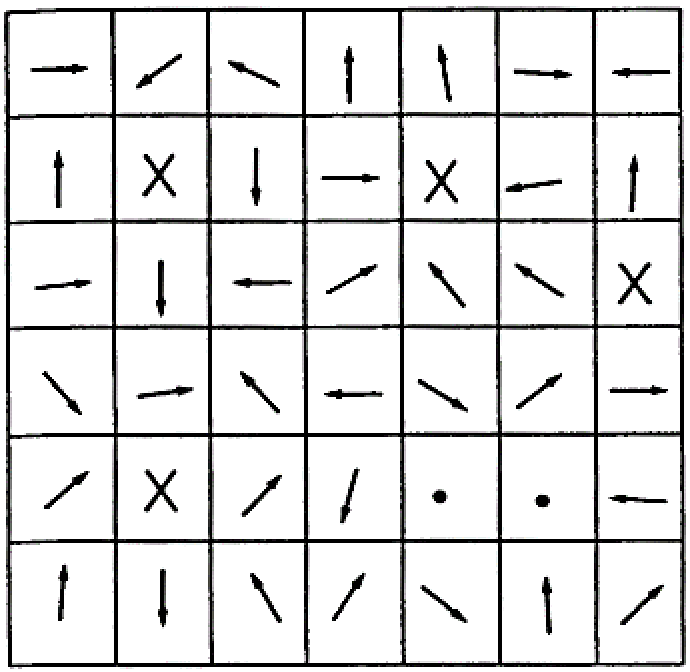
$$i = \frac{\mathcal{F}_{\text{TOT}}}{N} = \frac{651\text{A} \cdot \text{t}}{1000\text{t}} = 0.651\text{A}$$

The flux densities in the four sides of the core and the total flux present in the air gap were calculated above.

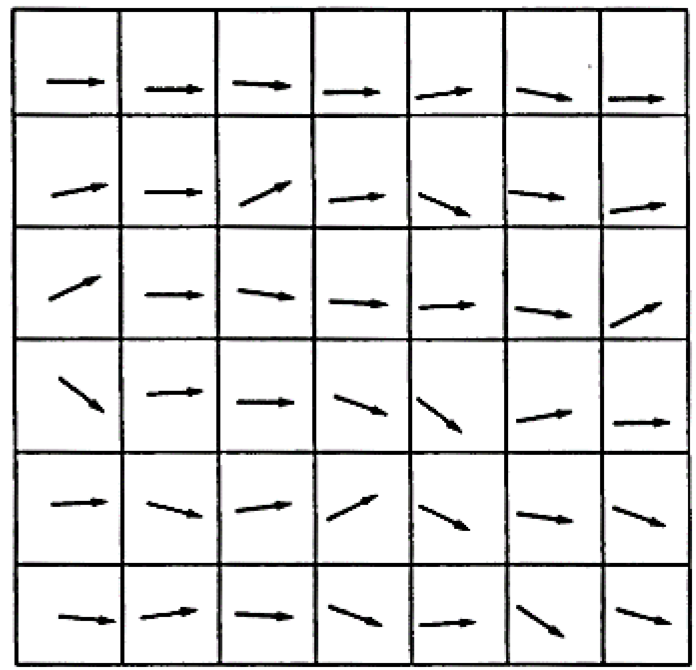
Energy loss in ferromagnetic core – hysteresis loss



Hysteresis loop – residual flux

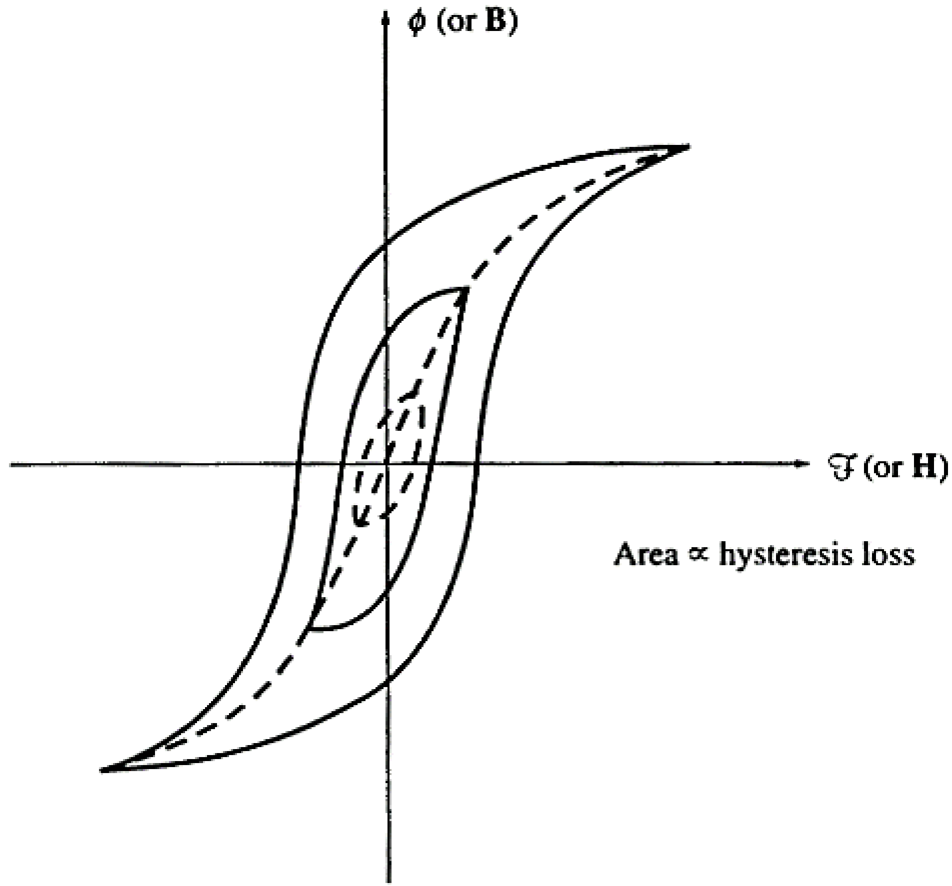


(a)

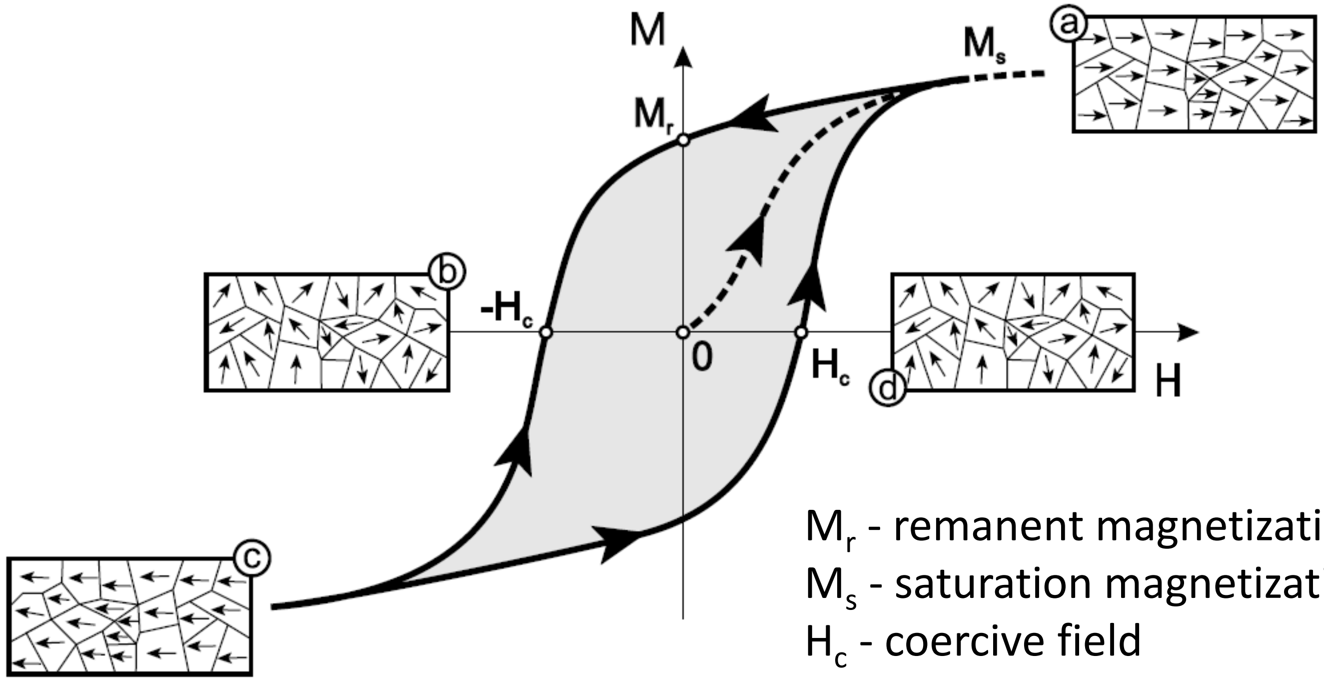


(b)

The effect of magnetomotive force on the hysteresis loop



Magnetization curve

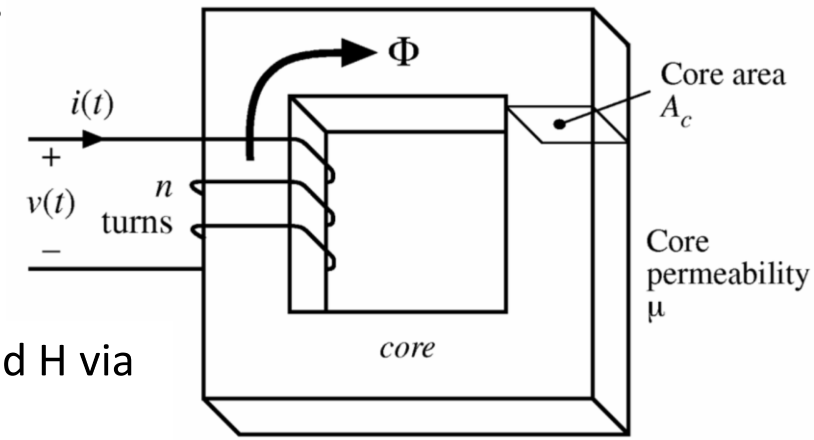


M_r - remanent magnetization
M_s - saturation magnetization
H_c - coercive field

Hysteresis loss

Energy per cycle W flowing into n-turn winding of an inductor. excited by periodic waveforms of frequency *f*:

$$W = \int_{\text{one cycle}} v(t)i(t)dt$$



Relate winding voltage and current to core Band H via Faraday's law and Ampere's law:

$$v(t) = nA_c \frac{dB(t)}{dt} \quad H(t)\ell_m = ni(t)$$

Substitute into integral:

$$\begin{aligned} W &= \int_{\text{one cycle}} \left(nA_c \frac{dB(t)}{dt} \right) \left(\frac{H(t)\ell_m}{n} \right) dt \\ &= \left(A_c \ell_m \right) \int_{\text{one cycle}} H dB \end{aligned}$$

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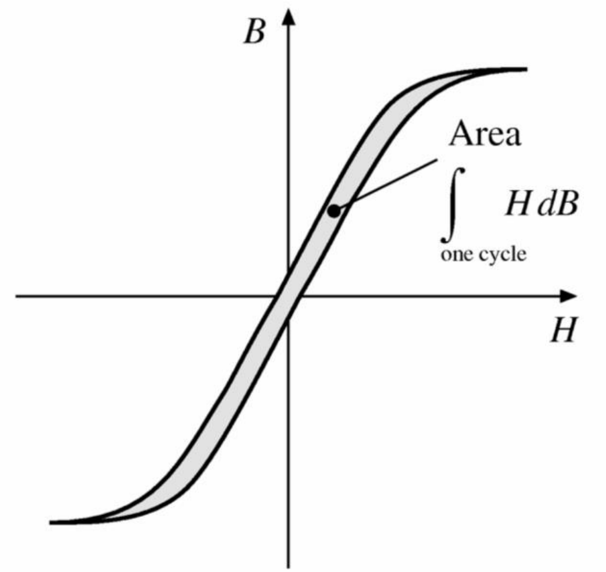
Hysteresis loss



$$W = \left(A_c \ell_m\right) \int_{\text{one cycle}} H\,dB$$

The term $A_c l_m$ is the volume of the core, while the integral is the area of the *B-H* loop.

(energy lost per cycle) = (core volume) (area of B-H loop)

$$P_H = (f)\left(A_c \ell_m\right) \int_{\text{one cycle}} H\,dB$$

Hysteresis loss is directly proportional to applied frequency

Units

Quantity	MKS	Unrationalized cgs	Conversions
Core material equation	$B=\mu_0\mu_r H$	$B=\mu H$	
B	Tesla	Gauss	$1T=10^4G$
H	Ampere / meter	Oersted	$1A/m=4\pi\cdot 10^{-3}Oe$
Φ	Weber	Maxwell	$1Wb=10^8Mx$ $1T=1Wb/m^2$

Faraday's law – induce voltage from a time-varying magnetic field

1. Induced voltage magnitude and polarity

$$e_{\text{ind}} = -\frac{d\phi}{dt}$$

$$e_{\text{ind}} = \sum_{i=1}^{N} e_i$$

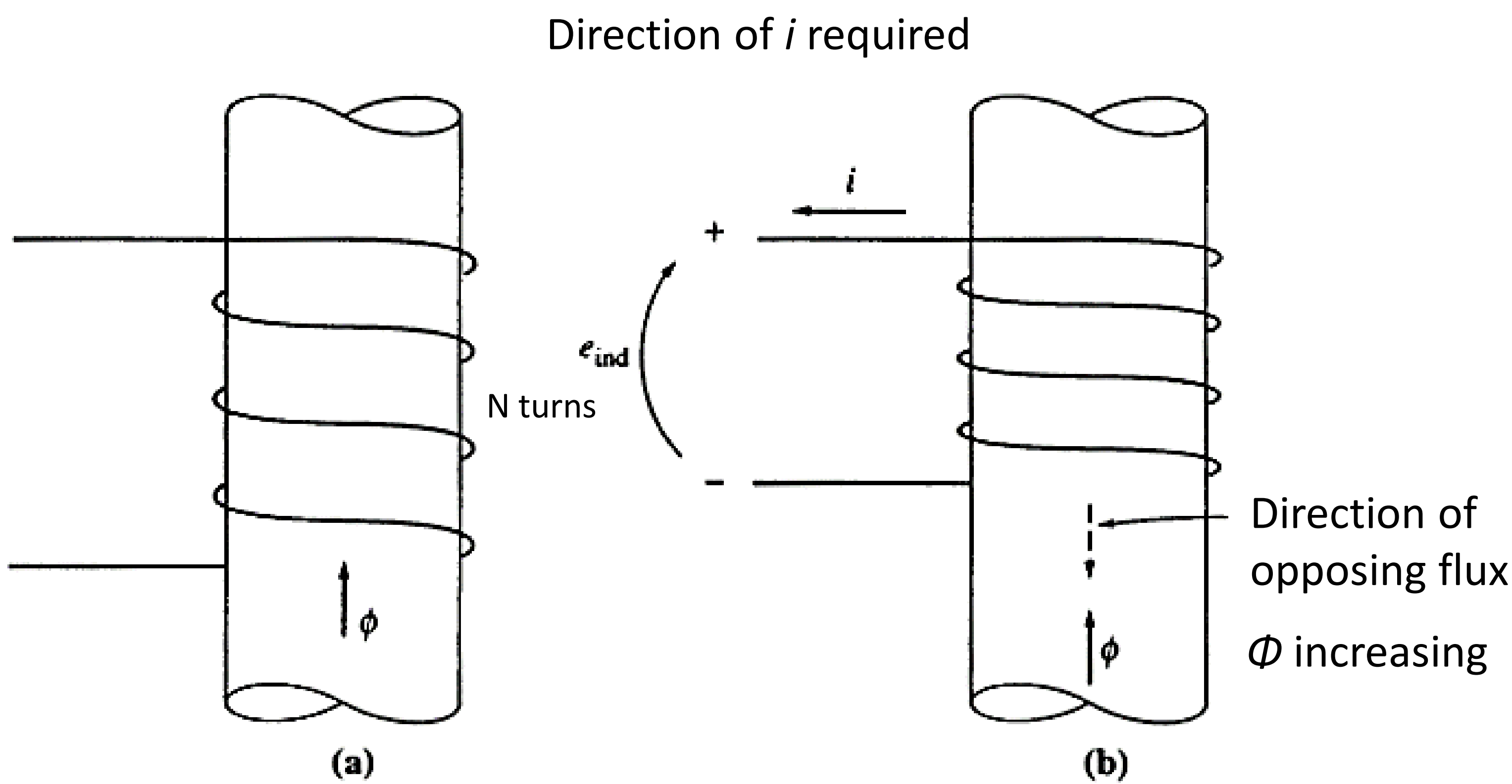
$$e_{\text{ind}} = -N\frac{d\phi}{dt}$$

e_{ind} = voltage induced in the coil

N = number of turns of wire in coil

ϕ = flux passing through coil

The induced voltage polarity – Lenz's law



Flux and flux linkage

The term in parentheses in the previous equation is called *the flux linkage λ* of the coil and Faraday's law can be rewritten in terms of flux linkage as

$$e_{\text{ind}} = \frac{d\lambda}{dt}$$

where

$$\lambda = \sum_{i=1}^{N} \phi_i$$

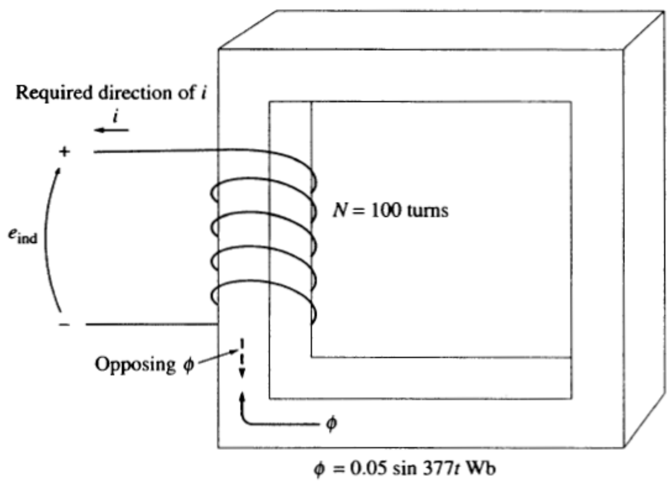
The units of flux linkage are weber-turns.

Example 1-6

Figure below shows a coil of wire wrapped around an iron core. If the flux in the core is given by the equation

$$\phi = 0.05 \sin 377t \quad \text{Wb}$$

If there are 100 turns on the core, what voltage is produced at the terminals of the coil? Of what polarity is the voltage during the time when flux is increasing in the reference direction shown in the figure? Assume that all the magnetic flux stays within the core (i.e., assume that the flux leakage is zero).



The core of Example 1-6. Determination of the voltage polarity at the terminals is shown.

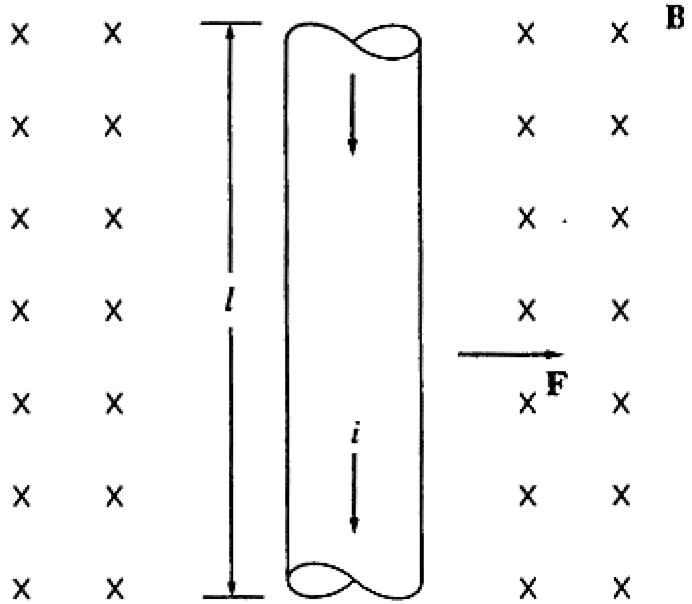
By the same reasoning as in the previous discussion, the direction of the voltage while the flux is increasing in the reference direction must be positive to negative. The magnitude of the voltage is given by

$$\begin{aligned} e_{\text{ind}} &= N\frac{d\phi}{dt} \\ &= (100 \text{ turns})\frac{d}{dt}(0.05 \sin 377t) \\ &= 1885 \cos 377t \end{aligned}$$

or alternatively.

$$e_{\text{ind}} = 1885 \sin\left(377t + 90^{\circ}\right) \text{V}$$

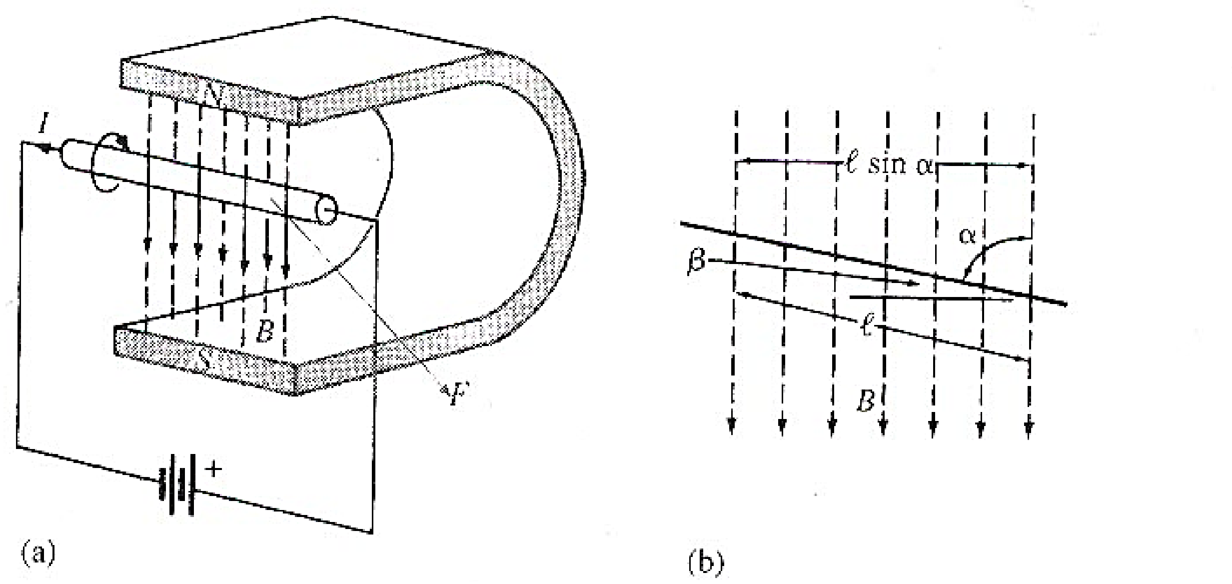
Produce an induced force on a wire



$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$
$$F = ilB\sin\theta$$

i = magnitude of current in wire
l = length of wire, with direction of l defined to be in the direction of current flow
B = magnetic flux density vector

Calculating the mechanical force: BℓI

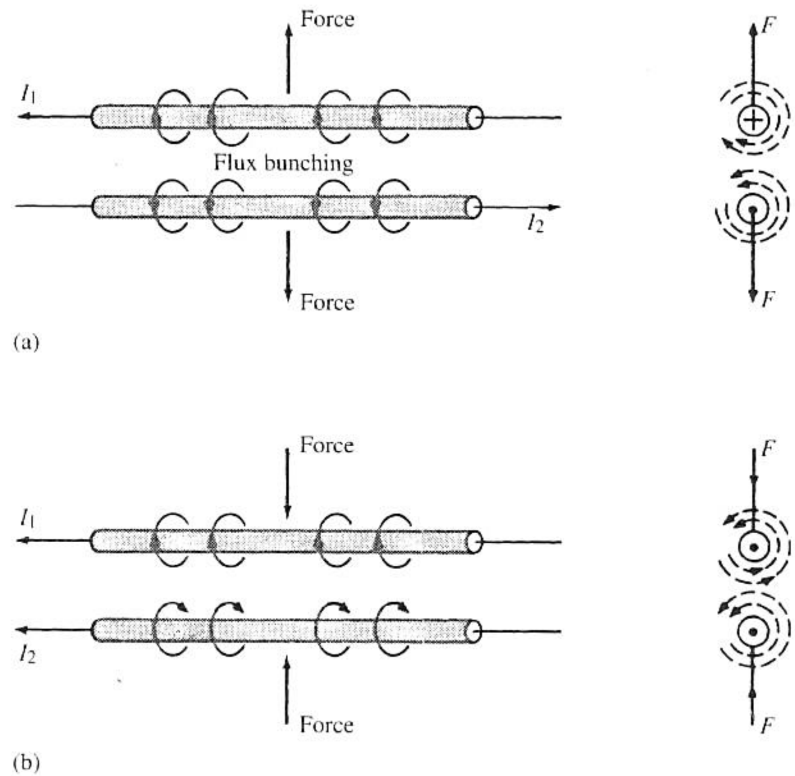


(a) Conductor carrying current, situated within and perpendicular to the B-field of a permanent magnet; (b) conductor skewed β°

$$F_{\text{mechanical}} = B \cdot \ell_{\text{eff}} \cdot I \text{ (Newtons)}$$

where l_{eff} is $l \cdot \sin \alpha$ or $l \cdot \cos \beta$
B is flux density and I is current

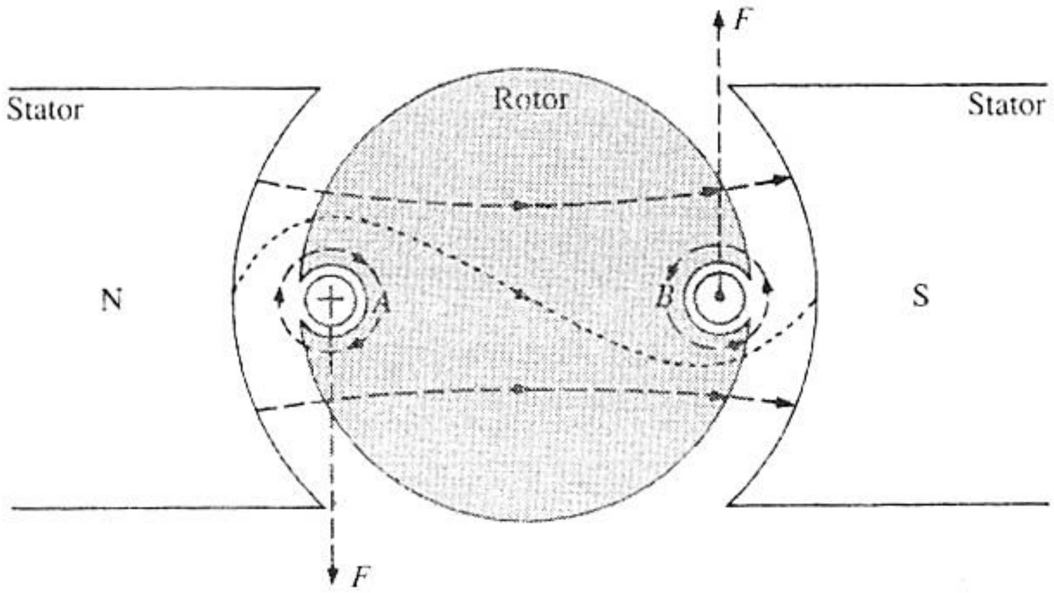
Flux bunching



interaction of magnetic fields of adjacent current-carrying conductors: (a) currents in opposite direction; (b) currents in same direction.

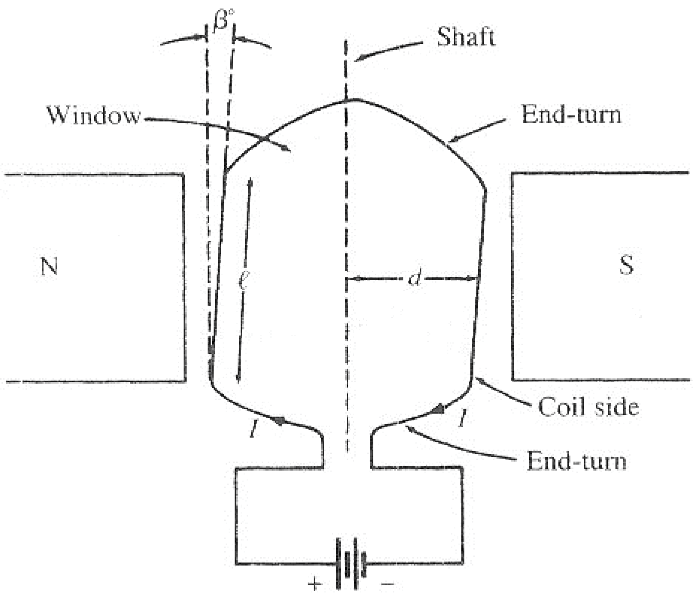
Flux polarity rule: flux flowing in the same direction are the same polarity and repel each other, flux flowing in opposite direction are of opposite polarity and attract each other.

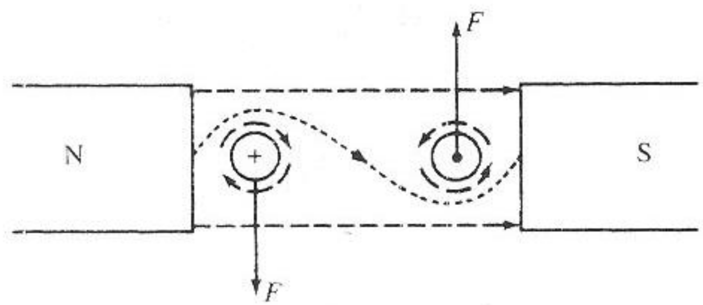
Application of flux bunching: motor action



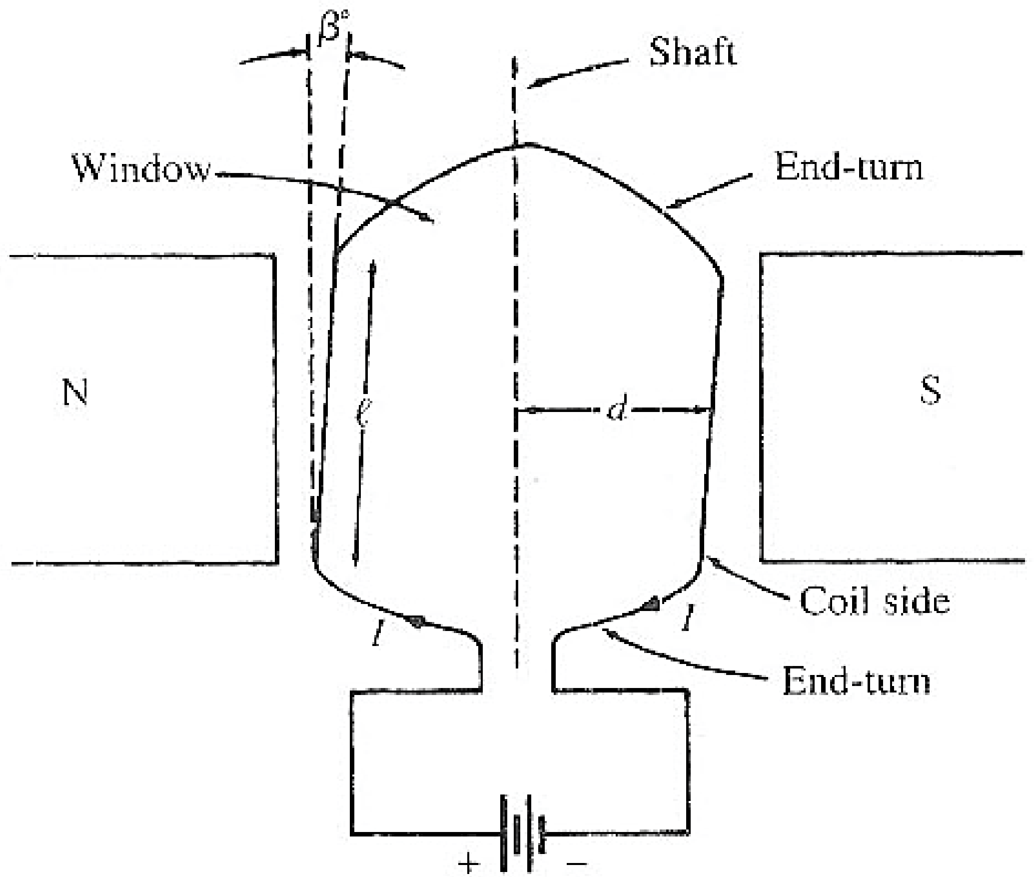
Counterclockwise rotational movement is generated from flux bunching with the application of current in the rotor winding.

Voltage driven motor action





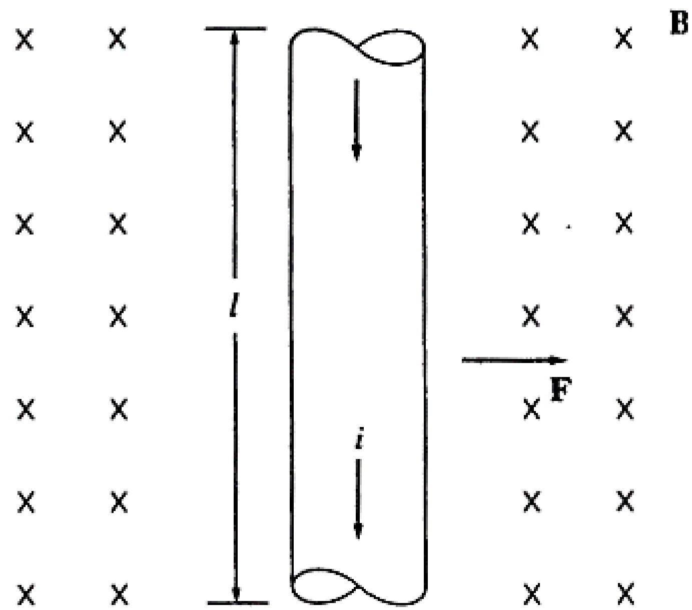
Torque using a simplified diagram



Distance d is the moment arm measured from the center of the shaft to the center of the conductor.
The force F is the mechanical force calculated using the BLI formula from the previous slide.
TORQUE (T_D) is the product of the mechanical force times the radius d (measured in meters) times the number of conductors: $T_D = 2 \cdot F_{mech} \cdot d$ (N·m)

Example 1-7

Figure below shows a wire carrying a current in the presence of a magnetic field. The magnetic flux density is 0.25 T, directed into the page. If the wire is 1.0 m long and carries 0.5 A of current in the direction from the top of the page to the bot-tom of the page, what are the magnitude and direction of the force induced on the wire?



Example 1-7

The direction of the force is given by the right-hand rule as being to the right. The magnitude is given by

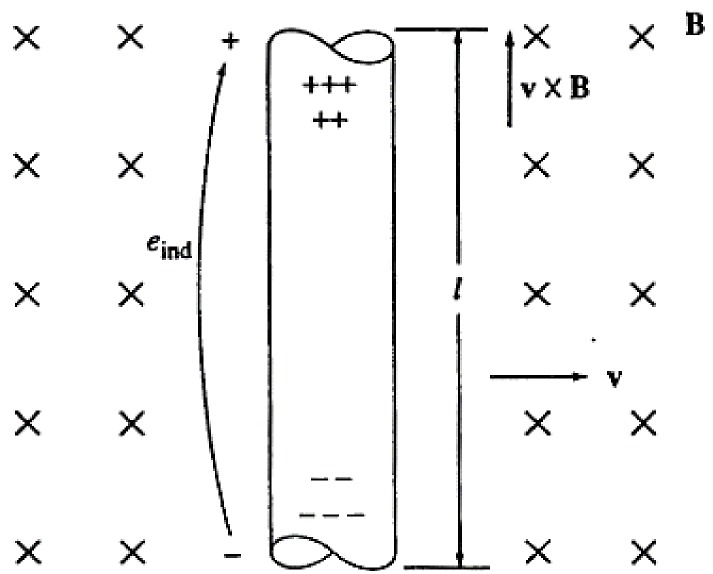
$$
\begin{aligned}
F &= ilB\sin\theta \\
&= (0.5\mathrm{A})(1.0\mathrm{m})(0.25\mathrm{T})\sin 90^{\circ} = 0.125\mathrm{N}
\end{aligned}
$$

Therefore,

$$\mathbf{F} = 0.125\mathrm{N}, \text{ directed to the right}$$

Example 1-8

Figure below shows a conductor moving with a velocity of 5.0 m/s to the right in the presence of a magnetic field. The flux density is 0.5 T into the page, and the wire is 1.0 m in length, oriented as shown. What are the magnitude and polarity of the resulting induced voltage?



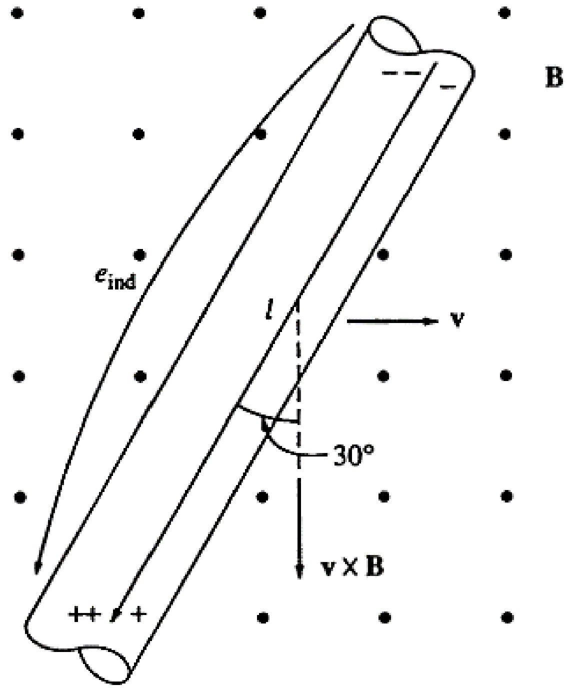
The direction of the quantity $\mathbf{v} \times \mathbf{B}$ in this example is up. Therefore, the voltage on the conductor will be built up positive at the top with respect to the bottom of the wire. The direction of vector $\mathbf{l}$ is up, so that it makes the smallest angle with respect to the vector $\mathbf{v} \times \mathbf{B}$. Since v is perpendicular to $\mathbf{B}$ and since $\mathbf{v} \times \mathbf{B}$ is parallel to $\mathbf{l}$, the magnitude of the induced voltage reduces to

$$\begin{aligned} e_{\text{ind}} &= (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \\ &= \left(vB \sin 90^\circ\right) l \cos 0^\circ \\ &= vBl \\ &= (5.0\text{m}/\text{s})(0.5\text{T})(1.0\text{m}) \\ &= 2.5\text{V} \end{aligned}$$

Thus the induced voltage is 2.5 V, positive at the top of the wire.

Example 1-9

Figure below shows a conductor moving with a velocity of 10 m/s to the right in a magnetic field. The flux density is 0.5 T, out of the page, and the wire is 1.0 m in length, oriented as shown. What are the magnitude and polarity of the resulting induced voltage?

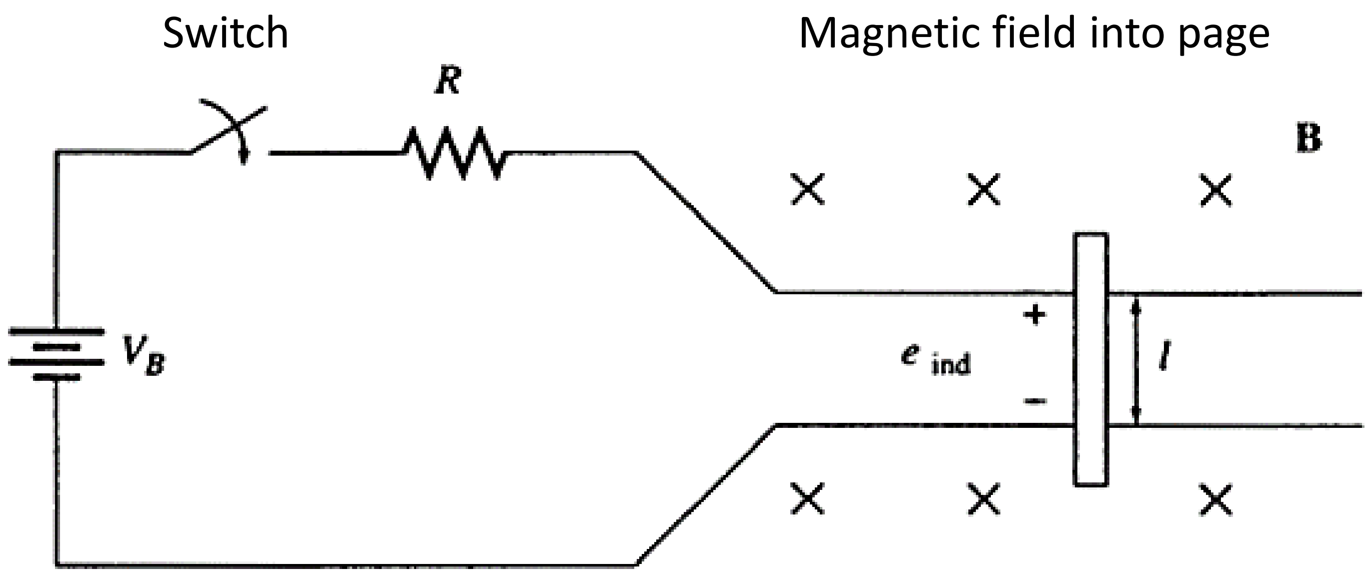


The direction of the quantity v×**B** is down. The wire is not oriented on an up-down line, so choose the direction of **l** as shown to make the smallest possible angle with the direction of v×**B** . The voltage is positive at the bottom of the wire with respect to the top of the wire. The magnitude of the voltage is

$$
\begin{aligned}
e_{\text{ind}} &= (\mathbf{v}\times\mathbf{B})\cdot\mathbf{l} \\
&= \left(vB\sin 90^{\circ}\right) l\cos 30^{\circ} \\
&= (10.0\text{m}/\text{s})(0.5\text{T})(1.0\text{m})\cos 30^{\circ} \\
&= 4.33\text{V}
\end{aligned}
$$

The linear DC machine – a simple example video

The linear DC machine – a simple example



A linear dc machine. The magnetic field points into the page.

A linear dc machine is about the simplest and easiest-to-understand version of a dc machine, yet it operates according to the same principles and exhibits the same behavior as real generators and motors. It thus serves as a good starting point in the study of machines.

A linear dc machine is shown in the previous figure. It consists of a battery and a resistance connected through a switch to a pair of smooth, frictionless rails. Along the bed of this "railroad track" is a constant, uniform-density magnetic field directed into the page. A bar of conducting metal is lying across the tracks.

How does such a strange device behave? Its behavior can be determined from an application of four basic equations to the machine. These equations are:

1. The equation for the force on a wire in the presence of a magnetic field:

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

where **F** = force on wire
i = magnitude of current in wire
l = length of wire, with direction ofl defined to be in the direction of current flow
B = magnetic flux density vector

2. The equation for the voltage induced on a wire moving in a magnetic field:

$$e_{\text{ind}} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

where e_{ind} = voltage induced in wire
v = velocity of the wire
B = magnetic flux density vector
l = length of conductor in the magnetic field

3. Kirchhoff's voltage law for this machine. And this law gives

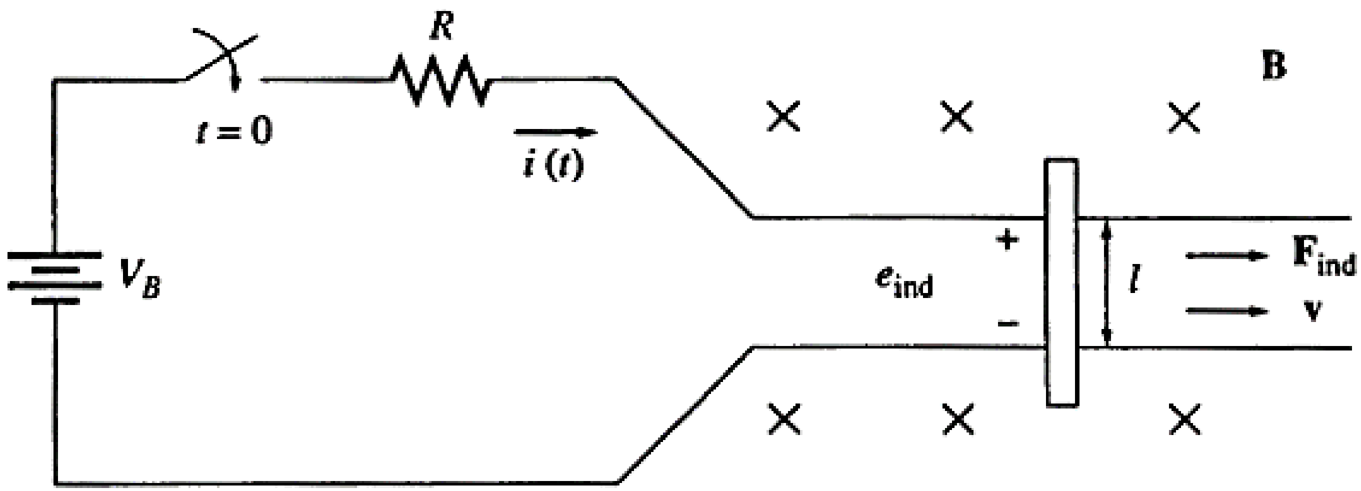
$$V_B - iR - e_{\text{ind}} = 0$$

$$V_B = e_{\text{ind}} + iR = 0$$

4. Newton's law for the bar across the tracks:

$$F_{\text{net}} = ma$$

Starting a linear DC machine



Starting a linear DC machine

1. Current

$$i = \frac{V_B - e_{ind}}{R}$$

2. Induced force

$$F_{\text{ind}} = ilB \quad \text{to the right}$$

3. Induced voltage

$$e_{\text{ind}} = vBl \quad \text{positive upward}$$

$$i \downarrow = \frac{V_B - e_{\text{ind}} \uparrow}{R}$$

Starting a linear DC machine

The result of this action is that eventually the bar will reach a constant steady-state speed where the net force on the bar is zero. This will occur when e_{ind} has risen all the way up to equal the voltage V_B. At that time, the bar will be moving at a speed given by

$$V_B = e_{\text{ind}} = v_{\text{ss}} Bl$$

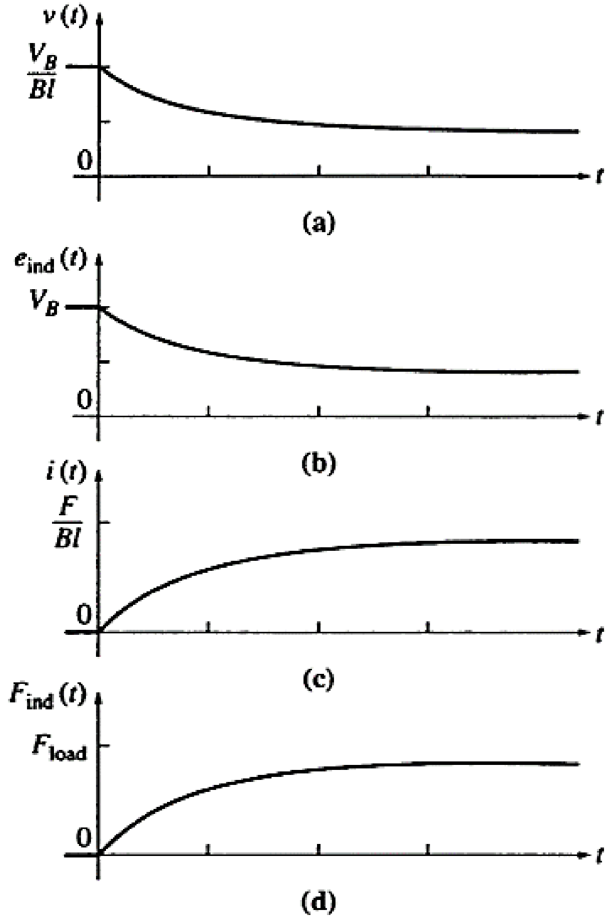
$$v_{ss} = \frac{V_B}{Bl}$$

The bar will continue to coast along at this no-load speed forever unless some ex-ternal force disturbs it. When the motor is started, the velocity v, induced voltage e_{ind} , current i, and induced force Find are as sketched previously.

Summarize of a dc machine starting

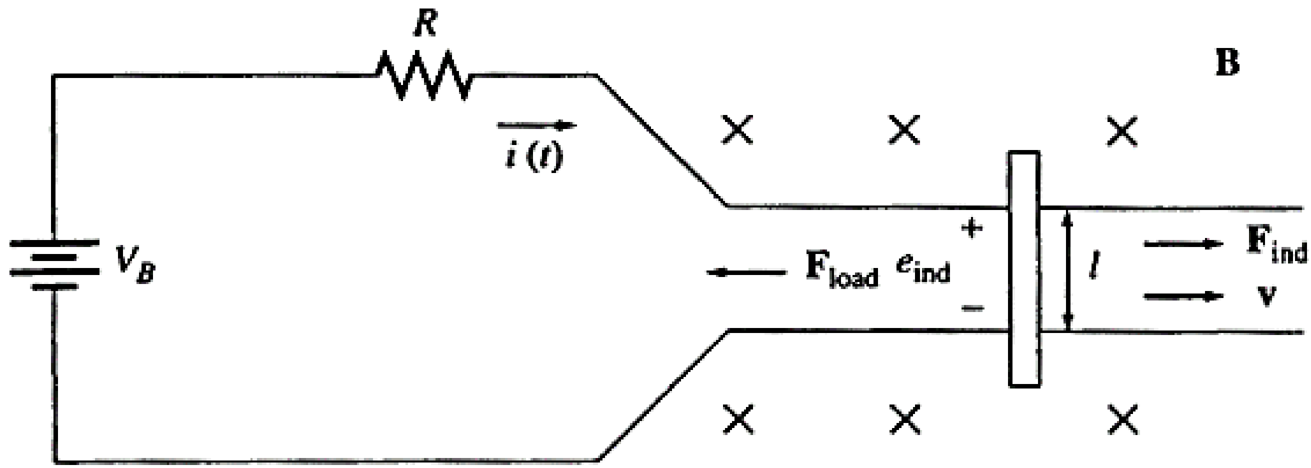
1. Closing the switch produces a current flow $i = V_B/R$
2. The current flow produces a force on the bar given by $F = ilB$
3. The bar accelerates to the right, producing an induced voltage e_{ind} as it speeds up.
4. This induced voltage reduces the current flow $i= (V - e_{ind})/R$.
5. The induced force is thus decreased ($F = iIB$) until eventually $F = 0$. At that point, $e_{ind} = V_B$, $i = 0$, and the bar moves at a constant no-load speed $V_{ss} = V_B/Bl$

DC linear machine operates at no-load condition



Linear dc motor

- While the load is applied



- The conversion power between mechanical and electrical

$$P_{\text{conv}} = e_{\text{ind}}\, i = F_{\text{ind}}\, v$$

Summarize of a dc motor operation

1. A force F_{load} is applied opposite to the direction of motion, which causes a net force F_{net} opposite to the direction of motion.

2. The resulting acceleration $a == F_{net} /m$ is negative, so the bar slows down ($v\downarrow$).

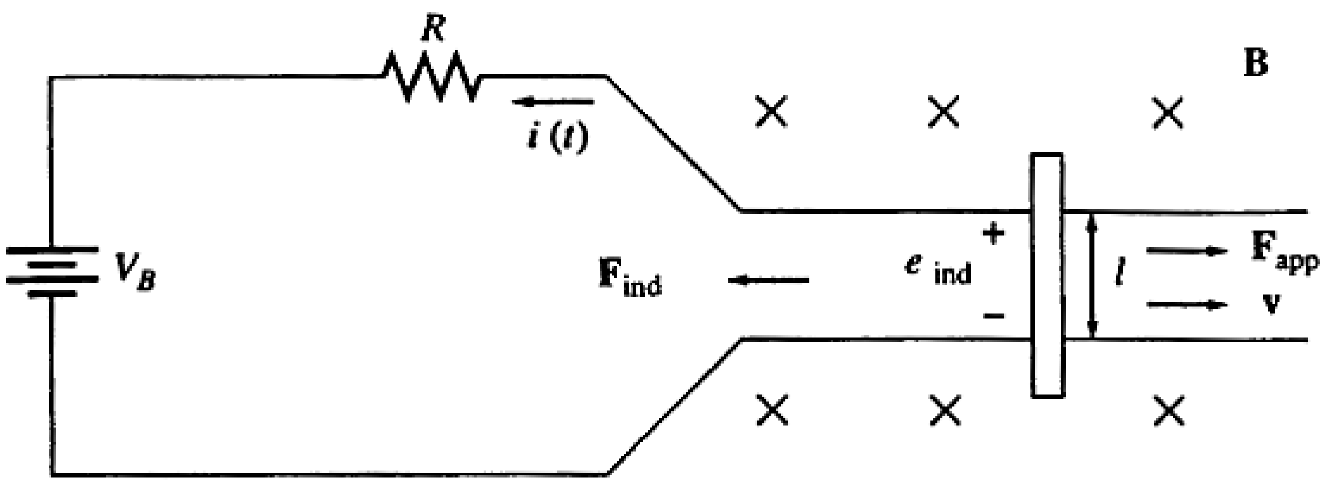
3. The voltage $e_{ind} = v\downarrow Bl$ falls, and so $i = (V_B - e_{ind}\downarrow)/R$ increases.

4. The induced force $F_{ind} = i\uparrow lB$ increases until $|F_{ind}|= |F_{load}|$ at a lower speed v.

5. An amount of electric power equal to $e_{ind}i$ is now being converted to mechanical power equal to $F_{ind}v$, and the machine is acting as a motor.

Linear dc generator

- While the external force is applied on the moving direction



$$P_{\text{conv}} = \tau_{\text{ind}}\,\omega$$

Summarize of a dc generator operation

1. A force F_{app} is applied in the direction of motion; F_{net} is in the direction of motion.
2. Acceleration $a = F_{net}/m$ is positive, so the bar speeds up (v↑).
3. The voltage $e_{ind} = i{\uparrow}Bl$ increases, and so $i = (eind{\uparrow}$-$V_B)/R$ increases.
4. The induced force $F_{ind} = i{\uparrow}lB$ increases until $|F_{ind}|= |F_{load}|$ at a higher speed v.
5. An amount of mechanical power equal to $F_{ind}v$ is now being converted to electric power $e_{ind}i$, and the machine is acting as a generator.

Example 1-10

The linear dc machine shown in the figure below has a battery volt-age of 120 V, an internal resistance of 0.3 , and a magnetic flux density of 0.1 T.

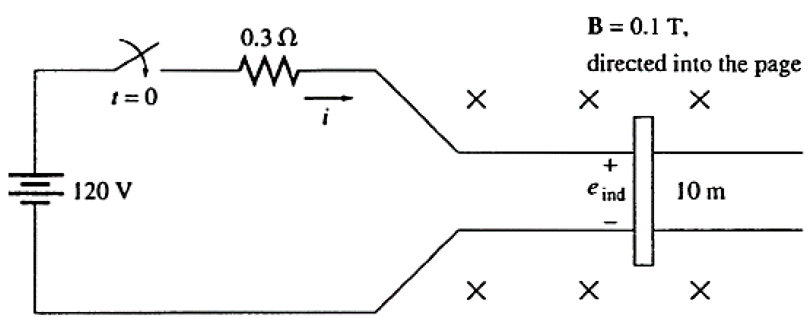
(a) What is this machine's maximum starting current? What is its steady-state velocity at no load?

(b) Suppose that a 30-N force pointing to the right were applied to the bar. What would the steady-state speed be? How much power would the bar be producing or consuming? How much power would the battery be producing or consuming? Explain the difference between these two figures. Is this machine acting as a motor or as a generator?

(c) Now suppose a 30-N force pointing to the left were applied to the bar, What would the new steady-state speed be? Is this machine a motor or a generator now?

(d) Assume that a force pointing to the left is applied to the bar. Calculate speed of the bar as a function of the force for values from 0 N to 50 N in 10-N steps. Plot the velocity of the bar versus the applied force.

(e) Assume that the bar is unloaded and that it suddenly runs into a region where the magnetic field is weakened to 0.08 T. How fast will the bar go now?



(a)

(a) At starting conditions, the velocity of the bar is 0, so $e_{ind} = 0$. Therefore,

$$i = \frac{V_B - e_{\text{ind}}}{R} = \frac{120\text{V} - 0\text{V}}{0.3\Omega} = 400\text{A}$$

When the machine reaches steady state, $F_{ind} = 0$ and $i = 0$. Therefore,

$$\begin{aligned} VB &= e_{\text{ind}} = v_{ss} Bl \\ v_{\text{ss}} &= \frac{V_B}{Bl} \\ &= \frac{120\text{V}}{(0.1\text{T})(10\text{m})} = 120\text{m/s} \end{aligned}$$

(b) If a 30-N force to the right is applied to the bar, the final steady state will occur when the induced force F_{ind} is equal and opposite to the applied force F_{app}, so that the net force on the bar is zero:

$$F_{\text{app}} = F_{\text{ind}} = ilB$$

Therefore,

$$\begin{aligned} i &= \frac{F_{\text{ind}}}{lB} = \frac{30\text{N}}{(10\text{m})(0.1\text{T})} \\ &= 30\text{A} \quad \text{flowing up through the bar} \end{aligned}$$

The induced voltage e_{ind} on the bar must

$$\begin{aligned} e_{\text{ind}} &= V_B + iR \\ &= 120\text{V} + (30\text{A})(0.3\Omega) = 129\text{V} \end{aligned}$$

and the final steady-state speed must be

$$\begin{aligned} v_{\text{ss}} &= \frac{e_{\text{ind}}}{Bl} \\ &= \frac{129\text{V}}{(0.1\text{T})(10\text{m})} = 129\text{m/s} \end{aligned}$$

The bar is producing $P = (129\ V)(30\ A) = 3870$ W of power, and the battery is consuming P =(120 V)(30 A) = 3600 W. The difference between these two numbers is the 270 W of losses in the resistor. This machine is acting as a *generator*.

(c) This time, the force is applied to the left, and the induced force is to the right. At steady state,

$$\begin{aligned} F_{\text{app}} &= F_{\text{ind}} = ilB \\ i &= \frac{F_{\text{ind}}}{lB} = \frac{30\text{N}}{(10\text{m})(0.1\text{T})} \\ &= 30\text{A} \quad \text{flowing down through the bar} \end{aligned}$$

The induced voltage e_{ind} on the bar must be

$$\begin{aligned} e_{\text{ind}} &= V_B - iR \\ &= 120\text{V} - (30\text{A})(0.3\Omega) = 111\text{V} \end{aligned}$$

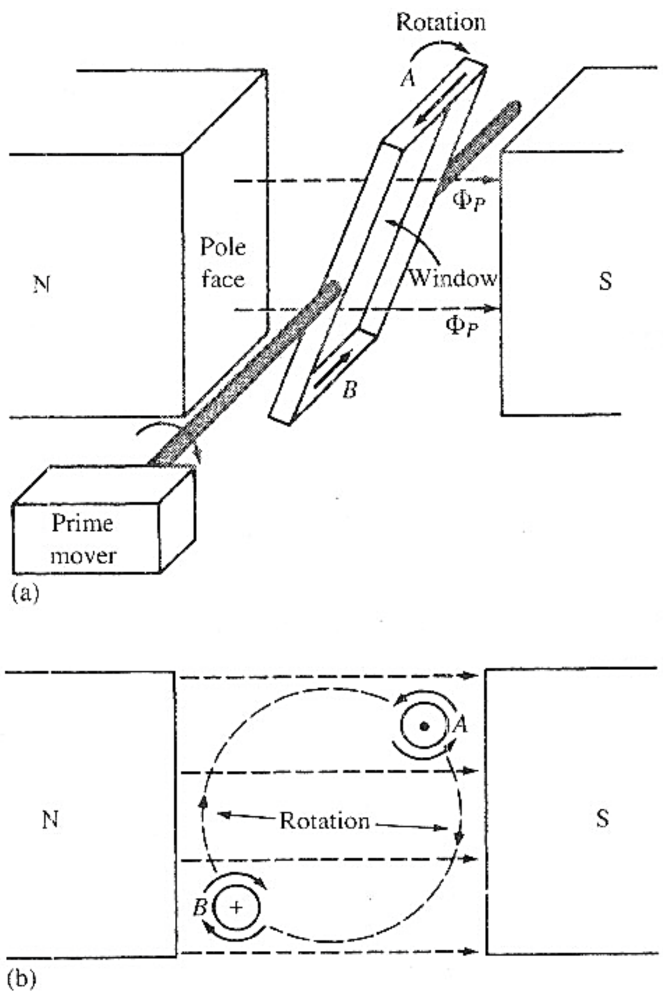
and the final speed must be

$$\begin{aligned} v_{\text{ss}} &= \frac{e_{\text{ind}}}{Bl} \\ &= \frac{111\text{V}}{(0.1\text{T})(10\text{m})} = 111\text{m/s} \end{aligned}$$

This machine is now acting as a motor, converting electric energy from the battery into mechanical energy of motion on the bar.

(e) If the bar is initially unloaded, then $e_{ind} = V_B$. If the bar suddenly hits a region of weaker magnetic field, a transient will occur. Once the transient is over, though, e_{ind} will again equal V_B

Sinusoidal current flow from motion



When a closed coil as seen to the left in a magnetic field is driven continuously, the current is created by generator action and for every 360º of rotation, the current changes direction twice. The flux field seen by the conductors varies in a sinusoidal fashion from zero when moving horizontally to maximum Φ.

$$\phi = \phi_{\max} \sin(wt)$$

The rate of rotation is *w* in radians

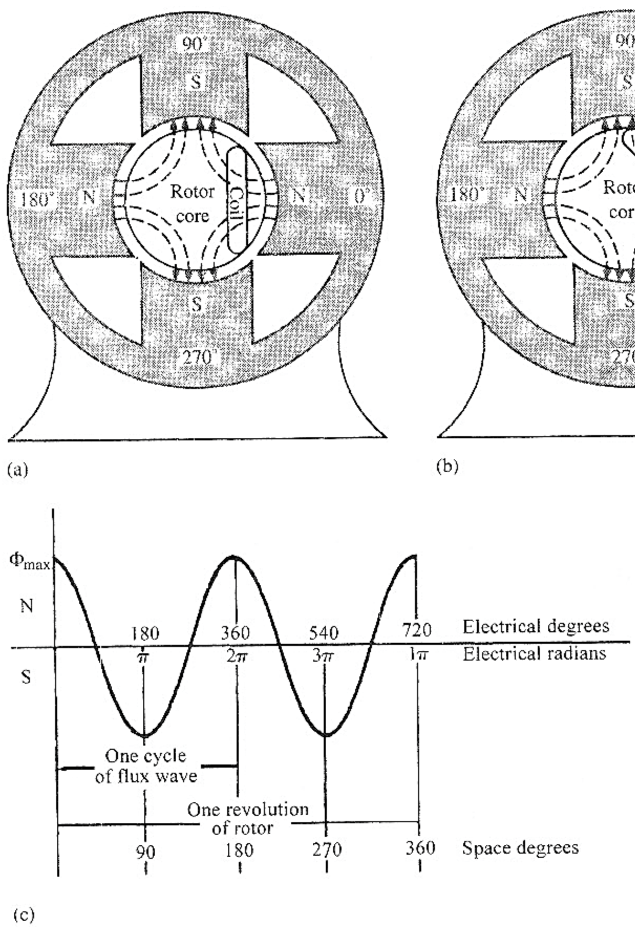
The voltage created is

$$E_{\max} = 2\pi f N \phi_{\max}$$

and is a sinusoidal waveform.

$$E_{rms} = 4.44 f N \phi_{\max}$$

Force multiplier: multiple poles



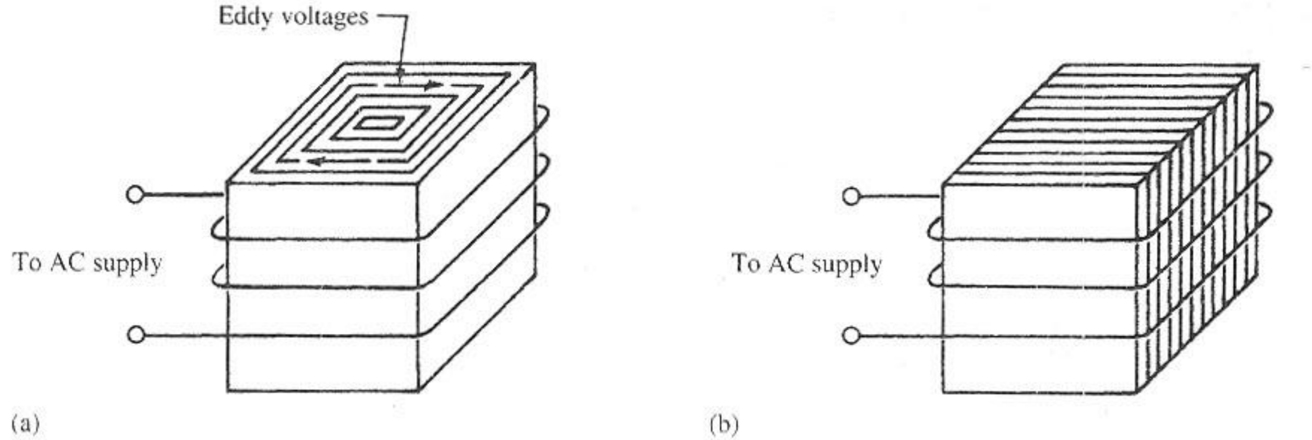
With multiple poles additional cycles are created by generator action provided the windings are properly positioned. The frequency created in one rotation is ½ the number of poles.

$$cycles = P_n/2$$

Multiply this value by the number of rotations in a second to get the frequency generated in Hertz. The position of the poles around the rotor are known as space degrees. The cycles are known as electrical degrees and can exceed 360º.

Flux power losses

While a coil generates flux flowing through an iron core, it also creates circular currents flowing in the material in the same pattern as the winding. These are called eddy currents. Naturally, a flowing current uses power. A solution to reduce eddy losses is to used insulated sheet metal for the core.



(a) Eddy currents in solid iron core, (b) laminated core.

This power loss is calculated using

$$P_e = k_e f^2 B^2_{max} \text{ (Watts/unit mass)}$$

k_e = constant
f = frequency of flux wave in Hertz
B_{max}= maximum value of flux density wave in Teslas

Reactive power Q and apparatus power S

1. Reactive power Q (var) is defined from instantaneous power

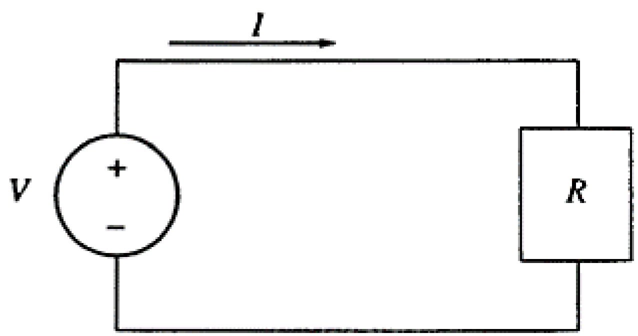
$$Q = VI\sin\theta$$

1. Apparatus power S (VA) is defined to represent the product of voltage and current magnitudes

$$S = V\ I$$

Real, reactive and apparatus power in AC circuits

- Power in DC circuit

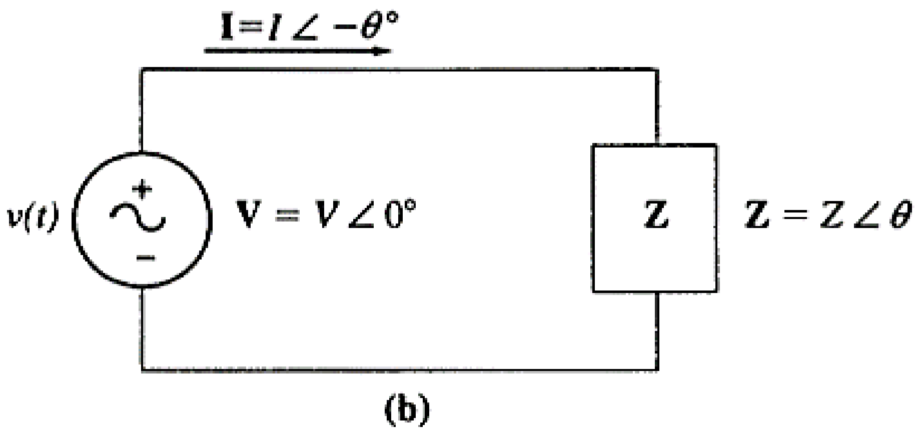


(a)

$$P = V\ I$$

Real, reactive and apparatus power in AC circuits

- AC source applies power to an impedance Z



$$
\begin{aligned}
v(t) &= \sqrt{2}V\cos\omega t \\
i(t) &= \sqrt{2}I\cos(\omega t-\theta)
\end{aligned}
$$

Instantaneous power

The instantaneous power supplied to this load at any time t

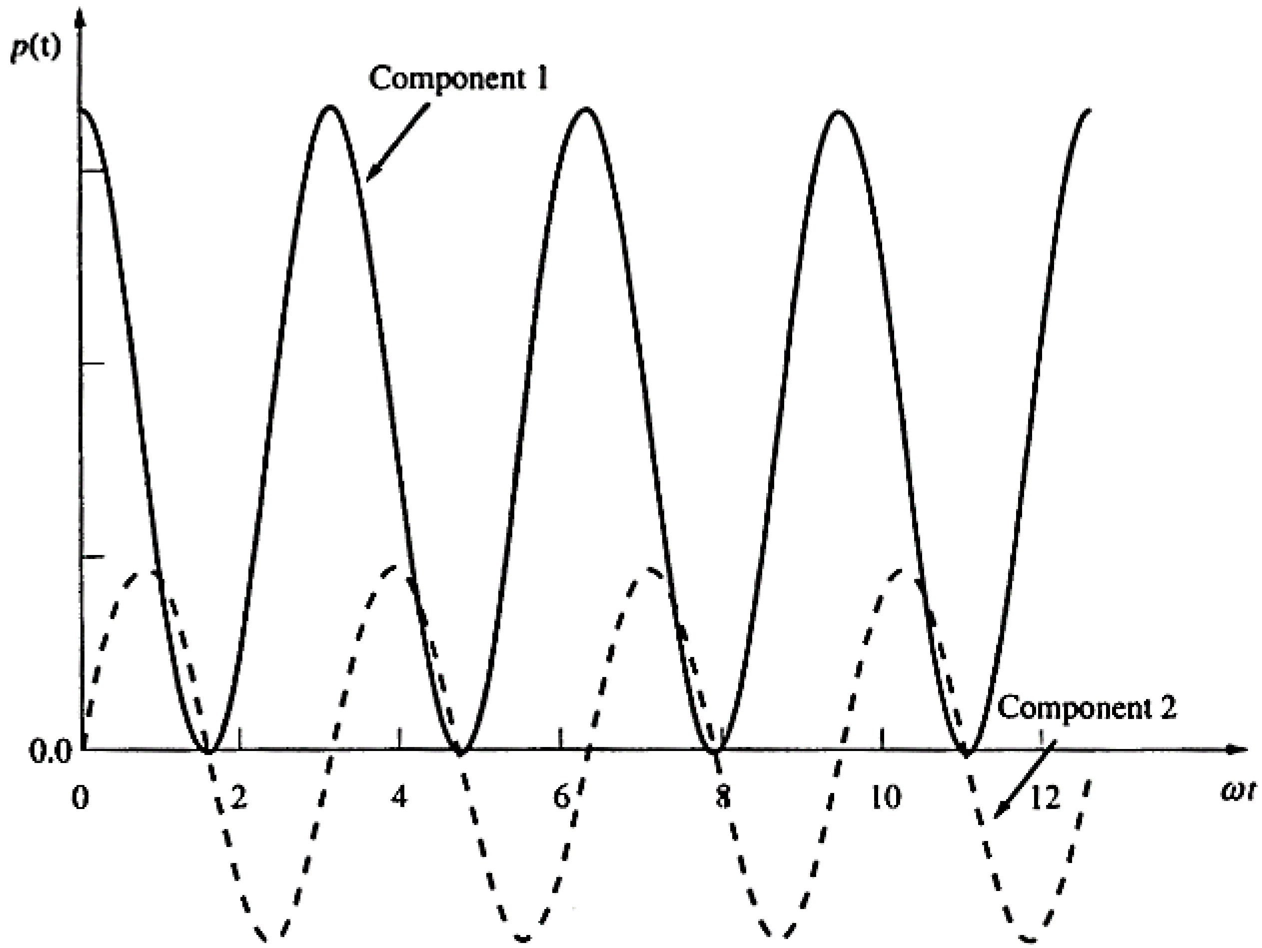
$$p(t) = v(t)i(t) = 2VI\cos\omega t\cos(\omega t - \theta)$$

The angle θ in this equation is the impedance angle of the load. For inductive loads, the impedance angle is positive, and the current waveform lags the voltage waveform by θ degrees.

If we apply trigonometric identities to previous equation, it can be manipulated into an expression of the form

$$p(t) = VI\cos\theta(1+\cos 2\omega t) + VI\sin\theta\sin 2\omega t$$

Instantaneous power



Average power and reactive power

Note that the *first* term of the instantaneous power expression is always positive, but it produces pulses of power instead of a constant value. The average value of this term is

$$P = VI\, cos\theta$$

which is the *average* or *real* power (P) supplied to the load by term 1 of the Equation (1-59). The units of real power are watts (W), where 1 W = 1 V X 1 A.

Note that the second term of the instantaneous power expression is positive half of the time and negative half of the time, so that *the average power supplied by this term is zero*. This term represents power that is first transferred from the source to the load, and then returned from the load to the source. The power that continually bounces back and forth between the source and the load is known as *reactive power* (Q). Reactive power represents the energy that is first stored and then released in the magnetic field of an inductor, or in the electric field of a capacitor.

Alternative Forms of the Power Equations

If a load has a constant impedance, then Ohm's law can be used to derive alternative expressions for the real, reactive, and apparent powers supplied to the load. Since the magnitude of the voltage across the load is given by

$$V = IZ$$

substituting this into previous equations produces equations for real, reactive, and apparent power expressed in terms of current and impedance

$$\begin{aligned} P &= I^2 Z \cos\theta \\ Q &= I^2 Z \sin\theta \\ S &= I^2 Z \end{aligned}$$

where |Z| is the magnitude of the load impedance Z.

Since the impedance of the load Z can be expressed as

$$Z = R + jX = |Z|\cos\theta + j|Z|\sin\theta$$

we see from this equation that $R = |Z|\ cos\theta$ and $X = |Z|\ sin\theta$ so the real and reactive powers of a lad can also be expressed as

$$P = I^2 R$$

$$Q = I^2 X$$

where R is the resistance and X is the reactance of load Z

Complex power representation

For simplicity in computer calculations, real and reactive power are sometimes represented together as a complex power S, where

$$\boldsymbol{S}=P+jQ$$

The complex power **S** supplied to a load can be calculated from the equation

$$\boldsymbol{S} = \boldsymbol{V}\boldsymbol{I}^*$$

where the asterisk represents the complex conjugate operator.

Complex power representation

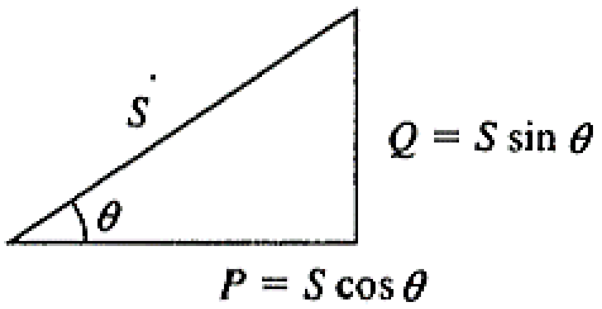
To understand this equation, let's suppose that the voltage applied to a load is $\mathbf{V} = V\angle\alpha$ and the current through the load is $\mathbf{I} = I\angle\beta$. Then the complex power supplied to the load is

$$\begin{aligned}\mathbf{S} &= \mathbf{VI^*} = (V\angle\alpha)(I\angle-\beta) = VI\angle(\alpha-\beta) \\ &= VI\cos(\alpha-\beta) + jVI\sin(\alpha-\beta)\end{aligned}$$

The impedance angle is the difference between the angle of the voltage and the angle of the current ($\theta=\alpha$-β), so this equation reduces to

$$\begin{aligned}\mathbf{S} &= VI\cos\theta + jVI\sin\theta \\ &= P + jQ\end{aligned}$$

Power factor



$$\cos\theta = \frac{P}{S}$$

$$\sin\theta = \frac{Q}{S}$$

$$\tan\theta = \frac{Q}{P}$$

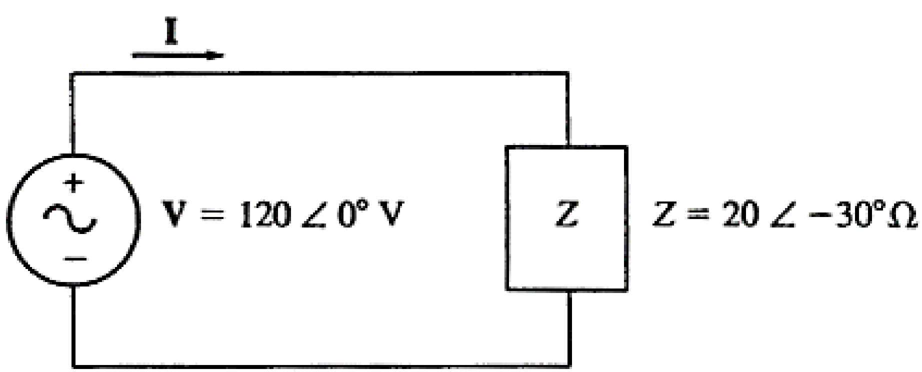
The quantity cosθ is usually known as the power factor of a load. The power factor is defined as the fraction of the apparent power S that is actually supplying real power to a load. Thus,

$$PF = \cos\theta$$

where 0 is the impedance angle of the load.

Example 1-11

Figure below shows an ac voltage source supplying power to a load with impedance Z = 20∠-30°Ω . Calculate the current **I** supplied to the load, the power factor of the load, and the real, reactive, apparent, and complex power supplied to the load.



The current supplied to this load is

$$\mathbf{I} = \frac{\mathbf{V}}{Z} = \frac{120\angle 0^{\circ}\,\mathrm{V}}{20\angle -30^{\circ}\,\Omega} = 6\angle 30^{\circ}\,\mathrm{A}$$

The power factor of the load is

$$\mathrm{PF} = \cos\theta = \cos\left(-30^{\circ}\right) = 0.866 \text{ leading}$$

(Note that this is a capacitive load, so the impedance angle θ is negative, and the current leads the voltage.)

The real power supplied to the load is

$$P = VI\cos\theta$$

$$P = (120\mathrm{V})(6\mathrm{A})\cos\left(-30^{\circ}\right) = 623.5\mathrm{W}$$

The reactive power supplied to the load is

$$Q = VI\sin\theta$$

$$Q = (120\mathrm{V})(6\mathrm{A})\sin\left(-30^{\circ}\right) = -360\mathrm{VAR}$$

The apparent power supplied to the load is

$$S = VI$$
$$Q = (120\text{V})(6\text{A}) = 720\text{VA}$$

The complex power supplied to the load is

$$S = VI^*$$
$$= \left(120\angle 0^\circ\,\text{V}\right)\left(6\angle -30^\circ\,\text{A}\right)^*$$
$$= \left(120\angle 0^\circ\,\text{V}\right)\left(6\angle 30^\circ\,\text{A}\right) = 720\angle 30^\circ\,\text{VA}$$
$$= 623.5 - j360\text{VA}$$

Introduction to machinery principles

1. Rotation motion, Newton’s law and power relationships
2. The magnetic field
3. Faraday’s law
4. Produce an induced force on a wire
5. Produce an induced voltage on a conductor
6. Linear dc machine examples
7. Real, reactive and apparatus power in AC circuits