EEE 321

Electromechanical Energy Conversion – I

By

Prof. Dr. A. Mete VURAL

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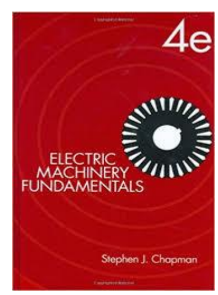
References

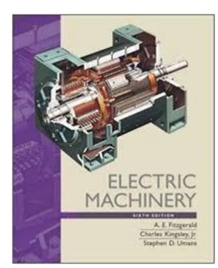
- Electric Machinery Fundamentals, Stephen Chapman, *4th Edition,* McGraw-Hill

(Course Book)



- Electric Machinery, A.E. Fitzgerald, Charles Kingsley, JR., Stephen D. Umans, *6th Edition, McGraw-Hill*

(Supplementary Book)



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Contents

Grading Policy

- Midterm-1 : **20%**
- Midterm-2 : **20%**
- Lab : **20%**
- Final : **40%**
- TOTAL : **100%**

✓Exams are closed-book

✓Homework(s)/Project can be assigned during the semester

(The performances of the students will be included into the grading policy)

✓Attendance is minimum 70% to class

✓Attendance is minimum 80% to laboratory works

*Students who has registered to EEE 321 **MUST follow** the web page of Dr. A. Mete VURAL for all announcements and getting other course related materials.*

http://eee.gantep.edu.tr/pages.php?url=akademik-personel-2

Some Advices !

- Keep attendance as much as poosible ! (70% or more)
- Take your own notes
- Practice is good. Do it as much as possible
- Do not try to summarize, try to learn the fundamental idea
- Solve examples, problems as many as possible
- Make your study plan by yourself
- Know yourself ! Study alone or within a group
- Do not postpone anything ! Do it now

Lecture Plan

- **1st Education:**
  - 09:30 → Lecture Begins
  - 10:30 → 1st hour ends
  - 10:45 → 2nd hour begins
  - 12:00 → 2nd hour ends

60 minutes LECTURE

15 minutes BREAK

75 minutes LECTURE

A Total of 135 minutes LECTURE

EEE 321 is a 3 hours course:

3 x 45 minutes = 135 minutes

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Lecture Plan

- **2nd Education:**
  - 17:00 → Lecture Begins
  - 18:00 → 1st hour ends
  - 18:15 → 2nd hour begins
  - 19:30 → 2nd hour ends

60 minutes LECTURE

15 minutes BREAK

75 minutes LECTURE

A Total of 135 minutes LECTURE

EEE 321 is a 3 hours course:

3 x 45 minutes = 135 minutes

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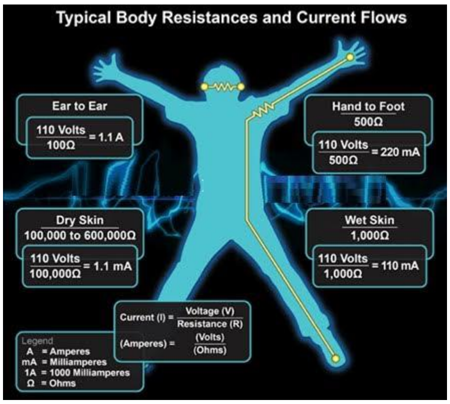
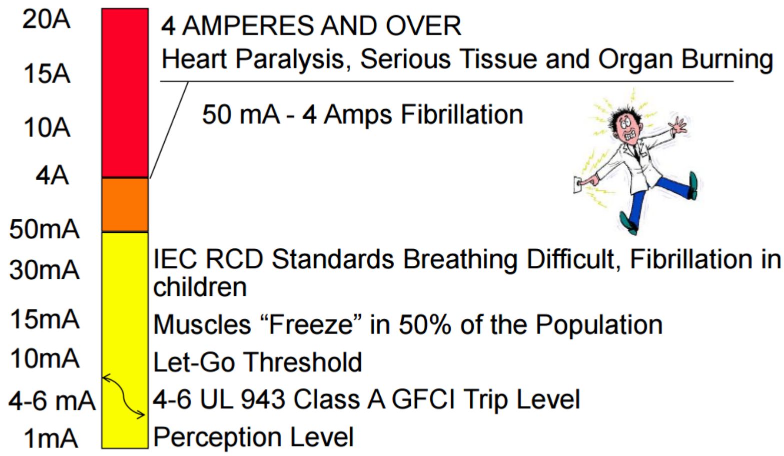
Effects of Electrical Shock





Source: http://www.nema.org

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The Prefixes Used with SI Units

Prefix	Symbol	Meaning	Scientific Notation
exa-	E	1,000,000,000,000,000,000	10^{18}
peta-	P	1,000,000,000,000,000	10^{15}
tera-	T	1,000,000,000,000	10^{12}
giga-	G	1,000,000,000	10^{9}
mega-	M	1,000,000	10^{6}
kilo-	k	1,000	10^{3}
hecto-	h	100	10^{2}
deka-	da	10	10^{1}
—	—	1	10^{0}
deci-	d	0.1	10^{-1}
centi-	c	0.01	10^{-2}
milli-	m	0.001	10^{-3}
micro-	µ	0.000 001	10^{-6}
nano-	n	0.000 000 001	10^{-9}
pico-	p	0.000 000 000 001	10^{-12}
femto-	f	0.000 000 000 000 001	10^{-15}
atto-	a	0.000 000 000 000 000 001	10^{-18}

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Greek alphabet letters used as symbols in electrical engineering

UPPER CASE

Α α	alpha	Ν ν	nu
Β β	beta	Ξ ξ	ksi
Γ γ	gamma	Ο ο	omicron
Δ δ	delta	Π π	pi
Ε ε	epsilon	Ρ ρ	rho
Ζ ζ	zeta	Σ σς	sigma
Η η	eta	Τ τ	tau
Θ θ	theta	Υ υ	upsilon
Ι ι	iota	Φ φ	phi
Κ κ	kappa	Χ χ	chi
Λ λ	lambda	Ψ ψ	psi
Μ μ	mu	Ω ω	omega

lower case

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English unit vs SI unit

English Unit	SI Unit	Conversion
Mile	Kilometer	1 mile = 1.609 Km
Foot	Meter	1 ft = .305 M
Inch	Centimeter	1 inch = 2.54 Cm
Pound	Grams	1 lb = 453.59 G
Ounce	Grams	1 oz = 28.35 G
Gallon	Liter	1 gallon = 3.79 L
Celsius	Kelvin	0 Degree C = 273.15 K

Torque unit conversion

lb-ft to Nm: 1 lb-ft Convert 1.356 Nm

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CHAPTER 1

INTRODUCTION TO MACHINERY PRINCIPLES

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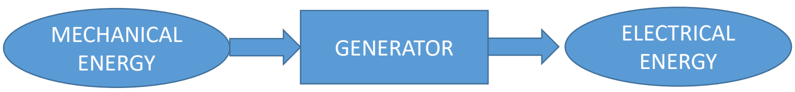
Definition of "Electrical Machine"

- An **electrical machine** is a device that converts either **mechanical energy** to **electrical energy** or vice versa.

- **Generator** is a device that converts **mechanical energy** to **electrical energy.**



- **Motor** is a device that converts **electrical energy** to **mechanical energy.**

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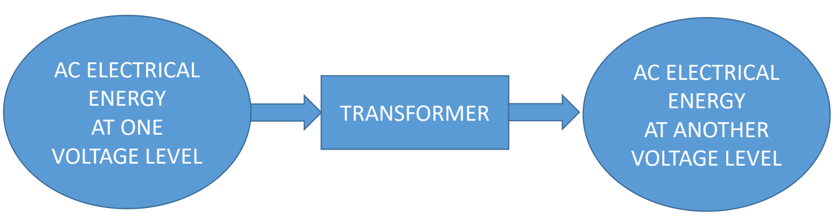
Definition of "Electrical Machine"

- **Transformer** is a device that converts ac electrical energy/power at **one voltage level** to ac electrical energy/power at **another voltage level**.



- ***Why is transformer an electrical machine ?***

Because transformers operate on the same principles as generators and motors, depending on the action of a **magnetic field** to accomplish the change in voltage level.

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Why are motors/generators/transformers are frequently used in modern daily life ?







Why are motors/generators/transformers are frequently used in modern daily life ?

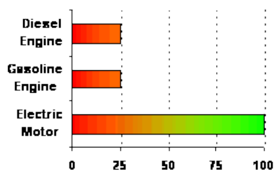
<u>The answer is simple:</u>

Electrical power is a **clean** and **efficient energy source** that is easy to transmit over long distances, and easy to control.



Why are motors/generators/transformers are frequently used in modern daily life ?

- An electric motor has **higher efficiency** when compared to internal-combustion engine.



Efficiency (%)

- An electric motor **does not need strong constant ventilation** (air/water) when compared to internal-combustion engine.

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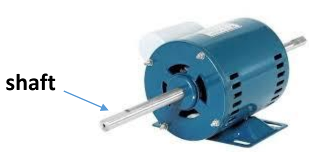
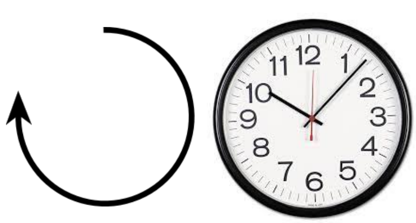
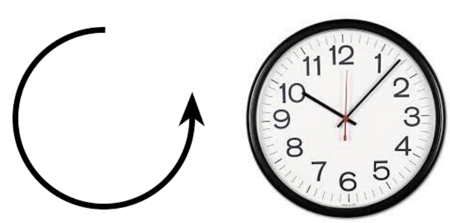
Rotational motion





Clockwise (CW)
Negative direction (-)



Counterclockwise (CCW)
Positive direction (+)

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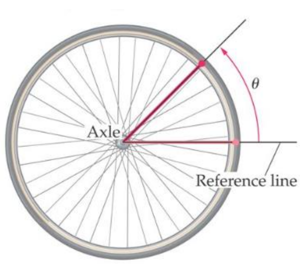
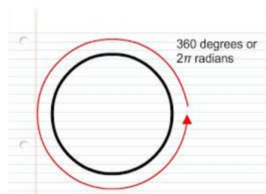
Angular position

- The **angular position (θ)** of an object is the angle at which it is oriented, measured from some arbitrary reference point.
- Angular position is usually measured in **radians or degrees**.
- Angular position corresponds to the linear concept of distance along a line.





2π radians = **360**° degrees

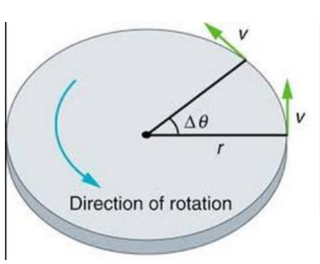
$$\text{Radians} = \left(\frac{\pi}{180^0}\right) \times \text{degrees}$$

$$\text{Degrees} = \left(\frac{180^0}{\pi}\right) \times \text{radians}$$

Angular velocity

The **angular velocity (or speed) (w)** of an object is the rate of change in angular position with respect to time.

- It is assumed **positive** if the rotation is in a **counterclockwise (CCW) direction**.
- It is assumed **negative** if the rotation is in a **clockwise (CW) direction**.
- Angular velocity is the rotational analog of the concept of velocity on a line.
- Angular velocity is usually measured in **radians/s or degrees/s**.



w → Angular velocity (rad/s)

v → Linear velocity (m/s)

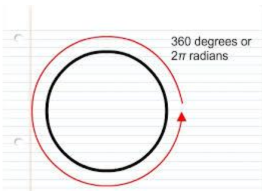
r → Radius of rotation (m)

$$w = \frac{d\theta}{dt}$$

$$w = \frac{v}{r}$$

Angular velocity

- In dealing with ordinary electric machines, engineers often use the unit of "**revolutions per minute (rpm) or (rev/min)**" instead of using "**radians per second**" to describe the **shaft speed**.



If there are ***n*** revolutions per minute

→ $\boldsymbol{2\pi n}$ radians (*travelled distance*) per minute → $\boldsymbol{2\pi n}$ radians (*travelled distance*) per **60 seconds** → $\boldsymbol{2\pi n/60}$ radians (*travelled distance*) per **1 second**

Example: Calculate the shaft speed of an electric motor in **rad/s** if the shaft speed is **1000 rpm (or rev/min)** ?

→ solution

Speed = $\frac{\mathbf{2\pi(1000)}}{\mathbf{60}} = \mathbf{104.7197}\ \boldsymbol{rad/s}$

Angular acceleration

- **Angular acceleration (α)** is the rate of change in angular velocity with respect to time.
- It is assumed **positive** if the angular velocity is **increasing** in an algebraic sense.
- **Angular acceleration** is the rotational analog of the concept of acceleration on a line.
- The unit of **angular acceleration** is **rad/s²**

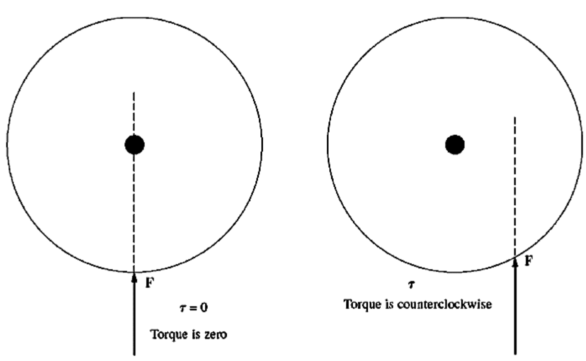
$$\alpha = \frac{dw}{dt}$$

Torque

- In linear motion, a force applied to an object causes its velocity to change. In the absence of a net force on the object, its velocity is constant or the object is stationary.
- The greater the force applied to the object, the more rapidly its velocity changes.
- There exists a similar concept for rotational motion: When an object is rotating, its angular velocity is constant unless a torque is present on it.
- The greater the torque on the object, the more rapidly the angular velocity of the object changes.

Torque

- In figure (a), a force applied to a cylinder so that it passes through the axis of rotation, so torque is **zero**.
- In figure (b), a force applied to a cylinder so that its line of action misses the axis of rotation. Here torque is **not zero** and it is in counterclockwise (**CCW**) direction.



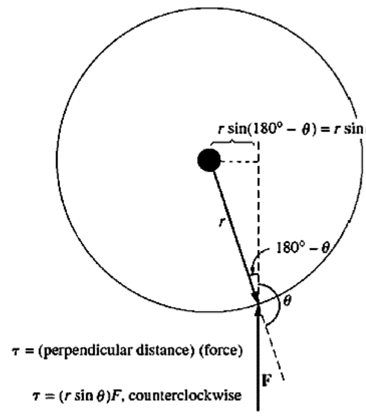
No rotation

Rotation

Torque is a measure of the force that can cause an object to rotate about an axis.

Torque

- The torque on an object is defined as the product of the force applied on the object and the perpendicular distance between the line of the applied force and the center of rotation.
- Torque is generally represented by the symbol **"τ"**
- The unit of torque is **(Newton) x (meter) ➔ Nm**



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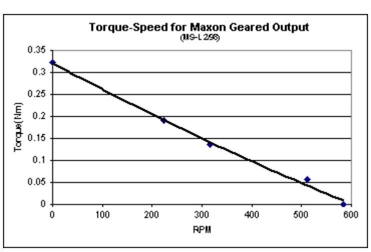
Torque

Typical Torque-speed curve of a DC motor (shown at right)



Source: http://lancet.mit.edu/motors/motors3.html

Source: http://lancet.mit.edu/motors/motors1.html

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Newton's law of rotation

- Newton's law for objects moving **along a straight line** describes the relationship between the force applied to an object and its resulting acceleration. This relationship is given by the equation:

$$F = ma$$

where,
F is the net force applied to an object (N)
m is the mass of the object (kg)
a is the resulting acceleration of the object (m/s^2)

- The similar idea can be thought for the **rotating objects:**

$$\tau = J\alpha$$

where,
τ is the net torque applied to an object (Nm)
J is the "**moment of inertia**" of the object (kg.m^2)
α is the resulting angular acceleration of the object (rad/s^2)

Moment of inertia: A quantity expressing a body's tendency to resist angular acceleration

Newton's law of rotation

Motor data			
Pole number	2p		6
Torque constant (100 K)	k_T	Nm/A	0.835
Voltage constant (at 20 °C)	k_E	V/1000 rpm	53.0
Winding resistance (at 20 °C)	R_{ph}	Ω	0.815
Rotating field inductance	L_D	mH	10.2
Electrical time constant	T_{el}	ms	12.5
Mechanical time constant	T_{mech}	ms	0.44
Thermal time constant	T_{th}	min	45
Moment of inertia	J_{Mot}	kgm^2	$0.126 \cdot 10^{-3}$
Shaft torsional stiffness	c_t	Nm/rad	9800
Weight without brake	m_{Mot}	kg	7.4

Source: https://electronics.stackexchange.com

Parameter		Value
Armature resistance	R_a	8.91 Ω
Armature inductivity	L_a	4.5 mH
Moment of inertia	J_e	2.93e-5 kg m^2
Coefficient of viscous friction	F_e	11.7e-5 kg m^2/rad/s
Electromechanical constant	k_{em}	0.103 Nm/A
Mechanical-electrical constant	k_{me}	0.103 V/rad/s
Tacho constant	k_{tg}	0.0191 V/rad/s

Source: https://www.researchgate.net/publication/268654073_Fuzzy_Model_Reference_Adaptive_Control_of_Velocity_Servo_System/figures?lo=1

Work

- For **linear motion**, work is defined as the application of a force through a distance:

$$W = \int F.dr$$

- If Force is constant;

$$W = Fr$$

- The unit of work is **Joules (J)**
- For **rotational motion**, work is the application of a torque through an angle:

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

- If Torque is constant;

$$W = \tau\theta$$

Power

- 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 or Watts (W)**, but also can be measured in **horsepower (hp)**:

$$1\ hp = 746\ Watts\ (W)$$

- If **Force** is constant **in linear motion**:

$$P = \frac{dW}{dt} = \frac{d}{dt}(Fr) = F\frac{dr}{dt} = F.v$$

- If **Torque** is constant **in rotational motion:**

$$P = \frac{dW}{dt} = \frac{d}{dt}(\tau\theta) = \tau\frac{d\theta}{dt} = \tau.w$$

Example: Calculate the torque on the shaft of a DC motor if shaft speed is 600 rpm and the motor's output power under this condition is 10 hp.

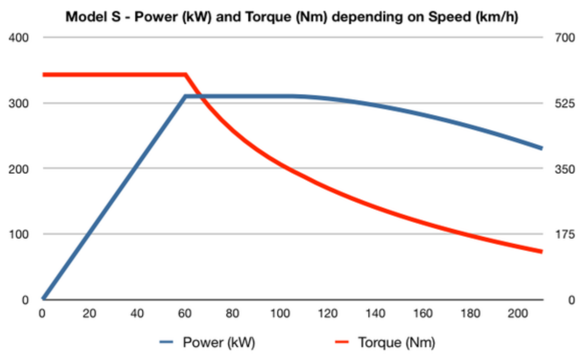
Solution:

$$P = 10hp = 10x746W = 7460W$$

$$w = \frac{2\pi n}{60} = \frac{2\pi(600)}{60} = 62.83\ rad/s$$

$$\tau = \frac{P}{w} = \frac{7460W}{62.83rad/s} = 118.73Nm$$

Torque & Power



Source: https://www.quora.com/

Tesla – Model S

Source: https://www.tesla.com/models

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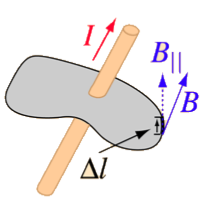
The Magnetic Field

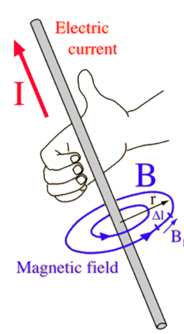
- **Magnetic fields** are the **fundamental mechanism** by which energy is converted from one form to another in **motors**, **generators**, and **transformers.**
- <u>**Four basic principles**</u> describe how magnetic fields are used in these devices:

1) A **current-carrying wire** produces a magnetic field in the area around it. **(Ampere's Law)**



$$\sum B_{||} \Delta l = \mu_0 I$$

Ampere's Law states that for any closed loop path, the sum of the length elements times the magnetic field in the direction of the length element is equal to the permeability times the electric current enclosed in the loop.



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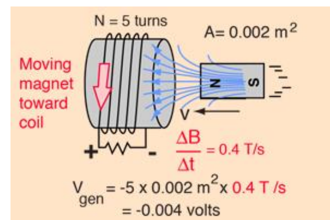
The Magnetic Field

- **Magnetic fields** are the **fundamental mechanism** by which energy is converted from one form to another in **motors**, **generators**, and **transformers.**
- **Four basic principles** describe how magnetic fields are used in these devices:

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

$$\text{Voltage generated} = -N\frac{\Delta(BA)}{\Delta t}$$

Faraday's Law



Note that the polarity of the induced voltage (*e*) is defined such that if the winding terminals were short-circuited, a current would flow in such a direction as to oppose the change of flux linkage.

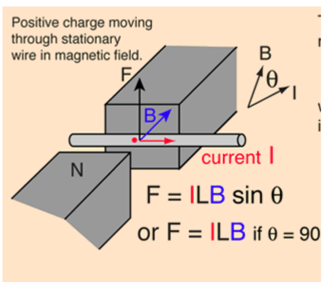
Self-study

- Solve the Example 1-6 at page 31 from Chapman

The Magnetic Field

- **Magnetic fields** are the **fundamental mechanism** by which energy is converted from one form to another in **motors**, **generators**, and **transformers.**
- **Four basic principles** describe how magnetic fields are used in these devices:

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***)



$$\vec{F} = \vec{I}L \times \vec{B}$$

$$F = ILB \sin \theta$$

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Self-study

- Solve the Example 1-7 at page 33 from Chapman

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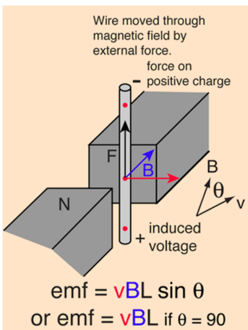
The Magnetic Field

- **Magnetic fields** are the **fundamental mechanism** by which energy is converted from one form to another in **motors**, **generators**, and **transformers.**
- **Four basic principles** describe how magnetic fields are used in these devices:

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



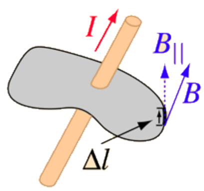
$$e = (v \: x \: B) \: . \: l$$

emf = vBL sin θ
or emf = vBL if θ = 90

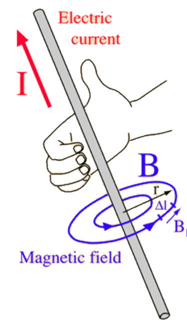
Self-study

- Solve the Example 1-8 at page 34 from Chapman
- Solve the Example 1-9 at page 34 from Chapman

Production of a Magnetic Field



$$\sum B_{||} \Delta l = \mu_0 I$$



Ampere's Law states that for any closed loop path, the sum of the length elements times the magnetic field in the direction of the length element is equal to the permeability times the electric current enclosed in the loop.

$$\oint H.dl = I_{net}$$

H ➡ Magnetic field intensity **(A/m) or (A-turns/m)**

dl ➡ Differential small distance parallel to H **(m)**

I_{net} ➡ Net current through closed path **(A)**

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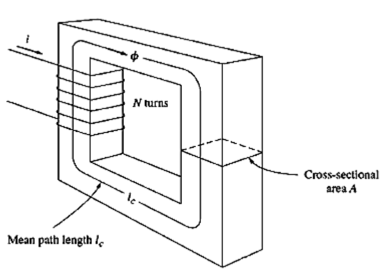
Production of a Magnetic Field



- The core is composed of **iron** or certain other similar metals (collectively called as «**ferromagnetic materials**»)
- We assume that all the magnetic field produced by the current will remain inside the core (**ferromagnetic material is assumed to be <u>perfect</u> or <u>ideal</u>**)

A very simple structure to generate magnetic field

By applying Ampere's law:

$$\oint H.dl = I_{net} \Rightarrow H.l_c = N.i \Rightarrow H = \frac{N.i}{l_c}$$ **(The magnitude of the magnetic field intensity in A-turns/m)**

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Production of a Magnetic Field

- **The magnetic field intensity H** is defined as the effort exerted by the current to establish a magnetic field.
- The relationship between the **magnetic field intensity H** and the resulting **magnetic flux density B** produced within a material is given by

$$B = \mu H$$

where
H is the magnetic field intensity **(A-turn/m)**
μ is the permeability of material (core) **(H/m)**
B is the resulting magnetic flux density **(Tesla (T) or Wb/m²)**

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Production of a Magnetic Field

- **Permeability μ** represents the relative ease of establishing a magnetic field in a given material.

$$B = \mu H$$

- So **the greater permeability**, **the greater amount of B** established for an existing H.

- The permeability of free space (air) is **constant**:

$$\mu_0 = 4\pi x 10^{-7} \quad \text{(H/m)}$$

- The permeability of any other material in nature compared to the permeability of free space is called «**relative permeability**» of that material:

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

- Although μ_0 is constant, the permeability of the materials in nature is **not constant** !

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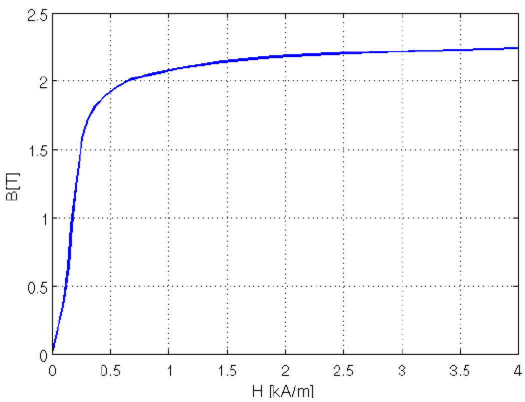
Production of a Magnetic Field



B-H curve for Cobalt-Iron alloy (Vacuumschmelze, 2011)

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Production of a Magnetic Field

- If we linearize (approximate) the **B-H curve** of the material for a given region or operating range),

μ_r can be thought as constant !

Material	Relative Permeability
Copper	0.9999906
Silver	0.9999736
Lead	0.9999831
Air	1.00000037
Oxygen	1.000002
Aluminum	1.000021
Titanium 6-4 (Grade 5)	1.00005
Palladium	1.0008
Platinum	1.0003
Manganese	1.001
Cobalt	250
Nickel	600
Iron	280,000

→ **Diamagnetic material (**repelled by a magnetic field**)**

→ **Non-magnetic material (**they are not magnetized**)**

→ **Paramagnetic material (**they become magnetized in a magnetic field but their magnetism disappears when the field is removed**)**

Ferromagnetic materials (attracted by a magnetic field and they can retain their magnetic properties even the magnetic field is removed**)**

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Production of a Magnetic Field

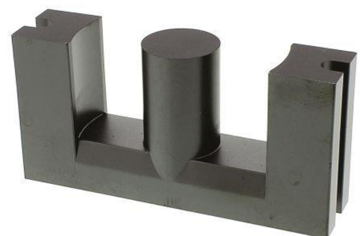
Relative permeability values for important types of ferromagnetic materials

Material	Max. μ_r value
Silicon-iron	7000
Cobalt-iron	10 000
Permalloy 45	23 000
Permalloy 65	600 000
Mumetal	100 000
Supermalloy	1 000 000
Typical dust core	10–100
Ferrite core	100–2000

Source: http://machineryequipmentonline.com

Silicon Steel Transformer Lamination

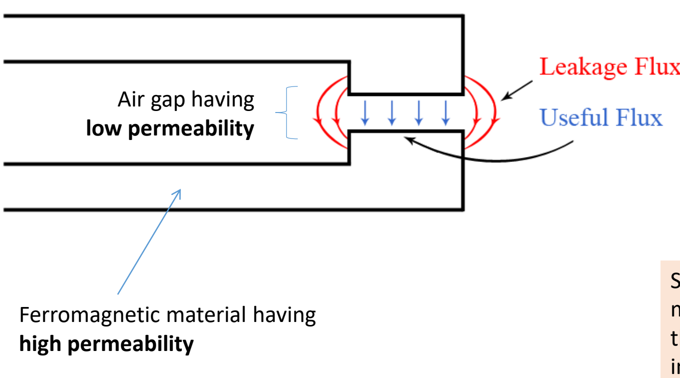
Source: https://www.indiamart.com



Transformer Ferrite Core

Source: https://uk.rs-online.com

Production of a Magnetic Field



Useful flux >> **Leakage flux**

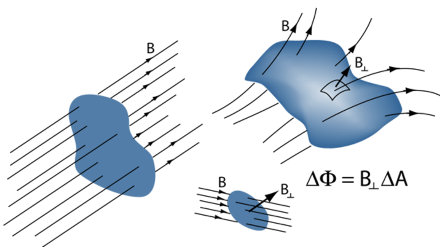
Since the permeability of the ferromagnetic material (*for example iron*) is so much higher than that of air, the great majority of the flux in the core remains inside the core and a very small portion of the flux travels through the surrounding air. **(FRINGING EFFECT)**

Production of a Magnetic Field

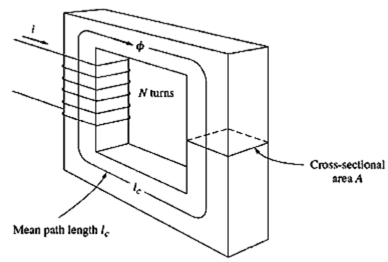
$$B = \mu H$$

$$H = \frac{N.i}{l_c}$$

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



$$\emptyset = B.A$$

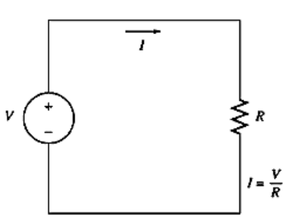


The current in a coil of wire wrapped around a core produces a magnetic flux (∅) in the core.

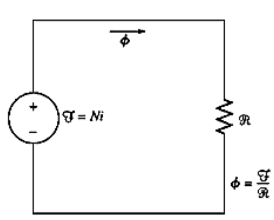
By combining two above equations: $\emptyset = \frac{\mu N.i.A}{l_c}$ **(Weber (W))**

Magnetic Circuits

- In an **electrical circuit**, a voltage or electromotive force **(EMF)** produces current in the circuit (***Figure (a)***).
- On the other hand, the current in a coil of wire wrapped around a core produces a magnetic flux (∅) in the core. ***(Refer to the previous slide)***
- Hence these two events can be considered to be **analogous** so that we can begin to think about **magnetic circuits**. In a **magnetic circuit**, the magnetomotive force **(MMF)** produces flux in the circuit (***Figure (b)***).



Electrical circuit



magnetic circuit

$\mathcal{F} = N.i$ **Magnetomotive force (Ampere-turns)**

$$\mathcal{F} = H.l_c$$

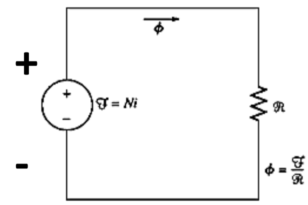
$\emptyset = \frac{\mathcal{F}}{\mathcal{R}}$ → **<u>Reluctance</u> of the magnetic circuit (Ampere-turns/Wb)**

Magnetic Circuits

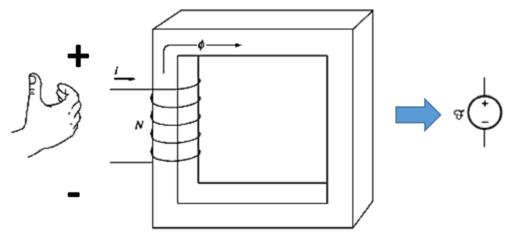
- Magnetic circuits do not exist in real-life.
- They are often used to model the magnetic behavior of electrical machines with **<u>up to the 5% of error</u>.**
- By this way, the analyzing/design stages are simplified.
- Like the **voltage source in the electrical circuit**, **the MMF in the magnetic circuit** has a **polarity** associated with it.
- The **positive end** of the MMF source is the end from which the flux **<u>exits</u>**.
- The **negative end** of the MMF source is the end at which the flux **<u>reenters</u>**.

The <u>polarity of the MMF</u> can be determined from the modification of the <u>right-hand rule</u>:

If the fingers of the right hand curl in the direction of the current in the coil, then the thumb will point in the direction of the positive MMF.



magnetic circuit



Production of a Magnetic Field

- The **permeance (P)** of a magnetic circuit is defined as the **<u>reciprocal</u>** of its reluctance:
- The **permeance** is analogous to the **conductance** in an electrical circuit.

$$P = \frac{1}{\mathcal{R}}$$

where
P is the permeance **(Wb/Ampere-turns)**
$\mathcal{R}$ is the reluctance **(Ampere-turns/Wb)**

- Since;

$$\emptyset = \frac{\mathcal{F}}{\mathcal{R}} \Rightarrow \emptyset = P.\mathcal{F}$$

Production of a Magnetic Field

- So far we know that **reluctance** is the ratio of MMF to flux in a magnetic circuit:

$$\emptyset = \frac{\mathcal{F}}{\mathcal{R}} \Rightarrow \mathcal{R} = \frac{\mathcal{F}}{\emptyset}$$

- Alternatively, can we calculate the reluctance with **physical parameters of the magnetic circuit**
- Since;

$$\emptyset = \frac{\mu N.i.A}{l_c}$$ (*previously derived on slide 44*)

- and;

$$\mathcal{F} = N.i$$

$$\emptyset = \frac{\mathcal{F}\mu A}{l_c} = \frac{\mathcal{F}}{\mathcal{R}} \Rightarrow \boxed{\mathcal{R} = \frac{l_c}{\mu A}}$$ **(H^{-1})**

Production of a Magnetic Field

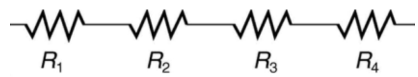
Comparison of magnetic circuit and electrical circuit parameters

Magnetic circuit	Electrical circuit
Magnetomotive force (MMF)	Electromotive force (EMF)
Flux	Current
Reluctance	Resistance
Permeance	Conductance

Production of a Magnetic Field

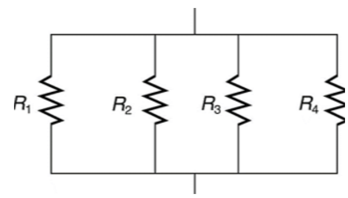
- Reluctances in a magnetic circuit obey the same rules as resistances in an electric circuit.
- The **equivalent reluctance** of a number of reluctances **in series** is just the sum of the individual reluctances:

$$\mathcal{R}_{eq} = \mathcal{R}_1 + \mathcal{R}_2 + \mathcal{R}_3 + \cdots$$



- Similarly, **reluctances in parallel** combine according to the equation:

$$\frac{1}{\mathcal{R}_{eq}} = \frac{1}{\mathcal{R}_1} + \frac{1}{\mathcal{R}_2} + \frac{1}{\mathcal{R}_3} + \cdots$$

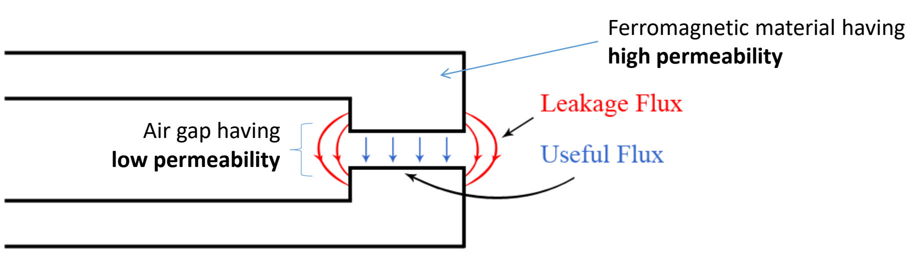


- **Permeances** in series and parallel obey the same rules as electrical **conductances.**

Production of a Magnetic Field

- Why are the calculations in a magnetic circuit **approximate** ? (*Accuracy is up to **5%***)
- There are **four** reasons:

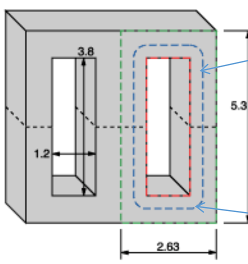
1) The magnetic circuit concept assumes that all the flux is confined within a magnetic core. Unfortunately, this is not quite true. Because the permeability of a ferromagnetic core is too much higher than that of air and a small fraction of the flux escapes from the core into the surrounding low-permeability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



Production of a Magnetic Field

- Why are the calculations in a magnetic circuit **approximate** ? (*Accuracy is up to **5%***)
- There are **four** reasons:

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**.



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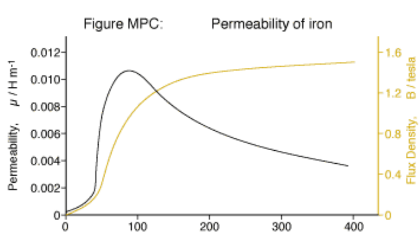
Production of a Magnetic Field

- Why are the calculations in a magnetic circuit **approximate** ? (*Accuracy is up to **5%***)
- There are **four** reasons:

3) In ferromagnetic materials, the permeability **varies** with the amount of flux already in the material. This nonlinear effect has been previously discussed in the slides. Because of this nonlinearity, in practice, the reluctance values are **not constant**.



Source: http://info.ee.surrey.ac.uk/Workshop/advice/coils/mu/

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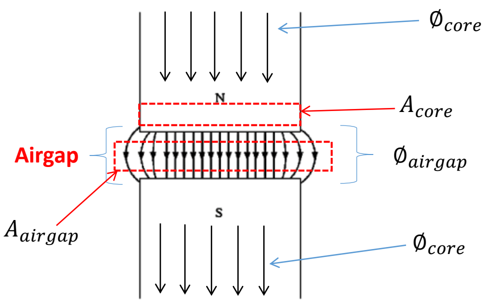
Production of a Magnetic Field

- Why are the calculations in a magnetic circuit **approximate** ? (*Accuracy is up to **5%***)
- There are **four** reasons:

4) If there are air gaps in the flux path in a core, the effective cross-sectional area of the air gap will be larger than the cross-sectional area of the iron core on either side. The extra effective area is caused by the "**fringing effect**" of the magnetic field at the air gap.



$\emptyset_{core} = \emptyset_{airgap}$ → Think like series connected resistances have the **same current**

$A_{airgap} > A_{core}$

Since;

$$B = \frac{\phi}{A}$$

$B_{core} > B_{airgap}$ **(Fringing Effect)**

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Production of a Magnetic Field

Example-1: The magnetic circuit shown in Fig. 1.2 has dimensions **Ac = Ag = 9 cm^2 (*fringing effect is neglected*)**, **g = 0.050 cm**, **lc = 30 cm**, and **N = 500 turns**. Assume the value **μ_r = 70,000** for the core material.

(a) Find the reluctances of the core and the air gap.
(b) Find the flux and the current for the condition that the magnetic circuit is operating with a magnetic flux density of **1.0 T**.

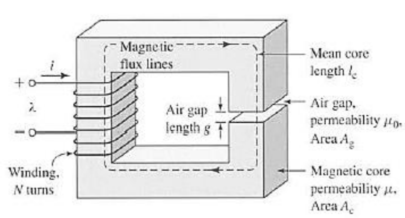

Figure 1.2 Magnetic circuit with air gap.

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Production of a Magnetic Field

Solution:

$$\mathcal{R}_c = \frac{l_c}{\mu_r \mu_0 A_c} = \frac{0.3}{70,000\,(4\pi \times 10^{-7})(9 \times 10^{-4})} = 3.79 \times 10^3 \ \frac{\text{A} \cdot \text{turns}}{\text{Wb}}$$ Reluctance of the core

$$\mathcal{R}_g = \frac{g}{\mu_0 A_g} = \frac{5 \times 10^{-4}}{(4\pi \times 10^{-7})(9 \times 10^{-4})} = 4.42 \times 10^5 \ \frac{\text{A} \cdot \text{turns}}{\text{Wb}}$$ Reluctance of the air gap

$$\phi = B_c A_c = 1.0(9 \times 10^{-4}) = 9 \times 10^{-4} \text{ Wb}$$

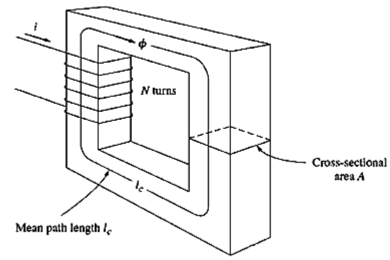
$$i = \frac{\mathcal{F}}{N} = \frac{\phi(\mathcal{R}_c + \mathcal{R}_g)}{N} = \frac{9 \times 10^{-4}(4.46 \times 10^5)}{500} = 0.80 \text{ A}$$

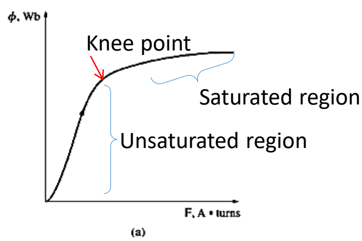
Self-study

- Repeat the previous example for a fringing effect of 5%
- Solve the following examples from Chapman
  - Example 1-1 at page 14
  - Example 1-2 at page 17
  - Example 1-3 at page 19

Magnetic Behavior of Ferromagnetic Materials

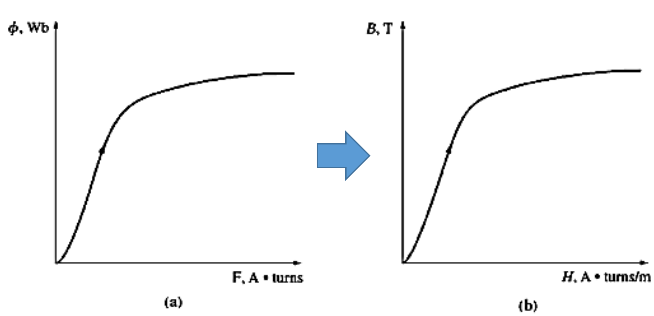
- We apply a **direct current (DC)** to the core shown in Figure.
- We start with **0 A** and slowly increasing the current up to the maximum permissible current.
- The produced **flux** in the core is plotted versus the magnetomotive force (MMF) producing it.
- This plot is called «**Saturation Curve**» or «**Magnetization Curve**», as shown below.





Magnetic Behavior of Ferromagnetic Materials

- From the magnetization curve, we can obtain **B-H characteristics of the core**, as shown below.



- Why are these figures **same in shape** ?

Because;

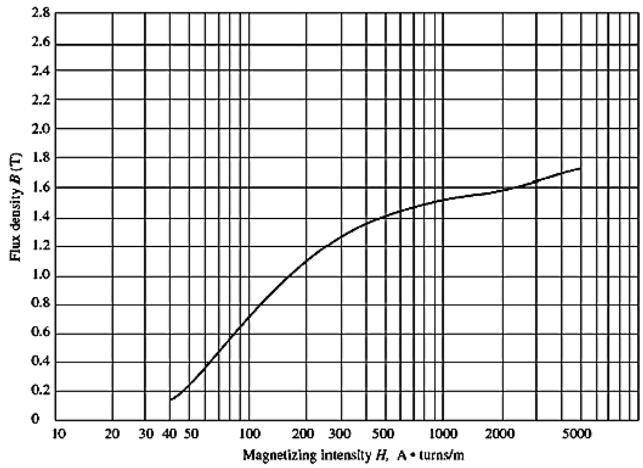
- Flux is proportional to B $\emptyset = B.A$

constant

- MMF is proportional to H $\mathcal{F} = H.l_c$

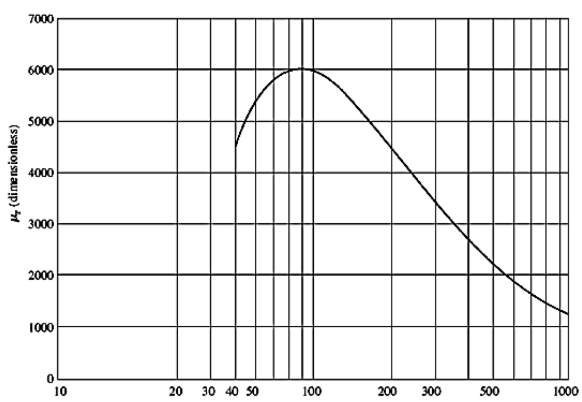
constant

Magnetic Behavior of Ferromagnetic Materials



Magnetization curve for steel

Magnetic Behavior of Ferromagnetic Materials

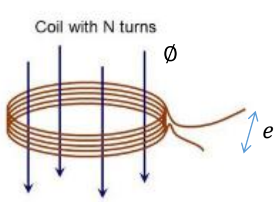


A plot of relative permeability as a function of magnetizing intensity for steel.

Magnetic Behavior of Ferromagnetic Materials

- The advantage of using a ferromagnetic material for cores in electrical machines and transformers is that one gets many times **more flux** for a given magnetomotive force with ferromagnetic material than with air.
- However, if the resulting flux has to be **proportional**, or nearly so, to the applied magnetomotive force, then the core must be operated in the **unsaturated region** of the magnetization curve.
- Since real generators and motors depend on magnetic flux to produce voltage and torque, they are designed to produce **as much flux as possible**.
- As a result, most real machines **operate near the knee of the magnetization curve**, and the flux in their cores is **not linearly related** to the magnetomotive force producing it.
- This nonlinearity brings design and analysis difficulties for the electrical machines.

Flux Linkage



Note that the polarity of the induced voltage (*e*) is defined such that if the winding terminals were short-circuited, a current would flow in such a direction as to oppose the change of flux linkage **(Lenz Law)**.

Flux linkage of a coil (*or winding*) is defined as:

$\lambda = N.\phi$ (Flux linkage is measured in units of **Weber-turns**)

Considering Faraday's Law:

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

Inductance

- The relationship between **flux** and the **current** will be **linear** under the following conditions:

1) For a magnetic circuit composed of a ferromagnetic material in the **unsaturated region** (*linear region*)
2) For a magnetic circuit having **no ferromagnetic material**
3) For a magnetic circuit having a **very big air gap**

- So we can define the term «**inductance**» as follows:

$$L = \frac{\lambda}{i} = \frac{N.\phi}{i}$$

$$\left.\begin{aligned} \mathcal{F} &= N.i \\ \emptyset &= \frac{\mathcal{F}}{\mathcal{R}_{total}} \\ \lambda &= N.\phi \end{aligned}\right\} \quad L = \frac{N^2}{\mathcal{R}_{total}}$$

➡ **The unit of inductance** ➡ $\frac{turn^2}{Ampere.turn/Wb}$ ➡ $\frac{Wb.turn}{Ampere}$ ➡ **Henry (H)**

Example for inductance calculation

The magnetic circuit shown below consists of an **N-turn** winding on a magnetic core of **infinite permeability** with two parallel air gaps of lengths **g1** and **g2** and areas **A1** and **A2**, respectively.

Find the inductance of the winding (*Neglect fringing effects at the air gaps*).

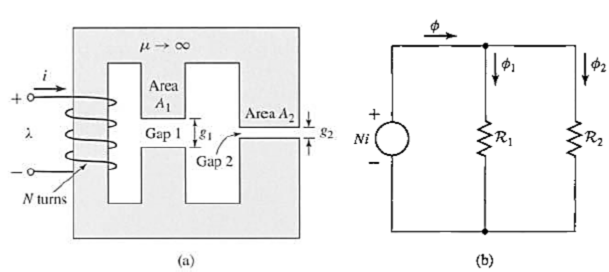


Figure 1.6 (a) Magnetic circuit and (b) equivalent circuit for Example 1.3.

■ **Solution**

a. The equivalent circuit of Fig. 1.6b shows that the total reluctance is equal to the parallel combination of the two gap reluctances. Thus

$$\phi = \frac{Ni}{\frac{\mathcal{R}_1\mathcal{R}_2}{\mathcal{R}_1+\mathcal{R}_2}}$$

where

$$\mathcal{R}_1 = \frac{g_1}{\mu_0 A_1} \qquad \mathcal{R}_2 = \frac{g_2}{\mu_0 A_2}$$ Reluctances of the air gaps

From Eq. 1.29,

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} = \frac{N^2(\mathcal{R}_1 + \mathcal{R}_2)}{\mathcal{R}_1\mathcal{R}_2}$$

$$= \mu_0 N^2\left(\frac{A_1}{g_1} + \frac{A_2}{g_2}\right)$$ Inductance of the winding

Self-study

- Solve the following examples from Chapman
  - Example 1-4 at page 24
  - Example 1-5 at page 25

Self-Inductance and Mutual Inductance

The total MMF of the magnetic circuit as shown:

$$\mathcal{F} = N_1 i_1 + N_2 i_2$$

If the core reluctance is neglected ($\mu_{core} \to \infty$) and assuming that there is no fringing effect:

$$\phi = (N_1 i_1 + N_2 i_2)\frac{\mu_0 A_c}{g}$$

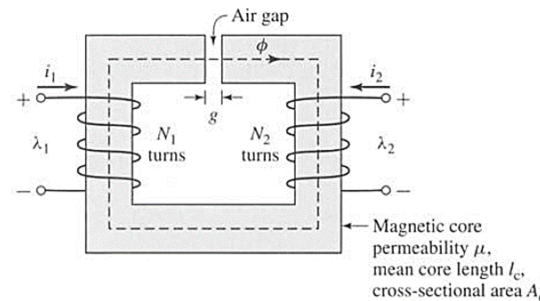


Figure 1.8 Magnetic circuit with two windings.

The flux linkage of coil 1 is

$$\lambda_1 = N_1\phi = \underbrace{N_1^2\left(\frac{\mu_0 A_c}{g}\right)}_{L_{11}} i_1 + \underbrace{N_1 N_2\left(\frac{\mu_0 A_c}{g}\right)}_{L_{12}} i_2$$

$$\lambda_1 = L_{11} i_1 + L_{12} i_2$$

L_{11} is called «**self-inductance** of coil 1

L_{12} is called «**mutual inductance**» between coils 1 and 2

Self-Inductance and Mutual Inductance

Similarly, the flux linkage of coil 2 is

$$\lambda_2 = N_2\phi = \underbrace{N_1 N_2\left(\frac{\mu_0 A_c}{g}\right)}_{L_{21}} i_1 + \underbrace{N_2^2\left(\frac{\mu_0 A_c}{g}\right)}_{L_{22}} i_2$$

$$\lambda_2 = L_{21} i_1 + L_{22} i_2$$

L_{22} is called «**self-inductance** of coil 2

L_{21} is called «**mutual inductance**» between coils 2 and 1

It is important to see that;

$$L_{21} = L_{12} = N_1 N_2\left(\frac{\mu_0 A_c}{g}\right)$$

Faraday's Law and Inductance

Faraday's Law states that

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

And the definition of flux linkage is

$$L = \frac{\lambda}{i}$$

Combining these two equations yields

$$e = \frac{d\lambda}{dt} = \frac{d(L.i)}{dt} = L\frac{di}{dt} + i\frac{dL}{dt}$$

- For **static magnetic circuits** (*no rotation*) L becomes **constant**. So;

$$e = L\frac{di}{dt}$$

- For **rotating magnetic circuits**, such as in **electrical machines**, L is **not constant** and **time-varying**. So;

$$e = L\frac{di}{dt} + i\frac{dL}{dt}$$

In electrical machines ***L*** is a ***time-varying quantity*** because of continuous change of the relative positions of the stator and rotor windings due to the rotation of the rotor.

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Power and Energy in Magnetic Circuits

The power at the terminals of a winding on a magnetic circuit is a measure of the rate of energy flow into the circuit through that particular winding. The **power, *p***, is determined from the product of the voltage and the current

$$p = ie = i\frac{d\lambda}{dt}$$

The unit of power is **Watts (W)**

Thus the change in **magnetic stored energy** ΔW in the magnetic circuit in the **time interval t_1 to t_2**

$$\Delta W = \int_{t_1}^{t_2} p\, dt = \int_{\lambda_1}^{\lambda_2} i\, d\lambda$$

The unit of energy is **Joules (J)**

$$\Delta W = \int_{\lambda_1}^{\lambda_2} i\, d\lambda = \int_{\lambda_1}^{\lambda_2} \frac{\lambda}{L}\, d\lambda = \frac{1}{2L}(\lambda_2^2 - \lambda_1^2)$$

If we assume $\lambda_1 = 0$ at $t = t_1$

$$W = \frac{1}{2L}\lambda^2 = \frac{L}{2}i^2$$

The **total magnetic stored energy** at any given value of λ

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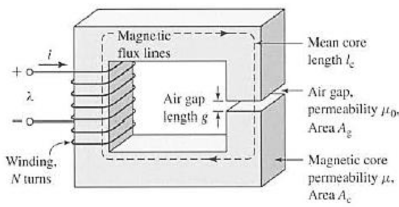
Self Study

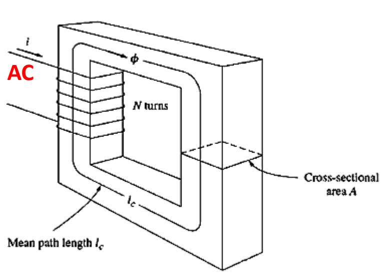
For the magnetic circuit shown below, find

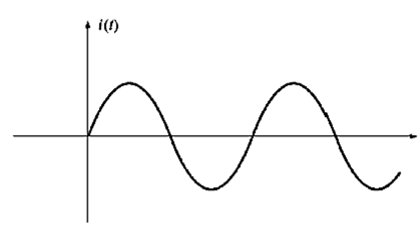
(a) the inductance L
(b) the magnetic stored energy for a core flux density of B = 1.0 T
(c) the induced voltage for a 60-Hz time-varying core flux density of B = 1.0 sin(wt) T where w = (2.π.f), f=60 Hz.



AC Excitation and Hysteresis Loop

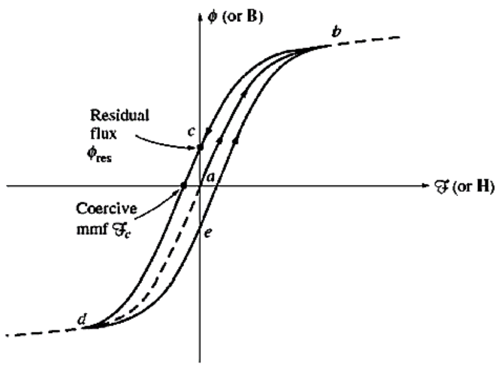
- In AC power systems, the **voltage** and **flux** waveforms are approximately **sinusoidal**.
- This section describes the **excitation characteristics** and **losses** associated with **steady-state AC operation** of ferromagnetic materials.
- Now, instead of applying a **DC current** to the windings on the core (*as we did before*), let us now apply an **AC current** to the magnetic circuit as shown below:



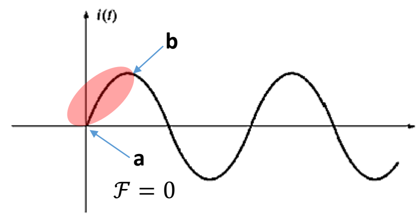


AC Excitation and Hysteresis Loop

- Assume that the flux in the core is initially zero.
- As the current **increases** for the first time, the flux in the core traces out **path *ab***

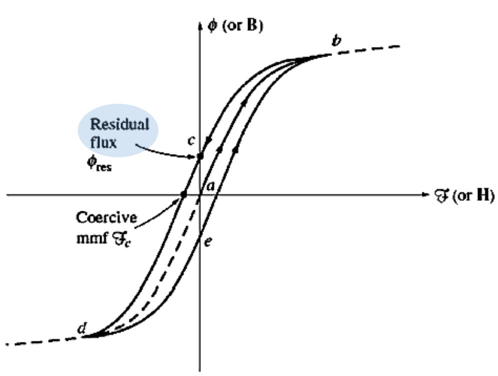


The hysteresis loop

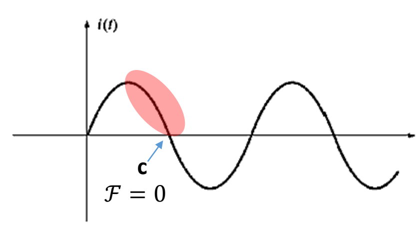


AC Excitation and Hysteresis Loop

- However, when the current falls **from + peak to zero**, the flux traces out **path *bc***.
- This is a **different path** from the one it followed when the current increased at the beginning.



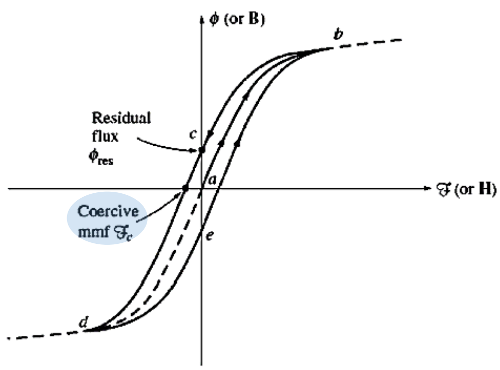
The hysteresis loop



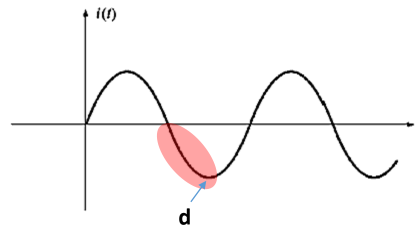
When the MMF force is removed, the flux in the core does not go to zero. Instead, a magnetic field is left in the core. This magnetic field is called the **residual flux** in the core.

AC Excitation and Hysteresis Loop

- When the current further decreases in the negative cycle, the flux decreases up to the **point *d***.



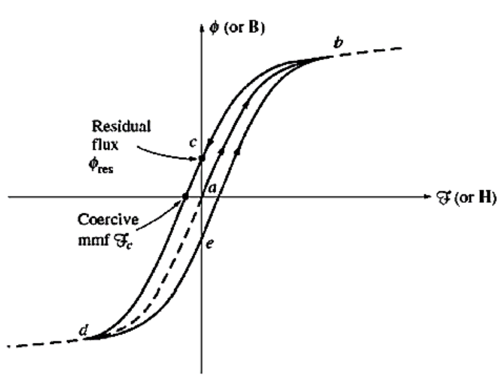
The hysteresis loop



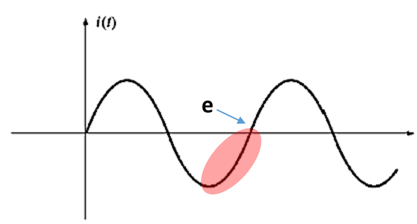
To force the flux to zero, an amount of MMF known as the **coercive MMF** must be applied to the core in the opposite direction

AC Excitation and Hysteresis Loop

- The change of the current **from - peak to zero**, the flux traces out **path *de***.

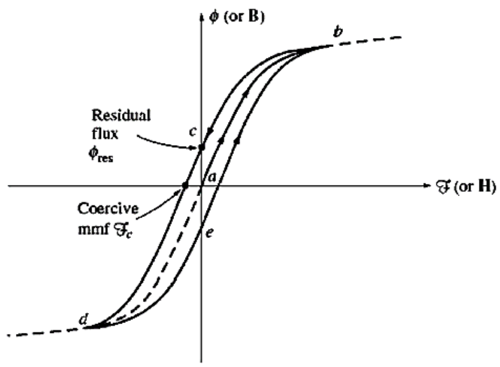


The hysteresis loop

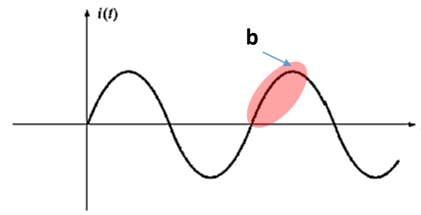


AC Excitation and Hysteresis Loop

- When the current further increases in the positive direction, the flux traces out **path *ab***.
- Since the current is periodic, this group of events occur periodically and the hysteresis loop of the core is formed.



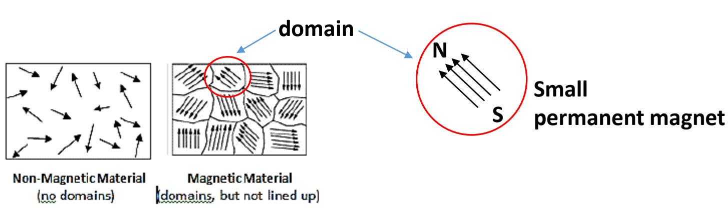
The hysteresis loop



AC Excitation and Hysteresis Loop

Why does hysteresis occur in a ferromagnetic material ?

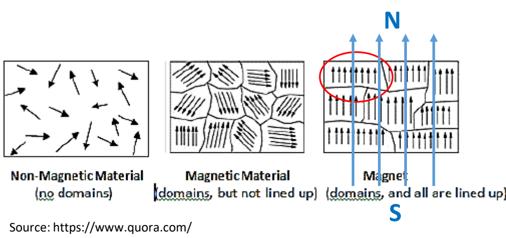
- ❑ In a ferromagnetic material (*iron, cobalt, nickel, etc*.), there are many small regions called "**domains**".
- ❑ In each domain, all the atoms are aligned with their magnetic fields pointing in the same direction, so each domain within the material acts as a **small permanent magnet**.
- ❑ Since the magnetic field orientation of each domain is **random**, the net magnetic field is **zero** in the ferromagnetic material.
- ❑ This is why an iron or cobalt is not a magnet.



Source: https://www.quora.com/

AC Excitation and Hysteresis Loop

- When an external magnetic field is applied to the ferromagnetic material, the magnetic fields of all domains are lined up in the direction of the applied field.
- Since all domains are lined up in the same direction, a magnetic field in the ferromagnetic material is generated like a magnet.
- This generated magnetic field and the externally applied magnetic field support each other and they are added together.
- Because of this addition, a ferromagnetic material has much bigger amount of magnetic field when compared with air under the same amount of H.
- As a result, a ferromagnetic material has a much higher permeability than air. (*for example* $\mu = 7000\mu_0$)



Source: https://www.quora.com/

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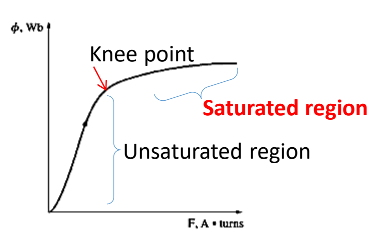
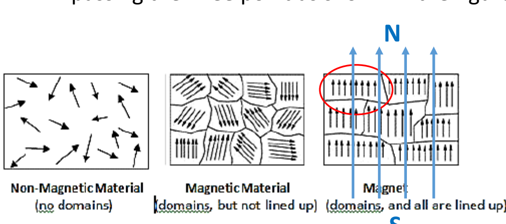
AC Excitation and Hysteresis Loop

So why does <u>saturation</u> occur in a ferromagnetic material ?

- When all the atoms and domains in the ferromagnetic material are **lined up** with the external field, any further increase in the current or MMF does not cause a further increase in the flux.
- At this point, the ferromagnetic material is **saturated** after passing the knee point as shown in the figure.





Source: https://www.quora.com/

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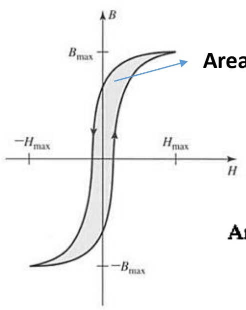
Hysteresis Loss

- **Turning and reorientation** the domains during each cycle of the alternating current in the ferromagnetic material requires some energy.
- This energy requirement is known as «**hysteresis loss**» in the ferromagnetic materials.
- **Hysteresis loss** causes **heating** in the core (*ferromagnetic*) materials.
- **Hysteresis loss** occurs in all **electrical machines** and **transformers**.
- The area of the **hysteresis loop** is **directly proportional** to the **hysteresis loss**.
- The smaller the applied current or MMF, the smaller the area of the resulting hysteresis loop.



Area ∝ hysteresis loss

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Derivation of Hysteresis Loss

- Assume the flux in the core is **sinusoidal**:

$$\emptyset(t) = \emptyset_{max}\sin(wt) = A_c B_{max}\sin(wt)$$

where

$\emptyset_{max}$ is the peak (*max*) value of flux
B_{max} is the peak (*max*) value of magnetic flux density
w=$2\pi f$ is the angular frequency of the flux

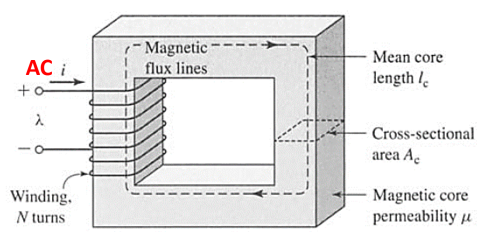

Figure 1.1 Simple magnetic circuit.

- The induced voltage in the winding is; (*Applying Faraday's Law*)

$$e(t) = N\frac{d\phi}{dt}$$

$$e(t) = N\frac{d}{dt}(A_c B_{max}\sin(wt))$$

$$e(t) = \underbrace{NwA_cB_{max}}_{e_{max}}\cos(wt) \Rightarrow e_{rms} = \frac{N2\pi f A_c B_{max}}{\sqrt{2}} = \sqrt{2}N\pi f A_c B_{max}$$ (Rms value of induced voltage)

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Derivation of Hysteresis Loss

- Remembering the following equation:

$$H = \frac{N.i}{l_c} \Rightarrow i_{rms} = \frac{H_{rms}.l_c}{N}$$

- The volt-ampere (*apparent*) power consumed by the core:

$$s = e_{rms}.i_{rms}$$

$$s = \sqrt{2}\cancel{N}\pi f A_c B_{max}.\frac{H_{rms}.l_c}{\cancel{N}}$$

$$s = \sqrt{2}\pi f B_{max}.H_{rms}\underbrace{(A_c l_c)}_{\text{core volume}}$$

- s is also called as «**rms exciting voltamperes required to excite the core**»

- So **hysteresis loss** is proportional to the
  1) Frequency of excitation
  2) Peak flux density
  3) Rms magnetic field intensity
  4) Core volume

- s can also be calculated in terms of **per unit mass**,

$$s_a = \frac{\sqrt{2}\pi f B_{max}.H_{rms}(A_c l_c)}{mass\ of\ the\ core} \quad mass\ of\ the\ core \Rightarrow \rho_c A_c l_c$$

$$s_a = \frac{\sqrt{2}\pi f B_{max}.H_{rms}}{\rho_c} \quad \rho_c \Rightarrow \text{Core density}$$

Derivation of Hysteresis Loss

- The ac excitation requirements for a magnetic material are often supplied by manufacturers in terms of **rms voltamperes per unit weight** as determined by laboratory tests on closed-core samples of the material.

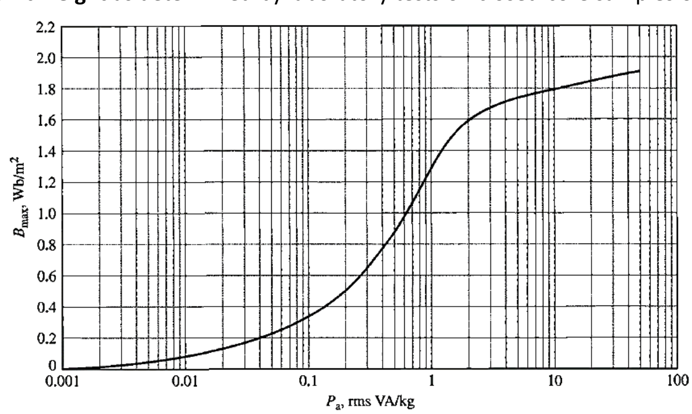


Figure 1.12 Exciting rms voltamperes per kilogram at 60 Hz for M-5 grain-oriented electrical steel 0.012 in thick. (*Armco Inc.*)

Eddy Current Loss

- A **time-changing flux** induces voltage within a **ferromagnetic core** (*Faraday's Law*).
- This is just the same manner as it would be in a wire wrapped around that core.
- These voltages cause **swirls of current** to flow within the core.
- Since these **eddy currents** flow in the core, the core **becomes warm** and some **energy is dissipated** by the core.

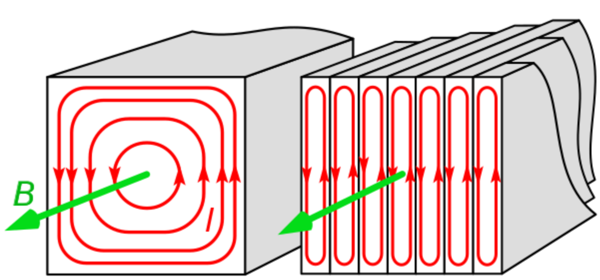
The equation for ***eddy current loss*** is given as:

$$P_e = K_e . B_{max}^2 . f^2 . th^2 . V$$

where
P_e is the eddy current loss (Watt)
K_e is the eddy current constant
B_{max} is the peak value of magnetic flux density (Wb/m^2)
f is the frequency (Hz)
th is the material thickness (m)
V is the volume (m^3)

Eddy Current Loss

- As observed from the eddy current loss equation, the amount of energy lost is proportional to the square of the thickness and the volume of the material.
- For this reason, it is customary to break up the ferromagnetic core into many small laminations.
- An insulating oxide or resin is used between these laminations.
- Because the insulating layers are extremely thin, this action reduces eddy current losses without changing too much the magnetic properties of the core.



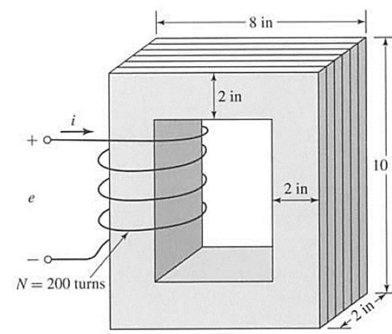
Eddy currents in laminated cores (*right*) are smaller than those in solid cores (*left*)

Source: https://www.motioncontroltips.com/hysteresis-loss/

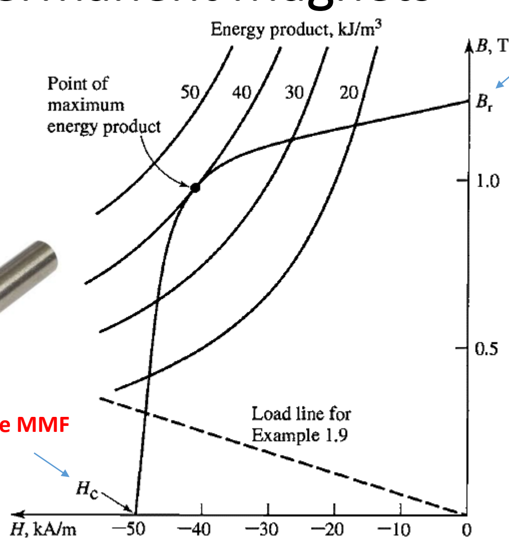
Self Study

The magnetic core shown in Figure is made from laminations of M-5 grain-oriented electrical steel. The winding is excited with a 60-Hz voltage to produce a flux density in the steel of B = 1.5 sin wt T, where w = $2\pi60$ rad/s. The steel occupies 94% of the core cross sectional area. The density of the steel is 7.65 g/cm^3.

Find
(a) the applied voltage,
(b) the peak current,
(c) the rms exciting current,
(d) the core loss.



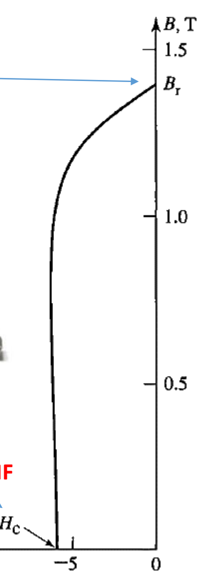
Permanent Magnets



Residual flux density. Also called «***remanent magnetization***»

Coercive MMF

Second quadrant of hysteresis loop for **Alnico 5**



Coercive MMF

Second quadrant of hysteresis loop for **M-5 electrical steel**

Permanent Magnets

- Permanent magnets have a **large residual flux**.
- Residual flux means that **<u>without excitation</u>** (*no current is applied*), the magnet produces a high flux **<u>by itself</u>**.
- Permanent magnets also have a **large coercive MMF**.
- **Coercive MMF** is the MMF that is required to make the flux in the permanent magnet zero.
- **Coercivity** can be thought of as a measure of the magnitude of the MMF required to **<u>demagnetize</u>** the material.
- Permanent magnets find application in many devices, including loudspeakers, ac and dc motors, microphones, and analog electric meters.

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Permanent Magnets

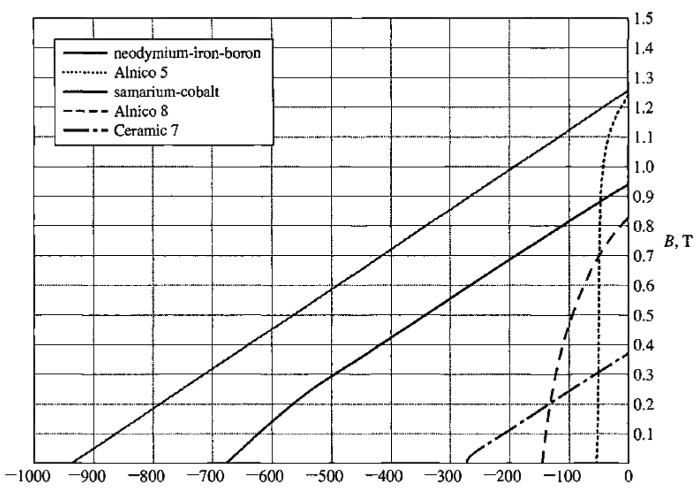
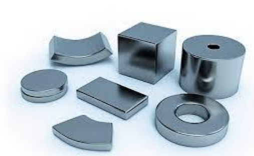


Figure 1.19 Magnetization curves for common permanent-magnet materials.

Alnico 5

Samarium-cobalt

Alnico 8



neodymium iron boron

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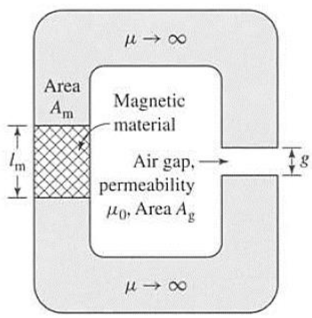
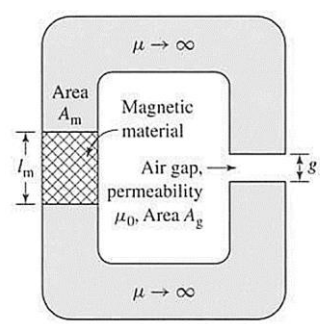
Permanent magnet example:

As shown in the Figure, a magnetic circuit consists of a core having **infinite permeability**, an air gap of length g = 0.2 cm, and a section of magnetic material of length lm = 1.0 cm. The cross-sectional area of the core and gap is equal to Am = Ag = 4 cm^2.

Calculate the **flux density B** in the air gap if the magnetic material is (a) **M-5 electrical steel** (b) **Alnico 5**



Permanent magnet example:



<u>Solution:</u>

- Since the **core permeability** is assumed **infinite**, **H** in the core is **<u>negligible</u>**.

$$\mu = \frac{B}{H}$$

∞ 0

- Since the **MMF** acting on the magnetic circuit is **zero** (*No windings*), we can write:

$$\mathcal{F} = 0 = H_g g + H_m l_m$$

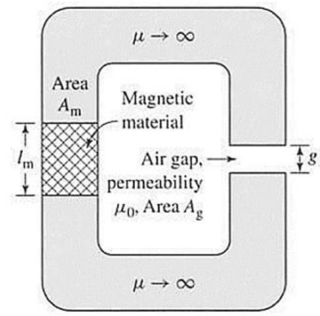
or

$$H_g = -\left(\frac{l_m}{g}\right) H_m \Rightarrow H_g = -\frac{1}{0.2} H_m \Rightarrow H_g = -5H_m$$

Permanent magnet example:

Solution:

- Since the flux **must be continuous** through the magnetic circuit (*magnetic material and the airgap are* ***connected in series*** *in the magnetic circuit*)



$$\phi = A_g B_g = A_m B_m$$

or

$$B_g = \left(\frac{A_m}{A_g}\right) B_m \Rightarrow B_g = \frac{4}{4} B_m \Rightarrow B_g = B_m$$

$$\left.\begin{aligned} H_g &= -5H_m \\ B_g &= B_m \end{aligned}\right\} \quad B_m = \mu_0 H_g = -5\mu_0 H_m \Rightarrow B_m = -6.2832e-06.\,H_m$$ (it is a line equation)

(This equation is called «**Load line**»)

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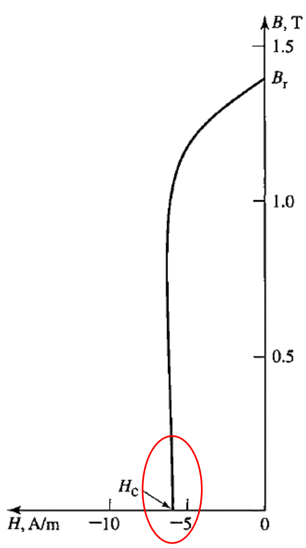
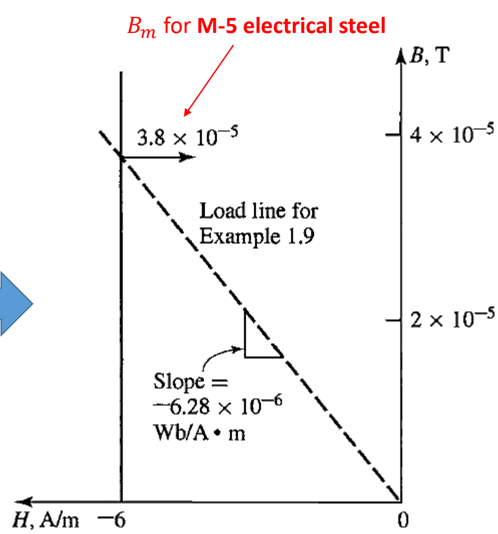
Permanent magnet example:

Solution a:





Second quadrant of hysteresis loop for **M-5 electrical steel**

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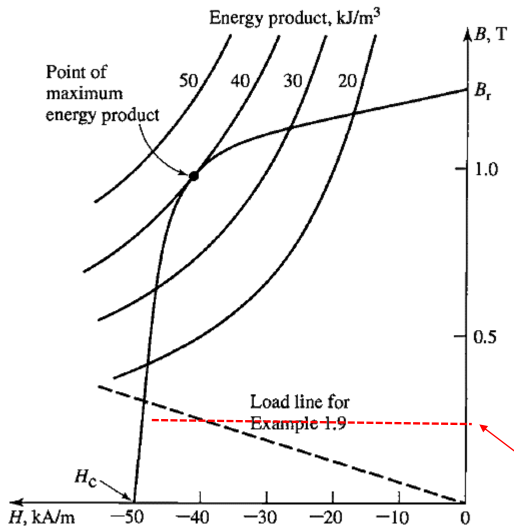
Permanent magnet example:

Solution b:

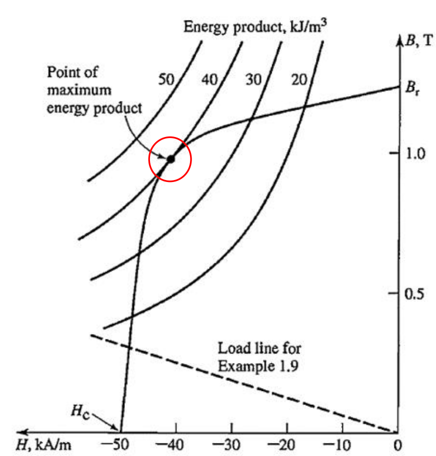


Second quadrant of hysteresis loop for **Alnico 5**

- **Alnico 5** is a ***hard magnetic material*** having a **large** coercivity.
- **M-5 electrical steel** is a ***soft magnetic material*** having relatively **small** coercivity ***.***
- Good permanent magnets are generally characterized by **large values** of **coercivity** (*considerably in excess of 1 kA/m*).

The Largest B-H Product of Permanent Magnet

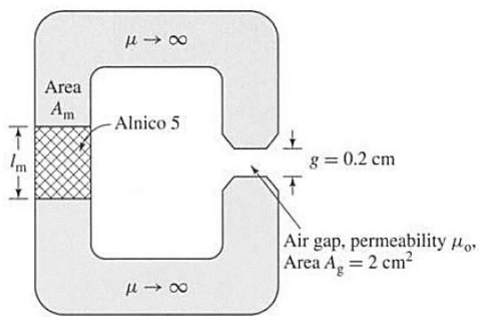
- A useful measure of the capability of permanent magnets is known as «**maximum energy product»**.
- This corresponds to the **largest B-H product** which corresponds to a point on the second quadrant of the hysteresis loop as shown in the figure.
- The permanent-magnet at this point will result in the **smallest volume** of that material required to produce a given flux density in an air gap.
-
- So, choosing a material with the **largest available maximum energy product** can result in the **smallest required magnet volume.**

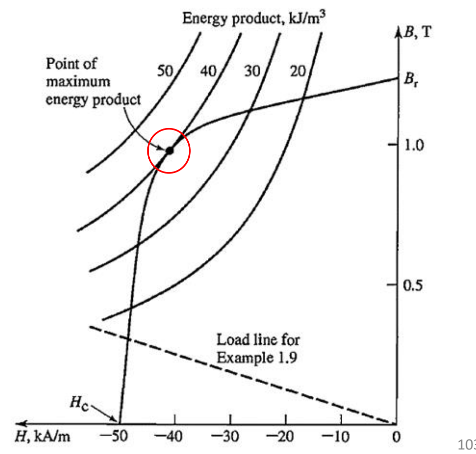


Second quadrant of hysteresis loop for **Alnico 5**

Self Study

The magnetic circuit of the following figure has an air-gap area of Ag = 2.0 cm^2. Find the minimum magnet volume required to achieve an air-gap flux density of 0.8 T.





Self-study

- Review and read Section 1.9 – "Real, Reactive, and Apparent Power in AC Circuits"
- Solve **all problems** of Chapter 1 from Chapman

Review Questions

1) What is torque? What role does torque play in the rotational motion of machines?
2) What is Ampere's law?
3) What is magnetizing intensity? What is magnetic flux density? How are they related?
4) How does the magnetic circuit concept aid in the design of transformer and machine cores?
5) What is reluctance?
6) What is a ferromagnetic material? Why is the permeability of ferromagnetic materials so high?
7) How does the relative permeability of a ferromagnetic material vary with magnetomotive force?
8) What is hysteresis? Explain hysteresis in terms of magnetic domain theory.
9) What are eddy current losses? What can be done to minimize eddy current losses in a core?
10) What is Faraday's law?
11) What conditions are necessary for a magnetic field to produce a force on a wire?
12) What conditions are necessary for a magnetic field to produce a voltage in a wire?
13) Will current be leading or lagging voltage in an inductive load? Will the reactive power of the load be positive or negative?
14) What are real, reactive, and apparent power? What units are they measured in? How are they related?
15) What is power factor?

END OF CHAPTER 1

INTRODUCTION TO MACHINERY PRINCIPLES