Welcome to

Electric Machines & Drives

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Session 1:
Fundamentals

Fall 2011

Welcome

Syllabus
Contact Information
Schedule
Homework
Tours
Project
Exams
Questions?

Topics Covered

Safety related issues
Electricity, Magnetism, Circuits, Mechanics, Heat
DC Motors and Generators
Induction and Synchronous Motors and Generators
Efficiency & Heat
Single and Three Phase Machines
Stepper Motors
Power Electronics
Reduced Voltage Start
DC Injection Break, Regenerative Break
Solid State AC / DC controls
PLCs & DCS Control Systems

Topics Covered

NEMA MG2 –
Safety Standard and Guide for Selection Installation and Use of Electric Motors and Generators
Text Book, Chapter 2
Fundamentals of Electricity, Magnetism, and Circuits
Text Book, Chapter 3
Fundamentals of Mechanics and Heat

Safety in Machine Installation, Testing, and Operation

What are some safety concerns with rotating machine installation, testing and operation?

Safety in Machine Installation, Testing, and Operation

HiPot Testing – (2*V + 1KV) * 85%(field test)
Grounded frame
Guards in place
Ground leads after test
Thermal Protection
Over speed protection
Load matched to machine

Safety in Machine Installation, Testing, and Operation

Enclosure for environment – classified area
Lubrication
HEC
Direction
Load configured for operation
Hold down bolts installed / torqued
Lifting requirements

Session 1: Introduction

- **Chapter 2 – Fundamentals of Electricity, Magnetism, and Circuits**
- **Chapter 3 – Fundamentals of Mechanics and Heat**

Chapter 2 – Fundamentals of Electricity, Magnetism, and Circuits

Chapter 2 – Electricity, Magnetism, & Circuits

Sign notation for current & voltage
Phasor representation
Harmonics
Energy in L & C
H & B
Lorentz Force
Hysteresis & eddy current losses
Kirchhoff voltage and current law
Solving circuits

Current Flow

Actual Current Flow -> - to +
Conventional Current Flow -> + to -

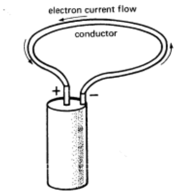


Figure 2.2
Electron flow.

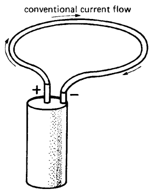
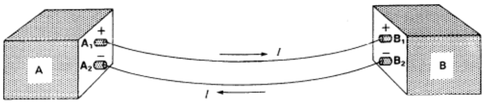


Figure 2.3
Conventional current flow.

Sources and Loads

Source – Current flows OUT of + terminal
Load – Current flows IN to + terminal



Double Script Notation

V_{AB} - Voltage at terminal A with respect to voltage at terminal B.
$V_{AB} = V_{AX} – V_{BX}$
$V_{AB} = +100V$, $V_{BA} = -100V$

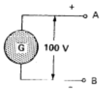


Figure 2.5
Double-subscript notation to designate a voltage

Sign Notation

E_1 - Voltage at + terminal referenced to opposite terminal.
$E_1 = +100V$
$E_1 = -100V$

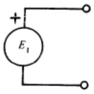


Figure 2.7
Sign notation to designate a voltage.

Example 2-1

What is voltage across resistor (V_{DB}) if source voltages are;
$V_1 = -4V$
$V_2 = +10V$
$V_3 = -40V$

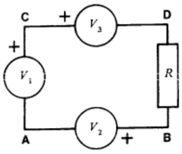


Figure 2.8
Circuit of Example 2-1.

Alternating Voltage

Value alternates positive to negative
E21 positive 0-1 sec
E21 negative 1-2 sec

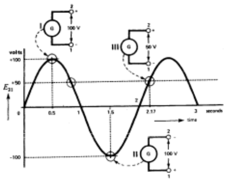
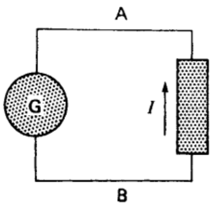


Figure 2.10
Graph of an alternating voltage having a peak of 100 V.

Current Flow

Reference direction indicated by arrow



Chapter 2

AC voltage in radians

$E = Em \cos(2\pi ft + \Theta)$ (2.1)

Where
E = instantaneous voltage (V)
Em = Peak value of sinusoidal voltage (V)
f = Frequency (Hz)
t = time (s)
Θ = a fixed angle (rad)

Chapter 2

AC voltage in degrees

$E = Em \cos(360ft + \Theta)$ (2.2)

Where
E = instantaneous voltage (V)
Em = Peak value of sinusoidal voltage (V)
f = Frequency (Hz)
t = time (s)
Θ = a fixed angle (degrees)
Φ = 360ft

Chapter 2 –
Example 2-3

Given $E_{ab} = E_M \cos(360{*}f{*}t+30^{O})$
$E_M = 100V$
f = 50 Hz
What is value of e_{ab} at times;
t = 0 sec
t = 27.144 sec

Chapter 2 –
Converting Sin and Cos Function

Convert the cos function to a sin function by adding 90^{O} to angle Θ
$E = Em \cos(2\pi ft + \Theta) =$
$E = Em \sin(2\pi ft + \Theta + 90^{O})$
Convert the sin function to a cos function by subtracting 90^{O} from angle Θ
$E = Em \sin(2\pi ft + \Theta) =$
$E = Em \cos(2\pi ft + \Theta - 90^{O})$

Chapter 2 –
Effective vs.. Maximum

RMS Value = sqrt of sum of squares
effective or heating value
FOR PURE SINE WAVE –

$Veff = Vm / \sqrt{2}$

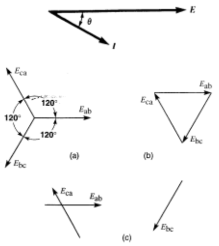
$Vm = Veff * \sqrt{2}$

Example 2-4, if Eeff = 240 and Im = 10,
What is Em and Ieff?

Chapter 2 –
Phasors

Magnitude & Direction
1 – Two phasors are in phase when
    a. Parallel
    b. Equal direction
2. Two phasors are synchronized when
    a. Parallel
    b. Equal direction
    c. Equal magnitude
3. Angles as if rotation was counter clockwise.
4. Origin does not have to be common

Phasors



Note: Difference between Vectors and Phasor notation;
Vector (algebra) – length based on max value
Phasor (power) – length based on effective value

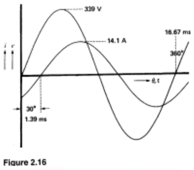


Figure 2.16

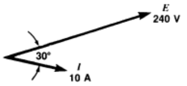


Figure 2.22
Phasor diagram of the voltage and current given in Fig. 2.16.

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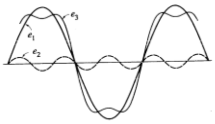
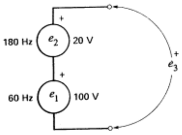
Harmonics

Mathematically representation
Fundamental – Harmonics
Rectifier = n*p +/- 1
Effects of harmonics on rotating equipment





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Chapter 2 –
Energy in an inductor

Energy stored in magnetic field

W = ½ L I ^{2}

W = Energy stored in the coil (J)
L = inductance of the coil (H)
I = current (A)

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Chapter 2 –
Energy in a capacitor

Energy stored in an electric field

W = ½ C E ^{2}

W = Energy stored in the capacitor (J)
L = capacitance of the capacitor (F)
E = Voltage (V)

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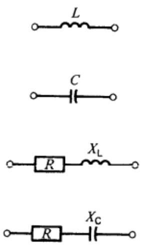
Impedance



$$X_L = 2\pi f L$$

$$X_C = \frac{1}{2\pi f C}$$

$$Z = \sqrt{R^2 + X_L^{\,2}}$$

$$Z = \sqrt{R^2 + X_C^{\,2}}$$

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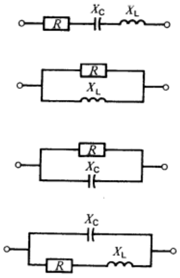
Impedance



$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \frac{R\,X_L}{\sqrt{R^2 + X_L^{\,2}}}$$

$$Z = \frac{R\,X_C}{\sqrt{R^2 + X_C^{\,2}}}$$

$$Z = \frac{X_C\sqrt{R^2 + X_L^{\,2}}}{\sqrt{R^2 + (X_L - X_C)^2}}$$

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Chapter 2 –
Example 2-6

An inductor of 10 mH is in series with a capacitor of 100 uF.
The instantaneous current is 40A and the instantaneous voltage on the capacitor is 800V.
What is the energy stored in the inductor and capacitor?
What is the impedance of the combination?

Chapter 2 –
Electromagnetism

H = U/l

Where
H = magnetic field strength (A/m)
U = magneto motive force acting on the component (A) (or ampere turn)
l = length of the component (m)

Chapter 2 –
Electromagnetism

B = φ/A

Where
B = magnetic flux density (T)
φ = flux in the component (Wb)
A = cross section of the component (m^2)

Chapter 2 –
Electromagnetism

Field Strength vs. Flux Density (vacuum)

B = μ_o H {alternate H = 800,000 B)

Where
B = magnetic flux density (T)
H = magnetic field strength (A/m)
μ_o = magnetic constant (4π X 10^{-7})

Alternately H = 800,000 B

B-H Curve

B = μ_o H

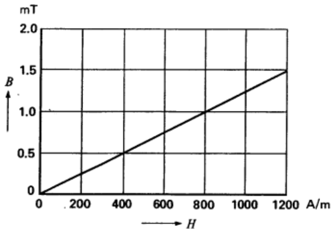


Figure 2.25
B-H curve of vacuum and of nonmagnetic materials.

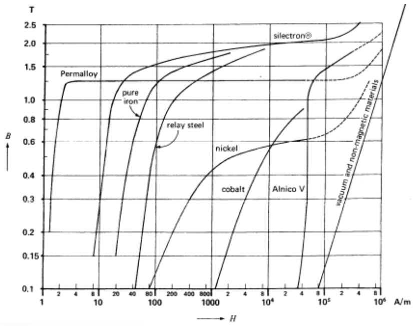
Chapter 2 –
Electromagnetism

Field Strength vs. Flux Density (magnetic material)

B = μ_o μ_r H

Where
B = magnetic flux density (T)
H = magnetic field strength (A/m)
μ_o = magnetic constant (4π X 10^{-7})
μ_r = Relative permeability

Alternately μ_r = 800,000 B/H



Chapter 2 – Faraday's Law

If the Flux linking a loop varies with time, a voltage is induced, the magnitude of which is proportional to the rate of change of voltage

$E = N\ (d\varphi\ /\ dt)$

E = induced voltage (V)
N = Number of turn of coil
$d\varphi$ = change of flux inside the coil (Wb)
dt = time interval during which the flux changes (s)

Example 2-8

A coil of 2000 turns surrounds an initial flux of 5mWb, when magnet is moved such that final flux is 2 mWb in 100mS. What is voltage induced due to change of flux?

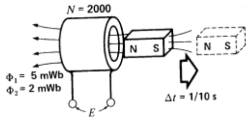


Figure 2.28
Voltage induced by a moving magnet. See Example 2-8.

Chapter 2 – Electromagnetism

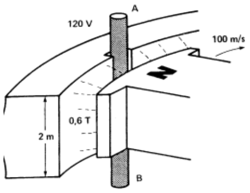
Voltage with reference to conductor movement (note only component of v perpendicular to B)

$E = B\ l\ v\ \sin\varphi = l\ (v \times B)$

E = induced voltage (V)
B = flux density (T)
l = active length of conductor in magnetic field (m)
v = relative speed of conductor (m/s)

Example 2-9

A conductor of length 2m is cut by a field of 0.6 Tesla at speed of 100 m/s.
What is voltage induced?



Lorentz Force

Force max when perpendicular, min when parallel (note: only i component perpendicular to B creates F)

$F = B\ l\ i\ \sin\varphi = l\ (i \times B)$

F = force acting on the conductor (N)
B = flux density of the field (T)
l = active length of the conductor (m)
i = current in the conductor (A)

Lorentz Force

F = B l i sin f = l (i X B)

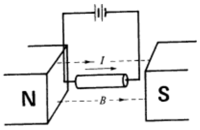


Figure 2.31
Force ≐ 0.

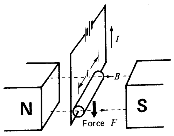


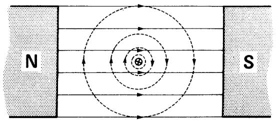
Figure 2.30
Force on a conductor.

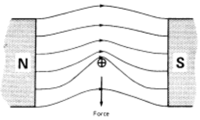
Example 2-10

3m long conductor carrying current of 200 A is in magnetic field density of 0.5 T.
If conductor is perpendicular to field, what is force on conductor?

Direction of Force

LHR – For motor
RHR – For generator
Thumb – Motion
Forefinger – Field (N to S)
Middle Finger - Current





Hysteresis

Residual Induction
Coercive Force
-> Energy Loss = Area

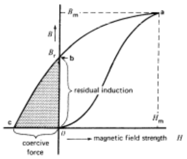
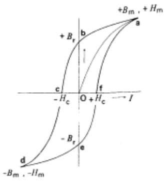


Figure 2.33b
Residual induction and coercive force.



Eddy Currents – Stationary Core

Currents induced in plate perpendicular to flux

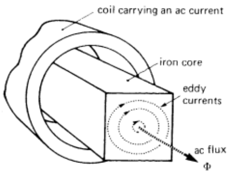


Figure 2.39a
Solid iron core carrying an ac flux.

Eddy Currents – Stationary Core

Loss proportional to square of # of Laminations

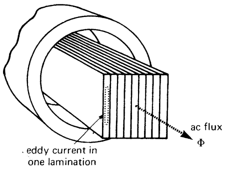
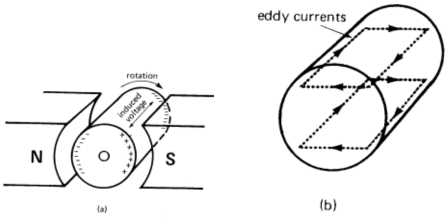


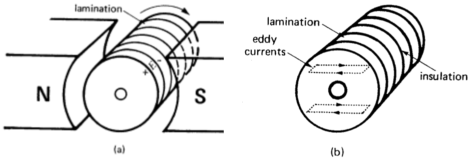
Figure 2.39c
Core built up of thin, insulated laminations.

Eddy Currents – Rotating Core



Eddy Currents – Rotating Core

Loss proportional to square of speed and square of flux density



Inductor Current

e = L (di/dt) or

di = (1/L) e dt

e = instantaneous voltage induced in the circuit (V)
L = inductance of het circuit (H)
di/dt = rate of change of current (A/s)

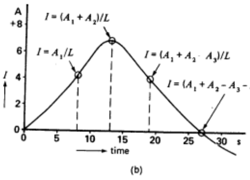
Inductor Current

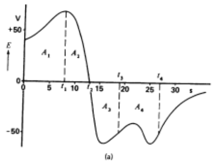
I = I1 + A/L

I1 = current at start of interval T
I = current after time interval T (A)
A = net area under the volt-time curve during time T (V*s)
L = inductance (H)

Inductor Current

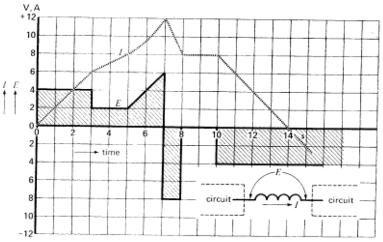
I = I1 + A/L





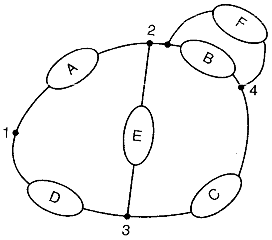
Example 2-11

Calculate I(t) if a) I(0) = 0 & b) I(0) = 7



Kirchhoff's Voltage Law

$\sum$ loop voltages = 0



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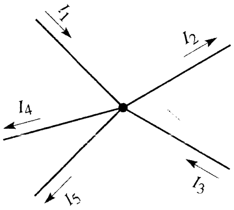
Kirchhoff's Current Law

$\sum$ node currents = 0



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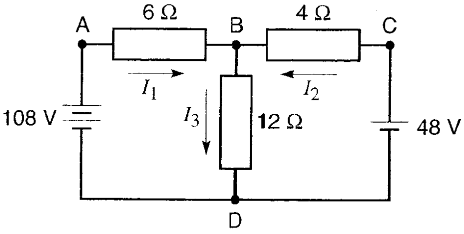
Example 2-13

Find I1, I2, & I3



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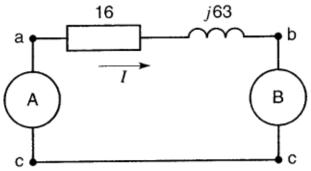
Example 2-14

Given Eac = 200 /_ 120^{O} &
Ebm = 100 /_ 150^{O}
Find I & Eab



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Chapter 3 – Fundamentals of Mechanics and Heat

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Chapter 3 -

Gravitational Force

F = 9.8 m

Where
F = force of gravity acting on the body (N)
m = mass of the body (kg)
9.8 = constant applied close to the surface of the earth.

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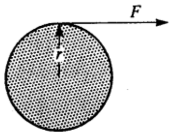
Example 3-3

If T = 150 Nm
r = 1 m
F=?

T = F * r

T = torque (N m)
F = force (N)
r = radius (m)



Linear vs. Rotational Speed

C = 2 π r
v = n C / (60 spm) = n 2 π r / (60 spm)
n = v (60 spm) / 2 π r
n = 30 v / (π r) = 60 v / (π d)

Where:
n = rotational speed (rpm)
v = linear speed (m/s)
r = radius (m)
D = diameter (m)

Work

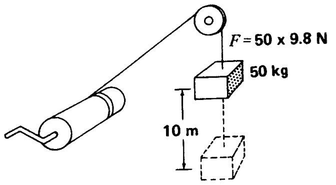
Work is force over distance

W = F d

Where
W = work (J)
F = force (N)
D = distance (m)

Example 3-4

A mass of 50 kg is lifted a vertical distance of 10m. What is work done?



Chapter 3 - Power

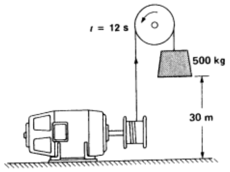
Power is rate which work is done

P = W / t

P = power (W)
W = work done (J)
t = time taken to do work (s)

Example 3-5

A motor lifts a mass of 500 kg a vertical distance of 30m in 12 s.
What is power developed by motor in kw and HP?



Chapter 3 – Power, Torque, Speed

Rotational Power - Torque and Speed

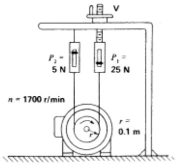
$P = n T / 9.55$

Where
P = mechanical power (W)
T = Torque (N m)
N = speed of rotation (rpm)
9.55 = constant ($30/\pi$)

P = [T (lb. ft.) n(rpm)]/5250

Example 3-6

During test, the spring scales indicate 25N and 5N force. If the motor speed is 1700 RPM and the radius of the motor is 0.1 m, what is the power output of the motor?



Chapter 3 - Efficiency

Ratio of power out to power in

η = (Pout/Pin) 100%

η = efficiency (%)
Pout = output power (W)
Pin = input power (W)

Example 3 - 7

A 150KW Electric Motor has an efficiency of 92% at full load.
What are full load losses in the machine?

Kinetic Energy - Linear

E = P * t

Ek = ½ m v^2

Ek = kinetic energy (J)
m = mass (kg)
v = speed (m/s)

Example 3 - 8

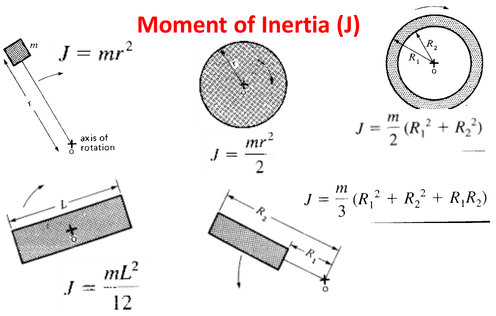
A bus with mass of 6000 kg travels at speed of 100 km/h. It carries 40 passengers with mass of 2400 kg.
What is total Kinetic Energy of bus and passengers?

Kinetic Energy - Rotation

Ek = 5.48 X 10^{-3} J n^2

Where
Ek = kinetic energy (J)
J = moment of inertia (kg m^2)
n = rotational speed (rpm)
5.48 X 10^{-3} constant (π^2/1800)

Moment of Inertia (J)



$$J = mr^2$$

$$J = \frac{mr^2}{2}$$

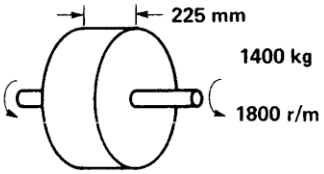
$$J = \frac{m}{2}(R_1^2 + R_2^2)$$

$$J = \frac{m}{3}(R_1^2 + R_2^2 + R_1R_2)$$

$$J = \frac{mL^2}{12}$$

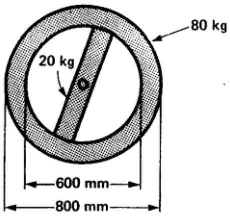
Example 3-9

What is Moment of Inertia (J) and Kinetic Energy (Ek)?



Example 3-10

What is Moment of Inertia (J)?



Chapter 3 -

Change in Speed

Δn = 9.55 T Δt / J

Where
Δn = Change in speed (rpm)
T = torque (N m)
Δt = interval of time that torque applied (s)
J = moment of inertia (kg m^2)
9.55 = constant (30/π)

Chapter 3 – Inertia

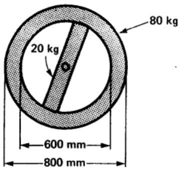
Inertia reflected to motor is proportional
To the SQUARE of the speed change.

J motor X n^2 motor = J load X n^2 load

Where
J = moment of inertia (kg m^2)
N = rotational speed (rpm)

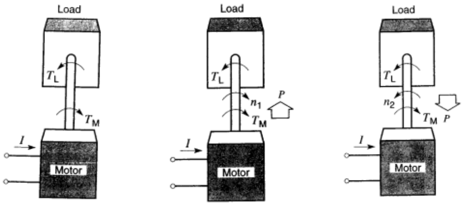
Example 3-11

Flywheel speed changed from 60 RPM to 600 RPM
using Torque of 20 N*m, what is accel time?



Motor vs.. Load Torque

TM = TL



Motor vs.. Load Torque

Change in Speed

$\Delta n = 9.55\ (Tm - Tl)\ \Delta t / J$

Where
Δn = Change in speed (rpm)
Tm = motor torque (N m)
Tl = load torque (N m)
Δt = interval of time that torque applied (s)
J = moment of inertia (kg m^2)
9.55 = constant ($30/\pi$)

Example 3-12

Paper reel has diameter of 1.8m, length of 5.6m, &
Moment of inertia of 4500 KG*M^2.
Motor Speed is 120 RPM.
Paper Tension is 6000N.

a. What is power of motor at 120 RPM?
b. If speed increased to 160 RPM in 5 s,
what is TM during accel time?
c. What is power of motor at 160 RPM?

Chapters 3 continued and Chapter 4 next session

Electric Machines & Drives

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End of Session 1: Fundamentals

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